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Energy Sustainability

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ABSTRACT: Investment by energy firms in innovation can have substantial economic and environmental impacts and benefits. Internal R&D is the main input and driver of the innovation process, but innovation involves other activities, including capital purchases and other current expenditures. While the R&D activities of energy firms have been analysed, few studies have examined the typology of their innovation activities. Here, we analyse the impact of the main characteristics of the sector's firms on their decisions to invest in each of three types of innovation activity: namely internal R&D; external R&D; and, the acquisition of advanced machinery, equipment or software. In conducting this analysis, we take the potential persistence of innovation activities into account. We also examine the role that different innovation objectives have on firms' investment decisions. Given that engagement in a specific type of innovation may result from decisions that are not taken independently of each other, we analyse whether there is any complementarity between the three innovation activities. In carrying out the empirical analysis, we draw on data for private energy firms included in the Technological Innovation Panel (PITEC) for Spanish firms for the period 2004-2013. We use panel triprobit models to examine potential complementarity.

JEL Codes: L94, Q40, O32

Keywords: Energy, R&D, innovation, regulation, complementarity

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1. INTRODUCTION

The energy sector is experiencing a major transformation and although innovation did not until recently occupy a central position in this industry, today it is one of the main the driving forces behind these transformative changes (Eurelectric, 2013; Bointner, 2014). Indeed, innovation would appear to be critical if energy firms hope to tackle successfully the challenges posed by increasing competitiveness, energy efficiency and climate change mitigation (Anadon, 2012; Economics for Energy, 2013; OECD, 2011).

Recent studies have analysed the R&D determinants of energy firms and the effects of the liberalisation of electricity markets on R&D investment (Costa-Campi et al., 2014; Jamasb and Pollit, 2008; Kim et al., 2012; Salies, 2010; Sanyal and Cohen, 2009; Sterlaccchini, 2012). Internal R&D is the main input when increasing the stock of knowledge and when innovating, but innovation has many sources other than internal R&D. Firms can also purchase external R&D or even acquire machinery in order to innovate and improve their technology level. The choice of R&D strategy has received considerable attention in the economics of innovation literature, especially as regards the decision as to whether to 'make or buy R&D'. However, to the best of our knowledge, few studies (an exception being Cohen and Sanyal, 2008) have examined the R&D choices of energy firms.

One of the main objectives of this paper, therefore, is to examine the main characteristics of firms in relation to their choice of innovation strategy. In undertaking the analysis, we consider not only internal and external R&D, but also the acquisition of advanced machinery, by applying the OECD's innovation expenditure classification (OECD, 2005). In this respect, capital purchases may represent an important means for energy firms to innovate, particularly as they seek to develop new or substantially improved processes. Indeed, in this industry, suppliers would appear to play an important role in innovation.

In this analysis, we take the potential persistence of innovation activities into account and examine whether differences occur with respect to the three innovation choices under study. In addition, and following recent literature (Cassiman and Veugelers, 2006; Cruz-Cázares, 2013; Catozzella and Vivarelli, 2014), we take into account potential complementarities between these innovation activities. We examine whether the decisions are taken independently or, on the contrary, whether firms combine different procedures in their innovation strategies.

Firms engage in innovation for different reasons and understanding these reasons may also help explain their R&D strategies and behaviour and the type of innovation they seek to achieve. This information may be helpful in defining proper measures of innovation and energy policy that can stimulate firms' R&D investments. Indeed, the role played by firms' objectives is receiving increasing attention in empirical research on innovation at the firm level (Costa-Campi et al., 2015b; Leiponen and Helfat, 2010).

Therefore, another important objective of this paper is to examine the effect that different innovation objectives – process innovation, product innovation, reducing environmental impact and meeting regulatory requirements – have on the decisions of energy firms to invest in either internal R&D, external R&D or advanced machinery.

Empirical analyses of the R&D and innovative behaviour of energy firms are frequently constrained by a lack of data (Anadon et al., 2011; GEA, 2012; Gallagher et al., 2012). In this paper, we rely on information drawn from the Spanish Technological Innovation Panel (PITEC) for the period 2004-2013 to carry out our econometric estimations. The data collected for this panel is based on information taken from the Community Innovation Survey conducted in Spain, adhering to the guidelines of the Oslo Manual of the OECD (OECD, 2005).

After this introduction, the rest of this paper is organised as follows. In the next section, we provide a brief discussion of what it is that motivates energy firms to innovate in the current liberalised situation. In this discussion, we consider the different ways firms opt to innovate. The third section presents the database and descriptive statistics illustrating the engagement of firms in R&D and innovation activities and the objectives they pursue when opting to innovate. The fourth section presents the model specification, the variables used and the results of the econometric estimations. In addition, we include a subsection with extensions and robustness checks. The last section concludes.

2. INNOVATION STRATEGIES OF ENERGY FIRMS

The transformation of the energy industry is occurring in both its upstream and downstream sectors thanks to the combination of different technologies and the application of innovations originating from other sectors (Gallagher et al., 2012). Additionally, the development of innovations in the energy field requires a combination of technologies and their use beyond their sector of origin (Bointner, 2014; GEA, 2012; Wangler, 2013).

