Using Ex Post Data to Estimate the Hurdle Rate of Abatement Investments - An Application to the Swedish Pulp and Paper Industry and Energy Sector

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Abstract: We propose a method for estimating hurdle rates for firms' investments in pollution abatement technology, using ex post data. The method is based on a structural option value model where the future price of polluting fuel is the major source of uncertainty facing the firm. The econometric procedure is illustrated using a panel of firms from the Swedish pulp and paper industry, and the energy and heating sector from 2000 to 2003. The results indicate a hurdle rate of investment of almost 3 in the pulp and paper industry and almost 4 in the energy and heating sector.

JEL codes: C33, D81, O33, Q48, Q53

Keywords: option value, fuel price uncertainty, investment decision, pollution abatement, panel data, pulp and paper industry, energy and heating sector.

1 Introduction

A polluting firm usually faces a choice between different abatement possibilities ranging from simple end-of-pipe technologies, that reduce emissions at the end of the production line, to highly complex clean technology systems that necessitate production process changes. Engineering studies normally show a range of feasible investment opportunities (with positive net present values), nevertheless, firms do not invest at the predicted level. Several explanations have been advanced to explain this apparent puzzle, including errors in the measurement of costs, heterogeneity in discount rates or, still, market failures (see for example Hausman, 1979; Sutherland, 1991; Jaffe and Stavins, 1994).

Here, we develop a structural approach to measure the impact of uncertainty in the future price of polluting fuel on a plant's decision to invest in abatement technology. The proposed model will assume that the abatement investment is irreversible, since the equipment normally is firm-specific and has little re-sale value. Fuel use is a major source of air pollution and a rational firm would normally consider both the pollution impact and any impact on the energy bill in deciding whether to undertake an abatement investment. Previous research on the U.S. steel industry, for example, showed that higher fuel prices had a significant positive impact on the decision to adopt fuel-saving technologies with a potential to reduce pollution (Boyd and Karlson, 1993).

Choice of irreversible investment under uncertainty relates directly to the option value theory (McDonald and Siegel, 1986; Dixit and Pindyck, 1994), which predicts that firms may delay investment because the value of waiting to resolve uncertainty exceeds the value of owning the asset during the waiting period. Several empirical applications of the option value theory of investment have been developed in order to explain the slow adoption of technologies that reduce emissions and the environmental impact of production.[1] Most of these use simulation techniques, though, and there are few ex post studies on investment data. The main contribution of this paper is to propose a method to estimate hurdle rates for abatement

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[1] We only consider sunk costs of investment and economic uncertainty. Kolstad (1996) and Pindyck (2000, 2002) analyse the more general social trade-off between sunk costs and foregone benefits as well as economic versus ecological uncertainty.

investments from a structural option value model, using ex post data.

Following Dixit and Pindyck (1994) we derive the threshold condition on the price of the polluting fuel for which a firm facing uncertainty will decide to invest in a new abatement technology. The proposed two-step estimation procedure is based on the fact that this threshold condition holds at the time of the investment. Necessary data are firm characteristic data (such as fuel consumption, input prices, and output) before and after the investment took place as well as information on the actual capital costs of investment. The model is adapted to air pollution from fuel use and the econometric procedure is illustrated using a panel of firms from the Swedish pulp and paper industry, and the energy and heating sector from 2000 to 2003. The Swedish energy and heating sector is the primary fuel-consuming sector in Sweden, representing over 30% of total fuel consumption in Sweden (in 2003), but also the pulp and paper industry is a major user of fuels (10% of total fuel consumption in 2003). Fuel costs on average account for around 20% of the sales value in the energy and heating sector, and 2% for the pulp and paper industry, so the model's assumption of the main uncertainty being the one surrounding the future price of polluting fuel is particularly relevant for the energy and heating sector, but is still of relevance for the pulp and paper industry as well. Over the period studied here, the Swedish pulp and paper industry and the energy and heating sector contributed to a high extent to industrial-source carbon dioxide (CO_2) emissions, as well as sulfur dioxide (SO_2) emissions and nitrogen oxides (NO_x) emissions.[2] The results indicate that the presence of an option value due to uncertainty in the price of polluting fuel multiplies the standard hurdle rate for investment by 2.8 in the pulp and paper industry, and by 3.9 in the energy and heating industry. Although other explanations are possible, firms in these two sectors may thus delay adoption of irreversible abatement technologies because of uncertainty in the price of polluting fuel. We also find evidence that investment in abatement technologies has not induced a significant decrease in CO_2 emissions in any of the two sectors.

We review the existing literature in Section 2. Section 3 presents the theoretical model. The data and background are described in Section 4. The econometric specification and the

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[2] The pulp and paper industry and the energy and heating sector together account for around 50% of stationary CO_2 emissions, 40% of stationary SO_2 emissions and 35% of stationary NO_x emissions in 2003.

method we propose are described in Section 5. The estimation results are presented in Section 6, and Section 7 concludes.

2 Abatement Investment Choice under Uncertainty

In standard investment theory, under certainty, there is no option value and investment is made following the simple Net Present Value (NPV) rule: invest when the present discounted value of the investment equals or exceeds the investment cost. In the option value theory of investment, the fact that investment is irreversible and undertaken under uncertainty leads the firm to consider an additional component in its investment choice, namely the value of waiting to invest. For example, following Dixit and Pindyck (1994), uncertainty on the value of a new technology can be modeled as a geometric Brownian motion. By definition, a Brownian motion is a Markov process, which implies that only current information is useful in forecasting the future path of the process. Hence, this kind of assumption about the form of uncertainty is well suited to financial assets because of the efficient market paradigm. Uncertainty surrounding an investment project can be assumed to follow the same process, since its payoff can be defined as the difference between the firm's discounted stream of profits using the new technology and its discounted stream of profits using the existing technology. Above all, though, the assumption of a Brownian motion allows for an analytical solution to the problem.

