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Increasing Energy and Resource Efficiency through Innovation

An Explorative Analysis Using Innovation Survey Data*

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Abstract
Energy and resource efficiency innovations (EREIs) are often seen as win-win opportunities for both the economic and the environmental performance of firms. It is thus worth asking how the innovation activities and performance of firms with regard to energy and resource efficiency look like: Do EREI firms follow distinct innovation strategies? Do EREIs spur or limit innovation success? And what are the particular features of EREI firms compared to conventional innovators? Using German innovation data, we find that EREIs are determined by a larger set of technology-push and market-pull factors. On the supply side, R&D budgets, research infrastructure and networking with other firms are important factors of influence, while on the demand side increased productivity and cost reductions are decisive, as well as improved product quality. On the other hand, EREIs are complex activities which also need regulatory incentives. Although EREIs are not more successful compared to conventional in-novations, they contribute substantially to the economic success of firms.

1. Introduction

The relationship between innovation and sustainable development has received increasing attention at the national (BMU, 2008) and international level (European Commission, 2008). Both technical and organizational innovations are regarded as important elements in meeting the goals of sustainable industrial policy. Environmental innovations may contribute to both improving the environmental quality of products and increasing the resource efficiency of products and processes (Rennings, 2000). In particular, *energy and resource efficiency innovations* (hereafter: EREIs) are seen as win-win opportunities. The German sustainable development strategy has also formulated the goal of doubling resource efficiency until 2020 compared to the reference year 1994. Between 1994 and 2007 resource productivity increased only by 35%, thus additional efforts are needed to reach this goal (Statistisches Bundesamt, 2008).

From a theoretical perspective, the Porter Hypothesis underscores the view that regulations may trigger environmental innovations and postulates that in a non--optimizing world strict environmental policy may stimulate "innovation offsets", that is, environmental innovations may offset the burden and costs induced by regulations and create new markets for environmentally desirable products and processes. In a series of case studies, Porter and van der Linde, 1995 find anecdotic evi-

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dence for their hypothesis. The Porter Hypothesis was, however, met with skepticism (see Jaffe and Palmer, 1996). While it is widely agreed that potentials for cost savings and improved efficiency exist in imperfect markets, it is frequently argued that these potentials are rather limited (Ulph, 1996). Nevertheless, the Porter Hypothesis may be valid for technology options due to the secondary benefits of an innovation--friendly environmental policy: EREIs could, for instance, increase the competitiveness of an industry that is the forerunner of an international trend. If a country imposes a specific regulation on an industry that requires end-of-pipe investments, in the long run firms might have gained a competitive "first mover" advantage once other countries adapt the same regulation (Beise and Rennings, 2005). From a long--term perspective, strict environmental regulation may also improve the competitiveness of firms by stimulating resource- and cost-efficient production measures.

Due to a lack of technology-specific firm data, empirical evidence on the determinants and impacts of environmental innovations in general and on energy and material efficiency innovations in particular is scarce. By analyzing the effects of a German environmental investment program, Horbach et al., 1995 show that in some cases energy and resource efficiency measures, as opposed to end-of-pipe technologies, lead to significant cost savings. The same results are obtained in a series of case studies carried out by Hitchens et al. (2003) for European SMEs. Furthermore, Walz (1999) shows that the introduction of new, integrated technologies in order to curb CO_2 emissions may lead to an increase in total factor productivity. Finally, industry surveys conducted by Pfeiffer and Rennings (2001); Rennings and Zwick (2002); and Rennings et al. (2006) confirm that EREIs have a small but nevertheless beneficial economic impact on sales and employment.

This raises the question of how well German and European firms perform with regard to energy and resource efficiency innovations. How do energy and material costs influence their innovation behavior? And what are the distinctive features of EREI firms compared to conventional innovators?

Against this background, this paper contributes to the literature one of the very few empirical econometric studies analyzing determinants and impacts of environmental innovations in the field of energy and material efficiency. The paper is structured as follows: The next section gives some key definitions and defines EREIs as a share of all environmental innovations. Moreover, we will review the determinants of environmental innovations as discussed in the literature, with a focus on determinants of EREIs. Section 3 describes the empirical results of the innovation survey regarding the role of energy and material costs with respect to the innovation behavior of German firms. As a first step it describes our sample and data, then presents sectoral differences, explains our matching approach and presents results. Finally, section 4 summarizes the findings, particularly with regard to the relation between EREIs and the factor productivity of firms.

2. Literature Review

2.1 Definition of Environmental Innovations

Environmental innovations consist of new or modified processes, techniques, practices, systems and products which make it possible to avoid or reduce environmental damage. Environmental innovations may be developed with or without the explicit aim of reducing environmental damage. They also may be motivated by the usual business goals such as profitability or enhancing product quality. Many environmental innovations combine an environmental benefit with a benefit for the firm or user (Kemp and Arundel, 1998; Rennings and Zwick, 2002). These innovations may be divided into technical and organizational innovation, while technical ones are subdivided into product and process innovations.[1]

Process-related measures are commonly subdivided into end-of-pipe technologies and cleaner-production technologies. According to VDI 2001, end-of-pipe technologies do not constitute an essential part of the production process, but are add-on measures so as to comply with environmental requirements. Incineration plants, waste water treatment plants, sound absorbers, and exhaust-gas cleaning equipment are typical examples. In contrast, cleaner-production technologies are seen as directly reducing environmentally harmful impacts during the production process. Innovations in the area of energy and material efficiency such as reducing the energy consumption of household appliances or using less material for packaging are examples. Typically, end-of-pipe technologies, such as filters utilized for desulphurization, aim at reducing harmful substances that occur as by-products of production. In contrast, energy and resource efficiency measures generally lead to reductions of both by-products and energy and resource inputs.