Disruptive technology changes are shaping a totally different model from that of conventional energy supply. The emergence of renewable energy is displacing conventional generation and impacting the transmission and distribution system and its operation. In turn, the incorporation of information technology allows more complete information to be given to consumers, who can now take a more active role on the demand side, which should change how the system works. Networks are no longer simply physical channels of electricity flows but operate in accordance with the information users make available about their consumption patterns. This management of large volumes of consumer data (big data) means the sector now functions in response to demand (pull) criteria. Moreover, these technological developments facilitate the provision of new energy services that can be expanded to meet the growth in demand (Bointner, 2014; GEA, 2012).

All these changes require the adoption of a business innovation approach and the investment of private companies in R&D, given that public funds have proven to be insufficient on their own (Wiesenthal et al., 2012). Yet, at the same time, there is a considerable degree of interdependence between the public and private sources of funding (Jamasb and Pollitt, 2015). Ultimately, the literature emphasizes the fact that innovation is the only way the industry can face the changes that are taking place (Richter, 2013).

The outcome of this process of transformation is an intensification of competition and the constant search for competitive advantages on the part of the companies. Entrants today are more aggressive and innovative, in a trend that is currently prevailing in the market. As Schumpeter (1942) pointed out, new entrants seek to take over the market dominated by incumbents and, so, increase their margins. The way to achieve their goal is by promoting innovations that can replace the services provided by the incumbents and thus win market share. The expectation is that incumbents respond to the threat by increasing their investments to obtain innovations so that they can reverse the process. The result is greater competition, which leads to continuous improvements in technology that ultimately should benefit consumers.

The data offer evidence in support of this trend. After nearly two decades of falling R&D investment in the energy sector, we are witnessing a recovery (Jamasb and Pollit, 2015; Bointner, 2014; Wiesenthal et al., 2012). The transformation experienced by the sector in the provision of services and the launching of new products onto the market seem to be the main drivers of this recovery. The new trend also reflects the innovation strategies being adopted by companies in the sector, a trend that is dominated by externally performed R&D, in contrast to the situation in other sectors. This could account for the low values presented in terms of R&D effort (Daim et al., 2013; Weisenthal et al., 2012) when considering energy companies only.

The investment in R&D and innovation by energy companies is aimed at strengthening their competitive advantage in line with the energy market's new coordinates. Their main objective, therefore, is to expand generation technologies, above all in relation to renewable energy; and, to achieve this, they buy new technologies from other companies in the group or market. Other objectives include improving both the flexibility of the process (through the purchase of new equipment) and of the product (by offering new services to satisfy customer needs). In short, they seek to increase their portfolio both in the upstream and downstream markets. Their objectives also include reducing costs in the medium term (especially in CAPEX), increasing innovation in operation and maintenance (OPEX), increasing energy efficiency, adapting to new environmental legislation, innovating in the network management of power evacuation and, finally, furthering decentralization. These processes of constant innovation mean the sector's industrial processes are yielding to a disruptive technological transfromation. In turn, firms are now having to work bottom up, rather than top down, as they have been to date (Daim et al., 2013).

This new model of technological development has led to the involvement of many companies in the energy innovation system from a range of sectors, including chemicals, electrical components, automotive and construction. Indeed, the literature documents that much of the research performed in the energy industry is carried out by energy equipment and material suppliers (Jacquier-Roux and Bourgeois, 2002). As a result of this interdisciplinary approach, new innovation strategies have been adopted in the energy sector in recent years.

The business strategies employed in promoting these innovation processes seem, according to the sector's own reports (Eurelectric, 2013) and the literature (Daim et al., 2013), to involve close cooperation with other companies, given the high costs and the diversity of activities and knowledge (both hard and soft) needed. The existence of high uncertainty in the sector (Sanyal and Cohen, 2008), combined with such aspects as capital-intensive innovation requirements, the long life of existing installations, the amount of time required for new technologies to mature and become competitive in the market, may have caused a slowdown in the internal R&D ratios of energy firms (Gallagher et al., 2012). To tackle this situation, companies have adopted a risk-sharing strategy, conducting R&D externally, which enables them to undertake various projects with the same amount of resources but using collaborative R&D as a hedge against uncertainty (Cohen and Sanyal, 2008), especially in light of the high volume of investments necessary to advance in this transformation process (Eurelectric, 2013).

In this current context, external R&D has become virtually obligatory, especially given the high number of skills that have to be brought together to develop the new products and services demanded by the energy sector. Moreover, external R&D seems to offer the possibility of developing new technologies faster. Likewise, the literature examining environmental innovations concludes that here too they are more likely to be developed in cooperation (Horbach, 2008; De Marchi, 2012).

Another strategy frequently employed by energy firms to innovate is that of the acquisition of new machinery. This strategy means that the company relies on its external suppliers when introducing innovations (Bönte and Dienes, 2013). The main drawback here is that such acquisitions may not improve the company's ability to absorb knowledge.

All in all, internal R&D seems to be more effective when carried out together with external R&D and the acquisition of machinery. Large innovative companies not only conduct in-house R&D but they also take steps to develop knowledge beyond their own institution. The motive underpinning this behaviour is the recognized existence of complementarity between actions to innovate internal and externally (Cassiman and Veugelers, 2006).

3. DATA

Our dataset is a sub-sample of the Technological Innovation Panel (PITEC) for Spanish firms. PITEC includes exhaustive information on the characteristics and innovative activities of more than 12,000 Spanish firms for the period 2003-2013. PITEC is the result of cooperation between the Spanish National Statistics Institute and the COTEC foundation and seeks to make data available from the Community Innovation Survey (CIS), conducted annually following the guidelines of the OECD's Oslo Manual. While the EU-wide CIS database offers information on cross-section observations, the Spanish PITEC is able to identify firms in several waves and, thus, provides a large panel of innovative firms. From the full sample of firms, we select those that correspond to the energy industry as defined below.

