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Abstract

We analyze sectors' investment decisions about emission abatement in a contest of a mixed good, of which for instance the emission abatement is the public component and the energy efficiency is the private component. The mixed good can be defined as the total amount of R&D efforts, namely a mixed capital good. The two components of the mixed good are, hence, typically complements. The investment decisions are then analyzed in a dynamic framework, and the steady state equilibrium solutions are investigated. We pay attention to the reaction function between one sector's investment in the mixed good (R&D and emission abatement) and the other sectors' investment in emission abatement. We show that the degree of complementarity among emission abatement and R&D affects the sign of the reaction functions. Intuitively, since for each sector the two components of the mixed capital are complements, an increase of the other sectors' investment in the public component (abatement) increases the benefits of accumulating the complementary private component (energy efficiency appropriable only by the sector under scrutiny). We demonstrate that as expected, the sensitiveness of the reaction function is higher when the two goods are complements. Empirical analyses compare within, first difference and GMM specifications and aim at accounting for sector spillovers – in R&D and abatement decisions - within and outside a country. An original 1995-2006 dataset that merges together NAMEA matrixes for major EU economies, with sector based data on innovation, energy, trade and environmental policy, is used. We show that for both CO_2 and SOx both R&D spillovers arising within the country and originating from the same sector at EU level matter. Weighting for distance and capital/labor ratio enhances the significance. The specific test on the reaction function shows that sector R&D is positively driven by (i) the emission abatement of the sector – the 'private' contribution to the public good – (ii) the abatement occurring in other manufacturing sectors within the country and (iii) the abatement occurring in the same sector in other countries. The last two effects prove the existence of a positive reaction function and thus confirm the theoretical implications in a dynamic strategic game over public good investments. Though GMM and first difference models outperform other static and dynamic approaches, results are fairly homogeneous and robust across all attempted estimates.

Keywords: sector abatement, spillovers, EU industry, complementarity, mixed goods, R&D.

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1. Introduction

The economic and policy issue of *Sustainable Consumption and Production Patterns is central for the achievement of EU long term economic and environmental performances and* calls for deeper analyses. Recent EU investigations asserted that "Three production branches cause the majority of environmental pressures: electricity, gas and hot water production; agriculture; and transport and communication services. In addition, direct pressures from private households (mainly for heating of housings and private transport) constitute a further important source. The performances of those sectors are crucial for cross-country differences in domestic environmental pressures with the national energy-mix playing a particularly important role. A second determinant for cross-country differences in domestic direct pressures is the role of exports. Some country's domestic production system has specialised on certain export goods". (Moll et al., 2007). In line with the increasing EU emphasis on resource efficiency and decoupling targets, this 'economics of SCP' framework will include as far as possible (environmental) innovation and its diffusion at sector and spatial levels as a key element of understanding (Kemp and Pearson, 2007; Popp, 2002). Research in economics and environmental sciences have thus taken more and more a macro/meso perspective to 'economic sectors sustainability'. The Economics of SCP at Eu level is an assessment activity that will seek to provide policy makers and others with the evidence base for moving from the prevailing economic model in Europe and globally – characterised by consumption growth that results in over-use of natural resources, increasing pressures on the environment and under-investment in the maintenance of resources and ecosystems today and tomorrow - towards a model that more into balance the two sides of the same coin.

We do believe that there is still a lack of analyses taking into consideration the meso level, relatively to firm based analyses and macro assessments. Nevertheless, the meso level is that in which we can fully understand specific innovation, environmental and economic performance behave, interact (Crespi and Costantini, 2008; Marin and Mazzanti, 2011). Economy-environment relevant spillovers are also mostly relevant at this level of analysis, within and outside the boundaries of a given country. We underline that the sector based reasoning and the consequential coherent emphasis on innovation is the key factor of this paper: a value added and a possible frontier of new research. Economic spillovers of innovation, spatial dimensions, sector and geographical spillovers are analysed through the implementation of a coherent set of theoretical and applied layers of reasoning.

In this paper we specifically propose a joint theoretical and applied framework where to analyze the emission efficiency/intensity performance and its drivers in a dynamic approach. Though the micro based reasoning could present a complement case , we frame our analysis primarily around a reasoning at sector level. We contribute to the 'production side' of SCP, paying specific attention to dynamic cooperative behavior and the effect of spillovers referring to environmental and economic realms.

We believe that in our case the sector level approach is crucial for both the necessity of targeting and differentiating innovation and environmental policies to increase efficiency and the idiosyncratic elements that characterize the economic-environmental relationship and performance. To some extent, the sector-based level behavior is more effective in explaining structural change and economic dynamics evolution. The core issue is to understand which drivers influence the most the investment decision of an economic sector regarding emissions abatement options, since they may depend both on internal factors such as Research and Development (R&D) efforts, productivity, structural factors, as well as investment behavior of the other sectors.

We believe that the sector perspective is for our purposes the most relevant from both applied and conceptual perspective. Regarding the former, it allows a sufficient extension of the data pool one exploits for econometric analysis, a good coverage at geographical level, still maintaining a degree of heterogeneity higher than in the macro type of analysis. It is worth noting that recent works that have analysed relationships between industry performances, environmental regulations and trade witness the importance of a sector based picture. Among others, Wagner and Timmins (2009) show how sector idiosyncratic the assessment of the pollution haven can be, while Cole et al. (2010) fully exploit the features of industry based datasets to analyse how environmental performances and trade flows are driven by regulations and agglomeration economies. They state that "an analysis of aggregate trade flows is unlikely to detect the impact of regulations on patterns of trade between high and low income economies" (p.1996). The exploitation of industry heterogeneity and inclusion of variables that are hidden by macroeconomic analyses is deemed crucial. Thus, the sector/industry level of the analysis appears to be crucial to provide a more robust possibility to explore more in depth economic-environmental performances without losing on the other hand generality of results. This discussion based on empirical works leads to more conceptual issues.

In fact, concerning theoretical layers of our research hypotheses, we observe that innovation and economic dynamics are most fruitfully analysed at sector level. The main reference is to seminal works by Malerba and Orsenigo (1997) that set out the paradigm of 'technological regimes'. They observe that 'technological regimes may be a fruitful concept for studying the different ways in which innovative activities are organized and industries evolve over time'. More relevant for us, on the basis of evidence on major economies, their main finding is that innovative activities are sector specific, insofar as the 'features of technological environments are common to groups of industries. Second, they are to some extent invariant with respect to the institutional environment'. They thus find differences across sectors in the patterns of innovation and dynamic economic performances, and similarities across countries. This is a key conceptual justification for studying sectors at various degree of aggregation in a realm, such as that of the PH, wherein innovation plays the major role. This is not aimed at excluding the relevance of 'national systems of innovation', which can be captured by country fixed effects in empirical analyses (Breschi et al., 2000). This is to affirm that an analysis based on sector/technological regimes or classes maximises the possibility of investigating the behaviour of agents in a dynamic innovative intense world. The empirical tools are empowered; the conceptual setting is strictly relevant to the PH framework. This is even truer in analyses dealing with export performance that is robustly connected to sector based idiosyncrasies. We add the homogeneity between firms of the same sector is likely to be on average higher than that between firms of different sectors.

