Explaining adoption of end of pipe solutions and clean technologies
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Determinants of firms' investments for reducing emissions to air in four sectors in Sweden *

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Sammanfattning

Miljöskyddsinvesteringar är av avgörande betydelse för möjligheten att minska utsläpp och samtidigt kunna bibehålla befintliga konsumtions- och produktionsmönster. I studien undersöks vad som påverkar företag att investera i miljöskydd för att minska luftutsläpp under perioden 2000-2003. Resultaten visar att miljöskyddsinvesteringar är vanligare om företaget satsat internt på forskning och utveckling (FoU) inom miljöområdet, s.k. grön FoU. Vidare framkommer att investeringar i behandlande och förebyggande åtgärder tenderar att göras samtidigt.

BAKGRUND

Miljöskyddsinvesteringar medför allmänt sett lägre utsläpp per producerad enhet. Investeringar av nya teknologier kan också innebära teknikspridning, vilket kan medföra både att kostnaderna för miljöskyddsinvesteringar på sikt sjunker och att positiva läroeffekter realiseras.

Studien baseras på data på företagsnivå under åren 2000-2003 för massa- och pappersindustrin (SNI 21), kemiindustrin (SNI 24), metallindustrin (SNI 27) och energisektorn (SNI 40). Miljöskyddsinvesteringar utgör vanligtvis en mindre del av ett företags totala investeringar och uppgick för de fyra sektorerna till mellan 2-10 procent. I termer av industrins totala luftutsläpp kommer 65 procent av CO_2-utsläppen, 72 procent av NO_x-utsläppen och 79 procent av SO_2-utsläppen år 2000 från de fyra sektorerna, vilket också gör en analys av dessa sektorers miljöskyddsinvesteringar relevanta.

Tidigare forskning pekar på att investeringsbeslut kan förklaras av en mängd olika faktorer, och att de också verkar skilja sig åt om de utgör s.k. förebyggande eller behandlande tekniker. Den principiellt viktiga skillnaden mellan åtgärderna är att de förebyggande påverkar utsläppen vid källan (t.ex. genom byte till mindre miljöpåverkande råvaror och bränslen, slutning av processer), medan de behandlande mer handlar om att minska och att kontrollera spridning av redan uppkomna utsläpp (t.ex. genom filter, mätutrustning). [3]

[3] Förebyggande åtgärder (s.k. clean technologies) kännetecknas av att: (1) de minskar utsläpp som genereras av själva produktionsprocessen; (2) de möjliggör användning av insatsvaror som har mindre miljöpåverkan, (3) de medför helt ny utrustning och nya processer som har mindre miljöpåverkan. De behandlande åtgärderna åtgärder (s.k. end of pipe solutions) kännetecknas av att de inte påverkar själva produktionsprocessen. Deras syfte är att ta hand om utsläppen efter att de skapats genom att minska spridningen eller att mäta utsläppsnivåer.

SYFTE OCH RESULTAT

Syftet är att undersöka företagens beslut att göra miljöskyddsinvesteringar. Mer specifikt undersöks om: (1) grön forskning och utveckling (FoU) påverkar investeringar i förebyggande och behandlande tekniker; (2) företagets energikostnader som andel av omsättningen påverkar beslutet att investera i de olika typerna av miljöskyddsteknologier; (3) förebyggande och behandlande tekniker är komplement eller substitut beträffande investeringsbeslutet.

Den första frågan motiveras av att företagsspecifikt lärande i form av grön FoU kan skilja sig mellan förebyggande och behandlande åtgärder. Tanken är att ett företags utgifter för FoU relaterat till skydd för miljön ökar det interna humankapitalet inom detta område, dvs. en form av ”learning by doing”. Sannolikheten för att företaget faktiskt väljer att investera kan förväntas öka som en följd av mer kunskap om tillgängligheten av möjliga utsläppsförebyggande tekniker och dess möjliga användning samt relevans för det specifika företaget. Empiriskt testas detta genom att se om de företag som har grön FoU investerar i reningsteknologier i större utsträckning. Resultaten visar att sannolikheten för att investera i förebyggande åtgärder är större om företagen tidigare haft utgifter för FoU relaterade till miljöskydd. Denna faktor verkar dock ha mindre betydelse för investeringar i behandlande åtgärder.

Den andra frågan utgår från att tidigare forskning visat att företagens val av förebyggande och behandlande åtgärder påverkas av energikostnader. I analysen används företagens energikostnader (i förhållande till företagets omsättning) som mått på hur angeläget det är för företaget att minska dessa kostnader. Det faktum att företag med höga energikostnader typiskt sett också har stora luftutsläpp innebär att det kan förväntas att denna faktor ökar sannolikheten att investera. Resultaten visar att höga energikostnader ökar sannolikheten för investeringar i behandlande åtgärder men har ingen betydelse för förebyggande åtgärder.