The option value theory of investment has led to a rich literature of empirical applications, also in environmental policy analysis. In energy policy, Herbelot (1992) used it to study utilities' choice of abating SO_2 emissions by installing scrubbers, substituting input or buying tradeable emission permits. Insley (2003) also studied the choice faced by U.S. power plants to install scrubbers to control sulphur emissions, assuming that SO_2 permit prices are stochastic and explicitly accounting for the long construction process. She estimated the critical price of tradeable permits that would cause the plant owner to install a scrubber and her results on firm investment behaviour are supported by data from the U.S. experience with sulphur emissions trading. Hassett and Metcalf (1993, 1995) analyzed residential energy conservation investments assuming that energy prices follow a Brownian motion. The resulting hurdle rate for energy conservation investment (4.23) is about four times higher than the standard hurdle rate when there is no uncertainty. In agricultural policy, Purvis et al. (1995) studied the adoption of free-stall dairy housing with stochastic milk production and feed costs, and found a hurdle rate around 2. Diederen, van Tongeren and van der Veen (2003) studied the adoption of energy saving technologies in Dutch greenhouse horticulture with uncertainty in the energy price and the energy tax and found a hurdle rate of almost twice the rate predicted by net present value calculations. Khanna, Isik and Winter-Nelson (2000) analyzed the adoption of site-specific crop management with stochastic output price and expectations of declining fixed costs of the equipment. When accounting for the option value, it was preferable to delay the investment for at least three years compared to the net present value rule, for most soil quality levels. The value of waiting to adopt this technology also increased the subsidy rates required for immediate adoption. Carey and Zilberman (2002) simulated the adoption of irrigation technology when water price and supply are stochastic, and derived a hurdle rate equal to 2.33.

The bulk of these applications use simulations to study the consequences of uncertainty on irreversible investment. Exceptions are Richards (1996), who analyzes hysteresis in dairy output quota investment and Maynard and Shortle (2001) that study clean technology adoption in paper and pulp mills. Richards (1996) uses a generalized Leontieff value function to derive investment demand equations which are estimated on panel data and which confirm an option value related to investment in dairy quota licences. Maynard and Shortle (2001) use a double hurdle rate model as in Dong and Saha (1998) which involves estimating two reduced-form simultaneous equations, one for the expected net present value of the investment, the other one for the negative value of waiting to learn more before investing in a clean technology. The majority of the variables used to proxy the firm's value of waiting with the investment were found to be significant.

The only real test of the option value theory that we are aware of is Harchaoui and Lasserre (2001), who use econometric methods to test whether Canadian copper mines' decisions on capacity are compatible with the notion of a trigger price. The results indicate that real option theory does indeed describe well the actual choices made by the firms facing irreversible investment choices under uncertainty.

The contribution of this paper is to present a new method that allows the estimation of sectoral hurdle rates on ex post data. In the application presented here, we present the first estimates (to our knowledge) of hurdle rates for pollution abatement investments by Swedish industry.

3 The Theoretical Model

We use a theoretical model based on the assumption that emissions derive from inefficient use of a polluting input (Khanna and Zilberman, 1997). Consider a plant using a non-polluting input (e.g. labour or a clean fuel such as biofuel) and a polluting input (such as fossil fuel) in its production process. To simplify the analysis, assume the plant produces a single output q using only these two input factors. Production is a standard increasing but concave function of the non-polluting input l: $\frac{\partial f}{\partial l} > 0$, $\frac{\partial^2 f}{\partial l^2} < 0$. The polluting input suffers heat losses, and its effective use in the production function depends on the efficiency of the process. The production function f can therefore be written as a function of useful input with technology i, e_i: $q_i = f(l_i, e_i)$ with decreasing returns in effective input use: $\frac{\partial f}{\partial e} > 0$ and $\frac{\partial^2 f}{\partial e^2} < 0$. The cross derivative is assumed negative: $\frac{\partial^2 f}{\partial l \partial e} < 0$, implying that the polluting and the non-polluting input are substitutes.[3] The parameter h_i is used to account for efficiency in the polluting input use with technology i, where h_i is the ratio of useful input (e_i) to applied input (a_i): $h_i(\theta) = \frac{e_i}{a_i}$. θ captures firms' heterogeneity (firms are heterogenous in that the input use efficiency depends on management or other firm characteristics). Applied input represents the amount of polluting input applied in the production process, whereas effective input is the amount that is effectively used in production, net of heat losses and other inefficiencies. The production function can thus be written $q_i = f(l_i, h_i(\theta)a_i)$. A plant can choose to invest ($i = 1$) or not ($i = 0$) in a new technology that will not reduce input-use efficiency: $h_1(\theta) \geq h_0(\theta)$. It is assumed that pollution is proportional to applied input: the total amount of emissions z is a constant share γ of the applied input. Equivalently, we have the relationship

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[3] In the Swedish context it is important to have clean fuel as a substituting input to polluting fuel, since most firms in the energy and heating sector and the pulp and paper industry face this substitution possibility.

$z_i = \gamma_i a_i$. All else equal, the adoption of a new abatement technology does not increase the pollution coefficient and $\gamma_1 \leq \gamma_0$. This modeling is well adapted to carbon and sulfur emissions from energy use, but constitutes only an approximation of the creation of NO$_x$ emissions.[4]

Investing in the new technology implies a fixed cost ($I_1 = I > 0$ and $I_0 = 0$). Plants are assumed to be price-takers both in the input and output markets. P is the unit output price, w the price of the non-polluting input, and m the price of the polluting input. We consider a "general" model which incorporates an emission tax τ that is to be paid for each unit of emitted pollutant.[5] At a given time, the private profit function reads $\Pi_i(l_i, a_i) = Pf(l_i, h_i(\theta)a_i) - wl_i - ma_i - \tau\gamma_i a_i$ and the value of the investment, $v(m)$, is measured by the increase in the profit flow due to the new technology:[6]

$$\begin{aligned} v(m) &= P[f(l_1, h_1(\theta)a_1^*) - f(l_0, h_0(\theta)a_0^*)] - w(l_1^* - l_0^*) - [(m + \tau\gamma_1)a_1^* - (m + \tau\gamma_0)a_0^*] \\ &= P\triangle y^* - w\triangle l^* - m\triangle a^* - \tau\triangle(\gamma a^*) \end{aligned} \tag{1}$$

where $\triangle y^* = [f(l_1, h_1(\theta)a_1^*) - f(l_0, h_0(\theta)a_0^*)]$, $\triangle l^* = l_1^* - l_0^*$, $\triangle a^* = a_1^* - a_0^*$, and $\triangle(\gamma a^*) = \gamma_1 a_1^* - \gamma_0 a_0^*$.