More deeply we want to investigate the reasons behind a sector decision investing in emission abatement actions that go beyond its legal and contractual obligations, on a voluntary basis. For this purpose, we analyze sectors' investment decisions about emission abatement in a contest of a mixed good, of which the emission abatement is the public component and the energy efficiency is the private component. In this work our mixed good can be defined as the total amount of R&D efforts, namely a mixed capital good. The two components of the mixed good are, hence, typically complements. The investment decisions are then analyzed in a dynamic framework, and the steady state equilibrium solutions are investigated. Particularly we pay attention to the reaction function between one sector's investment in the mixed good (R&D and abatement) and the other sectors' investment in emission abatement. We show that the degree of complementarity among emission abatement and R&D affects the sign of the reaction functions. Intuitively, since for each sector the two components of the mixed capital are complements, an increase of the other sectors' investment in the public component (abatement) increases the benefits of accumulating the complementary private component (energy efficiency appropriable only by the sector under scrutiny). Therefore, the single sector now wishes to increase its own investment of the private component (R&D) and, consequently, of the mixed capital. In this way, through the extra investment in R&D, each sector also determines an increase of its investment in emission abatement. Hence, its reaction curve has positive slope through the complementarity between the private and the public components of R&D, the investment in emission abatement by each sector is increased by the other sectors' investments.

These conclusions deserve some considerations in terms of policy implications: (i) the consequences of incentives/obligations proposed may be even more effective than initially supposed, because of the positive reaction of one agent's investment decision to the other agents' investment decisions; (ii) the incentive decision about emission abatement ought to envisage investments in complementary forms of capital that generate more appropriable types of rents.

The paper is structured as follows. Section 2 presents the dynamic model where the strategic choice of investment in a mixed good R&D/abatement is outlined. Section 3 presents the empirical strategy, the model and estimates. Section 4 concludes.

2. The theoretical model: dynamic investments, mixed goods and abatement

2.1 Main assumptions and framework

The aim of this section is to set up a theoretical model that analyzes what happens to sectors' investment decisions about R&D efforts and emission abatement in a contest of mixed good, in which the emission abatement is the public component and the energy efficiency is the private component of the mixed capital good.

We assume that there is a set of N sectors. Each sector employs and invests in a kind of capital, R, which has the characteristic of an impure public good. It generates either a private characteristic (z) which has no effects on the other agents, and a public characteristic (a) which has effects also on other agents.

The 'impure public' capital (R) can represent (environmental) R&D stock; and we can consider the private component (z) as "energy efficiency and/or reduction of dependence by fossil fuels", while the 'public component' (a), as, say, CO_2 emissions abatement.

Since R has the characteristic of an impure public good, each unit of R is such that:

(1) $$z = \alpha R \qquad \alpha > 0 \;\; \textit{given}$$

(2) $$a = \beta R \qquad \beta > 0 \;\; \textit{given}$$

where α and β are exogenously given coefficients reflecting a simple process, whereby z and a are jointly generated in fixed proportion by one unit of R.

Therefore, we are assuming that whenever a sector invests in one unit of R, it invests in α given units of a private characteristic and in β given units of emission abatement.

So, whenever a sector invests in one unit of R, its investment is in some percentage the creation of a private asset and in some percentage the creation of a public asset (emission abatement) and the two components of the stock are complements, hence increasing either one makes increasing the other more attractive (Milgrom and Roberts, 1995).

Moreover, since a exerts effects also on the other sectors and *vice versa*, we define the total investment amount in emission abatement by all sectors but sector i as follows:

(3) $$A_{\neq i} = \sum_{j \neq i} a_j = \sum_{j \neq i} \beta R_j \qquad \forall \; i, j$$

Hence in the complete set of sectors, the whole quantity of the public characteristic (A) is given by the sum of the single contributions by each single sector as:

(4) $$A = \sum_{i=1}^{N} a_i = \sum_{i=1}^{N} \beta R_i = a_i + A_{\neq i}$$

We adopt the Nash-Cournot assumption that the single sector *i* regards $A_{\neq}$ as exogenously given[2].
From equations (1), (2), (3) and (4) the investment of sector *i* in one unit of *R* has therefore three effects: (i) an increase in sector *i*'s private benefits due to the private characteristic ($z=\alpha R$); (ii) an increase in that sector's private benefits due to the public characteristic ($a=\beta R$)[3]; (iii) an increase in the total amount of the public component (*A*) available to all agents.
Sector *i*'s benefit function of the impure public capital good at time *t* (R_t) is represented in a CES function as:

(5) $$B(R_t)=\left[(\beta R_t+A_{\neq})^{\frac{\sigma-1}{\sigma}}+(\alpha R_t)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}},$$

or, from equations (1), (2), (3) and (4), we can re-write:

(6) $$B(R_t)=\left[(a_t+A_{\neq})^{\frac{\sigma-1}{\sigma}}+(\alpha R_t)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}},$$

where $\sigma\in[0,+\infty]$ is the elasticity of substitution between the two benefit components: (i) the public component (given by the contribution of sector *i* (*a*), and the contribution of all the other sectors, $A_{\neq}$); (ii) the private component (αR). As a usual assumption when working with a CES function, we can state that when $\sigma>1$, the two sorts (*A* e αR) are gross substitutes, while when $\sigma<1$, the two sorts (*A* e αR) are gross complements. We ignore the Cobb Douglas case of $\sigma=1$.
Sector *i*'s cost function of the R&D investments, at time *t* is defined as:

(8) $$K(I_t)=p(I_t)I_t,\ \text{with}\ p(I_t)\geq 0\ ,\ \frac{\partial p(I_t)}{\partial I_t}>0\ \text{and:}\ \frac{\partial^2 p(I_t)}{\partial I_t^2}\geq 0$$

Where $p(I_t)$ is the real price of the investment resources in R&D at time *t*. Following Goulder and Mathai (2000, p. 5) "we assume that $p(I_t)$ is non decreasing in I_t; that is the average cost of R&D investment increases with the level of R&D. This captures in reduced form the idea that there is an increasing opportunity cost (to other sectors of the economy) of employing scientists and engineers to devise new knowledge and research".
For what concerns the sector *i*'s adjustment cost function of R&D capital stock, it is defined, at time *t*, as:

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[2] For simplicity of notations, since in our analysis we always refer to sector *i*, we will omit the subscript *i* in the remaining test.
[3] That could also include CSR forms of benefits ('image' of the sector in the market driven by production of public goods). Corporate social responsibility (CSR) behaviour (Portney, 2008; Lyon and Maxwell, 2008; Reihnardt et al., 2008) can be present in economic/institutional frameworks characterized by regulated markets, wherein more innovative firms take a long run 'beyond compliance' perspective to profit making. CSR firms are oriented towards long run profit achievement by investing in mixed forms of capital. They can mitigate trade off between present and future performances, and jointly provide private rents and public goods in coherence with the Porter hypothesis (Mazzanti and Zoboli, 2010).