Our operational definition of the energy sector includes all activities related with the generation, transformation, distribution and retailing of energy. We do not include the oil industry (NACE 19) where the number of firms in PITEC is very low, with no more than two or three annual observations. In PITEC, the data for the two divisions of the NACE Rev. 2 classification, Electricity, gas, steam and air conditioning supply (NACE 35) and Water collection, treatment and supply (NACE 36), are aggregated. To separate water companies from energy companies, we rely on the fact that in Spain, following the energy liberalisation process of the late nineties, all gas and electricity companies are privately owned whereas almost all water companies are state-owned. Therefore, to ensure we focus on energy firms, we remove all the state-owned firms from the sample of utilities included in PITEC. Unfortunately, however, we are unable to identify firms any further than this.

This paper focuses specifically on the innovative strategies adopted by these energy firms. To control for the fact that some firms may simply not be willing to innovate, we follow the recent literature (Savignac, 2008; D'Este et al., 2012; Blanchard et al., 2013, Pellegrino and Savona, 2013) and focus exclusively on potential innovators. To do so, we also exclude from the sample firms that satisfy the following three conditions: they have never innovated; they do not perceive any obstacle to innovation; and they declare they have no need to innovate.

Although PITEC provides information for 2003, the data for that year are incomplete. However, as we use the lags of independent variables for some items in the estimations, we also use the data for 2003 to avoid the loss of information before removing all the observations corresponding to that particular year. After applying these filters, 532 observations are available for 90 energy companies forming an unbalanced panel for the period 2004-2013.

Spain's electricity and gas regulations are fully harmonised with European norms and the country's energy industry has undergone a similar process of liberalisation and transformation to that experienced in other European countries. This process has meant an increase in the number of firms and a corresponding reduction in market concentration. A comparison of Spanish firms with their European counterparts reveals that the former are close to the average in terms of their structural business indicators, including turnover and gross added value per employee, the proportion of personnel costs in production costs and investment rates (Costa-Campi et al., 2014).

Table 1 shows the main characteristics of Spain's innovative energy firms as included in the PITEC database. The table shows that they are big, with an average of 620 employees, although the median lies around 280. Similarly, the average firm has been operating for 33 years; however, the dataset includes firms with more than 100 years' experience as well as recently created start-ups. Other characteristics include an indicator as to whether a firm forms part of a larger group or not, if the firm has foreign capital participation in its ownership structure, and if the firm has received public subsidies for R&D activities.

This table also shows the descriptive statistics of our variables of interest, including firms that i) invest in internal R&D; ii) invest in external R&D; and, iii) invest in the acquisition of machinery, equipment and software. As defined by the Frascati Manual, internal R&D comprises all the R&D performed within the enterprise in order to increase the stock of knowledge and to devise new applications. External R&D comprises the acquisition of R&D services from private or public organisations. Finally, in the category of advanced machinery, we include, in line with the Oslo Manual's (OECD, 2005) definition, the acquisition of advanced machinery, equipment, computer hardware and software, and land and buildings that are required to implement product or process innovation. This category does not, however, include the capital expenditures that are part of R&D.

In the period under consideration, more than half the energy companies (52%) reported performing internal R&D activities, 42% reported subcontracting R&D activities and 24% reported acquiring advanced machinery, equipment or software. All three innovation activities are quite persistent. The transition probabilities for each strategy considered are quite high, ranging from 90% in the case of internal R&D, to 76.5% for the acquisition of machinery, equipment and software.

Table 1

Energy firms appear to adopt the innovation strategies at their disposal depending on their specific innovation objectives. PITEC allows us to undertake a comprehensive analysis of these objectives. In order to simplify this analysis, we group them in four main categories: i) product innovation; ii) process innovation; iii) reducing environmental impact; and, iv) meeting regulatory requirements. Firms are asked to declare the extent to which these four objectives are important (on a four-point scale). The results indicate that process innovation is currently recognized as being the most important innovation objective (high importance), but that the other objectives are also relevant.

Table 2 shows the frequency of multi-strategy use by energy firms; yet, it also indicates that 36.3% of firms do not perform any activity related to R&D. Almost 20% of the firms report using only one strategy; in this case, the most frequently used strategy is internal R&D (54% of the total), followed by the acquisition of machinery, equipment and software (35%) and external R&D activities (11%). However, when firms use two strategies simultaneously (which occurs in 35% of cases), the most frequently used pair of strategies is internal and external R&D, observed in almost 80% of cases. Hence, although external R&D activities are seldom adopted as an individual strategy, they are the most frequent complement of internal R&D activities. Correlation coefficients also show that internal and external R&D are highly related activities (coefficient value of 0.62). In contrast, the correlation between internal and external R&D, on the one hand, and the acquisition of machinery, equipment and software, on the other is weak (coefficients of 0.10 and 0.11, respectively). Finally, only in 9.6% of cases do firms use all three strategies.