Product innovations require improvements of existing goods (or services) or the development of new goods. Product innovations in machinery in one firm are often process innovations in another firm.

Finally, organizational measures include the re-organization of processes and responsibilities within the firm with the objective of reducing the impact on the environment. Environmental management systems (EMS) are typical examples of organizational measures. Organizational innovations contribute to the technological opportunities of a firm and may be supporting factors for technological innovations.

Thus, innovations in energy and resource efficiency may be regarded as a share of all environmental innovations. Examples of EREIs are new products that require a lower amount of raw materials or energy as well as new products that reduce the amount of material and energy needed during their use or modify production or distribution methods.

EREIs are characterized by a certain distinctive feature: In contrast to other environmental innovations, such as technologies to reduce noise, they are – at least partially – a private good since they reduce the costs that firms incur when paying for the use of energy and materials. However, the "double externality problem" (Rennings, 2000) still exists, since EREIs firstly produce general innovation spillovers and secondly reduce environmental burdens (such as climate change), i.e. a technological environmental external effect. Thus it may be expected that there are some private incentives for innovators to take energy and resource efficiency measures. The size of these incentives, however, may be small, perhaps too small to invest, if efficiency will probably merely increase by some additional percent after implementing the innovation. Thus the question of profitability of EREIs compared to other innovations is still open, and will be investigated in section 3 of this paper.

[1] This distinction is in accordance with the OECD Guidelines for Collecting and Interpreting Technological Innovation Data (the so-called Oslo Manuel, see OECD and Eurostat, 2005). It is also in line with the technical guidelines of the Association of German Engineers which set forth industrial environmental protection measures and their respective costs (VDI, 2001).

In the remaining part of this section, we will review the innovation literature with a focus on the general determinants of innovation decisions that may be decisive for the choice of EREIs.

2.2 The Technology-Push vs. Market-Pull Discussion

The general innovation literature intensely discussed whether technological innovation is triggered by supply-push or demand-pull factors, or by both. Often, these factors are also called technology-push and market-pull factors, respectively, with market-pull factors emphasising the role of consumer demand as well as firm and government demand as determinants of environmental innovation (Hemmelskamp, 1997). While corporate image and preferences for environmentally friendly products are typical examples of market-pull factors, technology-push factors include infrastructure measures or subsidies that promote research and development (R&D). Empirical evidence indicates that both market-pull and technology-push factors are relevant to stimulating technological progress and innovation (Pavitt, 1984). This also seems to be plausible with regard to EREIs. They may be promoted by certain supply factors such as clusters or networks, but also by market-pull factors such as increasing market prices for energy and resources.

Technology-push factors are important since it is argued in the literature that solutions often precede problems, i.e. that advanced technologies shape the demands of customers. The concept of technological capabilities was coined by Rosenberg (1974) and addresses the issue of access to knowledge about new processes and products. The important role of private R&D activities as a factor for the innovation activities of firms is supported by empirical evidence, particularly for knowledge intensive sectors (Janz et al., 2003). Financial resources and skilled employees (Czarnitzki, 2002), R&D activities, in particular activities dedicated to environmental issues, and the support of organizational structures, such as management systems, in particular EMSs, also represent important internal capabilities for successful innovation activities. Empirical evidence on the positive impact of EMSs on environmental innovation is found by Rennings et al. (2006) and Rehfeld et al. (2007), while Frondel et al. (2008) do not find any significant influence. Due to specific market situations and technology options the "modes of innovative search" and the technology choice between end-of-pipe and EREI measures differ from sector to sector (Dosi, 1988). EREIs typically include many organizational measures which may also be implemented in SMEs.

The main factor determining innovation activities in general is the expected market demand (Harabi, 1997). With regard to environmental product innovations, however, the conventional view, according to which strong marketing problems are assumed, persists (Rehfeld et al., 2007). This may be explained by the concept of customer benefit: The eco-marketing literature suggests that green product innovations which offer not only public but also private benefits such as health or taste, will generate stronger consumer demand (Kammerer, 2009). Exceptions are, for instance, products avoiding certain dangerous substances which enable them to achieve a (temporary) monopoly position in the market. Rennings et al., 2008 find a positive contribution of such innovations to the economic success of these firms. Regarding EREIs, the motivation of cost reduction may lead to stronger customer benefits and therefore generate more private demand compared to other environmental innovations.

2.3 Regulatory Push/Pull Factors

Beyond such technology-push and market-pull factors, regulation is often considered to be an important driving force for environmental innovation. The regulatory push/pull effect has been confirmed by several surveys, the latter including Cleff and Rennings (1999) and Brunnermeier and Cohen (2003). This may at least partially be explained by the public-good character of environmental innovation (Rennings, 2000) which leads to underinvestment in environmentally related R&D. It is argued that market forces alone would provide insufficient innovation incentives and that consumers' willingness to pay for environmental improvements would be too low.