(9) $C(R_t)$ with: $\dfrac{\partial C(R_t)}{\partial R_t} > 0$; and: $\dfrac{\partial^2 C(R_t)}{\partial R_t^2} \geq 0$

2.2 Equilibrium solutions

Each sector has an infinite lifespan and discounts the future with the discount factor ϱ. Each sector wants to maximise its net benefit function. R_t is the state variable and I_t is the costate variable.

For simplicity of the analysis we assume that net benefit is represented as:

$$\Pi(R_t) = B(R_t) - C(R_t).$$

Formally, the optimization problem of sector *i* becomes:

$$\textit{Maximize} \int_0^\infty [\Pi(R_t) - K(I_t)] e^{-\rho t} dt,$$

s.t.:

$$\dot{R}_t = I_t - \delta R_t$$

$$R_{t=0} = R_0.$$

where □ is the standard capital depreciation rate, and the current-value Hamiltonian associated with the optimization problem is:

$$H_C(R_t, I_t, l_t) = \Pi(R_t) - K(I_t) + l_t(I_t - \delta R_t).$$

The optimality conditions in terms of the current Hamiltonian are:

$$\frac{\partial H_C}{\partial I_t} = 0$$

$$\dot{R}_t = \frac{\partial H_C}{\partial l_t}$$

$$\dot{l}_t = \rho l_t - \frac{\partial H_C}{\partial R_t}$$

In explicit form they are:

$$-K'(I_t) + l_t = 0 \quad \textit{optimality of } H_C$$

$$\dot{R}_t = I_t - \delta R_t \quad \textit{state equation}$$

$$\dot{l}_t = -\Pi'(R_t) + (\delta + \rho) l_t \quad \textit{costate equation}$$

Assuming that $f(x) = (K'(x))^{-1}$, we get by the optimality equation of the current-value Hamiltonian: $I_t = f(l_t)$.

State and costate equations become:

$$\dot{R}_t = f(l_t) - \delta R_t$$

$$\dot{l}_t = -\Pi'(R_t) + (\delta + \rho) l_t$$

The equilibrium conditions ($\dot{R}_t = \dot{l}_t = 0$) are given by:

$$f(l_t) - \delta R_t = 0$$

and

$$-\Pi'(R_t)+(\delta+\rho)l_t=0\,.$$

The equations for the equilibrium are:

$$R^*=\frac{1}{\delta}f(l^*)$$

and

$$l^*=\frac{1}{(\delta+\rho)}\Pi_R(R^*)\,.$$

From which:

(10) $$R^*=\frac{1}{\delta}f\left(\frac{1}{(\delta+\rho)}\Pi_R(R^*)\right).$$

Differentiating equation (10), with respect to $A_{\neq}$ we get:

(11) $$R^*_{A_{\neq}}=\frac{\xi}{1-\xi\Pi_{RR}(R^*)}B_{RA_{\neq}}(R^*)\,,$$

where:

$$\xi=\frac{1}{\delta(\delta+\rho)}f'\left(\frac{\Pi_R(R^*)}{\delta+\rho}\right)>0\,,$$

since, by assumption: $f'=\frac{1}{K''}>0$.

Moreover, since we have: $\Pi_{RR}(R^*)=B_{RR}(R^*)-C_{RR}(R^*)$, with:

$$B_{RR}(R)=-\frac{\alpha^2A_{\neq}^2\left[(\beta R+A_{\neq})^{\frac{\sigma-1}{\sigma}}+(\alpha R)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{2-\sigma}{\sigma-1}}}{\sigma(\beta R+A_{\neq})^{\frac{\sigma+1}{\sigma}}(\alpha R)^{\frac{\sigma+1}{\sigma}}}<0$$

and, by assumption, $C_{RR}(R)\geq 0$, we get, for $R=R^*$:

$$\Pi_{RR}(R^*)<0$$

From which:

$$\frac{\xi}{1-\xi\Pi_{RR}(R^*)}>0$$

Finally, since we also get that:

$$B_{RA_{\neq}}(R)=\frac{\alpha A_{\neq}}{\sigma}\frac{\left[(\beta R+A_{\neq})^{\frac{\sigma-1}{\sigma}}+(\alpha R)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{2-\sigma}{\sigma-1}}}{(\beta R+A_{\neq})^{\frac{\sigma+1}{\sigma}}(\alpha R)^{\frac{1}{\sigma}}}>0,$$

for $R=R^{*}$ we obtain:

(12) $$R^{*}_{A_{\neq}}=\frac{\xi}{1-\xi\Pi_{RR}(R^{*})}B_{RA_{\neq}}(R^{*})>0$$

2.3 The reaction functions

In the present section we devote our attention to the study of the reaction function between one sector's investment in R&D and the other sectors' investment in emission abatement. As shown in the result in equation (12) ($R^{*}_{A_{\neq}}>0$), the reaction curve has positive slope.

It is worth deepening the behaviour of the reaction curve in some special cases.

(CASE I) The private component of R&D *is very small, that is a→0.*

In this case we have:

$$R^{*}=\frac{1}{\delta}f\left(\frac{\beta-C_{R}(R)}{\delta+\rho}\right),$$

Where:

$$R_{A_{\neq}}\approx\frac{\xi_{\alpha\to 0}}{1+\xi_{\alpha\to 0}C_{RR}(R)}\cdot\frac{A_{\neq}}{\sigma R}\begin{cases}(\beta R+A_{\neq})^{\frac{1-2\sigma}{\sigma}}(\alpha R)^{\frac{\sigma-1}{\sigma}} & if\,\sigma>1\\ \frac{1}{(\beta R+A_{\neq})^{\frac{\sigma+1}{\sigma}}}(\alpha R)^{\frac{1}{\sigma}} & if\,0<\sigma<1\end{cases}\to 0.$$

(CASE II) $\sigma\to\infty$ (*the two sorts of benefit are substitutes*):

In this case we have:

$$R=\frac{1}{\delta}f\left(\frac{\alpha+\beta-C_{R}(R)}{\delta+\rho}\right),$$

Where:

$$R_{A_{\neq}}\approx\left[\frac{\xi_{\sigma\to\infty}}{1+\xi_{\sigma\to\infty}C_{RR}(R)}\cdot\frac{\alpha A_{\neq}}{(\beta R+A_{\neq})(\beta R+A_{\neq}+\alpha R)}\right]\cdot\frac{1}{\sigma}.$$

(CASE III) $\sigma\to 0$ (*the two sorts of benefit are complements*):

$$R_{A_{\neq}}\approx\left[\frac{\xi_{\sigma\to 0}}{1+\xi_{\sigma\to 0}C_{RR}(R)}\cdot\frac{\alpha A_{\neq}}{\sigma}\right]\cdot\begin{cases}\left(\frac{\alpha R}{\beta R+A_{\neq}}\right)^{\frac{1}{\sigma}} & if\,\alpha R<\beta R+A_{\neq}\\ \left(\frac{\beta R+A_{\neq}}{\alpha R}\right)^{\frac{1}{\sigma}} & if\,\alpha R>\beta R+A_{\neq}\end{cases}$$

From (*CASE II*) and (*CASE III*) we get that the reaction curve is *more sensible* (sector i investments in R&D react more promptly to other sector emission abatement) for small values of the elasticity of substitution than for big values. In the first case ($\sigma \to 0$), the reaction function is exponential. In the second case ($\sigma \to \infty$), the reaction function is a power function. The effect of 'complements' and 'substitutes' cases are thus assessed on a relative basis.

