On the environmental impact of energy market liberalisation

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OCFEB Research Memorandum 0010, 'Environmental Policy, Economic Reform and Endogenous Technology', Working Paper Series 5

Key-words: uncertainty, liberalisation, investment behaviour, energy saving
JEL-codes: D81, Q40

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Abstract

In the literature, attention has been paid to the environmental consequences of lower energy prices caused by market liberalisation: the drop in energy prices reduces the attractiveness of investing in energy-saving technologies. In this paper we develop a simple model of investment decision-making emphasising the importance of not only levels but also volatility of energy prices for actual investment behaviour. The general finding is that lower energy prices and higher uncertainty reduce the propensity to invest. To empirically assess the importance of changes in both levels and volatility, we use US natural gas price data over the market liberalisation period and apply the information to the investment decision with respect to a specific energy-saving technology in the paper industry. We find that energy market liberalisation reduces the propensity to invest in energy-saving technologies substantially, not only because of the lower energy price but also because of its increased volatility.

1. Introduction

Liberalisation of energy markets is often argued to have detrimental consequences for the environment (*e.g.*, Elliott and Pye, 1998). By lowering energy prices, liberalisation is expected to result in increased energy consumption and less investments aimed at improving energy efficiency.[1] What is often neglected in these arguments is that consumption and investment decisions are not only driven by the level of energy prices, but also by their volatility. The uncertainty about future developments associated with higher volatility will tend to induce firms to become more prudent in their investment decisions (see also Hasset and Metcalf, 1993). Liberalisation can be expected to have important consequences for the volatility of energy prices, although the impact is ambiguous. On the one hand, liberalisation (as compared to the situation of administered prices) creates a more dynamic environment where energy prices react quickly to changes in demand and supply. On the other hand, the resulting lower energy prices may also be associated with lower price variability as governments face less incentives to intervene in energy markets. Indeed, in fully liberalised energy markets price levels and volatility are often positively correlated (*e.g.* Ferderer, 1996). Thus, lower prices may be associated with either higher or lower volatility. Which effect will dominate is an empirical question.

Our basic claim in this paper is that given the dynamic characteristics of investments, uncertainty about future prices can have an important (additional) impact on the decision whether or not to invest in energy-saving technologies. Higher uncertainty may induce firms to postpone the decision to invest in order to await the arrival of new information. Thus, the likelihood of investing in an energy-saving technology that, ex post, turns out to be unprofitable due to fallen (relative) prices of energy is reduced. Postponement is potentially important if (i) the investment decision is to a large extent irreversible, and (ii) there is persistence in the uncertain variable. In the case of investments in energy-saving technologies, these conditions are likely to be fulfilled. If a firm invests in an energy-saving technology and the price of energy turns out to be much lower than expected, the resale value will drop substantially and may even

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[1] Concerns about the (persistently) low energy prices and their associated difficulties of fostering energy saving were recently forcefully expressed in the Dutch policy plans for meeting the Kyoto targets (VROM, 1999).

become equal to (or less than) its scrap value. Furthermore, if the price of energy is low in the current period, it is very likely that it will be low in the next period as well.

This basic claim will be tested empirically by assessing the impact of the liberalisation of the US natural gas markets on investments in energy-saving technologies. Over the past twenty years, the US natural gas markets have been gradually deregulated. For example, price ceilings were removed in 1979 while the phasing out of price controls started in 1989. The liberalisation was completed in January 1993 (EIA, 1999a and 1999b). In particular, we assess the implications of this reform for energy price levels, their volatility, and the associated consequences for investment behaviour. We apply the results to the adoption decision of a specific energy-saving technology in the paper production process for which data are available on its energy-saving potential, its investment costs and the associated increase in operating and maintenance costs.

The set-up of this paper is as follows. In section 2, we develop a simple model to illustrate the effects of energy price levels and volatility on investment behaviour. In section 3, we analyse the development of the natural gas price in the US in the period 1984-1998. We thereby intend to assess the effect of liberalisation on the level and volatility of gas prices. In section 4 the empirical results are applied to the investment decision concerning an energy-saving technology in the paper production process to give a crude approximation of the effects of the liberalisation of the US gas markets on investment behaviour. We conclude in section 5.

2. An illustrative model

This section develops a straightforward model to illustrate the basic issues arising in an environment where firms make irreversible investment decisions under uncertainty. Suppose that currently firms are applying an energy-intensive technology to produce a certain amount of output, but that there is also an energy-saving technology available that can produce the same amount of output, but at different operating and maintenance costs. Define ΔE as the change in energy used to produce a unit of output if the current technology is replaced by an energy-saving technology, and ΔOC as the associated increase in operating and maintenance costs. [2] Furthermore, assume that the costs associated with the adoption of the (new) energy-saving technology are C_A.