Table 2

4. MODEL, ESTIMATION AND RESULTS

4.1. Model specification and variables

To analyse the firms' decisions to invest in internal R&D, external R&D and in the acquisition of advanced machinery, we use the following specification:

$$D_{it} = \begin{cases} 1 & \text{if } \alpha_1 D_{it-1} + \beta X + \gamma O + \delta C + \varepsilon_{it} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

In this equation, D corresponds to the dichotomous decision to engage or not in one of the three innovation activities considered. We conduct three different estimations for each of these activities.

The independent variables in the three estimations are the same. We include a lag of the dependent variable, a set of firm characteristics (X) and another set of variables capturing the firms' innovation objectives (O). In addition, we take into account the potential existence of cost barriers to innovation (C).

Recent analyses have underlined the persistence of innovation activities (Arqué-Castells, 2013; Raymond et al., 2010). The main reason for this persistence is that R&D activities present high degrees of cumulativeness and irreversibility. This evidence is supported by our data. The transition probabilities of engaging in R&D activities are very high. We, therefore, include lags of the dependent variables to control for this potential persistence.

In line with the literature on the determinants of the decision to engage in R&D and innovation in general (Crepon et al., 1998; Cohen, 2010; Griffith et al., 2006), but also specifically in energy firms (Costa-Campi et al., 2014; Salies, 2010), we include as explanatory variables size, age, foreign capital, belonging to a group and public financing.

Since Schumpeter's seminal contribution, size has always been a key variable in the analysis of R&D and innovation at the firm level. Indeed, empirical findings for the energy sector show that larger firms are more likely to invest in internal R&D (Costa-Campi et al., 2014; Jamasb and Pollit, 2008; Salies, 2010; Sanyal and Cohen, 2009). As such, we expect a positive relationship in our estimations. At the same time, the benefits obtained from external R&D are expected to be proportional to the size of the company. In the case of the acquisition of advanced machinery, the literature is less conclusive.

A firm's age may also influence its decision to invest in R&D and machinery. Recent papers show that the determinants of R&D investment are not the same for young firms as they are for older firms (García-Quevedo et al., 2014) with the former relying more heavily on the acquisition of machinery to innovate than older firms (Pellegrino et al., 2012). We also control for the participation of foreign investors in the firm and whether the firm belongs to a group of firms. Both characteristics may influence decisions to invest in R&D and advanced machinery and have been frequently included in analyses of R&D determinants. For instance, belonging to a group may help a firm overcome financial constraints.

We have included the variable public funds to control for the effects of subsidies on R&D and innovation decisions and to examine possible differences in their impact on the three innovation strategies. Public support is oriented, in principle, to promote internal and external R&D and not the acquisition of advanced machinery. The existence or otherwise of an additional effect of public support on private R&D has frequently been analysed in the empirical literature (David et al., 2000; Zúñiga-Vicente et al., 2014). In addition, most empirical studies of the determinants of R&D (Griffith et al., 2006; Hall et al., 2013) include it in their models. To minimise endogeneity concerns owing to the fact that public support is related to prior R&D and innovation performance, we conduct the estimations with the lag of this variable, in line with a common procedure employed in the literature (Costa-Campi et al., 2014).

We also include a set of variables capturing the objectives of innovation to examine the motives driving decisions to invest in each of the three categories. The objectives differ by type of innovation and meeting these objectives may equally require different innovation activities and strategies. Some, for example, may require investment in R&D; others may be achieved by purchasing new machinery or equipment.

Based on available information, we consider four groups of motives for innovating: first, those oriented towards product innovation (e.g., improving quality of services, increasing range of services, and entering new markets); second, those oriented towards process innovation (improving flexibility of production or service provision, increasing capacity of production and service provision, reducing unit labour costs, and reducing consumption of materials and energy); third, those oriented towards reducing environmental impact; and, fourth, those directed towards compliance with environmental, health and safety regulations.

Traditionally, in the energy industry, the implementation of new, or significantly improved, production processes has been the main motive for innovating, with the objective thereby of increasing capacity and improving efficiency. Such innovations are frequently achieved by acquiring new machinery that incorporates the new technological advances. Although these continue to be important motives underpinning innovation, the energy industry has undergone a significant transformation and other factors have emerged as drivers of innovation. Firms today innovate to reduce their environmental impact as well as in response to regulatory pressures closely tied to climate change targets. Successfully producing these innovations may require increasing the stock of knowledge with R&D investment, accessing new skills and services through external R&D or acquiring new machinery.

A major obstacle to innovation is the existence of financial constraints. Therefore, we have included a potential lack of funds within the energy firm in order to examine whether this limits R&D and innovation decisions and to determine whether the effects differ across the three categories of innovation. In principle, we expect that their effects on R&D investments (internal and external) may be greater than their impact on the acquisition of machinery. R&D investments are characterised by the uncertainty of results and returns, which may account for the existence of financial constraints (Hall, 2002). Nevertheless, specific empirical analyses for the energy industry suggest that financial constraints are not a significant obstacle to innovation for firms in this industry (Salies, 2010; Costa-Campi et al., 2014).

Finally, and in addition to the explanatory variables, in the equations we take into account time effects in order to control for possible shocks arising from changes in the economic cycle as well as regulatory changes that may have affected the firms' R&D and innovation decisions.