Förebyggande tekniker anses ofta vara bättre än behandlande, framför allt på lång sikt, eftersom dessa minskar utsläppen vid källan. Den tredje frågan är därför miljöpolitisk relevant för att få kunskap om de olika åtgärderna tränger ut eller stödjer varandra. Om ett styrmedel som stimulerar förebyggande åtgärder också medför att behandlade tekniker väljs i större utsträckning är detta ett uttryck för att de är komplement i investeringsbeslutet, och vice versa. Risken är då mindre att miljöskyddsinvesteringar tränger ut varandra. Tvärtom gäller om de är substitut när investeringsbeslut görs. I analysen testas om företagen tenderar att göra miljöskyddsinvesteringar av båda typer samtidigt (samma år) eller inte. Resultaten visar att investeringar i förebyggande och behandlande åtgärder tenderar att göras samtidigt, dvs. att de är komplement sett till investeringsbeslutet.

KONSEKVENSER FÖR POLITIKEN

Även om det är förhållandevis detaljerad information som ligger till grund för undersökningen bör det betonas att resultaten inte ska ses som slutgiltiga sanningar. Mer information, till exempel data över en längre tidsperiod, kan ge ytterligare kunskap om miljöskyddsinvesteringars bestämningsfaktorer. Med osäkerheten om resultatens giltighet i minnet kan följande policyimplikationer lyftas fram.

För det första, resultatet att förebyggande och behandlande tekniker är komplement sett till investeringsbeslutet, indikerar att de inte tränger ut varandra utan snarare stödjer varandra. Styrmedel som stimulerar den ena typen av tekniker kommer därmed också att stimulera den andra, dvs. en form av positiv sidoeffekt.

För det andra, resultaten indikerar att omfattningen av miljöskyddsinvesteringarna ökar om fler företag skulle bedriva grön FoU. I det fall samhället bedömer att det finns behov av en större teknikspridning än idag och att företags miljöskyddsinvesteringar är en viktig del av denna, så kan en mer direkt stimulans av företagens gröna FoU vara motiverad. En central fråga är om befintliga styrmedel är tillräckliga för att *både* minska utsläpp *och* säkerställa att det sker tillräckligt med miljöskyddsinvesteringar.

Abstract

We estimate firms' probability of technological adoption based on an unbalanced firm level panel data set from four major sectors during the 2000-2003 period. Technological adoption is measured by environmental protection investments (EPIs), and we focus particularly on differences between the decisions to adopt end of pipe solutions and clean technology. We find that the probability of a firm to undertake investments in clean technologies to reduce emissions to air increases if the firm has expenditures for R&D related to environmental protection (green R&D). We also find that firm specific energy expenditures contribute in explaining investments in end of pipe solutions, while this factor is not significant for investments in clean technologies. Furthermore, the results show that the two types of technologies are complements with respect to the investment decision, which indicates that policies that stimulate investments in one type of technology tend to affect investment in the other positively as well. In conclusion, policy makers might want to contemplate environmental policy measures that stimulate green R&D in order to stimulate technological adoption.

Introduction

The purpose of this paper is to contribute to our understanding of firms' decisions to adopt abatement technologies. Investment in abatement technology is generally seen as critical for reducing emissions from industry without compromising economic growth. Moreover, in addition to reducing emissions, such investments have the potential of contributing to the diffusion of new technologies. Hence, there are two important market failures related to investments in abatement technologies that can motivate policy intervention: negative externalities in the form of emissions and positive externalities related to technological diffusion (Jaffe et al., 2005). [4]

The decision to adopt abatement technologies is a critical part of technological diffusion, and there are a number of studies of different drivers of and barriers to technology adoption. The empirical literature can roughly be divided into two parts: the effect of firm and market specific characteristics on technology adoption (see e.g. Pizer et al., 2002; Millock and Nauges, 2006; Askildsen et al., 2006; Gonzalez, 2005) and the effect of specific policies on technology adoption (see e.g. Anderson and Newell, 2002; Kerr and Newell, 2003; Frondel et al., 2004). The studies found significant effects of e.g. regulatory measures (such as taxes, technology and performance standards, information programs for technology adoption and tradable emission schemes), cost savings, management systems, plant size, self-financing capacity, and revenue. Still, some empirical findings indicate that the effect of price instruments on technology adoption is less than expected. For example, Jaffe et al. (2002) refer to studies showing that, unexpectedly, energy price changes are of less importance than adoption-cost for firms investing in energy-efficiency technologies. Furthermore, several authors argue that there might be potential differences between two types of abatement technologies: clean technologies and end of pipe solutions.[5] Clean technologies are argued to be preferable to end of pipe solutions in the long run since clean technologies reduce emissions at the source, which means that the emissions are never discharged (Porter and van der Linde, 1995; Khanna and Zilberman, 1997; Frondel et al., 2004). Frondel et al. (2004) compare the decision to invest in cleaner production technologies with the decision to invest in end of pipe solutions. Their results show that regulatory measures and policy stringency are more important for end of pipe solutions, while