Uncertainty is introduced into the model in a fairly simple way. Investment costs and the increase in operating and maintenance costs (OC) are assumed to be known with certainty, but future energy prices (P_E) are subject to uncertainty. Consistent with reality, we assume a time trend for prices, but disturbances can shift the energy price away from its trend path. More specifically, the energy price is assumed to follow a Brownian motion:

$$dP_E = \alpha P_E dt + \sigma P_E dz \tag{1}$$

In this equation, α is the trend parameter and $dz = \varepsilon \sqrt{dt}$, where ε is a normally distributed independent variable with a zero mean and a standard deviation of one. This implies that the expected change of the energy price level over a short period dt is equal to $\alpha P_E\, dt$ with variance $\sigma^2 P_E^2 dt$ (Dixit and Pindyck, 1994, p. 70-71). Therefore, the expected energy price at time t equals:

$$\mathrm{E}(P_E(t)) = P_{E_0} e^{\alpha t}. \tag{2}$$

In this simple framework, we can now determine the costs and benefits of switching from the energy-intensive technology to the energy-saving technology. The change in technology results in savings on energy expenses, but requires additional expenditures in terms of operating and maintenance costs. Taking into account the adjustment or

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[2] In other words, we model firms as producing according to a Leontief production technology. This assumption is reasonable since substitution possibilities for inputs needed to operate technologies are limited once the technology has been installed. Generalisations could allow for (imperfect) substitutability among the various inputs but are not likely to affect the main results. Also note that adoption of an energy-saving technology does not necessarily result in an *increase* in operating and maintenance costs; the investor will always be confronted with a real trade-off as long as investment costs are positive.

installation costs (C_A),[3] the expected value of switching to the energy-saving technology equals:

$$\Omega(P_E) = \int_0^{\infty} \mathrm{E}(P_E)\Delta E e^{-rt} dt - \frac{\Delta OC}{r} - C_A = \frac{P_E \Delta E}{r-\alpha} - \left(\frac{\Delta OC}{r} + C_A\right), \tag{3}$$

where r is the (exogenously given) discount rate.[4]

The question now is at what energy price the firm will decide to switch towards the energy-saving technology. In each period, the firm compares the benefits of undertaking the investment (in terms of cost reductions achieved) with the benefits of postponing the decision one period. The latter include access to more information about energy prices in the next period. Given the uncertainty that the firm faces, postponing the decision reduces the probability of investing in a project that turns out to be unprofitable *ex post*. In mathematical terms, the firm maximises:

$$F(P_E) = \max\left\{\Omega(P_E), \frac{1}{1+rdt}\mathrm{E}\left(F(P_E) + dF(P_E)\right)\right\}. \tag{4}$$

The value $\Omega(P_E)$ is labelled the 'termination value'. When the firm decides to undertake the investment, its expected return is known. The expected return of waiting (the second term in brackets) is usually referred to as the 'continuation value'. The firm's optimal decision maximises the net present value of the investment option (F). As soon as the

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[3] Important for the argument to follow is that at least a significant part of the investment in the new technology is irreversible. For example, it may be impossible to sell the technology at its purchase price; second-hand markets may even be absent. But other important parts of the investment costs are generally not recuperable, such as re-organisational efforts and expenses aimed at incorporating the new technologies in the production process, acquisition of information, etc. Even if returning to the old technology is feasible at low or zero costs, the costs of installing the new technology can not be recouped and are therefore irreversible.

[4] The results have been derived using dynamic programming, which is based on the assumption that the price risk cannot be spanned by constructing an appropriate market portfolio. If we would have dropped this (implicit) assumption, contingent claims analysis could be used which would have enabled us to derive a risk-adjusted discount rate. Using the capital asset market pricing approach, this discount rate would be equal to $r + \phi\rho_{PM}\sigma$, where ϕ is the market price of risk and ρ_{PM} the correlation coefficient between market risk and the riskiness of the energy price (see Dixit and Pindyck, 1994, p. 185).

termination value exceeds the continuation value, the investment is undertaken. The energy price at which this point is reached will further be referred to as the critical energy price (P_E^*).

Applying Ito calculus, the following differential equation is obtained[5]:

$$rFdt = \mathrm{E}\left[F_P dP_E + \frac{1}{2}F_{PP}(dP_E)^2\right] = \left[F_P \alpha P_E + \frac{1}{2}F_{PP}\sigma^2 P_E^2\right]dt. \tag{5}$$

Try $F = AP_E^{\beta}$ as a solution to this differential equation. Solving the differential equation, two roots can be found:

$$\beta_{1,2} = \left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right) \pm \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}\ . \tag{6}$$

