Resource Conservation and Directed R&D as Strategic Complements

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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 multiple dynamic 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.

Key words: Technological change; Natural resources
JEL codes: O13, Q3, O31

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

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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 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).[2] 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 Rougé 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

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

resource, which make it analogous to a renewable resource (Smulders and de Nooij 2003, Bretschger and Smulders 2006, André and Smulders 2004, Di Maria and Valente 2006, Grimaud and Rougé 2006).[3]

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 superior[4] 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

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

[4] This 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.

in expectations between, on the one hand, R&D labs and, on the other hand, 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 energy industry'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 sells a lot $\bar{S}$ in 0 (and little $\underline{S} < \bar{S}$ in 1) or $\underline{S}$ in 0 and $\bar{S}$ in 1, where $\theta \equiv \bar{S}/\underline{S} > 1$
- the R&D lab invests or not

Assumptions:

A set of simplifying assumptions that presumably are not crucial

1. players act as price-takers[5];

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[5] With 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

2. players are risk-neutral;
3. the real rate of interest, r, is exogenous;
4. there is no uncertainty in the innovation process;
5. the Mine-owner and the R&D lab share the fossil sector value added (revenue) in exogenous shares β for the former, $1-\beta$ for the patent owner (either the incumbent or the successful R&D lab).

1.2 Production

The fossil sector (Y) competes with alternative resources (R) in energy production (E). Energy is combined with the other inputs (L, "labor") to produce an homogenous final good, Q, according to the following nested structure of production:

$$\begin{aligned}E &= g\left(Y,R\right)\\ Q &= h\left(E,L\right)\end{aligned}$$

It is assumed that

6. both technologies, $g(.)$ and $h(.)$, are characterized by constant returns to scale;
7. the elasticity of substitution is
   - high in $g(.)$, between Y and R
   - low in $h(.)$, between E and L

The fossil sector's production function is

$$Y = f\left(a,F\right)$$

F is the supply of primary resource. It equals $\underline{S}$ or $\bar{S}=\theta\underline{S}>\underline{S}$. It is available in finite quantity

$$S=\underline{S}+\bar{S}$$

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

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

in period 1 if and only if the R&D lab invests $K>0$ units of final good in period 0 (without uncertainty according to assumption 4).

I assume that

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acting strategically.

8. $f(.)$ is characterized by increasing returns to scale with respect to F and a together. I adopt the following specification:

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

9. L and R are available in exogenous supply.

Under assumption 8 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 first part of assumption 7. 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 $p_E E$. Thus the first part of assumption 7 is crucial for complementarity between resource conservation and directed R&D to emerge, and even more so under the second part of assumption 7. It should be noticed that assumption 7 is 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).

1.3 Markets

Assumption

10. All markets are perfectly competitive but for a, the technology, where the innovator and the incumbent (i.e. the previous innovator) are protected by a patent in supplying a to the fossil sector.[6]

Under these assumptions I can write the (inverse) demand functions for L, E, R and Y as follows:

$$\begin{aligned} p_L &= h_2(E, L) \quad ; \quad p_E = h_1(E, L) \\ p_R &= h_1(E, L)\, g_2(Y, R) \quad ; \quad p_Y = h_1(E, L)\, g_1(Y, R) \end{aligned}$$

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[6] Assumption 5 provides a sharing rule that is not otherwise obvious under assumption 8. One may think that assumption 10 contradicts assumption 5, because the monopolistic position of the a-supplier would justify a state contingent sharing rule. In this sense assumption 5 is in fact a simplification, but a useful one and most likely of minor consequence.

where subscript i represents partial derivative with respect to the ith argument of the function.

Note that F and a cannot be separately rewarded at their marginal product. Under assumption 5 an exogenous share $\beta \in (0,1)$ of the fossil sector's revenue, $p_Y Y$, accrues to the mine-owner who sells F and the complement accrues to the patent-holder who exerts a monopoly on the technology a.[7] I define the unit price of F from $p_F F = \beta p_Y Y$ using p_Y above, so that

$$p_F \equiv \beta h_1 (E, L) g_1 (Y, R) a$$

Using the price of final output as the numeraire, income distribution accounting is represented as follows

$$Q = \underbrace{p_L L}_{\text{labor}} + \underbrace{p_R R}_{\text{alternative}} + \underbrace{\beta p_Y Y}_{\text{mine-owner}} + \underbrace{(1-\beta) p_Y Y}_{\text{patent-holder}}$$

The supply of Y is a crucial feature of the analysis to which I turn next.

1.4 Behavior

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

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

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.

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

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

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[7] In period 0, there is an incumbent patent-holder who receives a share $1-\beta$ of the value of the fossil sector. In period 1, the same incumbent receives an income if there has not been R&D investment in the previous period. Otherwise the innovator receives the share $1-\beta$ of the fossil sector's new flow of revenue.