From these results we obtain some interesting considerations about one sector's investment decisions in R&D and the other sectors' decisions in emission abatement in a dynamic framework.

The first relevant consideration comes by equation (12): in equilibrium the reaction function between one sector's investment in R&D and the other sectors' investment in emission abatement is positive.

The first question that deserves an answer is: what does it imply?

Since by equation (2) whenever a sector invests in one unit of R&D, it invests in β units of emission abatement too, a positive reaction between one sector's investment in emission abatement and the other sectors' investment in emission abatement must also exist. This leads to evident positive implications on the free riding problem. It means that each sector reacts positively to the other sectors' investment in emission abatement. None relies on the others' contributions to emission abatement, but, on the contrary, the investment in emission abatement by each sector is increased by the other sectors' investments. This necessarily leads to an individual equilibrium choice of emission abatement that goes beyond legal and contractual obligations. We may add that 'cooperative' sector behavior is stimulated by the cumulativeness of past investments in this mixed good, including its public component. Theoretically speaking, this discussion again shows potential and fruitful connections between this mainstream framework and the interrelated neo-Schumpeterian notions of appropriability, complementarity and cumulativeness, that are pre conditions of innovation development along Schumpeterian mark II patterns of creative accumulation (Breschi et al., 2000). In the dynamics of such 'technological regimes', imitative behavior and networking/spillovers (Malerba, 2006) can consolidate 'positive reaction functions' both considering sectors belonging to a national industry or (same, different) sectors located in different countries. Even though one expectation may be that the benefit of joining a network (a production of public good) could be lower the more agents have already contributed, we stress that also positive incentives are present. Evidence is needed to assess in which geographical cases and for which sectors this is true.

The second question is consequentially: why is the reaction function positive?

R&D is an impure public capital good by assumption and the technological consequence is the complementarity between the private component (aR, energy efficiency) and the public component (βR, emission abatement). Actually, the only case in which the sector's investment in R&D doesn't react with respect to $A_{\neq}$ is when the private component of R&D is very small, that is when $a \to 0$ (see *CASE I* above). Hence, if R&D was a pure public capital, the single sector's investment in emission abatement wouldn't positively react to the other sectors' investment in emission abatement.

Moreover by (*CASE II*) and (*CASE III*), we have seen that, when the private and the public components of the benefit function are complement, the reaction of R with respect to $A_{\neq}$ is stronger than when the two sorts are substitutes. When the private and the public component are complements an increase of the other sectors' investment in the public component (emission abatement) increases the marginal benefit of accumulating the complementary private component (energy efficiency appropriable only by the investing sector). Therefore, the single sector now wishes to increase its own investment of the private component and, hence, of the mixed capital (R&D). In this way, through the extra investment in R&D, the single sector necessarily determines an increase of its investment in emission abatement too.

These conclusions deserve some considerations in terms of policy implications.

First of all, the pro-social behavior (which induces sector i's investment in emission abatement to positively react at the other sectors' investment in emission abatement) that we have pointed out in our

theoretical model has its foundation in the relationship of complementarity between the two components of an impure public capital good. Actually we have also shown that if the private component tends to zero ($a \rightarrow 0$, *CASE I* above), this behavior is no longer ensured.
Hence, for what concerns emission abatement it is possible to rely on sectors' voluntary behavior only in those cases in which they perceive benefits owed also to a complementary private component. In our model, sectors behave similarly to the *impure altruists* of Andreoni (1989, 1990), who in the contribution to a public good "get some private goods benefit from their gift per se, like a warm glow" (Andreoni, 1989, pp. 1448-1449). Whether the private component benefit is a capital (energetic efficiency) or acclaim or a warm glow doesn't matter, the relevant fact is that it must be complementary to the public component.

3. Empirical Framework and econometric analyses

3.1 Modelling strategy

3.1.1 The measurement of technological spillovers

The theoretical model presented in this paper has been empirically tested relying on the growing literature on the role of knowledge spillovers in explaining differences in economic growth and productivity path. More precisely we refer to knowledge spillovers as a key driver for the internal knowledge production function, where technology produced by other sectors or countries may be generally defined as the efforts in innovative activities (our impure public good) or better disentangled in its public component (our $A_{\neq i} = \sum_{j \neq i} a_j = \sum_{j \neq i} \beta R_j$). Both the 'sector private' contribution to the public good provision *ai* and the sum of aj (abatement of other sectors) positively contribute to the benefit of sector i. The ai contribution is exposed to free riding behaviour in a typical pure public good game, while in a mixed good game we outlined the possibility of positive reaction function. We will include both ai and the (weighted and un-weighted) sums of aj in the regressions as covariates of R&D.
This means that innovative efforts decision by sector i depends on the public component of the research activity defined as mixed good, and thus by the decisions taken by the other sectors/countries.
We pay attention to the reaction function between one (sector's) investment in the mixed good (R&D and emission abatement) and the other (sectors') investment in emission abatement (the public good factor). R&D is an impure public capital good by assumption and the technological consequence is the complementarity between the private component (say, energy efficiency) and the public component (say, emission abatement).
Before going into empirical result, some attention should be paid to how to model spillovers and decisions by the other sectors.
The public component of the mixed good is here represented by total emissions, in the sense that if total emissions are decreasing given a certain level of value added, we are implicitly assuming that emission intensity is decreasing as well (this explains the negative sign of the coefficient for a_i and $A_{\neq i}$).
We also consider spillovers as the influence of other sectors' decisions twofold. In a Jacob type externality problem, we argue that knowledge produced by other sectors may be a useful input for the domestic knowledge production function of each sector. In a Marshall type externality setting, knowledge flows only from homogeneous sectors. We may disentangle these two effect since our dataset has both a sectoral and a cross-country dimension. We control for Jacob type externality considering potential effects of RD choices by other sectors located in the same country, while we account for Marshall type externalities by considering the potential influence of innovation decisions by similar sectors located in other countries.