Market-based instruments were regarded as superior in the early environmental innovation literature, particularly with respect to the choice of the appropriate environmental policy instruments (Downing and White, 1986; Milliman and Prince, 1989). This characterization has been confirmed for situations of perfect competition and information. Yet, under conditions of imperfect competition, results originating from general equilibrium models of endogenous growth and game theory models suggest that regulation standards may be a more appropriate method for stimulating innovation, particularly when firms gain "strategic advantages" from innovation, see Carraro (2000) and Montero (2002). Furthermore, when the endogeneity of technological progress is taken into account, as it is done in evolutionary economics as well as in the new institutional and growth theory,[2] none of the policy instruments is generally preferable. According to Fischer et al. (2003), the welfare gain of environmental policy instruments critically depends on the circumstances involved.

The analysis and comparison of single policy instruments, however, has its limitations, as in most cases several instruments from several policy areas affect innovation decisions simultaneously, and regulation, among many others, is only one factor influencing innovation decisions (SRU 2002; Jaffee et al, 2002). Against this background, Blazejczak et al. (1999) criticize "instrumentalism" in environmental policy, i.e. the assumption that the choice of policy instruments determines policy success. According to their criticism, specific instruments as such (taxes, permits) are typically overestimated in the discussion while important elements of a successful environmental policy are not properly accounted for, as there are long-term goals and targets, the mix of instruments, different policy styles and actor constellations. Arimura et al. (2007) find empirical evidence that green R&D is stimulated by the stringency of environmental policy rather than by the choice of a certain policy instrument. In a similar vein, Frondel et al. (2007, 2008) find that generally policy stringency is more important than the choice of single policy instruments.[3]

With regard to EREIs, regulation may support both supply factors (e.g. by improving infrastructure and/or public R&D) and market forces (e.g. by public pro-

[2] For a comprehensive summary, see Aghion and Howitt (1998) or Bleischwitz (2003).

[3] Popp (2002) analyzed patent applications for private energy saving technologies in the US from 1970–
–1993 and their relation to energy prices. He found that "the most significant result is the strong, positive impact energy prices have on new innovations. This finding suggests that environmental taxes and regulations not only reduce pollution by shifting behavior away from polluting activities but also encourage the development of new technologies that make pollution control less costly in the long run." Similarly as Rennings et al. (2008), Del Rio Gonzalez (2005) found that regulation pressure and corporate image were the main drivers for adopting green technologies in the Spanish pulp and paper industry.

curement or eco-labels). It may be expected that EREIs require a certain regulatory push/pull effect to enforce weak market demand.

3. EREIs: Empirical Analysis of the German Innovation Survey

3.1 Data

In recent years, innovation surveys have been standardized across countries following the recommendations by the OECD and Eurostat, laid down in the Oslo Manual in 2005. Based on this manual, Eurostat has developed a harmonized innovation survey (Community Innovation Survey, CIS) which is used in all European countries and a number of other countries on a biannual basis. In our analysis, we employ data from the German variant of this innovation survey conducted in 2005. In contrast to the standard CIS, the German variant covers a wider set of sectors and includes a larger set of variables (see Peters, 2008). The German innovation survey focuses on firms with 5 or more employees from manufacturing (including mining; NACE 10–37) and selected service sectors (energy and water supply, wholesale, transport, computing and technical services, consultancy, producer services; NACE 41, 51, 60–67, 72–74, 90, 92.1, 92.2). The survey is based on a stratified random sample with disproportional drawing probabilities. Strata with a high variance in innovation activities have higher drawing probabilities in order to increase the accuracy of weighted results (see Janz et al., 2001). Strata are industry (NACE 2-digit), size (8 size classes) and region (Eastern and Western Germany). The gross sample consisted of 29,486 firms, which is a drawing quota of 13% (given a total population of approximately 233,500 firms). The net sample of valid responses was 5,476 which is equal to a response rate of 20%. Given this low response rate – which is typical of non--compulsory firm surveys in Germany – a comprehensive non-response survey was performed. Out of a sample of almost 5,000 non-responding firms, 4,230 firms responded to this non-response survey conducted by telephone. There were no statistically significant differences in the share of innovators between the net sample (61.5%) and the non-response sample (60.5%), indicating that there is no response bias in terms of innovation activity. For more details on the 2005 innovation survey in Germany, see Aschhoff et al. (2007).

The CIS questionnaire contains a question on the effects of innovations, including an item on “reduction of material and energy costs per unit/operation”. Specifically, the survey asked about the importance of cuts in material or energy costs per unit as an effect of innovations that had been introduced in the years 2002 to 2004. The extent of effects was measured on a four point Likert scale (ranging from “not relevant” over “little” and “medium” to “large”). Firms stating that for at least one innovation introduced between 2002 and 2004 such effects were *large* are categorized as “EREI firms”. EREIs may refer to both process innovation and product innovation (the latter may occur in case a new product requires less material to produce one unit of it, or if it consumes less energy when using it).