4.2. Estimation and results

To carry out the estimations we use a trivariate probit model. For three binary variables D_1, D_2, and D_3, the trivariate probit model supposes that:

$$D_1 = \begin{cases} 1 & \text{if } \alpha_1 D_{1t-1} + \beta X + \gamma O + \delta C + \varepsilon_1 > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$D_2 = \begin{cases} 1 & \text{if } \alpha_2 D_{2t-1} + \beta X + \gamma O + \delta C + \varepsilon_2 > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$D_3 = \begin{cases} 1 & \text{if } \alpha_3 D_{3t-1} + \beta X + \gamma O + \delta C + \varepsilon_3 > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

with

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix} \rightarrow N(0, \Sigma)$$

In this case, the evaluation of the likelihood function requires the computation of trivariate normal integrals. By way of example, consider the probability of observing $(D_1 = 0, D_2 = 0, D_3 = 0)$:

$$\Pr[D_1 = 0, D_2 = 0, D_3 = 0] = \int_{-\infty}^{A_1} \int_{-\infty}^{A_2} \int_{-\infty}^{A_3} \phi_3(\varepsilon_1, \varepsilon_2, \varepsilon_3, \rho_{12}\rho_{13}\rho_{23})\, \mathrm{d}\varepsilon_3 \mathrm{d}\varepsilon_2 \mathrm{d}\varepsilon_1$$

where $A_i = \alpha_0 + \alpha_1 D_{it-1} + \beta X + \gamma O + \delta C$, ϕ_3 is the trivariate normal p.d.f., and ρ_{ij} is the correlation coefficient between i and j. We rely on the triprobit command in Stata to perform the estimations, an estimation procedure that uses the GHK (Geweke-Hajivassiliou-Keane) smooth recursive simulator to approximate these integrals and estimate the coefficients by means of simulated maximum likelihood.

In the estimations, we begin with a parsimonious specification. In the first set of estimations, we only include the firms' structural characteristics. In the second, we expand this specification and include the objectives for innovating and potential financial obstacles to innovation. Finally, in the third, for the three dependent variables we include their corresponding lags. The main results from these estimations are as follows (Tables 3 and 4).

Tables 3 and 4

The estimation results show the persistence of R&D decisions in energy firms, similar in this respect to the findings of empirical analyses of manufacturing activities. This persistence also occurs in investments in advanced machinery, which suggests that innovation in energy firms requires a continuous flow of capital expenditures to improve the technological level of their equipment.

As for the firms' characteristics, the results show significant differences across the three innovation activities. First, larger firms in this sector are more likely to invest in internal R&D and to acquire R&D services. In contrast, size is not significant in the acquisition of advanced machinery. This result confirms the importance of firm size in undertaking R&D projects, while firms of all sizes acquire advanced machinery. Second, age does not seem to have a significant influence on R&D and innovation decisions, although older firms seem to be more likely to acquire advanced machinery.

Third, public funds have a positive effect on the decision to invest in R&D within the firm. In addition, there is some evidence of a positive relation with external R&D. However, this parameter is not significant in any of the estimations of the determinants of the decision to invest in advanced machinery. This result is consistent with the orientation and objectives of public policy to support internal and external R&D activities.

The results of the estimations also reveal significant differences in the effects of the objectives of innovation on decisions to engage in the three innovation activities. R&D, both internal and external, is strongly related with environmental motives and the goal of meeting regulatory requirements. In contrast, the goal of introducing process innovations is the main factor in the acquisition of advanced machinery. Estimations using the specific process innovation objectives (as opposed to the whole category) show that increasing capacity and improving flexibility of production are the two main reasons for innovating when implementing a new or significantly improved production process.

These results suggest that R&D and the acquisition of advanced machinery address different technological and market challenges. Specifically, they highlight that R&D projects are required in order to meet the objective of reducing environmental impacts and that this goal cannot be achieved solely with the introduction of new machinery and equipment.

The results also confirm previous evidence indicating that financial obstacles are not a major barrier to innovation in the energy industry (Salies, 2010; Costa-Campi, 2014) in contrast to empirical evidence that stresses the financial obstacles that firms face in conducting innovation activities (Hall, 2002; Popp and Newell, 2012; Blanchard et al., 2013).

Finally, the results also point to the possible existence of complementarities between internal and external R&D. In the three sets of estimations, the correlation coefficients of the error terms are positive and highly significant. These results support, in line with the recent literature on R&D decisions, the existence of interdependencies between undertaking internal R&D and acquiring R&D services. In contrast, there is no such interdependence between the decisions to perform R&D and the acquisition of advanced machinery. Indeed, the decision as to whether to invest in R&D or in advanced machinery is an independent one, which again suggests that the two activities pursue different innovation objectives. However, caution must be exercised in this analysis of potential interdependence, since we do not formally test the existence of complementarities. Moreover, the correlations may also be found if there are unobservable firm-specific factors affecting R&D and innovation decisions.

4.3. Extensions of the baseline model and robustness checks

The results of the previous subsection indicate the existence of complementarities between internal and external R&D strategies, and highlight some of the factors behind the firms' decisions to perform each type of R&D activity. In this subsection, we explore some extensions of the baseline specification, so as both to expand our understanding of some of the issues associated with innovation strategies in the energy sector and to check the consistency of the baseline results.

When dealing with firm-level data, controlling for individual effects is important to capture any heterogeneity in the decision-making process of the different production units. Unfortunately, the triprobit specification used here is unable to capture these individual effects. Therefore, to test whether firm heterogeneity is relevant in the determination of the optimal innovation strategy, we estimate three independent random effects panel probit regressions – one for each decision. This approach allows us to assess whether individual effects play a relevant role in the different R&D strategies and, in particular, whether they have an effect on the complementarity between them. Table 5 presents the results. It can be seen from the table that the results obtained are consistent with the main conclusions from the baseline model and, hence, we can safely conclude that the omission of individual effects from the triprobit baseline specification is not driving the results.