Especially when a Jacob type externality problem is considered, the concept of cognitive proximity and absorptive capacity is rather important. There is a growing consensus upon the necessity to account for the notion of cognitive proximity, since the probability of innovation to spill from one area to another strongly depends on the fact that the absorptive capacity is associated with the concentration of a particular sector in the two areas (Boschma and Frenken, 2009; Boschma and Iammarino, 2009, among the others). Hence, it is not only a matter of geographical distance which explains the existence and the strength of innovation spillovers, but also cognitive proximity, since knowledge will diffuse more likely when competences and knowledge stocks of the inventors and adopters are closely related.
To some sense, cognitive proximity and technological relatedness as well-known drivers for effective learning are here considered as factors influencing the adoption of similar production process techniques. To this purpose, Los (2000) and Frenken *et al.* (2007) propose adopting an index capturing the technological relatedness between industrial sectors by computing the similarity between two sectors' input mix from input-output tables that we can adapt to our case study if we consider that the two sectors are homogeneous from a classification point of view, but they may be rather different since they belong to two different countries (or sectors). Given data availability, we have taken as inputs the amount of capital stock (K) and number of employees (L) for each sector, resulting in a similarity matrix for technological relatedness (tr) in the form:

$$tr_k^{is} = \left(\frac{\left| (K/L)_k^i - (K/L)_k^s \right|}{\sqrt{(K/L)_k^i + (K/L)_k^s}} \right)^{-1} \quad \forall s \neq i \qquad [13]$$

This similarity matrix has been used a weighting system for aggregating innovation efforts produced by the other N-1 sectors (at the country level) or by the other C-1 countries (at the sector level). The final knowledge stock produced "abroad" results as a weighted sum of RD efforts as

$$T_{\neq i} = \sum_{s=1, s\neq i}^{N,C} T^s tr_k^{is} \qquad [14]$$

The resulting (q x q) matrix of spillovers for each *k-th* sector (with a vector of 0 in the diagonal dimension $\forall s = i$) is then synthesised into a linear vector by using or not geographical distances for aggregating the *s-th* elements when inter-country Marshall type spillovers are investigated. Following Bode (2004), we there are several alternative criteria for transforming geographical distances into spatial weights. For the sake of simplicity we have only considered the pure inverse distances, but further research should be done in this direction.
To some sense we assume that the intensity of inter-country knowledge spillovers may be subject to spatial transaction costs in the sense that the intensity of influences between any two regions diminishes continuously with increasing distance. In this case, we consider that the smaller the distance between *r* and any other region *s*, the higher the weight assigned to *s* with respect to its influence on *r*. Hence, the weight assigned to each country *s* ($\forall s \neq i$) is proportional to the inverse distance between *i* and *s*.

3.1.2 The dataset description

Our sample includes 15 EU countries (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom) and 23 manufacturing sector covering all industries STAN OECD classification, in a time span between 1995 and

2006. Besides exceptions like Italy, full data coverage of sector emissions in the NAMEA is not available after 2006 at EU level. Emissions data are based on the NAMEA approach (National Accounting Matrix including Environmental Accounts) available from EUROSTAT, while all data for RD, value added, capital and labour are taken by Eurostat and OECD.[4] It is worth noting that EUROSTAT is launching a full NAMEA for EU27 by 2011, covering 2000-2006.

The final dataset merges NAMEA data including value added, with R&D sector data, trade data (trade openness, export orientation, import penetration)[5]. Though it turns out to be a constraint in some cases, we decided to exploit only data available at sector (not country) level.

R&D and emissions data are included in the regressions either un-weighted or, to fully take into account of spillover effects, by weighting for K/L ratio, distance, and both.

3.1.3 The econometric strategy

The econometric strategy adopted is to use a dynamic panel data estimation based on a standard Error Correction Model, as the recently developed system GMM (sys-GMM) proposed by Arellano and Bover (1995). Even when coefficients on the lagged dependant variables are not of interest the use of dynamic model is justified on theoretical grounds on the one side and on empirical grounds, in order to recover consistent estimates of other coefficients. We recall the quasi inconsistency of within estimators when covariates are endogenous, even if N*T gets infinite. Efficiency flaws may instead affect other estimators such as dynamic LSDV when the panel is unbalanced. It is worth noting that contrary to within transformations, first differencing does not introduce all realisations of disturbances into the transformed error terms. This allows the use of internal instruments.

The main difference between the system GMM and difference GMM is that sys-GMM estimates the system of the level and first-difference equations using the lagged levels of the series as instruments for the difference series, and the lagged difference series as instruments for the level series. Difference GMM, on the other hand, estimates only the first-difference equation using the lagged levels of the series as instruments. We chose sys-GMM over difference GMM, as the latter has finite sample bias and poor precision when the series are persistent. As shown in Blundell and Bond (1998), when the number of time series observations is small while N is relatively large, as it is in our case, there are dramatic efficiency gains in using the system rather than the difference GMM.

Furthermore, a dynamic panel estimator is appropriate when the dependent variable is rather persistent over time, which is also our case (Wooldridge *F-test* equal to 129.86***, with *H0*=absence of autocorrelation of the residuals rejected). Finally, according to Bond *et al.* (2001), this choice is highly recommended when the value of the coefficient of the lagged dependent variable using a sys-GMM is in between the values of the same coefficient estimated with fixed effects (lower bound) and OLS (upper bound) while diff-GMM gives underestimation of the coefficient, which is what we actually verify performing these estimations.[6] The authors test the robustness of this methodology on an economic convergence framework, revealing that sys-GMM provide greater accuracy in those exercises. Moreover, Ulku (2007) shows that sys-GMM estimators is also more preferable when innovation and technological

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[4] As a background, the first NAMEA was developed by the Dutch Central Bureau of Statistics (De Boo *et al.*, 1993), and earlier contributions such as Ike (1999), Keuning *et al.* (1999), Steenge (1999), and Vaze (1999) provided empirical analyses related to the possible policy implications deriving from sector-specific environmental performance. In the NAMEA tables, environmental pressures, in particular air emissions, and economic data (value added, final consumption expenditures and full-time equivalent job) are assigned to the economic branches of resident units directly responsible for environmental and economic phenomena.

[5] Full description of data is available upon request.

[6] For the sake of simplicity we have not reported results on the validity of the chosen estimator in this version of the paper, but they are available upon request from the authors.

spillovers are tested as potential drivers of economic growth, as it is exactly our case. Ulku's paper and Becker and Pain (2008) are two papers close to our empirical specification, which is enriched by R&D and abatement decisions spillover effects.

It is worth noting that GMM can be outperformed by other dynamic estimators, such as corrected LSDV estimator (Judson and Owen, 1999; Bruno, 2005a,b; Kiviet, 1995), which turn out to be preferable in unbalanced panel on the basis of Montecarlo simulations. The unbalanced nature of our data, the potential endogeneity of main covariates and the dynamic features of the model are thus the three main reasons why to use GMM, which should be always recalled, suffer from finite sample bias. Though our dataset is large in its NxT matrix and thus in principle fully coherent with GMM tools, we adopt a 'comparative strategy' (Bond, 2002), by estimating OLS, within and within lagged (in the dependant variable) estimators, first difference procedures, LSDV dynamic model and GMM. We will specifically focus on comparisons between OLS, within lagged, first difference and GMM. Even if we do not show all results for brevity, the comparison is particularly useful for showing robustness in terms of signs and significance across models, for empirically verifying the superiority of GMM, and above all for checking whether the coefficient of the lagged dependant variable in GMM regressions is in between those of OLS and within estimators. This is a first but important test of GMM good performance in finite samples, which should not be taken for granted ex ante. That is why is relevant to reason around a series of static and dynamic models.