This term essentially captures the impact of price uncertainty on the critical energy price level at which the switch towards the energy-saving technology will be carried out. The general solution is of the form $F(P_E) = A_1 P_E^{\beta_1} + A_2 P_E^{\beta_2}$ where β_1 and β_2 represent the positive and negative roots, respectively. The higher the energy price, the higher the value of the energy-saving investment option will be. This implies that the term with the negative root can be ignored: A_2 equals zero. Then the critical value of the energy price can be determined by using two additional conditions (Dixit and Pindyck, 1994; Pindyck, 1991). First, in the optimum it must hold that at the critical energy price level, the value of the investment project is equal to the termination value: $F(P_E^*) = \Omega(P_E^*)$: given the fact the investment is undertaken, waiting apparently no longer has a positive net value (see equation 4). In the second place, optimality requires that the option value function $F(P_E)$ and the termination value function $\Omega(P_E)$ meet tangently at the critical price level: $F_P(P_E^*) = \Omega_P(P_E^*)$. Using these two additional conditions, it can be found that the critical energy price equals:

$$P_E^* = \left(\frac{\beta_1(\alpha,\sigma,r)}{\beta_1(\alpha,\sigma,r)-1}\right)\left(\frac{r-\alpha}{\Delta E}\right)\left[\frac{\Delta OC}{r} + C_A\right]. \tag{7}$$

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[5] Througout this paper, G_i and G_{ii} denote the first and second partial derivatives of function G with respect to variable i.

This expression can be understood as follows. The last two terms in expression (7) reveal the price at which the investment in the energy saving technology would be undertaken in the absence of uncertainty (according to a standard net present value rule).[6] Firms thus put a mark-up over this price equal to $\beta_1/(\beta_1-1)$. This mark-up depends negatively on β_1 and therefore positively on σ (see equation 6). Hence, a higher variability results in an increase of the critical price level above which the investment will be undertaken. Furthermore, the mark-up is lower (i) the higher the discount rate r and (ii) the lower the trend rate of growth α. With respect to the discount rate, the intuition is that heavier discounting gives lower weights to future developments (either positive or negative) and therefore leads to less prudent behaviour. A higher trend rate of growth increases the value of the option to invest (the continuation value). This means that the opportunity costs of investing increases and hence the mark-up will be higher.[7] Thus, appropriate consideration of uncertainty results in a critical price that exceeds the NPV critical price (P^{NPV}) by a factor $\beta_1/(\beta_1-1)$.

Using (2) and (7), the expected period in which the investment in energy-saving technology is undertaken can now be calculated. From (2) we know that $E(P_E(T^*)) = P_{E0}e^{\alpha T^*}$, so the expected investment lag is given by:

$$T^* = \frac{1}{\alpha}\ln\left(\frac{P_E^*}{P_{E0}}\right). \tag{8}$$

Taking the first derivatives of T^* with respect to P_{E0} and σ, it is clear that a lower initial energy price implies that the investment is expected to be postponed into the future while a decrease in uncertainty implies that the investment is expected to take place sooner. If increased competition results in lower energy prices and higher variance, both effects will induce the firm to postpone the investment in energy-saving technology. If,

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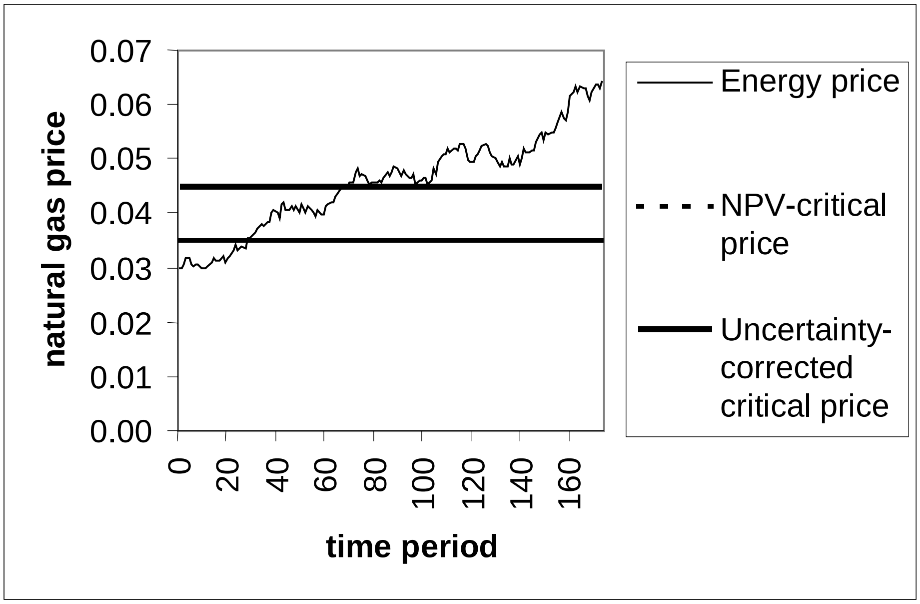
[6] This price is derived from the simple net present value rule of the investment according to which the investment should be undertaken as soon as $P_E^{NPV} > \left(\frac{r-\alpha}{\Delta E}\right)\left[\frac{\Delta OC}{r} + C_A\right]$.

[7] This does not imply that the investment will actually be postponed. A higher trend also increases the termination value. As this increase generally dominates the increase in the continuation value (see equation 4), the critical price in equation (7) tends to fall.

however, lower prices are associated with less volatility (as argued by, for example, Ferderer, 1996), energy price liberalisation will have an ambiguous effect on the propensity to invest in energy-saving technologies.