In order to focus on the uncertainty in the price of polluting fuel, and to keep the model simple, we assume constant prices for the output and the non-polluting input. We also assume that there is no uncertainty on polluting emissions tax rates, but depending on data availability and the specific case studied, this assumption can be relaxed (see the Model Specification and Estimation Procedure Section below for a further discussion).[7] The future price of polluting fuel is assumed to be represented by a geometric Brownian motion with

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[4] NO$_x$ emissions are largely due to the chemical reaction in the combustion chamber between nitrogen and oxygen from the air. The extent and speed of this reaction is highly nonlinear in temperature and other combustion parameters.

[5] Throughout, we consider a unique type of polluting emissions, z. It would be straightforward to extend the model to a vector of polluting emissions.

[6] As is standard, an asterisk denotes the optimal value of the variable.

[7] For models of policy uncertainty, see Larson and Frisvold (1996) for an analysis of tax uncertainty, and Isik (2004) for an analysis of uncertainty surrounding a cost-share subsidy and its impact on technology adoption.

positive drift α_m and variance rate σ_m:[8]

$$dm = \alpha_m m dt + \sigma_m m dz_m \quad \text{where } dz_m = \varepsilon\sqrt{dt}, \varepsilon \sim N(0,1). \tag{2}$$

The expected price of polluting fuel thus grows at a constant rate α_m.

We start by describing the investment choice when there is no uncertainty ($\sigma_m = 0$). The present discounted value (at the time of the investment, T) of the increase in profit flows over all future time periods is:

$$V(m) = \int_T^{\infty} \big[P\triangle y^* - w\triangle l^* - m_T e^{\alpha_m (t-T)} \triangle a^* - \tau\triangle(\gamma a^*)\big] e^{-\rho(t-T)} dt,$$

where ρ is the appropriate discount rate. The present value can be written

$$V(m) = \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{\tau\triangle(\gamma a^*)}{\rho} - \frac{m_T\triangle a^*}{\delta}. \tag{3}$$

where $\delta = \rho - \alpha_m$. The parameter δ is defined as the difference between the firm's cost of capital and the drift rate of the price of polluting fuel. It is necessary to assume that the discount rate exceeds the drift in the polluting fuel price in order for the option to invest to be exercised. The data we use confirm this assumption (the drift rate is estimated at 0.0240 and ρ is around 20%).

The present value of the investment depends on the price of polluting fuel through the term $(\frac{m_T\triangle a^*}{\delta})$. Given that δ is positive, $V(m)$ is an increasing [decreasing] function in the polluting fuel price when polluting fuel input use decreases [increases] following the investment. In the first case, an increase in the price of polluting fuel leads to an increase in the present value of investment, whereas in the second case, it is a decrease in the price of polluting fuel that will increase the present discounted value of the project.

Without any uncertainty, the firm would invest when the expected present discounted value of the investment exceeds the cost of the investment, here assumed constant, i.e., if $V(m) \geq I$ which is equivalent to a trigger price for investment, $m_T = \bar{m}$, equal to

$$\bar{m} = \frac{\delta}{\triangle a^*}\Big(- I + \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{\tau\triangle(\gamma a^*)}{\rho}\Big). \tag{4}$$

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[8] Berck and Roberts (1996) use time-series methods on data from 1946-1991 which tend to indicate that natural resource prices are random walks. Harchaoui and Lasserre (2001) tested the sensitivity of their results with regard to the assumption of a Brownian motion by also simulating the trigger price assuming that output price follows a mean-reverting process. This did not change significantly their results on the option value.

All else equal, if $\triangle a^* > 0$ (i.e. polluting fuel consumption is higher with the new technology) then investment will be valuable if the price of polluting fuel is less than or equal to $\bar{m}$. If $\triangle a^* < 0$ (i.e. polluting fuel consumption is lower with the new technology) then investment will be valuable if the price of polluting fuel is greater than or equal to $\bar{m}$.

Let us now compare the investment decision under the NPV rule with the investment decision when the uncertainty around the future price of polluting fuel is taken into account. The new investment threshold can be derived following Dixit and Pindyck (1994). A new term, called the hurdle rate (here $\beta_1/(\beta_1 - 1)$), enters the equation. The trigger price for investment changes to $\tilde{m}$ (derivation in Appendix):

$$\tilde{m} = \Big(\frac{\beta_1}{\beta_1 - 1}\Big)\frac{\delta}{\triangle a^*}\Big(- I + \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{\tau\triangle(\gamma a^*)}{\rho}\Big), \tag{5}$$

where $\frac{\beta_1}{\beta_1 - 1} \geq 1$.

If $\triangle a^* > 0$ investment will be valuable if the price of polluting fuel is less than or equal to the new trigger price $\tilde{m}$, whereas if $\triangle a^* < 0$ (i.e. polluting fuel consumption is lower with the new technology) then investment will be valuable if the price of polluting fuel exceeds or equals $\tilde{m}$.

This new trigger value for investment depends on a term based on the discount rate and the parameters of the stochastic process:

$$\beta_1 = \frac{1}{2} - \frac{\alpha_m}{\sigma_m^2} + \sqrt{\Big[\frac{\alpha_m}{\sigma_m^2} - \frac{1}{2}\Big]^2 + \frac{2\rho}{\sigma_m^2}} \quad > 1. \tag{6}$$

A comparison of the two trigger prices for investment (Equations 4 and 5) shows that irreversibility and uncertainty imply that the polluting fuel price has to be multiplied with $\beta_1/(\beta_1 - 1)$ for investment to take place in the case when the new technology leads to a reduction in polluting fuel consumption.

4 Background and Data

For the purpose of this paper, we consider firms belonging to the pulp and paper industry and the energy and heating sector, for which fuels are crucial inputs in the production process. Our data set is an unbalanced panel over the 2000-2003 period of 58 firms from the pulp and paper industry and 15 firms from the energy and heating sector. Data on firms' investment in air pollution abatement technology were collected at Statistics Sweden. This agency has administered the statistics on investment in air pollution abatement since 1981. The quality and method has changed over time, though, and comparable data is available only from 1999. The investment in air pollution abatement technology is defined as "…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). Statistics Sweden's survey includes firms in the manufacturing industry and the energy and heating sector 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 firm ID numbers allow to match the existing firm-level data with business data, such as turnover, value added, labor, and data on fuel consumption and fuel prices at the firm-level. More specifically, we have information on firms' consumption and purchases of 12 different types of fuels (among them oil, coal, coke, natural gas and different types of biofuel) as well as the annual average price of each fuel. From these data, we compute an annual average weighted price of polluting fuel as well as an average annual weighted price of clean (bio) fuel for each firm (in EUR per TJ).