Solution

$$y = \begin{cases} 0 & \text{if } E\left(V\right) < \left(1+r\right)K \\ 1 & \text{if } E\left(V\right) > \left(1+r\right)K \end{cases}$$

We have that $E(V) = E\left((1-\beta)p_{F1}F_1/\beta\right)$. It depends on the mine-owner choice of F_1, it can be $\underline{V} = (1-\beta)p_{F1}\underline{S}/\beta$ or $\bar{V} = (1-\beta)p_{F1}\bar{S}/\beta$, with p_{F1} to be determined endogenously.

1.5 *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	$y = 0$	$0, v$	$0, u$
	$y = 1$	$\frac{E(\underline{V})}{1+r} - K, t$	$\frac{E(\bar{V})}{1+r} - K, w$

Fig. 1. The reduced form game.

where

- $v \equiv E(p_{F0})\bar{S} + \frac{E(p_{F1})}{1+r}\underline{S}$ if $y = 0$;
- $t \equiv E(p_{F0})\underline{S} + \frac{E(p_{F1})}{1+r}\bar{S}$ if $y = 1$;
- $u \equiv E(p_{F0})\bar{S} + \frac{E(p_{F1})}{1+r}\underline{S}$ if $y = 0$;
- $w \equiv E(p_{F0})\underline{S} + \frac{E(p_{F1})}{1+r}\bar{S}$ if $y = 1$.

1.5.1 *Low (L) case* $(y, x) = (0, 0)$

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

- fossil sector output: $Y_0 = \underline{a}\bar{S} \equiv Y^M$ and $Y_1 = \underline{a}\underline{S} \equiv Y^L$
- energy output: $E_0 = g\left(Y^M, R\right) \equiv E^M$ and $E_1 = g\left(Y^L, R\right) \equiv E^L$
- resource price: $p_{F0} = \beta h_1(E^M, L)g_1(Y^M, R)\underline{a}$ and $p_{F1} = \beta h_1(E^L, L)g_1(Y^L, R)\underline{a}$
- value added[8]: $p_{Y0}Y_0 = VA^M \equiv h_1(E^M, L)g_1(Y^M, R)\underline{a}\bar{S}$ and $p_{Y1}Y_1 = VA^L \equiv h_1(E^L, L)g_1(Y^L, R)\underline{a}\underline{S}$

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[8] The definition of value added of the fossil sector that I use throughout the paper is not precise, because it excludes the cost of R&D (K) and is therefore a measure of revenue.

- 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 $v^* = \beta \left[VA^M + \frac{VA^L}{1+r} \right]$
    - for the R&D lab the payoff is zero.

1.5.2 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 output: $Y_0 = \underline{a}\underline{S} \equiv Y^L$ and $Y_1 = \underline{a}\bar{S} \equiv Y^M$
- energy output: $E_0 = g\left(Y^L, R\right) \equiv E^L$ and $E_1 = g\left(Y^M, R\right) \equiv E^M$
- resource price: $p_{F0} = \beta h_1(E^L, L) g_1(Y^L, R)\underline{a}$ and $p_{F1} = \beta h_1(E^M, L) g_1(Y^M, R)\underline{a}$
- value added: $p_{Y0}Y_0 = VA^L = h_1(E^L, L) g_1(Y^L, R)\underline{a}\underline{S}$ and $p_{Y1}Y_1 = VA^M = h_1(E^M, L) g_1(Y^M, R)\underline{a}\bar{S}$
- 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 $u^* = \beta \left[VA^L + \frac{VA^M}{1+r} \right]$
    · for the R&D lab the payoff is zero;

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

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

- fossil sector output: $Y_0 = \underline{a}\bar{S} \equiv Y^M$ and $Y_1 = \bar{a}\underline{S} \equiv Y^N$
- energy output: $E_0 = g\left(Y^M, R\right) \equiv E^M$ and $E_1 = g\left(Y^N, R\right) \equiv E^N$
- resource price: $p_{F0} = \beta h_1(E^M, L) g_1(Y^M, R)\underline{a}$ and $p_{F1} = \beta h_1(E^N, L) g_1(Y^N, R)\underline{a}$
- value added: $p_{Y0}Y_0 = VA^M = h_1(E^M, L) g_1(Y^M, R)\underline{a}\bar{S}$ and $p_{Y1}Y_1 = VA^N \equiv h_1(E^N, L) g_1(Y^N, R)\bar{a}\underline{S}$
- 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 $t^* = \beta \left[VA^M + \frac{VA^N}{1+r} \right]$
    - for the R&D lab $q^* \equiv \frac{1}{1+r} (1-\beta) VA^N - K$