We use this variable for identifying firms with EREIs assuming that a cut in unit costs for material and/or energy is equal to a decrease in the amount of material or energy used. This assumption may be invalid in certain cases. First, in case prices for materials or energy are falling, costs per unit may decrease without indicating higher resource efficiency. Secondly, innovations may lead to a change in the type of material used (e.g. substituting metals with plastics) or the source of energy applied (e.g. substituting electrical energy with natural gas) which may reduce the direct costs per unit, though not necessarily improving resource efficiency (particularly if prices for the newly applied materials or energy sources cover external environmental costs to a lesser extent than the materials or energy sources previously used).

It is important to note that the CIS allows for identifying EREI firms based on the achieved effect of implemented innovation projects rather than on the basis of the objectives that were envisaged at the start of innovation projects. While this is certainly an advantage of CIS data for analyzing EREI firms, one drawback is that the magnitude of the resource efficiency effect generated by innovations cannot be identified. We merely find out whether a firm had at least one EREI during a certain reference period or not. We do not know how many of such innovations have been introduced nor how large unit cost cuts with respect to material and energy costs were.

3.2 EREIs by Sectors

In the period 2002–2004, 3% of all German firms introduced innovations which significantly increased energy and/or material efficiency (*Figure 1*).[4] In absolute figures, approximately 6,600 firms in Germany (within the industries covered by the innovation survey and having 5 or more employees) may be classified as EREIs.

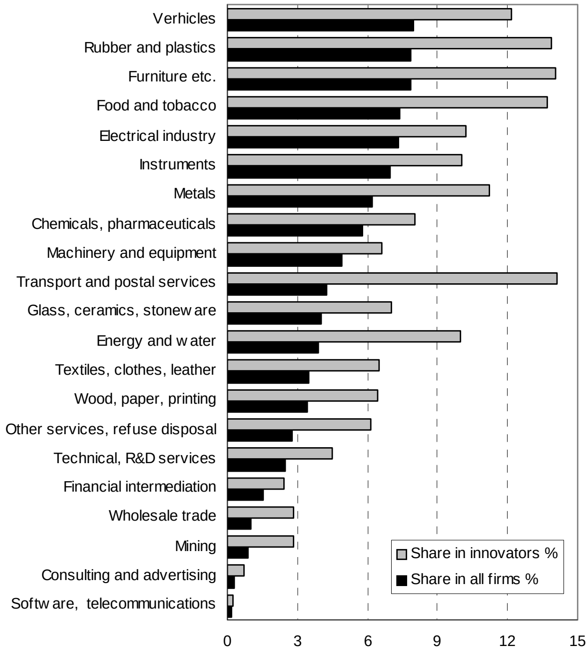
Highly innovative sectors in terms of resource efficiency are the manufacture of vehicles, the rubber and plastics industry and the furniture, sports goods, toys and recycling industry. In each of these sectors approximately 8% of all firms introduced innovations that facilitated savings of energy or material to a high extent. EREIs may be found in all other manufacturing sectors as well, though the textiles, clothing and leather industry (3.5%) and mining (1%) show very low shares. The comparably low value for wood, paper and publishing (3.5%) results from the large number of publishing firms, for which innovations increasing resource efficiency are hardly relevant because of their specific business activities. When it comes to services, transport and post as well as energy and water utilities remain ahead with a 4% share of environmentally efficient innovators. Furthermore, innovations increasing resource efficiency play a role in producer services/refuse disposal (almost 3% of all firms) and technical services (2.5%).

When looking at the share of EREIs in the total number of innovators in a sector, four sectors stand out: transport and postal services, manufacture of furniture, sports goods, toys (incl. recycling), manufacture of rubber and plastics products, and the food, beverages and tobacco industry show the highest proportion (approximately 14% each). Energy and material costs are a significant cost component in this sectors, and by introducing efficiency-enhancing innovations to cut these costs firms improve their environmental performance.

[4] All figures presented here are weighted in order to represent the weight of a responding firm in the total population of firms with 5 or more employees in the sectors covered by the innovation survey. Weighting is needed since the firms in the net sample do not represent the actual sector and size structure of the total firm population due to disproportional drawing probabilities by sector and size class. Weights have been adjusted for a likely non-response bias between innovating and non-innovating firms. For technical details of the weighting procedure, see Rammer et al. (2005).

Figure 1 Share of "Energy and Resource-Efficient Innovators" by Industry in Germany 2002–2004

Firms that in 2002–2004 introduced new products and/or processes which had significant effects on cuts in material or energy costs per unit as a percentage of all firms and as a percentage of all firms who introduced product and/or process innovations.



Notes: Firms having at least 5 employees in the sectors 10–41, 51, 60–67, 72–74, 90 in Germany. All figures are extrapolated to the total firm population in Germany.

Source: ZEW, Mannheim Innovation Panel, Survey 2005 – Calculations by ZEW.