The price of fuel includes all relevant taxes, among which the energy tax and the tax on CO_2 emissions are the most important. The energy tax and the CO_2 tax are paid based on the amount of fuel used.[9] These taxes are levied on fossil fuels such as oil, coal, coke and natural gas while biofuels are in general exempt from energy tax.[10] The use of prices including taxes has implications regarding the specification and estimation of the equation of interest (5), which is discussed further below in the Model Specification and Estimation Procedure Section.

Table 1 presents descriptive statistics of the overall sample. Over the period covered by the

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[9] The CO_2 tax varied during 2000-2003. The yearly levels are available from the Swedish Energy Agency for each polluting fuel. As an example the CO_2 tax for oil was: 1,058 SEK/m^3 in 2000, 1,527 SEK/m^3 in 2001, 1,798 SEK/m^3 in 2002, and 2,174 SEK/m^3 in 2003.

[10] Firms pay the sulfur tax in relation to the fuel used and sulfur content and the NO_x fee which is refunded back to firms in relation to production. In 2003 the total CO_2 tax payment in the pulp and paper sector was 45 million EUR, which can be compared to the total energy tax of 4.5 million EUR and the total sulfur tax paid by the sector of 2 million EUR. Corresponding figures for the energy and heating sector are 143 million EUR in total CO_2 tax, 31 million EUR in total energy tax and 14.5 million EUR in total sulphur tax (Statistics Sweden).

data, there were 84 decisions (68 in the pulp and paper industry and 16 in the energy and heating sector) by 47 different firms (36 firms in the pulp and paper industry and 11 firms in the energy and heating sector) to invest in abatement technology among the 73 firms. Investments in our sample either belong to the end-of-pipe category (for example filters, scrubbers and centrifuges) or to the clean technology category (above all equipment involving switching to less polluting raw materials and fuels). In the empirical application, the method will be illustrated on investments in clean technology affecting CO_2 emissions, consisting mainly of different types of biomass (fueled) heating plants (to a large extent doing reconstructions and conversions of furnaces from oil combustion). Table 2 provides the average characteristics of firms that invested and firms that did not invest in abatement technology. As expected, the plants that invested run more fuel-intensive production processes, and their average fuel cost is higher. Those plants also have on average higher CO_2 emissions.

5 Model Specification and Estimation Procedure

Under the assumption that the option value model is a correct representation of firms' choices, Equation (5) specifying the threshold price necessarily holds at the time when the firm undertakes the investment. Because the price of polluting fuel includes emission taxes in our data, we need to estimate a simplified version of Equation (5):

$$\tilde{m} = \Big(\frac{\beta_1}{\beta_1 - 1}\Big)\frac{\delta}{\triangle a^*}\Big(-I + \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho}\Big), \tag{7}$$

where $\tilde{m}$ is the price of polluting fuel including emission taxes.[11] This specification remains valid as long as we assume that there is no change in the emission coefficient, γ (see Appendix). This assumption holds only for clean technology investments, where emissions decrease because of increased efficiency in input use.[12] We propose to estimate Equation (7) taking the hurdle rate, $\beta_1/(\beta_1 - 1)$, as an unknown parameter to be estimated. This equation will be estimated on the sub-sample of firms which actually invested in clean technology during

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[11] An artifact from this simplified version, where price of polluting fuel includes emission taxes, is that we have a combination of price and policy uncertainty. That is, the hurdle rate results from the uncertainty in polluting fuel price *including* taxes.

[12] In terms of the theoretical model, $h_1 > h_0$ and $\gamma_1 = \gamma_0 = \gamma$.

the period covered by the data, using the observed variables in the year the investment took place. We will then test whether the hurdle rate is equal to or larger than one. The latter case would imply that there is a positive option value related to the investment.[13] The proposed estimation procedure requires the following set of data:

- $\tilde{m}$, the price of polluting fuel (including taxes) in the year that the firm undertakes the investment.
- $\delta = \rho - \alpha_m$, in our case the difference between the firm's cost of capital and the positive drift rate of the price of polluting fuel. The drift rate of the fuel price can be calculated by testing for, and then fitting, a Brownian motion to a long time series of fuel price data (in our case price inlcuding tax).[14]
- I, the total investment cost.
- $\triangle a^*$, i.e. the difference between polluting fuel use with the new technology compared to polluting fuel use if the old technology were still in place at the time of investment. We observe polluting fuel consumption in the year when the new technology was adopted (a_1^*), but do not know what the polluting fuel use would have been if the firm had not invested in the new technology (a_0^*). The latter can be predicted, though, from the data as long as some firms invested during the period of observation. The impact of the investment decision on fuel use can be derived from the estimation of a model fitting polluting fuel use, using the whole sample of firms. The coefficient of the investment decision indicator in combination with the data from the year when the firm has adopted the new technology enables us to predict the polluting fuel consumption if the firm had not invested in the new technology, $\hat{a}_0^*$.
- Likewise, $\triangle l^*$ [resp. $\triangle y^*$] represents the difference between clean fuel use [resp. output level] with the new technology and with the old technology. We will follow the same

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[13] In their test of the option value theory of investment, Harchaoui and Lasserre (2001) calculate the hurdle rate $\beta_1/(\beta_1 - 1)$ using Equation (6) and test whether the coefficient of this term equals one in a log-log specification under which the uncertain price is regressed on the hurdle rate and all other variables in the theoretical equation (capacity choice, discount factors, etc.).

[14] If historical fuel price data are not available at the firm level, one can use national fuel price data instead.

procedure as for predicting the difference in polluting fuel use, using the estimated coefficient of the investment decision indicator in a model fitting clean fuel consumption [resp. output].[15]

In this particular case, it is not necessary to estimate the change in polluting emissions after the investment took place since emission taxes are included in the price of fuel (and hence the change in emissions does not show in the right-hand-side term of Equation (7)). However, we propose to consider an equation fitting polluting emissions in order to test for the impact of the new technology on pollution in the two sectors.