1.5.4 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 output: $Y_0 = \underline{aS} = Y^L$ and $Y_1 = \bar{a}\bar{S} \equiv Y^H$
- energy output: $E_0 = g\left(Y^L, R\right) = E^L$ and $E_1 = g\left(Y^H, R\right) \equiv E^H$
- resource price: $p_{F0} = \beta h_1(E^L, L) g_1(Y^L, R)\underline{a}$ and $p_{F1} = \beta h_1(E^H, L) g_1(Y^H, R)\bar{a}$
- value added: $p_{Y0}Y_0 = VA^L = h_1(E^L, L) g_1(Y^L, R)\underline{aS}$ and $p_{Y1}Y_1 = VA^H \equiv h_1(E^H, L) g_1(Y^H, R)\bar{a}\bar{S}$
- payoffs
  - Mine-owner's payoff

$$w^* = \beta\left[VA^L + \frac{VA^H}{1+r}\right]$$

  - For the R&D lab

$$s^* \equiv \frac{1}{1+r}(1-\beta)VA^H - K$$

1.6 Equilibria

Let us consider the reduced form of the game in figure 2

Mine-owner

		$x = 0$	$x = 1$
R&D lab	$y = 0$	$0, v^*$	$0, u^*$
	$y = 1$	q^*, t^*	s^*, w^*

Fig. 2. The reduced form game with perfect foresight payoffs.

Proposition 1 *Two Nash equilibria, 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.[9]

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[9] This condition has to do with assumption 7 and the level of the elasticities between

This result is obtained from the following analysis.
For the Mine-owner

$$\text{if } y=0 \begin{cases} x=0 \Rightarrow \text{payoff} \quad v^* \\ x=1 \Rightarrow \text{payoff} \quad u^* \end{cases} \Rightarrow x=0 \quad \text{only if} \quad v^* > u^*$$

$$\text{if } y=1 \begin{cases} x=0 \Rightarrow \text{payoff} \quad t^* \\ x=1 \Rightarrow \text{payoff} \quad w^* \end{cases} \Rightarrow x=1 \quad \text{only if} \quad w^* > t^*$$

For the R&D lab

$$x=0 \begin{cases} y=0 \Rightarrow \text{payoff} \quad 0 \\ y=1 \Rightarrow \text{payoff} \quad q^* \end{cases} \Rightarrow y=0 \quad \text{only if} \quad q^* < 0$$

$$x=1 \begin{cases} y=0 \Rightarrow \text{payoff} \quad 0 \\ y=1 \Rightarrow \text{payoff} \quad s^* \end{cases} \Rightarrow y=1 \quad \text{only if} \quad s^* > 0$$

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.

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

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

L and E on the one hand, and between Y and R, on the other hand.

- Conservation is profitable with technical progress

$$w^* > t^* \quad \Leftrightarrow \quad VA^H - VA^N > (1+r)\left(VA^M - VA^L\right) \tag{4}$$

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

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

- resource conservation is rational in the High case

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

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.

The value added function for the fossil sector, VA, is

$$VA \equiv p_Y Y = h_1(g\,(Y,R)\,,L)g_1(Y,R)Y$$

It is assumed to be an increasing and quasi-concave function of Y[10]. Fossil sector's output can take four values (see analysis and definitions in section 1.5):

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

Since $VA\,(Y)$ is a concave function, condition (4) requires

$$\theta > \gamma \tag{7}$$

In fact (4) implies $VA\left(Y^H\right) - VA\left(Y^N\right) > VA\left(Y^M\right) - VA\left(Y^L\right)$. This inequality requires that $Y^H - Y^N > Y^M - Y^L$, which is satisfied if and only if $Y^M > Y^N$ since $Y^N, Y^M \in \left(Y^L, Y^H\right)$.

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

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[10] The properties of function VA depend on assumption 7 of course.

on the sector's output. Greater resource supply allows the sector's output to increase more than can be obtained with R&D alone.

Condition (4) also requires that

$$\gamma > 1 + r \tag{8}$$

This can be shown as a necessary condition in the case of a value added function VA proportional to output Y. If $VA = kY$, the conditions above imply

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

All three conditions hold for under the parametric restriction in proposition 1, i.e. if (1), (7) and (8) are satisfied.

The parametric restriction (8) 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, $g_Q \equiv \frac{dQ/dt}{Q}$. 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 $\gamma > 1 + r > 1 + g_Q$ is possible.

Finally, since the three inequalities hold strictly under the parametric restriction of proposition 1 in the linear case, they must also hold, by continuity, for a concave valued added function that is sufficiently close to linearity. I have proved the proposition.

When specifying CES production functions as follows

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

it is possible to identify patterns of parameters under which conditions (2)-(6) hold simultaneously.[11]

2 Work in porgress as a conclusion

I am currently checking how robust the results are with respect to some generalizations. In particular 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. Another dimension along which the model can be generalized is the lifetime of the mine, i.e. considering a model with infite horizon where the date of full exhaustion of the non renewable resource is determined endogenously.

The model will be used to analyze the interaction between R&D and technological developments in the competing sub-sectors of the energy industry. I plan to extend the model to include 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.

Last but not least, I will gather empirical evidence to test the plausibility of the conditions set up in proposition 1.

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[11] For instance they hold for parameters $\sigma = 2$, $\psi = .75$, $L = 1000$, $R = 100$, $K = 7$, $\beta = .1$, $\underline{S} = 10$, $\theta = 2$, $\underline{a} = 1$, $\gamma = 1.8$, $r = .25$.

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