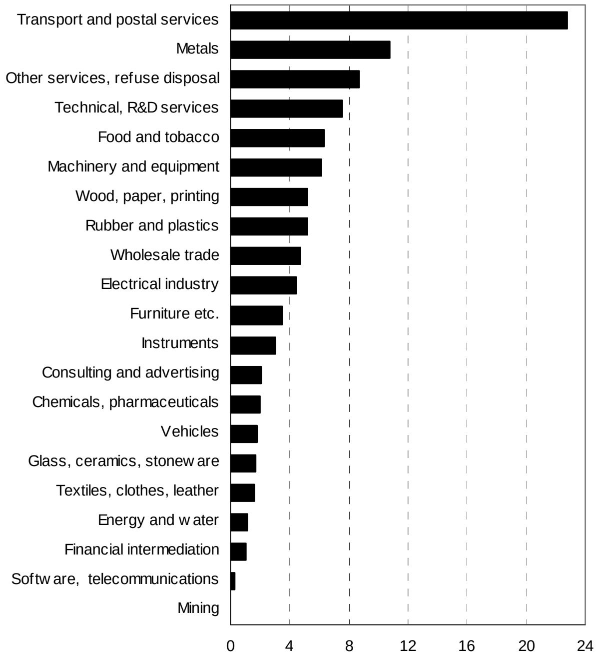
A sector classification of all EREI firms shows that 22% belong to transport services (*Figure 2*). Most transport services such as road transport, railways, airlines or water transport are highly energy intensive, and increasing the energy efficiency of vehicle fleets may significantly reduce costs. This sector is also a main target group for an environmental policy aiming at improving energy efficiency since a substantial share in all external environmental effects from energy use originates from the transport sector.

This high percentage also results from the fact that transport accounts for more than 15% of all firms in the economic sectors examined here. The number of firms with EREIs does not directly correspond to the environmental effects achieved since the latter greatly depend on the size of a firm and the impact of innovation on reducing the energy and material consumption of a firm. The proportion, however, provides information about the size of certain sectors as a target group of environmental policy which aims to increase environmental benefits through innovations.

Other sectors with a high share of EREIs among all innovators are the metals industry, producer services (incl. refuse disposal), manufacture of food, beverages and tobacco, manufacture of wood and paper products (incl. printing and publishing)

Figure 2 Distribution of "EREIs" by Industry in Germany 2002–2004

Number of firms with EREIs 2002–2004 in a certain sector as a percentage of the total number of firms with EREIs 2002–2004 across all sectors surveyed.



Notes: Firms having at least 5 employees in the sectors 10–41, 51, 60–67, 72–74, 90 in Germany. All figures are extrapolated to the total firm population in Germany.

Source: ZEW, Mannheim Innovation Panel, Survey 2005 – Calculations by the ZEW.

and the rubber and plastics industry. Technical services and manufacture of machinery and equipment also play an important role. One may assume that EREIs in these two sectors do not refer to in-house process innovations but rather to new products and services that help increasing resource efficiency for the users of these new products. Such product innovation includes engineering and technical consulting for adapting processes to higher levels of resource efficiency as well as developing new machinery and equipment with a higher level of energy or material efficiency.

3.3 Characteristics of EREIs: A Matching Approach

The key research question of our paper is about differences between EREIs and other innovators in terms of innovation input, innovation strategies, innovation output and firm performance. In order to analyze possible differences, we use a matching approach. The basic idea behind this approach is to establish two groups of firms which are almost identical in terms of variables determining a certain feature – which in our case is the introduction of an EREI – with one group showing this feature while the other does not.

Matching approaches have been developed for evaluation purposes (see Heckman et al., 1997) but are increasingly used in other fields today, including innovation analysis (see Almus and Czarnitzki, 2003; Aschhoff, 2009; Deguet, 2004; Czarnitzki and Licht, 2006; Czarnitzki et al., 2007). The specific advantage of the matching method is to compare two groups of observations for a large number of target variables by simply evaluating the means of these variables and whether there are statistically significant differences between these means.[5]

Technically, we evaluate whether EREI firms show the same value for a target variable Y as firms without EREIs do while both groups do not differ significantly in a vector $\boldsymbol{X}$ of exogenous variables that determine the introduction of an *EREI*:

$$E(Y \mid EREI = 1, \boldsymbol{X}) = E(Y \mid EREI = 0, \boldsymbol{X})$$

The vector $\boldsymbol{X}$ of exogenous variables should include variables that explain the decision of a firm to introduce an EREI. We suppose that this decision is determined by the internal resources of a firm (measured by size and a dummy variable for being part of an enterprise group), its knowledge capacity (measured by the share of graduates among all employees), its age, its industry, its location (measured by a dummy variable for a location in Eastern Germany in order to capture the specific economic and environmental situation in this part of the country), and its pressure to cut costs (measured through a dummy indicating whether price competition is the key competitive factor). It turned out that only size and industry are statistically significant for explaining the EREI status of a firm (out of a sample of innovative firms), while an Eastern German location, the knowledge capacity of a firm or its belonging to an enterprise group had little and other factors virtually no impact. We thus choose to restrict the model variables to the one shown in *Table A1 in the Appendix*. All model variables were directly taken from the CIS questionnaire (see Aschhoff et al., 2007 for a copy of the questionnaire). The probit model was estimated for innovating firms only, consequently the sample size reduces to 3,061.

The following matching procedure was applied (see Czarnitzki et al., 2004):

– Step 1: Estimating a probit model to obtain the propensity scores $P^*(\boldsymbol{X})$.

– Step 2: Restricting the sample to common support, i.e. deleting all observations of EREI firms with probabilities larger than the maximum and smaller than the minimum in the potential control group.

– Step 3: Choosing one observation from the subsample of EREI firms and delete it from that pool.