To further illustrate the model, we refer to Figure 1. In this Figure, we have drawn a hypothetical development of the energy price. In addition, we have drawn the critical energy price that results from a standard net-present value decision rule and the critical energy price that holds when controlling for the effects of uncertainty on investment behaviour. The Figure reveals the moments at which adoption of the new technology takes place according to the alternative investment decision rules. The difference in the timing of adoption is caused by the uncertainty regarding energy prices: under uncertainty and irreversibility, firms will postpone adoption to reduce the likelihood of taking the wrong decision.

Figure 1: The timing of the investment in a hypothetical energy-saving technology

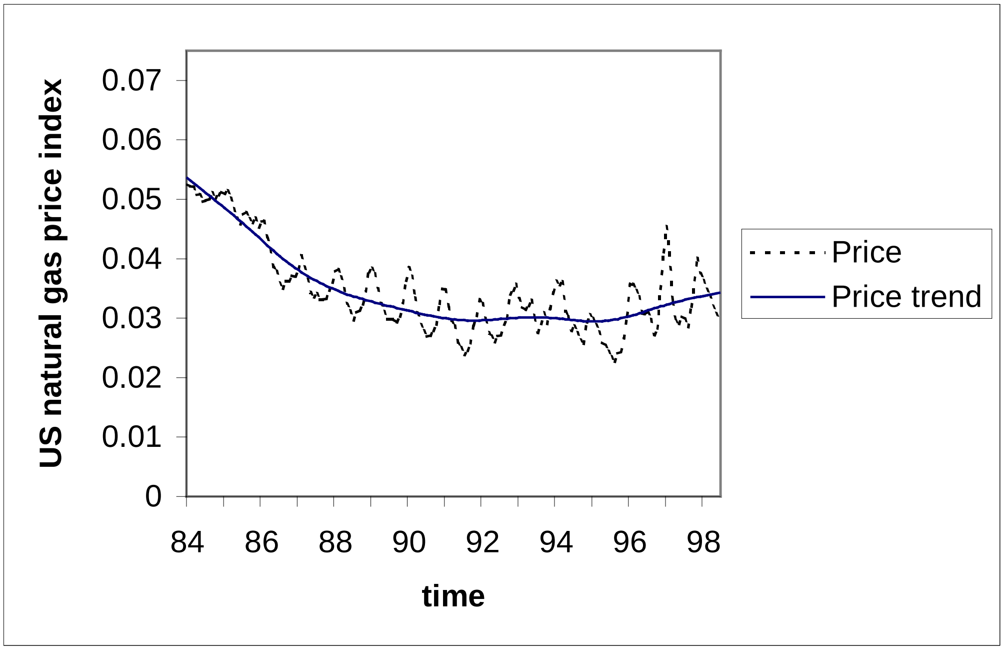


In the remainder of this paper, we will empirically assess the effects of liberalisation of the US gas market on the level and uncertainty of gas prices. Using the simple framework developed in this section, we will subsequently assess the likely impact of this liberalisation on investments in energy-saving technologies.

3. Empirical application

Let us take a closer look at data on natural gas prices in the US over the period 1984-1998 (data were taken from EIA, 1999a). In this period, the national gas market was gradually liberalised, with liberalisation being completed in 1993. Figure 2 depicts the US natural gas price (deflated with the producer price index[8]) and its long-term trend[9] over the entire sample period.

Figure 2: The deflated US natural gas price index and its trend.



Inspection of the data yields two observations. First, the deflated natural gas price fell continuously during the liberalisation process, but stabilised (on average) after 1993 (when market liberalisation was completed). Second, price volatility seems to have