[4] There is a large body of literature on different aspects of technological change. Jaffe et al. (2002) give a description of technological change, and to summarize, this can be divided into three stages (originating from Schumpeter in 1942): invention, innovation, and diffusion. The first two stages are closely related to *basic* research and development, while the diffusion stage is the actual adoption of the technology. Our focus on technological adoption does in different ways abstract from other aspects relevant for explaining technological change, such as what explains the availability of new technology (Bosetti et al. 2005), rate of technical change (Lundmark and Söderholm, 2004; Jaffe et. al., 2002; Grübler et al., 1999), the timing of technological adoption (Larson and Frisvold, 1996, van Soest, 2005), and further, studies on how uncertainty about future policies and prices affects investment decisions (see Dixit and Pindyck, 1994 for an overview, and also Diederen et al., 2003; Maynard and Shortle, 2001; Pindyck, 1993 and 2000; Insley, 2003; Hassett and Metcalf, 1993, 1995; Löfgren et al., 2007). For an overview of technological change related to environmental issues see Jaffe et al. (2003).

[5] The difference between clean technologies and end of pipe solutions is that the former affect the production investment itself and the following characteristics apply: (1) They reduce emissions and discharges generated by the production process itself. (2) They make it possible to use production inputs that have less of an impact on the environment. (3) They involve completely new equipment and processes that have less environmental impact. The distinguishing feature of end of pipe solutions is that they do not affect the production process itself. Their purpose is to take care of and treat the impact on the environment caused by the activities of the enterprise, to prevent the spread of and measure the level of pollution. Hence, an investment in clean technology increases the efficiency in input use and thereby increases production without increasing emissions. An investment in end of pipe solutions only reduces emissions without having a positive effect on the efficiency of input use (the investment does not affect the production process).

cost savings and management systems are more important for cleaner technologies. This indicates that more conventional policy instruments might have a larger impact on the adoption of end of pipe solutions (and hence potentially on diffusion of end of pipe solutions) than the adoption of clean technology (and hence potentially on diffusion of clean technology).

Hence, previous research indicates that technological adoption can be explained by numerous factors, including different explanations for the decision to invest in clean technologies and end of pipe solutions. In this paper we test whether: (1) internal learning by doing is more important for the adoption of clean technology than for the adoption of end of pipe solutions; (2) energy expenditures as share of revenues differ between end of pipe solutions and clean technology with respect to the decision to invest. Furthermore, (3) we test for complementarity (or substitutability) between end of pipe solutions and clean technologies with respect to the decision to invest.

The first hypothesis that internal learning by doing is more important for adoption of clean technologies than for adoption of end of pipe solutions is based on that R&D expenditures related to environmental protection increase human capital within the firm. Better knowledge of the availability of more complex clean technologies and knowledge about how to use them can be expected to increase the probability of adoption. We empirically test this hypothesis by quantifying the effect of "green" R&D on adoption of clean technology and end of pipe solutions.

The second hypothesis addresses the potential economic benefit for a firm adopting the technology. Based on previous research (e.g. Frondel et al., 2004), we expect that this can differ between end of pipe solutions and clean technologies. Clearly, this is not a test of the effect of environmental taxes on the diffusion of abatement technology, but rather a proxy of the firm's incentive to search for cost savings.

The third hypothesis tests whether end of pipe solutions and clean technologies are substitutes or complements with respect to the investment decision. Knowledge of this is of policy concern since if they are complements, a policy that stimulates adoption of clean technologies will also stimulate end of pipe solutions, while they will tend to crowd each other out if they are substitutes.