3.2 Econometric outcomes

We focus our comments on GMM results for CO_2 and SO_X specifications (tables 1-4). We also present some static specifications using within lagged and first difference (in the appendix, tables A1 and A2), in order to show homogeneity of results, differences and consistency of GMM. As expected, dynamic LSDV models we also tested are performing not very well in this context, given the unbalanced nature of the panel data. The comparisons and presentation of some static models outcomes as a complement to final GMM results is instead worth noticing. All results are fully available upon request for all models.

Tables 1-4 present the GMM-sys results for various specifications trying to understand what is driving the investment in R&D for a sector. Tables 1-2 shows estimations where $CO_{2\ related}$ covariates are included.

The lagged coefficient of the R&D dependant variable is extremely significant as expected[7]. More interestingly, as expected in the presence of sector specific effects, the OLS levels are un upward estimate of the lagged coefficient, while the within (lagged) estimator generate a lower bound level. In our case, there is no overlapping and the rule of thumb that the GMM level is in between OLS and within is satisfied, suggesting that finite sample bias should not be present[8]. Further Montecarlo tests might well add robustness to finite sample bias performance.

Value added (*ValAdd*) of sector i positively relates to R&D investments. This is expected and a common evidence in this stream of literature (Becker and Pain, 2008).

We exploit a procedure that starts from a narrower reduced form, then extending one by one, in any case parsimoniously the additional covariates. This is also useful to mitigate collinearity flaws.

The effect of abatement decision of the sector itself, *ai,* is associated to a negative coefficient, that means that the lower emission the higher R&D. This is true for both emissions taken in levels or normalised by value added. This is a confirmation that abatement and R&D investments, a purely public (in principle)

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[7] As a rule of thumb, 10% significance is nevertheless enough to maintain a dynamic specification.

[8] The rule is satisfied in all the regressions presented in tables 1-4. As example, for the one in column 1 in table 1, the OLS level is 0.966 and the within lagged level 0.832. Though it is common to observe a GMM value closer to within, the two are not overlapping.

and a private/mixed investment, are positively correlated. The ai effect is robust across all results in table 1.

When *RDspill*$_{s\neq i}$ *(no weight)* is included (the variable captures the effect of R&D carried out in other sectors on R&D in sector i), we highlight the importance of weighting R&D spillovers (by K/L ratios, that we define 'cognitive or specialization proximity). In fact if column 3 shows a negative coefficient, the weighted factor presents a more plausible positive coefficient. In line with the literature and the necessity of weighting technological sector flows, we retain column 3 results as more significant. The ai coefficient is not affected. Column 4 tests the core of the theoretical model, the reaction function associated to abatement decisions. The covariate $A_{s\neq i}$ shows a sign that is fully coherent with the testable implication deriving from (12) and section 2.3. The factor is economically and statistically very significant. It is worth noting that the level of the coefficient is ten times that of ai. This proves that the spillover effect associated to the abatement (the variable is effectively constructed as abatement in time T minus abatement in time t-1) carried out by other sectors increase the investment in the mixed good R&D. There is no free riding, and the 'public' part (within the country in this case) weights more than individual abatement[9].

As far as control dummies are concerned, we note the positive role often observed for the euro period after 2002, which denotes an upsurge of R&D in the final period we observe (2002-2006). Trade factors are used as main control as usually found in the knowledge production function literature. In our case all three covariates (trade openness, export orientation and import penetration).

Table 2 presents in six columns the outcomes for the spillovers effect that are associated to R&D and abatement decisions taken by 'the same sector (e.g. Food, DA) in other countries'. It is then a filiere sector specific effect which should capture the spillover arising from partnership and technological flows occurring within a branch.

We test four different R&D spillover effects: un-weighted, weighted by K/L, weighted by distance, weighted by both factors (respectively included as covariates in columns 1-4). They are all highly significant from a statistical point of view, and show an increasing level of the economic significance from the un-weighted to the fully weighted case. It is again confirmed the relevance of weighting R&D sector effects. Comparing results between table 1 and 2, it appears that R&D spillovers are stronger at EU level (within the sector) than within a country (from other sectors). Comparing GMM and within estimations, we note that in the latter case only *RDspill*$_{c\neq i\ (geo\ dist;\ cogn\ prox\ +\ geo\ dist)}$ were (highly) significant. The same applies to first difference regressions.

Columns 5 and 6 of table 2 present the effects for $A_{c\neq i}$ *(abatement occurred from T-1 to T* in the same sector in other countries) on sector R&D. Though the sign is in line with theoretical expectations, statistical significance is low (it is close to 10% for the weighted case). We may affirm that in this specification the issue at stake is that R&D sector spillovers at EU level overwhelms other drivers through their explanatory power. Table 1 – Effects of R&D spillovers and abatement spillovers (within country, other sectors)

[9] In the first difference regression (see appendix) the signs and significant are confirmed besides ai, which shows a negative but not significant coefficient. The significances in the within model are instead weaker and dominated by the lagged value of R&D and value added. Only ai is negative and significant at 10%. Without the lag, the weighted R&D spillover is highly significant.

We note that though first difference results are robust, the unbalanced nature of the panel can generate flaws. In addition, some differences between within and first differences could lead to hypothesise problems regarding the strict exogeneity assumption. Both 'problems' give support to the use of GMM in our case.

Table 1 – R&D spillovers effects and abatement decisions (within country other sectors)

CO2 emissions	(1)		(2)		(3)		(4)	
RD_i(t-1)	0.853	***	0.883	***	0.882	***	0.896	***
$ValAdd_i$	0.038	***	0.054	***	0.064	***	0.112	***
a_i	-0.049	***	-0.052	***	-0.044	***	-0.033	***
$RDspill_{s\neq i}$ (no weight)			-0.074	***				
$RDspill_{s\neq i}$ (cogn prox)					0.020	**	0.030	***
$A_{s\neq i}$							-0.345	***
Constant	2.489	***	2.531	***	0.591	***	3.050	***
Euro (dummy)	0.042	***	0.058	***	0.010		-0.010	
Country fixed effects	Yes		Yes		Yes		Yes	
Year dummies	Yes		Yes		Yes		Yes	
No Obs.	3,378		3,336		3,378		3,378	
Wald test	5.80E+05		7.50E+04		9.60E+04		2.00E+05	

** for p<0.05 *** for p<0.01

T=11 years

CO2 emissions	(1)		(2)		(3)		(4)		(5)		(6)	
RD_i(t-1)	0.877	***	0.878	***	0.852	***	0.858	***	0.860	***	0.866	***
$ValAdd_i$	0.063	***	0.052	***	0.043	***	0.065	***	0.047	***	0.054	***
a_i	-0.003		0.003		-0.020		-0.045	***	-0.010		0.006	
$RDspill_{c\neq i}$ (no weight)	0.019	***										
$RDspill_{c\neq i}$ (cogn prox)			0.020	***								
$RDspill_{c\neq i}$ (geo dist)					0.078	***						
$RDspill_{c\neq i}$ (cogn prox + geo dist)							0.091	***	0.104	***	0.106	***
$A_{c\neq i}$ (no weight)									0.003			
$A_{c\neq i}$ (geo dist)											-0.014	
Constant	0.308		0.703	***	0.184		0.120		0.000		-0.627	***
Euro (dummy)	0.013		0.009		0.023	***	0.005		0.000		-0.005	
Country fixed effects	Yes		Yes		Yes		Yes		Yes		Yes	
Year dummies	Yes		Yes		Yes		Yes		Yes		Yes	
No Obs.	3,378		3,373		3,378		3,378		3,378		3,378	
Wald test	9.00E+04		1.10E+05		6.80E+04		8.00E+04	1	3.00E+04		1.40E+05	