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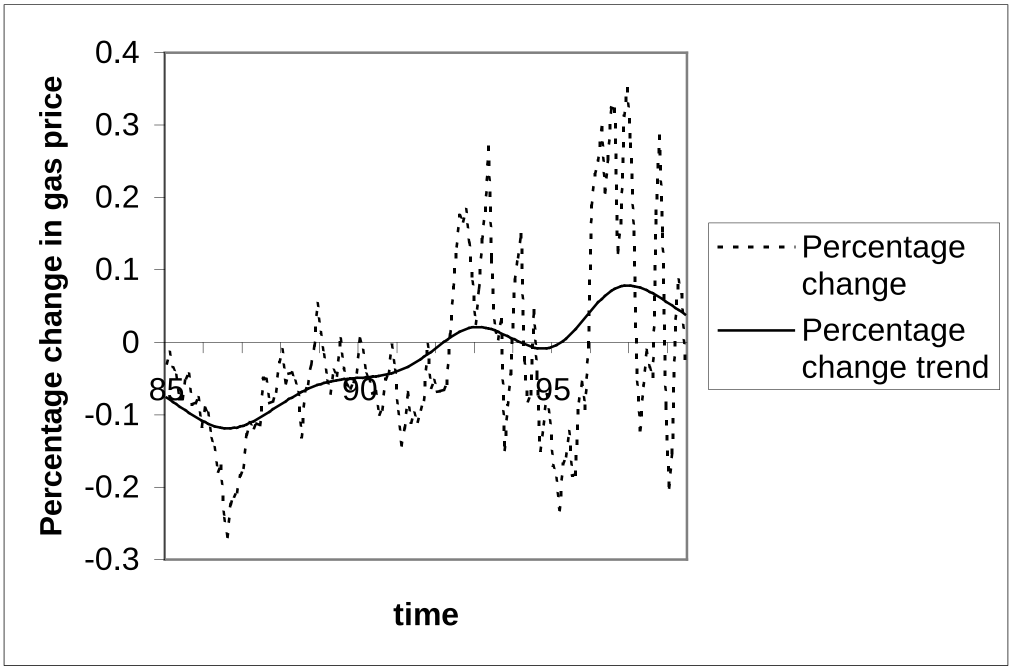
[8] Producer prices were taken from the IFS database. Annual data were converted to monthly data using linear intrapolation. Using the price index of capital as a deflator does not alter the qualitative results of the analysis.

[9] The trend has been derived by applying a Hodrick-Prescott filter to the deflated natural gas price time series. Another way of establishing the same result is to run regressions of the seasonally adjusted data on a time trend.

increased considerably over the liberalisation period, and continued to do so after 1993. This seems to indicate that the market becomes increasingly responsive to demand and supply imbalances.

Of course, the fluctuations shown in Figure 2 arise partly because of seasonal variance. In order to correct for that, we have plotted the 12-months percentage change in the natural gas price (and its trend, which was again obtained by applying a Hodrick-Prescott filter) in Figure 3.

Figure 3: The 12-months percentage change in the US natural gas price and its trend.



This Figure yields the same observations as Figure 2: up until 1993 the natural gas price fell, showing a slight recovery afterwards, while volatility increased over the entire 1984-1998 period.

To determine the trend and volatility of the US-gas prices, we have checked whether the development of US gas prices can be described by a geometric Brownian motion (see Conrad, 1997). The details of the estimation procedure can be found in Appendix 1. The analysis shows that the US natural gas price indeed follows a geometric Brownian motion. Splitting the time-span in two (the pre-1993 period and the post-1993 period), we find a significantly negative trend in the gas price in the pre-1993 period and an insignificantly positive trend in the post-1993 period. Uncertainty turns out to have increased from 16 to 20% (on an annual basis). Obviously, apart from liberalisation, other factors may have caused these developments such as technological developments and instability in OPEC. Nevertheless, it seems fair to conclude that the liberalisation of the US gas market has indeed resulted in lower gas prices and that it has at the same time resulted in an increase in the volatility of these prices, strengthening the uncertainty surrounding investments in energy-saving technologies.

As a first attempt to assess the effects of liberalisation on investment behaviour, we use the estimates for the volatility of energy prices to determine the mark-up that firms put over the critical price that would hold in the absence of uncertainty. Results are indicated in Table 1, where *monthly* values of the discount rate and trend- and uncertainty parameters are used.

Table 1. Pre- and post-liberalisation mark-ups on the critical energy price

	Pre-liberalisation		Post-liberalisation	
	r=0.01	r=0.02	r=0.01	r=0.02
β_1	3.48	4.78	2.91	3.93
Mark-up	1.40	1.26	1.52	1.34

Note: pre-liberalisation information is based on α=0.0004 and σ=0.045; post-liberalisation information is based on α=0.0004 and σ=0.056.

In this Table, we abstained from including the effect of a change in the structural growth rate of energy prices. The reason for this is that we see no a priori reason why the structural development of energy prices would be affected by liberalisation.[10] We do account for a change in the level of energy price as a result of liberalisation as will become apparent in the next section. However, such a change leaves unaffected the mark-up over the critical price that holds in the absence of uncertainty. From this Table it is clear that the mark-up has increased as a result of liberalisation with about 7.5% (the increase depending on the discount rate; see also section 2).

4. Assessing the impact of liberalisation on energy-saving investments

Having established that during the liberalisation process the general energy price level has fallen while uncertainty has increased, we can now assess the impact of these developments on investment behaviour. For this aim, we take the simple model laid out in section 2 as a starting point. According to theory, both the lower energy prices and the increased uncertainty about future energy prices will lengthen the period in which no investment in cleaner technologies takes place.

To illustrate the quantitative effect of liberalisation, we consider an energy-intensive industry where substantial reductions in energy use can be achieved, namely the paper and pulp industry. In a research report issued by the Dutch paper industry (Versluijs *et al.*, 1993), several potential energy-saving technologies are listed; it is estimated that 22% of the energy currently used can be reduced cost-effectively (*i.e.* with a pay-back period of less than 7 years). By means of an example, we focus on one specific energy-saving technology which is associated with the drying process. This part of the production process is highly energy-intensive. Substantial reductions can be achieved by introducing the ‘long nip press’, which increases the fibre concentration (thus lowering the water content of the raw material) so that substantial savings can be achieved in the drying phase in terms of the amount of steam needed. The resulting reduction in energy consumption is estimated at about 16%.