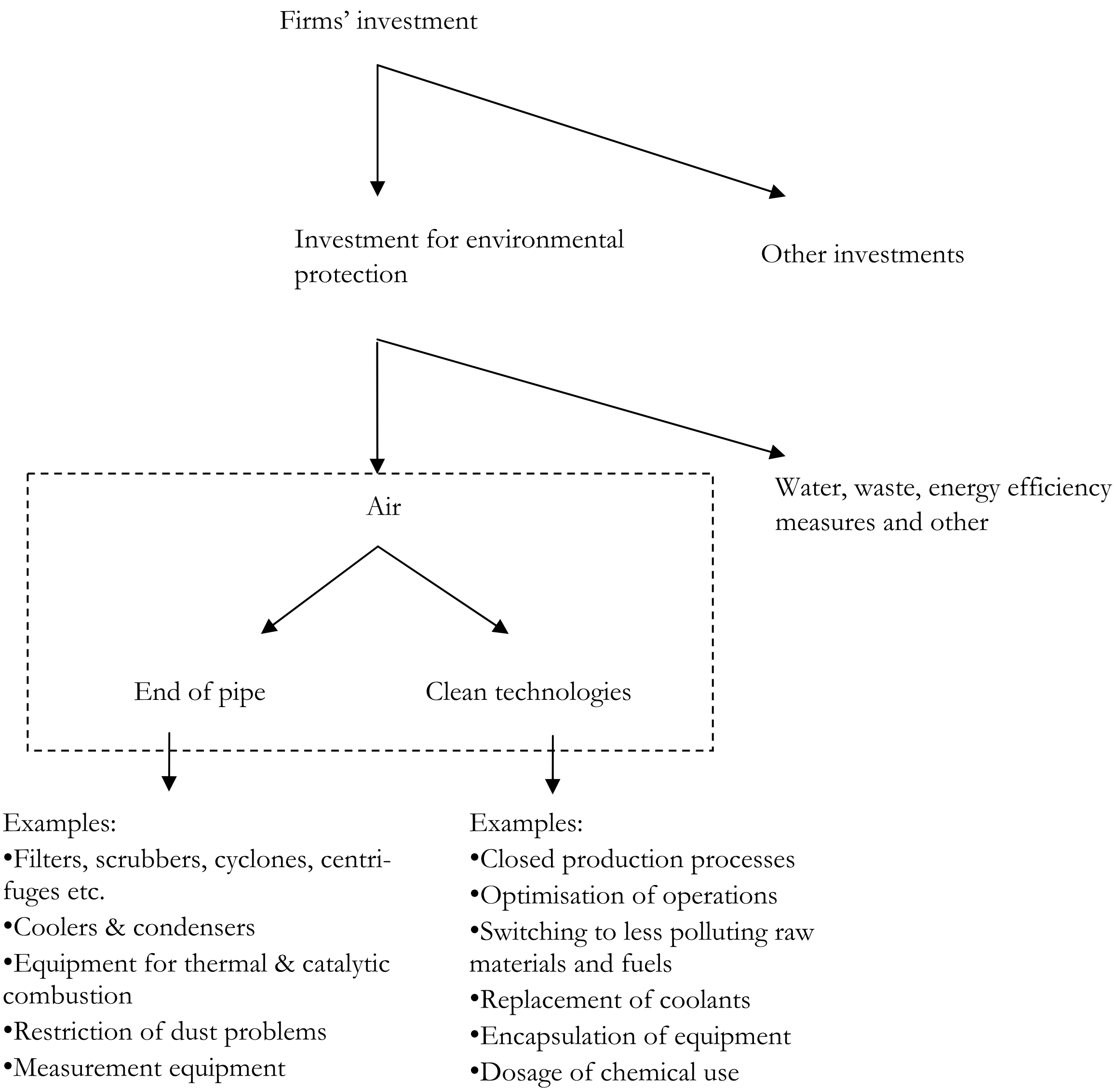
We use an unbalanced firm level panel data set on technology adoption, measured by environmental protection investments (EPI), for four sectors in Sweden between 2000 and 2003: the pulp and paper industry, the chemical industry, the manufacture of basic metals, and the energy and heating sector. EPI typically constitute a minor part of a firm's total investment, and the four sectors' total EPI roughly amounted to between 2-10 percent of total gross investments in 1999-2002 (SCB, 2004). The focus on these sectors is motivated since they are responsible for a majority of emissions to air from the Swedish industry. In terms of emissions from industry, these four sectors gave rise to 65 percent of CO_2 emissions, 72 percent of NO_x emissions, and 79 percent of SO_2 emissions in 2000 (SCB, 2006).

The paper starts with a presentation of EPI, followed by the modeling specification, and data. After presenting the estimation results, the paper ends with conclusions and policy implications.

Environmental Protection Investments

Data on technology adoption is provided by Statistics Sweden and is collected through a yearly survey on environmental protection investments (EPI).[6] EPI´s internationally agreed upon definition is, *"…the money spent on all purposeful activities directly aimed at the prevention, reduction and elimination of pollution or any other degradation of the environment"* (Eurostat, 2005). The data on EPI is categorized into different subgroups and our focus is on investments aiming at reducing emissions to air and whether the investments are categorized as clean technologies or end of pipe solutions. An overview of the categorization and subgroups of EPI, and examples of clean technologies and end of pipe solutions are given in Figure 1.

Figure 1. Description of firms' investments



[6] See Olsson and Eberhardson (2003) for an evaluation of the investment expenditures for environmental protection statistics from a data quality and collection perspective, and for an English version of the questionnaire.

Statistics Sweden's survey includes firms with more than 20 employees. Samples of roughly 1,000 firms are drawn from a population of 4,500 firms, and firms with more than 250 employees are surveyed each year. The response rate varied between 87 percent and 96 percent in 2003 (SCB, 2004), but was significantly lower in 2000 and is also lower for firms with less than 250 employees. The higher response rate in more recent years is due to the fact that the survey became better known among the responding firms, along with the fact that some of the questions became compulsory.