– Step 4: Calculating the Mahalanobis distance (MD) between this EREI firm i and all non-EREI firms j in order to find the most similar control observation:

$$MD_{ij} = (Z_j - Z_i)\, \boldsymbol{\Omega}^{-1}\, (Z_j - Z_i)$$

where $\boldsymbol{\Omega}$ is the empirical covariance matrix of the matching arguments Z based on the sample of all non-EREI firms.

– Step 5: The group of potential control firms is restricted to those non-EREI firms that are active in the same industry group of the EREI firm, that are located in the same region (Eastern vs. Western Germany) and that show the same innovation orientation in terms of having introduced product or process

[5] Alternatively, one could conduct regression analyses on each performance variable of interest, including EREI as one explanatory variable, which would require a separate regression for each target variable.

innovations. From the remaining sample of *j* firms, the observation with the minimum *MD* is selected. This firm is not removed from the pool of potential controls, however, so that it may be used as a control for another EREI firm.

– Step 6: Steps 3 to 5 are repeated for all observations on EREI firms.

– Step 7: The average effect of having introduced an EREI on a target variable *Y* is calculated as the mean difference of the two samples of EREI firms and control group firms (*CG*):

$$\alpha = 1/n\ (\Sigma_i Y_i^{EREI} - \Sigma_i Y_i^{CG})$$

with Y^{CG} being the control group observation for *i* and *n* is the sample size of EREI firms.

The matching was performed for $n = 226$ EREI firms that provided full information on the probit model variables. 208 individual firms from the control group were matched with the EREI firms, with 16 CG firms matched with 2 different EREI firms, and 1 CG firm matched with 3 different EREI firms. Note that all control group firms are innovators, and that the share of product innovators and process innovators is identical for both groups as is the sector composition and size distribution.

As a robustness check of our matching results, we performed the matching also for an alternative definition of EREI firms. Instead of only considering firms that report a high impact of their innovative efforts on materials and energy savings, we also added firms reporting a medium impact ("extended" EREI definition). This enlarged group consists of $n = 790$ firms.

3.4 Results of the Matching

The results of the matching with regard to innovation strategy, innovation success and firm performance are shown in *Table 1*, while *Table A1 in the Appendix* reports the results of the probit estimation (step 1 of the matching). *Table 1* lists a large number of variables *Y* for which mean differences between the samples of EREI firms and CG firms have been evaluated. The right-hand part of the table reports results for the "core" sample of EREI firms, the left-hand part for the "extended" sample. For each variable *Y*, the mean values for EREI and CG firms after the matching are shown. The number of CG firms is thus identical to the number of EREI firms, and CG firms comprise those non-EREI innovators that are most similar to EREI firms with regard to the variables used for matching. The column *α* reports the difference between the means of both samples. A two-tailed *t*-test is used to evaluate whether the mean difference is statistically different from zero.

The first two line in *Table 1* show that there is no statistically significant difference in the propensity score of EREI firms and firms of the matched control group, while there were substantial differences between EREI firms and other innovators in the full sample. The matching thus has been successful in terms of establishing a control group with similar structural characteristics to the group of EREI firms.

It turns out that EREI firms tend to show higher innovation performance both in terms of inputs and outputs, and report somewhat stronger economic results. First and foremost, they follow significantly different innovation strategies in terms of cooperation and information sourcing, and they have a much more active approach

Table 1 Mean Values of Variables on Firm Performance, Innovation Input, Innovation Activities and Innovation Output for EREI Firms and Firms from a Control Group

	Sample 1 – EREI (core)				***Sample 2 – extended EREI***			
	EREI	***CG***	***α***	***t-value***	***EREI***	***CG***	***α***	***t-value***
Propensity score before matching	0.104	0.071	0.033	10.43***	0.314	0.243	0.071	15.31***
Propensity score after matching	0.104	0.103	0.001	0.25	0.314	0.315	-0.001	-0.12
Firm performance								
Profit margin (OS)	3.60	3.71	-0.11	-0.59	3.70	3.64	0.06	0.59
Share of exports in total sales (%)	23.9	24.9	-1.0	-0.37	24.0	21.0	3.0	2.13**
Sales per employee (m€)	0.441	0.340	0.101	2.77***	0.388	0.413	-0.024	-0.72
Innovation input								
Innovation expenditure in total sales (%)	7.8	6.0	1.8	1.37	8.0	7.7	0.3	0.32
R&D expenditure in total sales (%)	4.4	2.2	2.2	2.10***	4.0	3.2	0.8	1.29
Firms with continuous in-house R&D (%)	56.3	49.0	7.3	1.47	53.0	45.8	7.2	2.70***
Innovation output								
Share of sales with new products (%)	20.4	23.3	-2.9	-1.23	22.7	22.5	0.3	0.20
Share of sales with new products (%)	6.5	4.6	2.0	1.76*	6.7	6.0	0.7	0.89
Share of firms having introduced quality improving process innovation (%)	55.7	45.5	10.2	2.10**	50.3	45.1	5.3	2.02**
Cost savings due to process innovation (%)	6.5	3.6	2.9	3.56***	5.4	3.1	2.2	5.11***
Importance of information sources								
own enterprise (LS)	2.63	2.48	0.15	2.13**	2.53	2.42	0.11	2.99***
suppliers (LS)	1.89	1.74	0.15	1.89*	1.86	1.68	0.18	4.17***
customers (LS)	2.12	2.14	-0.02	-0.26	2.15	2.11	0.04	0.84
competitors (LS)	1.66	1.48	0.17	2.04**	1.64	1.50	0.14	3.06***
universities (LS)	1.17	0.96	0.21	2.19**	1.09	0.88	0.21	4.44***
public research institutes (LS)	0.72	0.54	0.18	2.40**	0.70	0.52	0.18	4.66***
fairs, exhibitions, conferences (LS)	1.71	1.53	0.19	2.29**	1.62	1.46	0.16	3.84***
scientific publications (LS)	1.53	1.32	0.21	2.66***	1.51	1.29	0.22	5.62***
industry associations (LS)	1.07	0.78	0.29	3.60***	1.01	0.83	0.18	4.36***
Firms cooperating in innovation								
with own enterprise group (%)	20.8	14.2	6.6	1.86*	15.8	8.9	6.9	4.15***
with suppliers (%)	22.1	13.7	8.4	2.34**	18.2	12.1	6.1	3.38***
with customers (%)	23.9	15.9	8.0	2.13**	18.7	11.8	6.8	3.79***
Importance of obstacles to innovation								
too high economic risk (LS)	1.72	1.53	0.19	1.85*	1.74	1.70	0.04	0.71
lack of external funding (LS)	1.34	1.11	0.23	2.00**	1.31	1.18	0.14	2.35**
uncertain demand (LS)	1.20	1.03	0.17	1.81*	1.25	1.12	0.13	2.72***
regulations (LS)	1.34	0.99	0.35	3.37***	1.31	1.08	0.23	4.09***
red tape (LS)	1.28	0.94	0.34	3.11***	1.24	1.01	0.23	3.98***
lack of partners (LS)	0.95	0.67	0.28	3.14***	0.92	0.78	0.13	2.86***