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[10] Theoretically, one could bring forward that liberalisation leads to a steeper time profile of energy prices as it results in lower initial prices but faster exhaustion of resources. Alternatively, one could argue that liberalisation speeds up technological progress in the sector and thereby lowers costs of gas recovery and thereby flattens the time profile. For the purpose of this paper in which we are mainly interested in the effects of liberalisation-induced uncertainty we abstain from these issues.

The analysis in this section will be based on the costs and benefits of the new technology *per tonne of paper produced*. It takes about 5 GigaJoule (GJ) to produce one tonne of paper.[11] Using the estimate of a 16% reduction in energy use, annual energy savings can be achieved of about 0.75 GJ per tonne of paper. Using the international average caloric content of natural gas (1000 m^3 yields 31.7 GJ), the amount of gas annually saved equals 23.5 m^3 per tonne of paper produced. The costs associated with this new technology consist of two parts: the investment costs and operating and maintenance costs. The investment costs associated with the adoption of a long nip press are US$ 18.75 per tonne of paper and the additional operating and maintenance costs are $US 0.50/tonne (all figures are derived from De Beer *et al.* 1994, pp. 53-56).

Using these data, we determine critical gas prices at which investment is predicted to take place according to a standard net present value rule and according to the modified net present value rule, accounting for uncertainty. The results are given in Table 2.

Table 2. Critical energy price in the paper case

	$\Phi = 0.045$	$\Phi = 0.056$
β_1	3.82	3.21
Mark-up	1.35	1.45
P_E^{NPV}	0.030	0.030
P_E^*	0.041	0.044

Note: prices are derived on the basis of $\forall=0.0004$, $r=0.0125$, $C_A=18.75$, $\Delta OC=0.5$, and $\Delta E=23.5$.

To get a feeling for the impact on the investment timing, we performed a Monte Carlo analysis. We took three different combinations of parameter values for the initial energy price level and its volatility. These were subsequently used to generate 1000 time paths for the gas prices for each set of parameter values. Confronting these time paths with the critical energy price corresponding to each parameter constellation, we determined the time at which the switch from the energy-intensive to the energy-extensive

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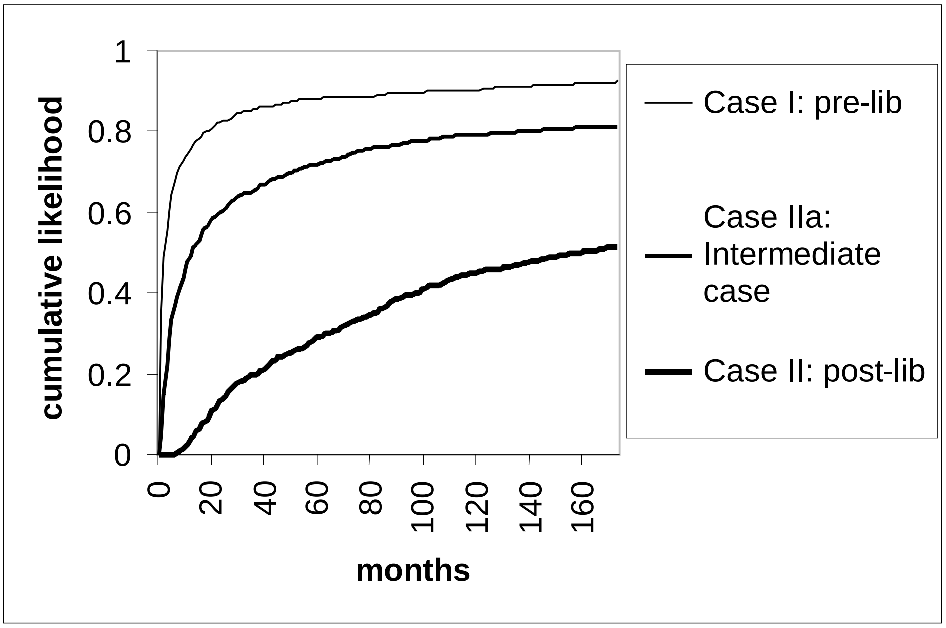
[11] Energy use may be somewhat higher or lower, depending on the desired quality of paper.

technology is made. The initial natural gas price index for the pre-liberalisation period (i.e., the 1984.1 value) was about 0.04 while the monthly price volatility in that period was about 0.045. At the end of the liberalisation period, the natural gas price index had fallen to a level of about 0.03, while the volatility in the post-liberalisation period was about 0.056. Using these figures in the Monte Carlo simulations yields the results as represented in Figure 4, where Case I (P_{E0} = 0.04, σ= 0.045) and Case II (P_{E0} = 0.03, σ= 0.056) respectively represent the pre- and post-liberalisation situations.