As a second extension, in each equation, we include not only the lagged dependent variable to test for persistence in R&D activities, but also the lagged dependent variables of the other two dependent variables of the triprobit system. The purpose of this specification is to detect the direction of the complementarity beyond persistence, i.e., does the fact of having invested in some type of innovation activity in time period t-1 increase the probability of investing in some other type of innovation in time period t? The results, shown in Table 6, indicate first that innovation persistence by type of innovation activity is preserved when we introduce additional lagged variables. Second, the table shows that the path of complementarity between internal and external R&D expenditure indicates an increased probability of firms performing internal R&D activities in t that have invested in external R&D in period t-1. The table also indicates that there is no other direction of complementarity (or substitutability, as in the case of the coefficient of lagged internal R&D expenditure in the machinery equation) that is statistically significant. In addition, all the main results obtained in the baseline model are maintained. Two alternative explanations may account for the result. First, once firms contract external R&D, they need to invest internally in order to enhance their absorptive capacity. Second, in order to reduce the risks associated with innovation, energy firms first sub-contract R&D and, subsequently, they launch internal R&D activities.

Finally, we include a fourth equation in the multivariate probit system in order to capture a fourth strategic choice, namely disembodied technical change. This includes the acquisition – or use under license – of patents or non-patented inventions and technical knowledge to be used in the innovation process of the acquiring company. Although only 7% of the firms in our sample use this strategy, exploring how disembodied technical change is related to more traditional strategies is relevant. The results are presented in Table 7. First, it can be seen in the table that the results of the baseline model are preserved. Second, we find that persistence is also significant in the case of disembodied technical change. Third, the probability of spending on this type of R&D is mostly explained by the objective of reducing environmental impacts. Finally, we also detect strong complementarities between disembodied technical change and external R&D strategies.

In short, our extensions corroborate the robustness of the results obtained from the baseline model. This means that we can safely conclude that the persistence of R&D activities is a relevant issue in the energy sector, and that financial barriers do not represent an obstacle to innovation in this industry. In relation to a firm’s characteristics, a larger size has an effect on its probability of performing internal and external R&D. Public funds, on the other hand, affect the probability of engaging in internal R&D activities. Finally, with respect to R&D objectives, our results indicate that environmental motives and regulatory requirements mostly affect the probability of incurring spending on internal and external R&D. Environmental concerns also affect the probability of performing disembodied technical change strategies, while the process innovation objective is the main factor in the acquisition of advanced machinery.

Tables 5, 6 and 7

5. CONCLUSIONS

The energy industry is undergoing a major transformation together with substantial technological changes. As such, the sector’s investment in innovation is essential for improving energy efficiency and competitiveness and for facing the challenges of climate change.

This paper has sought to shed further light on the innovation activities of energy firms. First, we have examined the main characteristics of energy firms in relation to the innovation strategies they adopt. For this analysis, we have used the three main innovation activities: internal R&D, external R&D and the acquisition of advanced machinery. Second, we have analysed the role that different innovation objectives play in the decisions of energy firms to invest in R&D and innovation.

The main conclusions to be drawn from our econometric analysis can be summarised as follows. First, innovation investments are highly persistent. This persistence is evident not only in the case of internal and external R&D decisions but also in that of the acquisition of advanced machinery. Second, the characteristics of the energy firms that opt to engage in each of these innovation activities differ. Large firms and those in receipt of public subsidies are more likely to invest in internal R&D. In contrast, these characteristics are found not to be significant in the estimation for the acquisition of advanced machinery. Third, financial costs do not seem to be a major barrier in the energy industry to engagement in innovation.

Our results also reveal significant differences in the effects that the objectives sought by innovating have on decisions to engage in one or more of the three innovation activities. While internal and external R&D are undertaken to address environmental objectives and to fulfil regulatory requirements, the objective of developing process innovations is the main driver of the acquisition of advanced machinery and equipment.

Finally, our results point to the existence of interdependencies between undertaking internal R&D and acquiring R&D services. In contrast, the decision as to whether to invest in R&D or in advanced machinery seem to be independent; moreover, they appear to address different technological challenges.

The outcomes of this study have a number of policy implications, especially, as regards how best to foster innovation in the energy industry. First, our results suggest that public support to private R&D and the need to adhere to environmental regulations are positively related with the R&D activity of private firms. These findings are in line with reports in the literature that show that environmental and technology policies are more effective when they operate in tandem (Popp et al., 2010). Second, to face the challenges of innovation requires energy firms to combine internal and external sources of R&D and to increase their cooperation with firms in other sectors as well as with public institutions and agents.