More efficient parameter estimates will be obtained by estimating a system of equations fitting simultaneously polluting fuel use, clean fuel use, polluting emissions, and output. A general form of the system is:

$$\begin{cases} a_{it} = f_1(X'_{1,it}, \beta_1) + \varepsilon_{1,it} \\ l_{it} = f_2(X'_{2,it}, \beta_2) + \varepsilon_{2,it} \\ z_{it} = f_3(X'_{3,it}, \beta_3) + \varepsilon_{3,it} \\ y_{it} = f_4(X'_{4,it}, \beta_4) + \varepsilon_{4,it} \end{cases} \tag{8}$$

where i and t are respectively the index for firm and year, and f is an unknown function of the set of explanatory variables ($X_{k,it}$, $k = 1, \ldots, 4$) and parameters (β_k, $k = 1, \ldots, 4$). The sets of explanatory factors ($X_{k,it}$, $k = 1, \ldots, 4$) should include a variable measuring the total amount of the investment by firm i in year t. The usual idiosyncratic error term, $\varepsilon_{k,it}$, $k = 1, \ldots, 4$, is assumed of mean 0 and homoscedastic in each equation, but it may be correlated across equations (i.e. $E(\varepsilon_{k,it}\varepsilon_{k',it}) \neq 0 \quad \forall k, k'$). A three-stage-least squares (3SLS) estimator is thus recommended.

The only parameter of interest at this stage is the estimated coefficient of the investment variable in each equation. This parameter is used to compute the predicted changes in polluting fuel consumption, $\widehat{\triangle a^*}$, clean fuel consumption, $\widehat{\triangle l^*}$, and output, $\widehat{\triangle y^*}$. To make it clear, let us

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[15] If the data contain information on turnover (Py^*) only and not on output separately (y^*), then $\triangle(Py^*)$ can be estimated in place of $P\triangle y^*$.

describe how we compute the predicted difference in polluting fuel use for firm i that adopted a new abatement technology. In year t, polluting fuel consumption with the new technology, a^*_{i1}, is observed. We predict the change in polluting fuel use with and without the new technology, $\widehat{\triangle a^*_i}$, as follows:

$$\widehat{\triangle a^*_i} = \frac{\partial f_1(X'_{1,it}, \hat{\beta}_1)}{\partial I_{it}} I_{it}.$$

The same procedure is applied to compute the predicted changes in clean fuel consumption, $\widehat{\triangle l^*}$, and output, $\widehat{\triangle y^*}$. These predicted changes are used in the second-stage model where the hurdle rate b $(= \beta_1/(\beta_1 - 1))$ is the only unknown parameter. By applying Ordinary Least Squares (OLS) on the model:

$$\tilde{m}_{it} = b\frac{\hat{\delta}}{\widehat{\triangle a^*_{it}}}\Big(- I_{it} + \frac{P_{it}\widehat{\triangle y^*_{it}}}{\rho} - \frac{w\widehat{\triangle l^*_{it}}}{\rho}\Big) + u_{it}, \qquad (9)$$

we get a consistent estimate of b. The error term u is assumed of mean 0 and constant variance. This model is estimated on the sub-sample of firms i which have invested in clean technology at time t. If our specification is valid, the estimated hurdle rate, $\hat{b}$, should exceed or equal 1. A simple *Fisher*-test will be applied to check whether the hurdle rate is significantly different from 1.

6 Estimation Results

6.1 First stage: estimation of the system of simultaneous equations

We retain a three-equation system, fitting polluting fuel consumption, clean fuel consumption, and CO_2 emissions. Several systems (combining different equations with different functional forms and sets of explanatory variables) have been estimated and the system presented here corresponds to the best fit obtained with our data.[16] The equation fitting output (we used turnover since we do not observe output in our data) was removed from the system because of its low fit. This result may not be surprising, though, since investment in air pollution abatement represents on average a very small share of firms' total investments (between 5-10% of total gross investments in 1999-2002, SCB 2004). The lin-lin functional form was found to

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[16] In particular, we also tried incorporating equations for other pollutants (SO_2 and NO_x). Comparison of models was made based on the R-square of each equation, and significance of the estimated parameters.

perform the best. We finally retain the following sets of explanatory variables in the model for polluting fuel consumption, clean fuel consumption, and CO_2 emissions in year t, respectively: $X_{1t} = X_{2t} =$ (price of labour in year t, price of polluting fuel in t, price of clean fuel in t, net turnover in t, pollution abatement investment in $t-1$) and $X_{3t} =$ (polluting fuel consumption in t, clean fuel consumption in t, number of employees in t, net turnover in t, pollution abatement investment in $t-1$). The investment variable is lagged one year in order to avoid endogeneity bias. We allow the coefficient of the investment variable to vary between the two sectors and types of investment (clean technology and end-of-pipe), in each equation of the system, and we incorporate unobserved firm-specific effects, $\eta_{k,i}$, $(k = 1, \ldots, 3)$, that are assumed to be fixed parameters that enter additively in each equation. To control for any correlation between the firm-specific unobservable effect, $\eta_{k,i}$, and the explanatory variables, we estimate the system using three-stage least squares (3SLS) on the equations where the Within transformation has been applied.[17] The Within transformation eliminates the firm-specific effects $\eta_{k,i}$, $(k = 1, \ldots, 3)$, and the resulting 3SLS estimator is thus robust to any form of correlation between the firm-specific effects and the explanatory variables.

Also, because some firms do not use any clean fuel, we face censoring problems. To estimate simultaneous equations with censored variables, we use the approach by Shonkwiler and Yen (1999). The equation describing consumption of clean fuel, after Within transformation, reads:

$$\bar{l}_{it} = \Phi(q_{it}\hat{\nu}) f_2(\bar{X}'_{2,it}, \beta_2) + \xi\phi(q_{it}\hat{\nu}) + \bar{\varepsilon}_{2,it},$$

where $\bar{l}_{it}$, $\bar{X}'_{2,it}$, and $\bar{\varepsilon}_{2,it}$ correspond to l_{it}, $X'_{2,it}$, and $\varepsilon_{2,it}$, after the Within transformation has been applied. q_{it} is the set of explanatory factors for the decision to use clean fuel at time t, and ν is the corresponding vector of coefficients obtained from estimation of a Probit-type model by Maximum Likelihood. $\Phi(q_{it}\hat{\nu})$ and $\phi(q_{it}\hat{\nu})$ are respectively the univariate standard normal cumulative distribution and probability density functions computed over Probit results. ξ is an unknown parameter to be estimated. The set of explanatory variables in the Probit-type model is the following: sectoral dummy variables, net turnover, solidity, and

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[17] The Within operator transforms each variable in deviation from its mean over the period: in place of any variable x_{it} in the model, we use $x_{it} - \bar{x}_i$ where $\bar{x}_i = 1/T_i \sum_{t=1}^{T_i} x_{it}$, T_i being the number of years firm i is observed in the sample.

productivity.[18] We report the 3SLS estimation results of the system in Table 3.