Figure 4: The cumulative likelihood of adoption of the energy-saving technology over time.



In this Figure, the cumulative likelihood of adoption is depicted (indicated on the vertical axis) for a certain period (indicated on the horizontal axis) is depicted. As is clear from this Figure, the implementation lag increased substantially since the natural gas market liberalisation was completed (compare Cases I and II). In order to separate out the price level effect and the uncertainty effect, an intermediate third case is also shwon in the Figure. Case IIa is based on the pre-liberalisation energy price leve (P_{E0} = 0.04) and on the post-liberalisation volatility level (σ = 0.056). Thus, the difference between Cases I and IIa reflects the pure impact of higher uncertainty while the difference between Cases II and IIa reflects the pure impact of a lower energy price level. Loosely stated, the experiment indicates that uncertainty decreases the probability that adoption of the new technology takes place within 10 years (*i.e.* 120 months) from 90% to 79% (from Case I to Case IIa) whereas the lower energy price (from Case IIa to Case II) further reduces this probability to 41%.

5. Conclusions

Energy market liberalisation is often indicated to have adverse environmental consequences as the resulting decrease in energy prices would reduce the attractiveness of investing in energy-saving technologies. However, lower price levels are not the only consequence of liberalisation: the variability of energy prices may go up (because markets become more responsive to differences in energy demand and supply) or go down (as there is often a positive correlation between energy price levels and volatility). Higher volatility (implying higher uncertainty) will reduce the attractiveness of energy-saving investments because of the irreversibility of the investment decision: if the prices are highly volatile (implying that they may increase or decrease substantially between periods), the likelihood of taking the wrong decision (*i.e.*, ex post) increases, and hence firms are likely to become more prudent in their investment behaviour. The higher the variability, the higher the critical energy price at which an energy-saving technology will be adopted (*ceteris paribus*).

Using US data, we established that indeed the liberalisation of the natural gas market will have a substantial detrimental impact on the willingness to invest in more energy-efficient technologies. Not only did the price level fall, its variability increased substantially resulting in a large increase in the implementation lag. Applying these insights to the investment decision with respect to one specific technology (the adoption of the long-nip press in the paper production process), we find that there is indeed a substantial impact of both the lower energy price and the increased volatility in energy price as a consequence of the liberalisation of gas markets.

This means that from a social point of view, there is a trade-off between energy market liberalisation and environmental protection for two reasons. The first reason is that, obviously, lower energy prices depress the return on investment in energy-saving technologies. However, our analysis shows that there is a second reason that the trade-off occurs: the volatility of the energy price has also increased over the liberalisation period. The increased variance results in a higher mark-up over the standard expected net present value criterion; hence, liberalisation results in a higher critical energy price to trigger investments in energy-saving technologies. In assessing the desirability of energy market liberalisation, not only the environmental consequences of a lower energy price should be taken into account but also of its higher volatility.

Daan van Soest and Henri de Groot would like to thank the Dutch National Science Foundation (NWO) for financial support.

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Appendix 1: Estimating the growth rate and variance of the energy price

This appendix describes the procedure that we used to determine whether US natural gas prices can be described by a geometric Brownian motion. After having established that it does, we continue determining the parameter values that can best describe the price development.

Determining whether indeed the energy price follows a geometric Brownian motion boils down to determining whether $dP_E = \alpha P_E dt + \sigma P_E dz$. Although the trend and uncertainty parameters will be slightly different, testing whether the *natural logarithm* of the energy price follows an *ordinary* Brownian motion is econometrically more convenient (see, for example, Conrad, 1997). In general, the first derivative of the natural logarithm of a specific variable (in this case the energy price, P_E) equals:

$$d\ln(P_E) = \frac{1}{P_E} dP_E - \frac{1}{2P_E^2}\left(dP_E^2\right). \tag{A.1}$$

Substituting $dP_E = \alpha P_E dt + \sigma P_E dz$ in (A.1) and applying Ito's Lemma (see Dixit and Pindyck, 1994, p. 81), we find:

$$d\ln(P_E) = \alpha dt + \sigma dz - \frac{1}{2}\sigma^2 dt = (\alpha - \frac{1}{2}\sigma^2)dt + \sigma dz = adt + sdz. \tag{A.2}$$

Hence, after having tested whether the log of the energy price follows an ordinary Brownian motion, we can determine the trend and uncertainty parameters by using the relationship between a, s, α and σ as presented in (A.2).