** for $p<0.05$ *** for $p<0.01$ T=11 years

Table 2 – R&D spillover effects and abatement decisions (outside the country, same sectors)

Table 3 and 4 replicate the results of tables 1 and 2 for SOx. Given that results for R&D covariates should be unaffected, we comment on SOx related ai and $A_{c,s\neq i}$ effects. Table 3 confirms as table 1 the significance and negative coefficient for ai. Column 4 of table 2 shows that though negligible in economic significance – if compared to the carbon dioxide $A_{s\neq i}$ effect, the sign is positive[10]. This would mean that in this case a free riding effect is present: the abatement occurring in other sector of the country reduces the incentive for sector i to invest in innovation, which is including an abatement component, if we follow the model outlined in the first part of the paper.

Table 4 concludes our comments. As for CO_2, the level of the coefficient increases from column 1 to 4 that is from the un-weighted to the fully weighted specification. The fully weighted R&D spillovers show a relevant size of the coefficient.

As far as the SOx abatement spillover effect ($A_{c\neq i}$) coming from what the same sector in other EU countries has done, we observe that both weighted and un-weighted factors are relevant, with the latter being more significant from an economic point of view. First difference regressions (see appendix) show very similar evidence.

The evidence we find is telling that R&D spillovers are playing an enormous role in sector R&D investments, and cognitive proximity and distance heavily matter. In terms of reaction function empirical estimations, we can compare the effect of ai with that of $A_{c,s\neq i}$, in two ways: comparing results for CO_2 and SOx, and comparing results for internal to the country – other sectors effects (s) and foreign – same sector effects.

The ai coefficient is significant in most cases, but or both carbon dioxide and SOx its economic significance is lower with respect to that of A. Regarding A' effects, $A_{s\neq i}$ shows a terrific impact on sector R&D in the case of CO_2, while free riding behaviour seems to emerge for SOx. Instead, $A_{c\neq i}$ appears to play a robust role only for SOx. Table 5 summarises the outcomes. Thus, theoretical expectations are confirmed, in terms of reaction function shapes (signs), for the 'within country – other sectors' spillovers in the case of CO_2 and 'foreign country – same sector' abatement spillovers for SOx.

[10] It is actually negative in the first difference regression, with the weighted R&D factors also significant.

Table 3 – R&D spillovers effects and abatement decisions (within country other sectors),

SOX emissions	(1)		(2)		(3)		(4)	
$RD_i(t-1)$	0.850	***	0.869	***	0.859	***	0.864	***
$ValAdd_i$	0.072	***	0.076	***	0.072	***	0.118	***
a_i	-0.019	***	-0.022	***	-0.016	***	-0.028	***
$RDspill_{s\neq i}$ (no weight)			-0.075	***				
$RDspill_{s\neq i}$ (cogn prox)					0.035	***	0.015	***
$A_{s\neq i}$							0.045	***
Constant	1.061	**	2.723	***	0.479	**	-0.693	***
Euro (dummy)	0.017	***	0.058	***	0.010		-0.010	
Country fixed effects	Yes		Yes		Yes		Yes	
Year dummies	Yes		Yes		Yes		Yes	
No Obs.	3,346		3,304		3,346		3,346	
Wald test	4.30E+04		6.30E+04		5.60E+04		1.40E+05	

** for p<0.05 *** for p<0.01

T=11 years

Table 4 – R&D spillover effects and abatement decisions (outside the country, same sectors), T=11 years

SOX emissions	(1)		(2)		(3)		(4)		(5)		(6)	
RD_i(t-1)	0.884	***	0.872	***	0.840	***	0.852	***	0.864	***	0.861	***
$ValAdd_i$	0.074	***	0.070	***	0.067	***	0.054	***	0.061	***	0.079	***
a_i	-0.014	**	-0.010	**	-0.007		-0.017	***	-0.009	**	-0.008	**
$RDspill_{c\neq i}$ (no weight)	0.027	***										
$RDspill_{c\neq i}$ (cogn prox)			0.031	***								
$RDspill_{c\neq i}$ (geo dist)					0.106	***						
$RDspill_{c\neq i}$ (cogn prox + geo dist)							0.126	***	0.114	***	0.110	***
$A_{c\neq i}$ (no weight)									-0.009	**		
$A_{c\neq i}$ (geo dist)											-0.018	***
Euro (dummy)	-0.011		-0.001		0.012		-0.013		-0.014	**	-0.021	***
Country fixed effects	Yes		Yes		Yes		Yes		Yes		Yes	
Year dummies	Yes		Yes		Yes		Yes		Yes		Yes	
No Obs.	3346		3341		3346		3346		3346		3346	
Wald test	7.60E+04		1.10E+05		7.00E+04		7.10E+04		1.20E+05		1.60E+05	

** for $p<0.05$ *** for $p<0.01$

Table 5 – Effects of abatement decisions on sector R&D

	SOx	CO_2
a_i *abatement of the sector*	It increases R&D	It increases R&D
$A_{s\neq i}$ *abatement of other sectors in the country*	It decreases R&D (potential free riding)	It increases R&D
$A_{c,\neq i}$ *abatement of same sector in other countries*	It increases R&D	Not significant

Size of the effects

- $A_{s\neq i\ CO2} > a_{i\ CO2}$
- $a_{i\ CO2} > a_{i\ SOx}$
- $A_{s\neq i\ CO2} > A_{c\neq i\ SOx}$

4. Conclusions

We analyze sectors' investment decisions about emission abatement in a contest of a mixed good. The mixed good can be defined as the total amount of R&D efforts, namely a mixed capital good. We pay attention to the reaction function between one (sector's) investment in the mixed good (R&D and emission abatement) and the other (sectors') investment in emission abatement. R&D is an impure public capital good by assumption and the technological consequence is the complementarity between the private component (*say,* energy efficiency) and the public component (*say,* emission abatement).

We demonstrate that the only case in which the sector's investment in R&D doesn't react with respect to $A_{\neq}$ is when the private component of R&D is very small. Hence, if R&D was a pure public capital, the single sector's investment in emission abatement wouldn't positively react to the other sectors' investment in emission abatement. This is a typical free riding issue that nevertheless would not explain what is often observed in markets when agents present some cooperative behavior in 'dynamic games', show CSR efforts, generate networking alliances of formal and informal nature. Those actions often jointly provide, intentionally or unintentionally, public and private goods.

Though compatible with mainstream settings to a certain extent, we recognise that this framework has a neo Schumpeterian flavour: the dynamics of innovation is linked and co evolves with appropriability conditions and generation of (new) economic performances. The lack of recognition of the 'dynamic properties' of a mixed good structure may hinder the achievement of efficiency and efficacy benefits for both firms and policy makers.