These estimation results confirm some typical ex ante hypotheses on fuel use and emissions: polluting fuel use is found to decrease (increase) when the price of polluting fuel (clean fuel) increases, showing that the two types of fuels are substitutes. The sign of the price of clean fuel in the clean fuel equation is positive which may be surprising at first sight. This may be explained by the rapid (and maybe unexpected) increase in demand for biofuel over the period studied (approximately 47%), which most likely affected the price positively. The insignificance of the price of polluting fuel on clean fuel demand could on the other hand be explained as follows: if a firm has already invested in a biofuel furnace, then it is unlikely to switch back to a coal burner if there is some price changes (like cheaper dirty fuel), because the long term trend is that the relative price of dirty fuel will increase in Sweden (and elsewhere) because of climate change policies. Our results also confirm that a higher fuel consumption translates into higher polluting emissions (CO_2 emissions here). The coefficients of interest at this stage are the coefficients of the investment variable, and we separate between investments made in clean technology and end-of-pipe solutions. We find that investing in clean technology has significantly decreased the consumption of polluting fuel in the energy and heating sector, while investments in end-of-pipe solutions have decreased the consumption of polluting fuel in the pulp and paper sector. Our results also reveal that, in the pulp and paper sector, the investments in end-of-pipe solutions have induced an increase in the use of clean fuel. We do not find evidence of such an effect in the energy and heating sector. If we retain the 15 percent level of significance, we find evidence of a significant effect of the investment in end-of-pipe solutions in the energy and heating sector on CO_2 emissions, but surprisingly the effect is positive. The aim of this paper, though, is not to analyse the effect of investment in abatement technologies on CO_2 emissions, and we should interpret this result with caution.[19]

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[18] Estimation results for the Probit model are not shown here but are available from the authors upon request.

[19] In our data we do not only have investments affecting CO_2 emissions, but also NO_x and SO_2. These investments could potentially affect CO_2 emissions, and we do not control for that. Another reason could be the so called rebound effect, i.e., when the relative price of the polluting input decreases its use increases, but this remains to be studied more in depth.

6.2 Second stage: estimation of the hurdle rate

The predicted differences in polluting fuel use, $\widehat{\triangle a^*}$, and clean fuel use, $\widehat{\triangle l^*}$, are used in the computation of the right-hand-side term of Equation (7).[20] We need also a measure of δ, which is defined as the difference between the risk-adjusted rate of return ρ, and α_m, the drift in the price of polluting fuel. Estimates of ρ are computed using sector-specific data on economic/business indicators (source: Statistics Sweden). Because information on economic indicators were only available by quartile, we were only able to derive an upper bound of the rate of return. This upper bound was estimated at 0.237. In what follows we will test the sensitivity of our results to various levels of the rate of return. α_m is estimated using the method proposed by Slade (1988) (see also Harchaoui and Lasserre, 2001). We use annual data on oil prices (including taxes) over the 1980-1999 period (source: OECD).[21] The geometric Brownian motion is approximated by

$$\triangle m_t = \alpha m_t + \nu_t, \qquad t = 1, \ldots, T, \tag{10}$$

where $\nu_t = \sigma m_t \varepsilon$ is heteroscedastic. The null hypothesis of a random walk cannot be rejected on our data. The estimated α (0.0240) is used as a proxy for α_m.

We estimate Equation (9) on the sub-sample of the 61 investment decisions in clean technology, using observations at the time of investment. We allow for sector-specific hurdle rates. The overall fit of the model is good since the adjusted R-square is 0.82. The estimated hurdle rate is found greater than 1 for both sectors, which confirms the validity of our approach. The hurdle rate is estimated at 2.84 (standard error 0.1880) in the pulp and paper sector and 3.89 (standard error 0.5072) in the energy and heating sector.[22] $Fisher$-tests indicate that the two coefficients are significantly greater than 1 (at the 1 percent level). Hence our results show that firms in the pulp and paper industry and energy and heating sector have delayed their abatement investment decisions over the 2000-2003 period because of uncertainty

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[20] We consider only the coefficients that are significant at the 15 percent level. More precisely, the change in clean energy in the energy and heating sector is considered to be 0.

[21] Historically in Sweden, oil price and natural gas price (oil and gas are the two main fossil fuels) have covaried. Hence, the oil price seems an appropriate proxy for the price of polluting energy in this country.

[22] Because this procedure involves two steps, more accurate standard errors could be obtained using bootstrap techniques.

on the future price of polluting fuel (including taxes). The estimated hurdle rates are in the range of what has been found in previous studies (based on simulation methods): 4.23 (Hassett and Metcalf, 1993), 2.28 (Purvis et al., 1995), and 2.33 (Carey and Zilberman, 2002). These figures are not fully comparable to ours, though, as they were derived from simulation studies, and were concerned with different countries, sectors, and sources of the main uncertainty facing the firm.

We now check the sensitivity of the hurdle rate estimates to the cost of capital, ρ. Because the cost of capital that we used could be considered as an upper bound for the Swedish industry, we test how hurdle rate estimates would change with lower costs of capital. We re-estimate the model in two cases: in the first case ρ is assumed lower by 10 percent ($\rho = 0.213$), and in the second case ρ is assumed lower by 20 percent ($\rho = 0.190$). As predicted by the theoretical model, a decrease in the cost of capital increases the estimated hurdle rates. When ρ is decreased by 10 percent, the hurdle rate is estimated at 3.19 in the pulp and paper sector and 4.38 in the energy and heating sector (in both cases significantly different from 1). When ρ is decreased by 20 percent, the hurdle rate is estimated at 3.65 in the pulp and paper sector and 5.01 in the energy and heating sector.

In our sample, some firms have invested more than once over the period covered by our data. We test whether the estimated hurdle rates vary, within each sector, for firms that invested only once and for firms that invested several times. In both sectors, estimation results show that hurdle rates are lower for firms that have invested more than once (2.48 versus 3.56 in the pulp and paper sector, and 3.75 versus 4.12 in the energy and heating sector). Hurdle rates for firms that invested once and firms that invested several times are found statistically different in the pulp and paper sector only (the $p - value$ of the $Fisher$-test is 0.0060).