The empirical analysis is based on an unbalanced panel data set of 181 firms, corresponding to 477 observations, over the 2000-2003 period. 114 firms made at least one investment in either an end of pipe solution or a clean technology during the period. Of these firms, 38 belong to the pulp and paper industry, 37 to the chemical industry, 23 to the manufacture of basic metals industry, and 16 to the energy and heating sector. We treat the investments as dummy variables (one for clean technology and one for end of pipe solutions) indicating whether a firm made *at least* one investment in either an end of pipe solution or a clean technology in a specific year. In Table 1 we compare investments in clean technologies and end of pipe solutions in our sample.

Table 1. Investments in clean technologies and end of pipe solutions by sector, %

Variable	Clean technologies		End of pipe solutions	
	Non-investors	Investors	Non-investors	Investors
Pulp and paper industry	69	31	69	31
Chemical industry	62	38	61	39
Manufacture of basic metals	64	36	84	16
Energy and heating sector	64	36	66	34

As can be seen, it is just as common to make an investment in clean technology as it is to make an investment in an end of pipe solution. Around 30-40 percent of the observations in each sector (and hence of the total sample) are clean technology investments. The same proportion holds for decisions to adopt end of pipe solutions. This pattern is true for all sectors except for the basic metals industry, where investments in end of pipe solutions are more common than investments in clean technologies (only 16.5 percent of the observations are clean technology investments in this sector).

The investments in monetary terms are on average higher for investments in clean technology. However, for the basic metal industry, average investments in end of pipe solutions are higher, and in the chemical industry they are roughly the same. Furthermore, the investments in the four sectors are approximately of the same magnitude, with one clear exception: investments in clean technology in the energy and heating sector are on average significantly higher than investments in other sectors.[7] This is

[7] Average investment in clean technology: 629 kEUR in the pulp and paper industry, 258 kEUR in the chemistry industry, 425 kEUR in the basic metal industry and 2448 kEUR in the energy and heating sector. Average investment in end of pipe solutions: 407 kEUR in the pulp and paper industry, 309 kEUR in the chemistry industry, 341 kEUR in the basic metal industry, and 433 kEUR in the energy and heating sector.

largely driven by one firm that during the period made huge investments in clean technology.[8]

Table 2 summarizes the characteristics of investors compared to non-investors. Investors do in general run more energy intensive production processes and their average total expenditure on energy is higher. Furthermore, those plants on average have higher emissions of CO_2, NO_x, and SO_2.

Table 2. Average characteristics of investors and non-investors

Variable	Non-investors (67 firms)	Investors (114 firms)
Total energy use (TJ/year)	437.3	2147.2
Total energy expenditure (kEUR/year) [a]	$0.33*10^7$	$1.33*10^7$
Wage (kEUR per employee and year) [a]	30.4	33.0
CO_2 emissions (ktonnes/year)	14.0	107.4
NO_x emissions (ktonnes/year)	0.03	0.23
SO_2 emissions (ktonnes/year)	0.03	0.24
Number of observations	130	347

[a] 1 EUR=9.27 SEK

[8] Average investment in clean technology in the energy and heating sector decreases to 748 kEUR if we drop this particular firm (compared to 2448 kEUR when it is included). 1EUR=9.27 SEK. Our results, presented below, do not change significantly by dropping the firm with the huge investment.

Model specification and data

We assume that a firm chooses to invest (adopt the technology) at time *t* if the net profit of investing is positive (including future profits). If we normalize output prices to one, the decision to adopt is a function of input prices, firm characteristics, and the cost of the investment (see e.g. Jaffe and Stavins, 1995; Kerr and Newell, 2003; Anderson and Newell, 2004; Millock and Nauges, 2006 for similar modeling). The net profit of firm *i* at time *t* can be written as $\pi_{it}^* = f(P_{it}, C_{it}, Z_{it})$, where P_{it} is a vector of input prices, C_{it} is the cost of the investment, and Z_{it} is a vector of firm characteristics. If $\pi_{it}^* > 0$, then the firm chooses to invest at time *t*. Since the actual net profit, π_{it}^*, is not observed (is a latent variable), a dichotomous variable π_{it} is created such as:

$$\pi_{it} = \begin{cases} 1 \text{ if } \pi_{\text{it}}^* > 0 \\ 0 \text{ otherwise} \end{cases} .$$

The probability that a firm invests in abatement technology can be estimated by a random effects model applying maximum likelihood, where the panel-level component can be either individual firms or sectors. Furthermore, it is possible to control for both the firm and sector dimensions by applying a multilevel model where firms are nested within a sector. Several estimations were made by applying both a nested multilevel model and random effects logit model, where we varied the panel-level between sectors and firms. The main results are robust between model specifications, and the results presented in the *Estimation results* section correspond to the model with the best fit given our data: the random effects logit model controlling for sectors in the error component.[9] Before turning to our results, let us discuss the variables included in our estimations and present the summary statistics of our sample.