Notes: *α* = difference of the mean value of environmentally efficient innovators from the mean value of the comparison group; ***,.**, * indicate statistically significant differences at the 0.99, 0.95 and 0.90 level, respectively. *CG*: control group. *OS*: Ordinal scale: 1 = below 0%, 2 = 0% to below 2%, 3 = 2% to below 4%, 4 = 4% to below 7%, 5 = 7% to below 10%, 6 = 10% to below 15%, 7 = 15% or more. *LS*: Likert scale ranging from 0 (not relevant) to 3 (high). Data refer to 2004 / the innovation period 2002–2004.

concerning obstacles to innovation. These results basically also hold when EREI firms are defined less restrictively by also including firms reporting a medium impact on material and energy cost reduction from their innovative efforts.

In detail, the following statistically significant differences between EREIs and control group firms have been identified (remember that all control group firms are innovators as well). They show that:

– Firms with EREIs are more productive, i.e. sales per employee are approximately 30% higher. This result does not hold for the wider concept of EREI, however.
– EREI firms spend a significantly higher share in their sales on R&D (about twice as much), while there is no statistically significant difference for the share of total innovation expenditure (which includes R&D, capital expenditure and expenditure for training, marketing and design etc.) in sales. Using the wider concept of EREI, there is no statistically significant difference in terms of R&D expenditure, but the share of firms conducting in-house R&D continuously is substantially higher.
– In compliance with the definition of EREIs, firms with EREIs achieve much higher cost savings from process innovations (6.5% average cost reduction, against 3.6% for the control group). Interestingly, they also more often achieve an improvement in the product quality from process innovation. This reveals that successful resource efficiency efforts also tend to alter product characteristics. More efficient processes have to meet higher quality standards and thus improve product quality.
– Firms with EREIs search for innovation impulses more broadly (i.e. they use more and different information sources) and assign a higher importance to most of these sources, indicating an open innovation approach (see Laursen and Salter, 2006). EREI firms more often use suppliers, competitors, universities, public research institutes, scientific publications and industry associations as a source of information, but they also rely more strongly on internal sources. This search pattern may point to more complex innovation activities that require knowledge inputs from a diverse set of sources.
– In line with this finding is a higher share of EREI firms that co-operate within their own enterprise group as well as with suppliers, while the share of EREI firms cooperating with universities, competitors or public research institutes is not higher compared to the control group. Interestingly, customers are more frequently chosen as cooperation partners by EREI firms. This may indicate a specific challenge of marketing new products with a better environmental performance, particularly if users find it difficult to evaluate the value added by an environmentally more efficient product compared to its likely higher costs.
– Firms with EREIs perceive innovation barriers more intensely. In particular, this applies to regulation, red tape, uncertain demand and a lack of co-operation partners, but also to the availability of external sources to fund innovation activities. The frequent references to legislation and bureaucratic processes as barriers suggest that at least some of the innovations improving resource efficiency had been introduced because of government regulations, which were in turn perceived as a barrier to business activities and other innovation efforts.

Another informative insight is provided by examining the areas where there is no difference between firms with EREIs and other innovators. This applies to the share of innovation expenditure in sales, to the success of product innovations, to the overall economic success of the firm in terms of profit margin, and to its human capital. These results show that firms with EREIs make use of similar resources for innovation as other innovators and all in all achieve similar economic returns. Furthermore, EREI firms are as likely to receive public funding as other innovators: when it comes to government support of innovation, there is no preference for, but also no "discrimination" against EREIs.