Finally note that we could have computed the hurdle rate in each sector directly from Equation (6), using the estimates of the drift and variance rate from the Brownian motion ($\hat{\alpha} = 0.0240$, $\hat{\sigma} = 0.0292$) and the cost of capital ($\rho = 0.237$). On our data, the calculated hurdle rate is found equal to 1.37, which is lower than what is found using our econometric procedure (2.84 in the pulp and paper sector and 3.89 in the energy and heating sector). We believe that the econometric approach presented here provides a more accurate estimate of the hurdle rates since it is based on sector-specific observations instead of being computed using national averages. The econometric approach described in this paper is thus better suited when one does not have at hand sector-specific measures of capital cost and/or sector-specific estimates of the drift and variance rate of the Brownian process.

7 Discussion and Conclusions

The lack of hurdle rate estimates for pollution abatement investments together with the increased availability of data from firms surveyed over several periods of time call for the development of econometric approaches based on observed data. We propose one such technique, which is appropriate when one observes data before and after the investment decision is taken. This method uses ex post abatement investment data to estimate the hurdle rate of investment linked to an option value from irreversible investment when there is uncertainty on the future price of polluting fuel. We illustrated the method on a panel of firms from the Swedish energy and heating and pulp and paper industry, with information before and after the investment took place. The null hypothesis of firms following a NPV rule is rejected as we find a hurdle rate of 2.8 for the pulp and paper industry and 3.9 in the energy and heating industry. Although other explanations are possible, firms in these two fuel-intensive industries may thus have rational reasons to delay adoption of irreversible abatement technology because of uncertainty in the price of polluting fuel. The hurdle rate in the energy and heating industry is significantly higher than that found for the pulp and paper industry, which may be a reflection of the higher relative part of energy costs over sales value for that industry. Uncertainty in the energy price would thus matter more for this industry.

Since the substitution between polluting fuel and clean fuel is important in the two sectors, we estimated the impact of investments on consumption of polluting and clean fuel in an intermediate stage. End-of-pipe investments increased the use of biofuel and decreased the use of polluting fuel in the paper and pulp industry. Clean technology investments decreased polluting fuel use in the energy and heating sector. We could not find any significant reduction in CO_2 emissions from the abatement investments in our sample, the only significant effect being a slight increase in CO_2 emissions from investments in end-of-pipe abatement in the energy and heating industry. Gaining a better understanding of abatement decisions within fuel-intensive sectors like the energy and heating and pulp and paper industry is important, since these sectors are important sources of CO_2 emissions, a greenhouse gas, but also of SO_2 and NO_x emissions. Since the proposed model is based on uncertainty on the future price of polluting fuel, it would be suited to apply for further study on investment in air pollution emission reduction in other sectors as well. The proposed method could hopefully provide insights into the potential for policy measures to reduce carbon emissions as well as conventional pollutants.

One limitation of our study was that we could not include variable costs of abatement investments, nor depreciation costs, in the model since the data were not available. Future extensions could include additional aspects of uncertainty related to irreversible abatement investment, in particular the future cost of investment. If pollution-reducing technology becomes cheaper over time, then an additional explanation for firms delaying investment could be the expected gain from a fall in the investment cost. Issues related to research and development of the new technology were also absent from our analysis.[23]

Our main result that the hurdle rate is significantly greater than one in these two sectors has some direct implications for environmental policy. First, it confirms that uncertainty on the future price of polluting energy is one reason why there may be delay in adopting irreversible less polluting technologies. One obvious conclusion is that the policymaker should try to minimize the value to wait with adoption for the firm by attempting to reduce the uncertainty facing the firm through a reduction in price volatility.[24] On the other hand, frequent adjustments of tax rates carry transaction costs. As argued by Dosi and Moretto (1997), the policymaker has to try to reduce the uncertainty of new technology adoption, and either a consistent tax policy or announcements of stringent pollution standards might do this. A

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[23] Even if the new technology is valuable, its arrival date could be uncertain. In this case, van Soest and Bulte (2001) have shown that the option value related to waiting for an even better technology makes the impact on the adoption lag ambiguous.

[24] That kind of policy would have distributional consequences, though, that are outside the scope of this paper.

policy recommendation must be based on each specific case and in our empirical application the price of polluting energy is subject to a combination of two uncertainties, the uncertainty in the price excluding policy and the policy uncertainty. Further, we study investment decisions to reduce CO_2 emissions, and for this particular case it might be wise to reduce the policy uncertainty through a more consistent tax policy with high constant taxes on carbon emissions, since this would correspond to the seriousness of the problem of climate change, and hence over time the policy component is likely to become of greater importance than the price uncertainty itself.

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Tables

Table 1: Descriptive statistics (at the firm level)

	Mean	Std. Dev.	Min	Max
CO_2 emissions (tonne/year)	94	276	0.02	2,066
Total fuel consumption (TJ/year)	1,520.9	2,299.4	0.21	16,723.5
Total clean fuel consumption (TJ/year)	809.8	1,341.1	0	7,373.9
Total polluting fuel consumption (TJ/year)	711	1,302.9	0.21	11,024
Total fuel price (kEUR/TJ)	7.12	3.62	1.52	17.53
Price of clean fuel (kEUR/TJ)	2.11	2.33	0	7.94
Price of polluting fuel (kEUR/TJ)	7.92	3.39	0.95	17.53
Number of workers	577	557	27	3,938
Total wages (kEUR/(worker*year))	33.86	4.54	22.03	52.45
Turnover (kEUR/year)	206,726	279,260	5,126	2,420,681
Number of plants	73			
Number of observations	166			

Note: 1 EUR = 9.04704 SEK, using values from Monday, December 18, 2006.

Table 2: Average characteristics of investors and non-investors

Variable	Non-investors	Investors
CO_2 emissions (tonne)	28	124
Fuel use (TJ/year)	534	1,959
Fuel cost (kEUR/year)	3,826	8,722
Number of workers	324	689
Turnover (kEUR/year)	76,692	264,393
Number of plants	26	47

Note: 1 EUR = 9.04704 SEK, using values from Monday, December 18, 2006.