Firm specific learning by doing and knowledge

Expenditures for green R&D are defined as, "*Total costs for R&D, tests etc. aimed at reducing the impact of the enterprise´s operations on the environment*" (Olsson and Eberhardson, 2003, p.32). We argue that investments in green R&D increase environmentally related human capital, which in turn creates better knowledge of the availability of more complex technologies and knowledge about how to use them. Hence, such knowledge can positively affect the probability of a firm investing in more advanced technologies. We test this hypothesis by analyzing whether firm specific green R&D has any effect on the adoption of clean technology and end of pipe solutions. A variable such as investment in green R&D can be subject to endogeneity problems, and in order to address this potential problem we use a dummy for investment in green R&D in 1999 (=zero if the firm made no investment in green R&D in 1999 and =1 if the firm made a positive investment in R&D), i.e. the year *before* our first observed year. The reason for using a dummy variable can further be motivated since there can be a qualitative difference between firms that have made investments in green R&D and those that have not. A statistically significant and positive (negative) parameter indicates that

[9] Comparisons of models were made based on significance of estimated parameters and likelihood ratio tests. The estimates from the multilevel mixed-effects linear regression are very similar to the results from the random effects logit model. The firm dimension (as panel-level) was insignificant in several estimations. The results are available upon request.

green R&D implies that the firm is (not) more likely to invest in environmental protection related to air.

Potential economic benefit of investments

We test for the effect of energy expenditures in relation to revenues on the decision to invest in clean technologies and end of pipe solutions, respectively. The rationale for our hypothesis is that the larger the energy expenditures (in relation to revenues), the larger the firm's incentive to adopt a new technology that reduces emissions to air and hence also reduces the cost to the firm (energy use is the major source of emissions to air). It should be noted that the effect of energy expenditure is, clearly, not a test for the effect of environmental taxes on the adoption of abatement technology, but rather a proxy for the effect of the potential gain to a firm from adopting the technology.[10] A statistically significant and positive (negative) parameter of energy expenditure indicates that high energy costs imply that it is (not) more likely to invest in environmental protection related to air.

Complementarity between clean technology and end of pipe solutions

If end of pipe solutions and clean technologies are complements, it has important policy implications. In particular, a policy that stimulates adoption of clean technologies will also stimulate end of pipe solutions, while they will tend to crowd each other out if they are substitutes. Given the discussion regarding the superiority of clean technology to end of pipe solutions (Porter and van der Linde, 1995; Frondel et al., 2004), it is of interest to test whether the two types of technologies are substitutes or complements (or potentially uncorrelated) in the investment decision. We test for this by including a dummy in the end of pipe solution regression if the firm invested in a clean technology, and vice versa. A statistically significant positive (negative) parameter implies that they are complements (substitutes), while statistical insignificance indicates that they are uncorrelated.

Earlier investment

Since we run a random effects logit model where sectors represent the panel level, we do not control for individual firms. As already mentioned, however, controlling for individual firms does not change our results significantly. Still, there is one particular firm characteristic that might be interesting to control for, and that is earlier investments in environmental protection. We therefore create a dummy variable that is equal to one if the firm has made an investment before time t. This variable is not technology specific, i.e. it is equal to one irrespective of whether the earlier investment is an end of pipe solution or a clean technology.

Input prices

We have two firm specific input prices in our model: energy price and wage. The energy price is an annual average weighted by energy consumption. Firms have different energy prices depending on contract and their different types of energy sources. Energy prices were, for example, shown to be of importance for adoption of energy-saving technology in Pizer et al. (2002), but the effect was smaller than expected. Wages are average annual wages per employee.

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[10] It is not possible to disentangle environmental taxes from the energy price in the data. However, it is straightforward to calculate energy expenditures in relation to revenues using firm specific data on energy prices (including taxes), energy use, and revenues.

Other firm characteristics

Financial characteristics have been shown to be of importance in many technology adoption studies (see e.g. Anderson and Newell, 2002; Millock and Nauges, 2006). We control for self-financing capacity through a variable measuring firm solidity (share of equity in relation to total capital). The results by Pizer et al. (2002) and Millock and Nauges (2006) indicate that larger plants are more likely to use abatement equipment. We therefore include a size variable, measured by revenues. Other factors shown to be of statistical significance for the use of abatement equipment are controlled for through the panel dimension.[11]

Data

We match the data on EPI with firm specific data from other surveys, such as business data and data on energy prices and energy use at the firm level, derived from Statisics Sweden. Energy prices include the related taxes relevant for the firm (of which the energy tax and the CO2 tax are the most important). From the energy specific prices we calculate an annual weighted average energy price from the price and use of electricity, district heating, fossil fuel,[12] and bio fuel[13] for each firm.[14] Missing data on prices are replaced by the average price for that particular sector and year. Table 3 presents summary statistics for our sample.