More specifically, the analysis shows how two cases (*CASE II: substitutes*; *CASE III: complements*) compare in terms of 'dynamic accumulation' properties and behavior of the reaction function. We have demonstrated that, when the private and the public components of the benefit function are complement, the reaction of R with respect to $A_{\neq}$ is stronger than when the two sorts are substitutes. When the private and the public component are complements an increase of the other sectors' investment in the public component (emission abatement) increases the marginal benefit of accumulating the complementary private component (energy efficiency appropriable only by the investing sector). Therefore, the single sector now wishes to increase its own investment of the private component and, hence, of the mixed capital (R&D). In this way, through the extra investment in R&D, the single sector necessarily determines an increase of its investment in emission abatement too. From the previous reasoning some other implications derive. In the first place when the emission abatement is complementary to a private component in an impure public capital, the consequences of incentives/obligations proposed may be even more effective than initially supposed, because of the positive reaction of one agent's investment decision to the other agents' investment decisions. Moreover, always in case of impure public capital, to strength the efficiency of the incentive decisions about emission abatement it would be necessary to envisage also the investment in complementary forms of capital.

The empirical analyses mainly test the slope of such reaction function in a context which has as reference a 'knowledge production function'. Within this framework we thus investigate what the main drivers of sector R&D are. We enrich the setting by focusing on spillover effects that are related both to R&D decision of other sectors and to abatement decisions. Evidence specifically grounds on an original integrated dataset that merges together NAMEA matrixes for major EU economies with sector based data on innovation, trade, covering large part of EU over 1995-2006.

The results of dynamic and first difference estimates are coherent with the theoretical testable implications. The core hypothesis of the paper, the possibility that reaction functions are positive, is tested by specifying two types of 'abatement spillovers': internal to the country and thus associated to what other sectors have done; external to the country, and thus associated to the activity of the same sectors abroad. The hypothesis is not rejected except in one case (internal to the country, SOx). In two cases (SOx, external to the country spillover; CO_2, internal to the country) the effects are highly significant and outweigh that related to the specific abatement investment of the sector, that is its contribution to the public good (definable either as 'sector or national industry abatement'). Spillovers effects, when significant, noteworthy outweigh sector internal effect as far as the relationship between R&D decisions and abatement efforts is concerned. When considering CO_2, the sector R&D is triggered by national 'interactions' (what other sectors in my country have been doing matters to me, and the evidence is that I tend not to free ride on CO_2 abatement), oppositely, we observe signals of free riding for SOx with respect to national sectors, while on the other hand R&D responds in that case to what 'my sector' has done for abatement in other countries. Technological differences and policy issues, regarding abatement in the two cases surely matter here. The fact that the link R&D-CO_2 abatement is mostly significant at national level is coherent with the facts that carbon reduction policies have been historically shaped at national level. The appearance of the EU ETS is just marginally touched by our dataset; ETS also include only 4-5 manufacturing sectors. CO_2 abatement technologies heavily regard energy efficiency, that provides joint private public benefits. Thus, the fact that a sector positively reacts by investing more when others abate is theoretically justified by the nature of the good and by the content of technology involved.

The fact that SO_X abatement by others impacts R&D investments positively 'from abroad' means that sectors have an eye to EU frameworks and not to internal ones. This could be coherent with the longer history of EU actions on emissions, compared to CO_2, on the one hand. Sectors are

regulated and follow what others in other countries are doing. Technological options are also more sectors specific in SOX abatement.
We also show that R&D spillovers are relevant explanatory factors, as expected. It is fairly interesting to notice that weighting spillover by cognitive proximity and/or distance is needed, and that spillover effects increase when 'external to the sector' R&D is weighted.
Overall, the investment in the mixed public good R&D is heavily influenced by different spillover effects that pertain to national and sector specific environments. Strategic games are played over different directions. It appears coherent with a strategic public good provision game that spillovers matter, though not to be taken for granted. The mixed good of the innovation investment might help mitigating free riding behavior, as we show, though this effect is likely to be strongly emission specific (technology specific) and also sector specific. This sector disentangling of evidence is scope for further research.
The extent to which the reaction function is affected over time by structural temporal breaks such as Kyoto Protocol or the entry into force of the European Emission Trading Scheme (ETS) is scope for further research. In addition to how economic productivity impacts emission intensity in the dynamics, how energy intensity and environmental policy stringency have influenced the dynamic performance is also food for new applied research. Fruitful analyses linking innovation to income-environmental relationship will also generate from the upcoming release of a full EU27 NAMEA in 2011, which represents a silver bullet for EU research.

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APPENDIX

Table A1 - within (lagged) and first difference regressions (CO_2)

	Within		FD		Within		FD	
$RD_i(t-1)$	0.834	***			0.825	***		
$ValAdd_i$	0.137	***	0.233	***	0.132	***	0.219	***
a_i	-0.052		-0.004		-0.051		0.004	
$RDspill_{s\neq i}$ (cogn prox)	-0.018		0.165	***				
$RDspill_{c\neq i}$ (geodist)					0.077	***	0.948	***
$A_{s\neq i}$	-0.008		-0.082	***				
Dummy euro (after 2020)	0.022	***						
No Obs.	3378		3376		3378		3376	
** for p<0.05	*** for p<0.01							

	Within		FD	
$RD_i(t-1)$	0.830	***		
$ValAdd_i$	0.132	***	0.249	***
a_i	-0.052		-0.006	
$RDspill_{c\neq i}$ (cogn prox + geo dist)	0.027	**	0.032	***
$A_{c\neq i}$ (geo dist)	-0.003		-0.013	
No Obs.	3378		3376	
** for p<0.05	*** for p<0.01			

Within estimates are corrected for heteroskedasticity and autocorrelation after Breusch Pagan and Wooldridge tests rejected the null. Wald and F tests present significant rejection of the null (all covariates jointly not significant) for the overall fit of the regression., T=11 years

Table A2 - within (lagged) and first difference regressions (SOx)

	Within[11]		FD		Within		FD	
RD_i(t-1)	0.843	***						
$ValAdd_i$	0.146	***	0.225	***			0.241	***
a_i	-0.006[12]		-0.025	***			-0.030	***
$RDspill_{s\neq i}$ (cogn prox)			0.142	***				
$RDspill_{c\neq i}$ (cogn prox +geodist)	-0.019						0.025	**
$A_{c\neq i}$ (geo dist)	-0.006		-0.091	***			-0.028	***
Dummy euro (after 2020)	0.165	**						
No Obs.			3341					

** for p<0.05 *** for p<0.01

Within estimates are corrected for heteroskedasticity and autocorrelation after Breusch Pagan and Wooldridge tests rejected the null. Wald and F tests present significant rejection of the null (all covariates jointly not significant) for the overall fit of the regression, T=11 years

[11] In the within specification with no lag and time trend included, all covariates regarding spillovers are significant with the expected sign.

[12] For both SOx and CO2, the coefficient of ai loses significance when cluster correction is operated.