Testing whether the natural logarithm of the energy price follows an ordinary Brownian motion boils down to jointly testing the significance of a trend parameter and the level of the natural log of the energy price in the previous period. This requires running of two regressions, an unrestricted and a restricted version (Stewart, 1991, pp. 199-203). Denoting the natural logarithm of the energy price as p_E, the unrestricted regression equation is

$$\left(p_{Et} - p_{Et-1}\right) = \gamma d + \beta t + (\rho - 1)p_{Et-1} + \lambda\left(p_{Et-1} - p_{Et-2}\right) + \varepsilon_t, \tag{A.3}$$

where d is the vector of dummies to capture differences in monthly growth rates (and γ is the associated vector of coefficients). The null hypothesis that p_E follows a

Brownian motion is $H_0 : \beta = 0, \rho = 1$. That means that the following restricted version should also be estimated:

$$(p_{Et} - p_{Et-1}) = \gamma d + \lambda(p_{Et-1} - p_{Et-2}) + \xi_t . \qquad \text{(A.4)}$$

By calculating the *F*-statistic using the sums of squared residuals of these two equations, the joint null hypothesis can be tested.

The results for the two sub-periods are presented in Table 1. The *F*-test is $F = \left(\frac{\widetilde{T} - k}{q}\right)\left(\frac{SSR_R - SSR_U}{SSR_U}\right)$, where $\widetilde{T}$ is the number of observations corrected for the monthly dummies, k and q are the number of variables in the unrestricted and restricted regressions respectively (ignoring the dummy variables), and $\mathrm{SSR_R}$ and $\mathrm{SSR_U}$ are the sum of squared residuals of, respectively, the restricted and unrestricted regressions. The F-values for both periods are 2.6805 for the 1984-1992 period and 5.1974 for the 1993-1998 period. The Dicky-Fuller critical F-value at the 5% level (for $\widetilde{T}$ >50) is 6.49, and hence the null hypothesis of a Brownian motion cannot be rejected (Stewart, 1991, p. 203).

Now the appropriate α and σ of the energy price series can be found by calculating the mean (*a*) and standard deviation (*s*) of the $d\ln(P_E)$-series and applying the correction indicated in (A.2). Indeed, for the 1984.2-1992.12 period, *a* is found to be -0.00585 and s^2 equals 0.00200; that means that α equals -0.00485 and σ equals 0.0447. For the period 1993.1-1998.6 *a* is found to be 0.00717 and s^2 equals 0.003187; that means that α equals 0.008764 and σ equals 0.05646. Note that the uncertainty parameters are much higher (in absolute terms) than the trend parameters. Converting these figures to yearly trends and uncertainty parameters, the annual trends are approximately zero while the annual uncertainty parameters are 0.1549 and 0.1956 for respectively the first and second sub-period.

Table A1: Regression results of the restricted and unrestricted models for both time periods (t-values are in parenthesis)

Variable	Unrestricted, 1984.3-1992.12	Restricted, 1984.3-1992.12	Unrestricted, 1993.1-1998.6	Restricted, 1993.1-1998.6
JAN	-0.278230	0.006374	-0.863977	0.015330
	(-2.164077)	(0.490711)	(-3.118613)	(0.562095)
FEB	-0.306441	-0.025914	-0.917877	-0.049630
	(-2.421462)	(-2.102930)	(-3.353747)	(-1.887478)
MRT	-0.328520	-0.049252	-0.913311	-0.043169
	(-2.608023)	(-4.239514)	(-3.328405)	(-1.630893)
APR	-0.312476	-0.030854	-0.930609	-0.048481
	(-2.460463)	(-2.431950)	(-3.345836)	(-1.802267)
MAY	-0.328021	-0.041943	-0.905550	-0.008677
	(-2.543220)	(-3.389493)	(-3.203158)	(-0.318467)
JUN	-0.296263	-0.005973	-0.937300	-0.029432
	(-2.263896)	(-0.469313)	(-3.277509)	(-1.125082)
JUL	-0.301955	-0.007889	-0.926400	-0.011520
	(-2.278153)	(-0.675473)	(-3.216123)	(-0.400081)
AUG	-0.280658	0.014781	-0.939296	-0.017162
	(-2.107882)	(1.278801)	(-3.235891)	(-0.601231)
SEP	-0.282219	0.013330	-0.900989	0.026983
	(-2.118243)	(1.157395)	(-3.084459)	(0.944550)
OCT	-0.264191	0.029675	-0.915888	0.012492
	(-1.994494)	(2.561570)	(-3.133945)	(0.437819)
NOV	-0.255258	0.036001	-0.805169	0.118997
	(-1.943630)	(3.008012)	(-2.766682)	(4.174603)
DEC	-0.255920	0.031210	-0.871009	0.035609
	(-1.976292)	(2.527955)	(-3.044825)	(1.086841)
DLNP(-1)	0.357236	0.292406	0.390523	0.277770
	(3.460543)	(2.949473)	(3.065148)	(2.109997)
TREND	-0.000503		0.000441	
	(-1.754093)		(1.098530)	
LNP(-1)	-0.094987		-0.241221	
	(-2.194921)		(-3.221285)	
Adjusted R-squared	0.534087	0.517245	0.450798	0.363809
Sum squared resid	0.103986	0.110112	0.177600	0.213798
No of observations	106	106	66	66