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Table 1: Descriptive statistics

	Nº	Mean	Std. Dev.	Min	Max
Size	532	620.2	1087.9	1	7900
Age	473	33.2	33.3	0	113
Public funds	532	0.412	0.493	0	1
Foreign capital	532	0.195	0.397	0	1
Group	532	0.673	0.470	0	1
Internal R&D	532	0.523	0.500	0	1
External R&D	532	0.415	0.493	0	1
Machinery, equipment or software	532	0.237	0.426	0	1
Disembodied technical change	532	0.070	0.255	0	1
Product	532	0.387	0.488	0	1
Process	532	0.414	0.493	0	1
Environment	532	0.306	0.461	0	1
Regulations	532	0.242	0.429	0	1
Financial constraints	532	0.083	0.276	0	1

Table 2: Frequency of multi-strategy use

Nº of strategies	Freq.	Percent
0	193	36.3
1	104	19.6
2	184	34.6
3	51	9.6

Table 3: Triprobit estimation with characteristics, objectives and cost barrier

	(1)	(2)	(3)	(4)	(5)	(6)
	IntRD	ExtRD	Machinery	IntRD	ExtRD	Machinery
Size (in logs)	0.336***	0.289***	0.0185	0.339***	0.291***	0.00330
	(0.0498)	(0.0468)	(0.0467)	(0.0521)	(0.0504)	(0.0480)
Age (in logs)	-0.124*	-0.0574	0.140**	-0.0823	-0.0224	0.121*
	(0.0740)	(0.0667)	(0.0676)	(0.0775)	(0.0720)	(0.0688)
Public funds (t-1)	1.487***	0.937***	0.0953	1.504***	0.807***	-0.0742
	(0.154)	(0.140)	(0.149)	(0.170)	(0.155)	(0.161)
Foreign capital	0.487***	0.516***	0.233	0.539***	0.486***	0.157
	(0.179)	(0.165)	(0.164)	(0.192)	(0.180)	(0.169)
Group	-0.113	-0.0259	0.737***	-0.0891	-0.0888	0.694***
	(0.180)	(0.174)	(0.201)	(0.194)	(0.188)	(0.211)
Product				0.198	-0.170	0.205
				(0.190)	(0.172)	(0.164)
Process				-0.502**	0.0321	0.425**
				(0.202)	(0.173)	(0.171)
Environment				0.254	0.767***	0.0705
				(0.204)	(0.189)	(0.196)
Regulations				0.707***	0.450**	-0.156
				(0.202)	(0.186)	(0.196)
Cost barrier				0.249	0.154	-0.239
Constant	-1.592***	-1.715***	-1.042***	-1.799***	-1.954***	-0.979***
	(0.387)	(0.360)	(0.357)	(0.407)	(0.383)	(0.363)
athrho12 / 45		0.919***			0.889***	
		(0.124)			(0.131)	
athrho13 / 46		-0.111			-0.0983	
		(0.0926)			(0.0939)	
athrho23 / 56		-0.0791			-0.101	
		(0.0786)			(0.0831)	

The number of observations is 472. Standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All regressions include time-dummies to control for year-specific effects. The multivariate probit (assuming normality of the error terms) provides with ρ, a correlation parameter that informs about the covariation of the error terms of the two decisions. If ρ=0, the probability of one decision is independent of the probability of the other decision.

Table 4: Triprobit estimation with characteristics, objectives, cost barrier and lagged dependent variables

	(1) IntRD	(2) ExtRD	(3) Machinery
Lag of dependent	2.105***	1.966***	0.904***
	(0.228)	(0.194)	(0.170)
Size (in logs)	0.322***	0.218***	0.00181
	(0.0721)	(0.0705)	(0.0523)
Age (in logs)	-0.0627	0.0706	0.0213
	(0.0994)	(0.0983)	(0.0776)
Public funds (t-1)	0.588**	0.184	-0.0907
	(0.237)	(0.218)	(0.177)
Foreign capital	0.486**	0.377*	0.0816
	(0.240)	(0.221)	(0.185)
Group	0.0989	0.101	0.443*
	(0.248)	(0.246)	(0.228)
Product	0.240	-0.153	0.262
	(0.237)	(0.231)	(0.177)
Process	-0.441*	0.0814	0.478***
	(0.245)	(0.218)	(0.184)
Environment	0.484*	0.728***	-0.0174
	(0.252)	(0.232)	(0.210)
Regulations	0.483*	0.448*	-0.241
	(0.255)	(0.255)	(0.211)
Cost barrier	-0.0541	0.126	-0.249
	(0.431)	(0.433)	(0.324)
Constant	-2.706***	-2.499***	-0.450
	(0.578)	(0.543)	(0.426)
athrho12		0.879***	
		(0.225)	
athrho13		-0.0740	
		(0.105)	
athrho23		-0.127	
		(0.0971)	

The number of observations is 431. Standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All regressions include time-dummies to control for year-specific effects. The multivariate probit (assuming normality of the error terms) provides with ρ, a correlation parameter that informs about the covariation of the error terms of the two decisions. If ρ=0, the probability of one decision is independent of the probability of the other decision.

Table 5: Random effects panel probit estimation

	(1) IntRD	(2) ExtRD	(3) Machinery
Lag of dependent	2.205***	2.002***	0.859***
	(0.231)	(0.194)	(0.202)
Size (in logs)	0.319***	0.237***	0.00421
	(0.0715)	(0.0664)	(0.0540)
Age (in logs)	-0.0768	0.0526	0.0150
	(0.101)	(0.0943)	(0.0811)
Public funds (t-1)	0.524**	0.0954	-0.0767
	(0.240)	(0.213)	(0.179)
Foreign capital	0.482**	0.369*	0.100
	(0.237)	(0.213)	(0.192)
Group	0.0725	0.0764	0.444*
	(0.254)	(0.240)	(0.240)
Product innovation	0.265	-0.135	0.263
	(0.238)	(0.207)	(0.180)
Process innovation	-0.407*	0.0103	0.506***
	(0.247)	(0.209)	(0.195)
Environmental impact	0.380	0.742***	-0.0339
	(0.252)	(0.232)	(0.213)
Regulations	0.572**	0.255	-0.213
	(0.257)	(0.232)	(0.213)
Cost barrier	-0.0643	-0.0447	-0.231
	(0.419)	(0.374)	(0.327)
Constant	-2.693***	-2.502***	-0.470
	(0.590)	(0.553)	(0.444)

The number of observations is 431, and the number of firms is 59. Standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All regressions include time-dummies to control for year-specific effects. The number of observations is 431. The number of firms is 59.