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[11] Other potential candidates for being included as control variables are, for instance, emissions and vintage of the capital stock. However, for emissions the endogenity problems related to explaining EPI and high correlation between emission categories are methodologically cumbersome. The available proxy of vintage of capital stock – firm specific start year of industrial activity – is too poor of a proxy considering that start year is not the same as vintage of capital. It should also be mentioned that the proxy does not contribute with any statistical significance if included.

[12] The fossil fuel price is a weighted average of the fossil fuels used by each firm. When calculating this weighted fossil fuel price we are restricted to use fossil inputs where there are corresponding prices. The most important fossil fuels are listed below, supplemented with information about whether or not a corresponding price is available. If a price is not available, the corresponding fuel was removed from the calculation of the average price. The pulp and paper industry: fuel oil (price available). The chemical industry: fuel oil (price available), propane (no prices available), other solid fossil fuels (no prices available), natural gas (price available), refinery gas (no prices available); the basic metal industry: fuel oil (price available), propane (no prices available), blast furnace gas (no prices available); the energy and heating sector: bio fuel (price available), waste (no prices available), natural gas (price available), coal (price available).

[13] For the energy and heating sector the price on bio fuel is a weighted average of waste and bio fuel prices, while it is only the price of bio fuel for the other three sectors. Many firms in the pulp and paper industry state that they have a zero price for bio fuel, since it is a residual from production. In the creation of a weighted energy price, and hence also the estimations, we use zero price for bio fuel in the pulp and paper industry.

[14] The most important energy inputs differ among sectors. The pulp and paper industry: fossil fuel (average use 30%), electricity (average use 60%) and bio fuel (average use 9%); the chemical industry: fossil fuel (average use 32%), electricity (average use 59%), and district heating (9%); the basic metal industry: fossil fuel (average use 29%) and electricity (average use 69%); the energy and heating sector: fossil fuel (average use 50%) and bio fuel (average use 50%).

Table 3. Summary statistics at the firm level

Variable	Variable description	N	Mean	Std. Dev.	Min	Max
Investment in end of pipe solution	=1 if investment in end of pipe during a year	477	0.35	0.48	0	1
Investment in clean technology	=1 if investment in clean technology during a year	477	0.30	0.46	0	1
Energy price [a,b]	Energy price weighted by energy consumption, EUR*10^8/TJ	477	0.08	0.04	0.013	0.65
Energy expenditures	Energy use*energy price/revenues, %	477	6.90	9.53	0.02	69.45
Wage [a]	Average salary per employee and year, kEUR	477	32.3	4.95	18.7	56.1
Solidity	Equity in relation to total capital, %	477	40.5	16.7	1.38	93.35
Green R&D	=1 if firm have costs for R&D related to environmental protection in 1999	477	0.24	0.42	0	1
Firm size [a]	Revenues, EUR*10^9	477	0.21	0.42	0.002	4.10
Made investment in other EPI type	=1 if has invested in other technology	477	0.17	0.38	0	1
Earlier EPI	=1 if firm has invested in end of pipe or clean technology before	477	0.34	0.47	0	1

[a] 1 EUR=9.27 SEK.

[b] For readers more familiar with the unit of MWh, this corresponds to an average price of SEK262/MWh.

Estimation results

Table 4 below presents marginal effects of the independent variables at sample mean on the latent variable π_{it}^{*}. The parameter estimates from the random effects logit estimations are presented in Table A.1 in the appendix.

Table 4. Determinants of the probability of investments to reduce emissions to air, marginal effects (standard errors in parentheses)

	Investment in end of pipe technology	Investment in clean technology
Energy price	-0.02087	**-0.17331
	(0.06748)	(0.08023)
Wage	**0.00127	***0.00164
	(0.00063)	(0.00063)
Solidity	0.00066	-0.00100
	(0.00150)	(0.00142)
Green R&D	0.01804	***0.27599
	(0.05981)	(0.06499)
Energy expenditures	***0.00076	0.00026
	(0.00029)	(0.00024)
Firm size	**0.02372	-0.00246
	(0.01045)	(0.00661)
Made investment in other EPI type	***0.20392	***0.19203
	(0.05604)	(0.05214)
Earlier EPI	***0.14800	**0.10272
	(0.05403)	(0.05171)

*p<0.10; **p<0.05; ***p<0.01.

Our hypothesis regarding the importance of learning by doing for the adoption of clean technology is supported by our findings. Green R&D is significant for the adoption of clean technologies, while it is insignificant for the adoption of end of pipe solutions. The probability is 0.28 higher that firms invest in clean technologies if they had internal expenditures on green R&D.[15]

Furthermore, we find that energy expenditures as share of firm revenues is statistically significant for the adoption of end of pipe solutions, while this effect is not found to be of any statistical significance in explaining investment in clean technologies.

Investment decisions in clean technologies and end of pipe solutions are found to be complements, judging from the positive effect of including a dummy for clean technology investment decision as an argument for the adoption decision of end of pipe solutions, and vice versa. If a firm invests in one of the two technologies, the probability is roughly 0.20 higher that the firm invests in the ”other” technology as well.