Table 3: 3SLS Estimation results - System of simultaneous equations

	Coef.	Std. Err.	P-value
Equation for polluting fuel use (fossil fuel)			
Price of labour	1.8129	1.6334	0.267
Price of polluting fuel	-5.8920	2.3637	0.013
Price of clean fuel	9.7965	2.7888	0.000
Net turnover	0.0002	0.0001	0.054
Clean technology investment (sector 21)	-0.0100	0.0070	0.155
Clean technology investment (sector 40)	-0.0140	0.0043	0.001
End of pipe investment (sector 21)	-0.0353	0.0184	0.055
End of pipe investment (sector 40)	0.0214	0.0207	0.300
χ^2-test (p-value in parenthesis): 37.79 (0.0000)			
Equation for clean fuel use (biofuel)			
Price of labour	-11.3413	3.1712	0.000
Price of polluting fuel	-0.9738	4.5503	0.831
Price of clean fuel	8.9421	4.6107	0.052
Net turnover	0.0005	0.0001	0.000
Clean technology investment (sector 21)	0.0131	0.0094	0.163
Clean technology investment (sector 40)	0.0012	0.0060	0.846
End of pipe investment (sector 21)	0.1350	0.0252	0.000
End of pipe investment (sector 40)	0.0016	0.0257	0.949
Additional term	61.0512	79.0347	0.440
χ^2-test (p-value in parenthesis): 57.11 (0.0000)			
Equation for CO_2 emissions			
Total polluting fuel use	0.0522	0.0076	0.000
Total clean fuel use	-0.0004	0.0076	0.962
Number of employees	0.0056	0.0262	0.832
Net turnover	3.63E-06	5.840E-06	0.534
Clean technology investment (sector 21)	-0.0003	0.0004	0.483
Clean technology investment (sector 40)	-0.0001	0.0002	0.719
End of pipe investment (sector 21)	-0.0007	0.0013	0.553
End of pipe investment (sector 40)	0.0017	0.0011	0.116
χ^2-test (p-value in parenthesis): 93.36 (0.0001)			

Number of observations: 166.

Appendix

Derivation of the trigger price for investment under uncertainty (Equation 5 in the text):

The future price of polluting fuel is represented by a geometric Brownian motion with positive drift α_m and variance rate σ_m:

$$dm = \alpha_m m dt + \sigma_m m dz_m \quad \text{where } dz_m = \varepsilon\sqrt{dt}, \varepsilon \sim N(0,1).$$

Denote the option value as a function of the fuel price $F(m)$. Let ρ be the firm's opportunity cost of capital, assumed exogenous here. The Bellman equation is

$$\rho F(m)dt = E[dF(m)],$$

which means that, over the interval dt, the rate of return of the option to invest should equal the expected rate of its capital appreciation. Applying Ito's Lemma to expand $dF(m)$ gives[1]

$$\frac{1}{2}\sigma_m^2 m^2 F''(m) + \alpha_m m F'(m) - \rho F(m) = 0. \tag{1}$$

$F(m)$ should satisfy the above differential equation plus the boundary conditions (2)-(4):

$$F(0) = 0 \tag{2}$$

The value of the option is zero when the energy price is zero.

$$F(\tilde{m}) = V(\tilde{m}) - I \tag{3}$$

The value-matching condition: at the trigger price, the value of the option to invest equals the net value of the investment.

$$F'(\tilde{m}) = V'(\tilde{m}) \tag{4}$$

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[1] Partial derivatives denoted by a prime.

The smooth-pasting condition: at the trigger price, the change in the value of the option should equal the change in the expected present value of the investment.

Given the boundary conditions, the general solution to the problem can be reduced to the form $F(m) = A_1 m^{\beta_1}$.

The expected present value of the investment at the trigger price is defined as

$$V(\tilde{m}) = \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{\tilde{m}\triangle a^*}{\delta} - \frac{\tau\triangle(\gamma a^*)}{\rho} \tag{5}$$

where $\delta = \rho - \alpha_m$. Equations (2) to (5) then imply that

$$V(\tilde{m}) - I = -\frac{\triangle a^* \tilde{m}}{\delta\beta_1} \tag{6}$$

where β_1 is the positive root of the fundamental quadratic equation

$$\frac{1}{2}\sigma_m^2\beta_1(\beta_1 - 1) + \alpha_m\beta_1 - \rho = 0. \tag{7}$$

Substituting (5) into (6) and rearranging gives the trigger price $\tilde{m}$:

$$\tilde{m} = (\frac{\beta_1}{\beta_1 - 1})\frac{\delta}{\triangle a^*}(-I + \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{\tau\triangle(\gamma a^*)}{\rho}). \tag{8}$$

Derivation of Equation 7:

The last term in Equation (1) in the text can be rewritten as follows:

$$-\tau\triangle(\gamma a^*) = -\tau[\gamma_1 - \gamma_0]a_1^* - \tau\gamma_0[a_1^* - a_0^*] \tag{9}$$

We then have that $v(m)$, in the notation from the text, can be written as:

$$v(m) = P\triangle y^* - w\triangle l^* - m\triangle a^* - \tau\gamma_0\triangle a^* - \tau\triangle\gamma a_1^* \tag{10}$$

In the case of CO_2 emissions, no end-of-pipe abatement technology exists to date, so we will study clean technology investments, for which $h_1 > h_0$ but $\gamma_1 = \gamma_0 = \gamma$, that is abatement investments that increase the efficiency with which a polluting input is used, but does not directly reduce the emission coefficient. Hence, we have $\triangle\gamma = 0$, and

$$v(m) = P\triangle y^* - w\triangle l^* - m\triangle a^* - \tau\gamma\triangle a^* \tag{11}$$

The present discounted value (at the time of the investment, T) of the increase in profit flows over all future time periods is:

$$V(m) = \int_T^\infty \left[P\triangle y^* - w\triangle l^* - (m_T + \gamma\tau_T)e^{\alpha_m(t-T)}\triangle a^*)\right]e^{-\rho(t-T)}dt, \tag{12}$$

where ρ is the appropriate discount rate. The present value can be written

$$V(m) = \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho} - \frac{(m_T + \gamma\tau_T)\triangle a^*}{\delta}. \tag{13}$$

where $\delta = \rho - \alpha_m$.

The new trigger price under uncertainty is

$$(m_T + \gamma\tau_T) = (\frac{\beta_1}{\beta_1 - 1})\ \frac{\delta}{\triangle a^*}\Big(-I + \frac{P\triangle y^*}{\rho} - \frac{w\triangle l^*}{\rho}). \tag{14}$$