Table 6: Triprobit estimation with lags for all dependent variables

	(1) IntRD	(2) ExtRD	(3) Machinery
IntRD (t-1)	2.084***	0.401	-0.310
	(0.242)	(0.251)	(0.221)
ExtRD (t-1)	0.406*	1.941***	0.157
	(0.240)	(0.211)	(0.193)
Machinery (t-1)	0.183	0.321	0.870***
	(0.256)	(0.228)	(0.170)
Size (in logs)	0.306***	0.210***	0.0120
	(0.0725)	(0.0705)	(0.0537)
Age (in logs)	-0.0589	0.0534	0.0149
	(0.100)	(0.0962)	(0.0773)
Public funds (t-1)	0.448*	-0.0362	0.0339
	(0.243)	(0.256)	(0.218)
Foreign capital	0.462*	0.364	0.0913
	(0.241)	(0.223)	(0.183)
Group	0.0399	0.0242	0.442*
	(0.259)	(0.249)	(0.228)
Product innovation	0.272	-0.162	0.275
	(0.239)	(0.228)	(0.176)
Process innovation	-0.442*	0.136	0.438**
	(0.246)	(0.217)	(0.185)
Environmental impact	0.390	0.773***	-0.0450
	(0.257)	(0.237)	(0.212)
Regulations	0.468*	0.368	-0.201
	(0.259)	(0.259)	(0.214)
Cost barrier	-0.146	0.139	-0.242
	(0.445)	(0.424)	(0.321)
Constant	-2.637***	-2.495***	-0.411
	(0.585)	(0.552)	(0.429)
athrho12		0.836***	
		(0.203)	
athrho13		-0.0572	
		(0.0978)	
athrho23		-0.107	
		(0.0868)	

The number of observations is 431. Standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All regressions include time-dummies to control for year-specific effects. The multivariate probit (assuming normality of the error terms) provides with ρ, a correlation parameter that informs about the covariation of the error terms of the two decisions. If ρ=0, the probability of one decision is independent of the probability of the other decision.

Table 7: Quatriprobit adding disembodied technical change

	(1)	(2)	(3)	(4)
	IntRD	ExtRD	Machinery	Technical
Lag of dependent	2.113***	1.845***	0.884***	0.939***
	(0.250)	(0.198)	(0.176)	(0.312)
Size (in logs)	0.359***	0.227***	0.00957	0.117
	(0.0750)	(0.0665)	(0.0541)	(0.112)
Age (in logs)	-0.0871	0.0779	0.0326	0.219
	(0.107)	(0.0964)	(0.0822)	(0.134)
Public funds (t-1)	0.484*	0.143	0.0210	-0.187
	(0.256)	(0.218)	(0.188)	(0.303)
Foreign capital	0.485*	0.268	0.133	0.132
	(0.248)	(0.218)	(0.184)	(0.331)
Group	0.0622	0.147	0.226	4.220
	(0.266)	(0.246)	(0.239)	(152.4)
Product innovation	0.415*	-0.128	0.194	0.0333
	(0.248)	(0.209)	(0.185)	(0.287)
Process innovation	-0.486*	-0.0495	0.602***	-0.438
	(0.265)	(0.211)	(0.196)	(0.340)
Environmental impact	0.555**	0.731***	-0.0521	0.758**
	(0.268)	(0.234)	(0.226)	(0.339)
Regulations	0.498*	0.380	-0.300	-0.526
	(0.270)	(0.232)	(0.223)	(0.364)
Cost barrier	-0.0976	0.0342	-0.155	-0.404
	(0.436)	(0.378)	(0.324)	(0.597)
Constant	-3.466***	-3.328***	-2.123***	-7.472
	(0.699)	(0.594)	(0.475)	(152.4)
atrho21		0.569***		
		(0.156)		
atrho31		-0.0350		
		(0.122)		
atrho41		0.183		
		(0.216)		
atrho32		-0.0230		
		(0.105)		
atrho42		0.461**		
		(0.198)		
atrho43		0.302*		
		(0.173)		

The number of observations is 398. Standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All regressions include time-dummies to control for year-specific effects. The multivariate probit (assuming normality of the error terms) provides with ρ, a correlation parameter that informs about the covariation of the error terms of the two decisions. If ρ=0, the probability of one decision is independent of the probability of the other decision.

2012

2012/1, Montolio, D.; Trujillo, E.: "What drives investment in telecommunications? The role of regulation, firms' internationalization and market knowledge"
2012/2, Giesen, K.; Suedekum, J.: "The size distribution across all "cities": a unifying approach"
2012/3, Foremny, D.; Riedel, N.: "Business taxes and the electoral cycle"
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