When comparing the left-hand part of *Table 1* with the right-hand part on the extended definition of EREI firms, one discovers a large number of similarities. For both definitions of EREI firms, the same differences with regard to information sourcing, co-operation and innovation obstacles are found. Innovation output effects tend to be very similar as well. In general, the differences between "core" EREI firms and the control group are larger than for EREI firms based on the extended definition and the CG. This is not necessarily obvious since the CG for the "core" EREI firms may include firms that fall under the category of "extended" EREI firms and thus may show a similar innovation strategy and output level. One may thus conclude that the "core" EREI firms are particular outstanding with regard to their strong focus on open innovation, the significance of innovation barriers, and the high innovation success in terms of cost savings and quality improvements. However, both innovation input and firm performance effects differ between the samples of "core" and "extended" EREI firms, showing that the "extended" definition is not simply enlarging the sample of EREI firms by those that introduce energy and resource efficiency innovations with less success or a smaller magnitude of cost saving impacts. Compared to the "core" EREI firms, the extended sample consist of less productive firms that are more strongly oriented towards international markets.

4. Conclusions

EREIs are often seen as win-win opportunities for both the economic and environmental performance of firms. In this paper EREIs are regarded as new products that require a lower amount of raw materials or energy in order to produce one unit compared to previous products as well as new products that reduce the amount of material and energy needed during their use. Another example are process innovations that modify production or distribution methods and thus make it possible to produce or deliver with less material or energy input than before.

Analyzing German innovation data, we find statistically significant differences in the innovation activities between firms with EREIs and other innovators: For example, firms with EREIs are more productive, i.e. sales per employee are approximately 15% higher. In compliance with the definition of EREI firms, their process innovations are more strongly aimed at cost reduction, since increasing energy and/or material efficiency is associated with lower costs per unit. Interestingly, they also more often aim at and achieve an improvement in the quality of processes. This reveals that successful resource efficiency efforts also tend to change product characteristics. More efficient processes have to meet higher quality standards and thus improve product quality. EREI firms also achieve higher rationalization effects of their process innovations. This clearly indicates that a main incentive for investing in higher resource efficiency are cost savings. Moreover, firms with EREIs perceive innovation barriers more intensely, and more often introduce knowledge management systems and innovative marketing improvements in the field of design and packaging.

It may be concluded that – as expected – EREIs are determined by many technology-push and market-pull factors. On the supply side, R&D budgets, research infrastructure and networking with other firms are important distinguishing factors, while on the demand side increased productivity and higher cost reductions are decisive, as well as improved product quality. On the other hand EREIs are complex activities which also need regulatory incentives. Although EREIs are not more successful compared to conventional innovations, they contribute substantially to the economic success of firms.

APPENDIX

Table A1 Results of Probit Estimations on Having Introduced an EREI

	Model 1 – EREI (core)		Model 2 – extended EREI	
	coefficient	*t* value	coefficient	*t* value
size (ln no. of employees)	0.069	3.23**	0.063	4.03***
part of an enterprise group (d)	0.073	0.90	0.152	2.64***
share of graduated employees	-0.168	-0.83	-0.275	-2.03**
location in East Germany (d)	-0.012	-0.15	-0.140	-2.42**
Mining (d)	0.099	0.19	0.637	1.99**
Manuf. of food, beverages (d)	0.750	2.38**	0.503	2.26**
Manuf. of textiles, clothing (d)	0.178	0.50	0.389	1.70*
Manuf. of wood, paper; printing (d)	0.359	1.20	0.359	1.84*
Manuf. of chemicals (d)	0.449	1.50	0.444	2.22**
Manuf. of rubber, plastics (d)	0.546	1.77*	0.452	2.18**
Manuf. of glass, ceramics, concrete (d)	0.438	1.27	0.435	1.84*
Manuf. of metals (d)	0.605	2.12**	0.412	2.17**
Manuf. of machinery (d)	0.300	1.02	0.445	2.32**
Manuf. of electrical equipment (d)	0.545	1.87*	0.479	2.46**
Manuf. of instruments (d)	0.443	1.49	0.437	2.23**
Manuf. of vehicles (d)	0.615	1.95*	0.411	1.86*
Manuf. of furniture (d)	0.374	1.10	0.502	2.20**
Energy, water supply (d)	0.457	1.39	0.075	0.32
Retail trade (d)	0.169	0.40	0.013	0.05
Wholesale trade (d)	-0.056	-0.15	0.013	0.06
Transport (d)	0.359	1.19	0.273	1.36
Financial intermediation (d)	-0.236	-0.69	-0.467	-2.13**
Computer services, telecommunication (d)	-0.666	-1.48	-0.575	-2.45**
Engineering services (d)	0.007	0.02	-0.056	-0.29
Consulting services (d)	-0.213	-0.54	-0.075	-0.33
Other producer services (d)	0.086	0.27	0.091	0.44
Constant	-2.076	-7.29***	-1.141	-6.24
No. of observations	3,061		3,021	
No. of observations with EREI = 1	226		790	
Log Likelihood	-755.1		-1619.2	
Pseudo R^2	0.06		0.07	

Note: ***,.**, * indicate statistically significant effects at the 0.99, 0.95 and 0.90 level, respectively.
Source: Mannheim Innovation Panel, 2005 survey.

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