[15] It can be mentioned that the effect of green R&D on investment in clean technologies is also found when using alternative definitions of this variable such as having green R&D at some point during 2000-2003. The statistical insignificance found for end of pipe solutions is, however, less consistent. This indicates that green R&D can be of importance even for these techniques.

Moreover, if a firm previously makes an investment in abatement technology, it affects its probability of making an additional investment positively: the probability is 0.10 higher for clean technologies and 0.15 higher for end of pipe solutions. The results do not change if we make the dummy variable technology specific.

The negative effect of energy prices is statistically significant for investments in clean technologies. We know from the descriptive statistics that firms that invest on average run more energy intensive production processes compared to those that do not invest. Hence, we expect that higher energy prices affect the probability of making an investment negatively. However, this effect is not found for end of pipe solutions. The interpretation of the effect of wage share is positive and significant, and broadly consistent with the findings of Askildsen et al. (2006). Note that solidity is statistically insignificant, even though it has the expected positive sign. We also see that the larger the firm, in terms of revenues, the more likely it is to invest in end of pipe solutions. This is consistent with earlier findings, although Anderson and Newell (2002) find no such effect (on energy efficiency improvements). Their finding is instead in line with our results regarding adoption of clean technologies: firm size (in terms of revenues) is insignificant as an explanation for investment in clean technologies.

Conclusions and policy implications

Our results provide evidence of the determinants of technological adoption and, specifically, contribute to the discussion regarding different incentives for adoption of clean technologies and end of pipe solutions. According to our results, the probability of a firm adopting clean technologies is larger if the firm has R&D expenditures related to environmental protection, while this factor seems to be of less importance in explaining adoption of end of pipe solutions. We also find that firm specific energy expenditures as share of revenues contribute in explaining adoption of end of pipe solutions, while this factor is not significant for clean technologies. Moreover, end of pipe solutions and clean technologies seem to be complements: when firms decide to invest, they are likely to invest in both types of technologies.

In empirical papers there can at best only be a close correspondence between what is empirically measurable and what is theoretically preferred. In our case we believe that we have quite unique and relatively well measured firm level data on environmental protection investments (i.e. technological adoption) and a set of relevant explanatory variables. Still, it is difficult to argue that we have all the relevant explanatory variables and that these are correctly measured in every case. With this reservation in mind, we would like to draw attention to some policy implications of our results.

First, the investment complementarity indicates that adoption of one of the technologies stimulates investments in the other. However, we also find that green R&D and energy expenditures affect investment choice of the two types of environmental protection investments differently. This indicates that in order to increase adoption of clean technologies and end of pipe solutions, different policies can be motivated. Still, even though clean technologies are, typically, preferred due to their generally higher potential of reducing emissions and the possibility to spur technological diffusion, it is hard to argue that clean technologies should always be preferred. From an environmental policy perspective it can be relevant to stimulate both types of technologies.

Still, the effects of technology type specific policies should according to our results support each other due to investment complementarity.

Second, even if we in this paper have not explicitly studied the effect of R&D policies, our results show that earlier investment in R&D is important for adoption of clean technology, supporting the notion that R&D policies (e.g. subsidies) stimulate adoption of clean technologies. The results indicate that there is a rationale for looking for complimentary policies other than the use of environmental taxes. By this we do not mean that taxes should be abandoned as a policy tool, but rather that policy measures that support the taxes can be useful.

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Table A.1. Determinants of the probability of investments in end of pipe and clean technologies that aim to reduce emissions to air. Parameter estimates from random effects logit estimation (standard errors in parentheses)

	Investment in end of pipe technology	Investment in clean technology
Energy price	-0.0948	**-0.9048
	(0.3066)	(0.4100)
Wage	**0.0058	***0.0086
	(0.0029)	(0.0033)
Solidity	0.0030	-0.0052
	(0.0068)	(0.0074)
Green R&D	0.0813	***1.2824
	(0.2678)	(0.2737)
Energy expenditures	***0.0035	0.0014
	(0.0013)	(0.0013)
Firm size	**0.1077	-0.0128
	(0.0467)	(0.0346)
Made investment in other EPI type	***0.8892	***0.9463
	(0.2398)	(0.2382)
Earlier EPI	***0.6537	**0.5168
	(0.2339)	(0.2476)
Constant	***-3.4573	***-3.5871
	(0.8990)	(1.0941)
Number of observations	477	477
Log likelihood	-264	-241
Additional panel-level variance component	-3.355	-1.857
Variance component originating from the panel-level	0.187	0.395
Proportion of the total variance contributed by the panel-level variance component	0.011	0.045
Likelihood-ratio test of rho=0 [a]	0.46	4.09**

*p<0.10; **p<0.05; ***p<0.01.

[a] The likelihood ratio test shows that the panel dimension is significant at the 25% level for the end of pipe regression while significant at the 5% level for clean technology.

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