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Asymmetric Adaptations to Energy Price Changes*

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Abstract

The effectiveness of policies to reduce the use of energy depend on the elasticity of substitution between the various inputs and on the rate of technological progress. This paper presents a theoretical model emphasising energy investments' characteristics of uncertainty and irreversibility that result in testable hypotheses concerning the relative values of substitution parameters and rates of technological change in periods of high and increasing energy prices and in periods of low prices.

Estimation results for a panel of sectors of the Dutch economy show that the elasticity of substitution between energy and other inputs is low in periods of low energy prices, whereas it is significantly higher in the preceding period of high and increasing energy prices. Furthermore, energy-saving technological progress in periods of high and increasing energy prices is also significantly higher than if energy prices are low and falling.

The regression results suggest that, due this asymmetric response of firms to changes in energy prices, taxing energy in the current period of low energy prices will not yield substantial reductions in energy use of Dutch industry.

Keywords: energy substitution, technological progress, environmental policy

JEL-classification: C23, D21, Q43

1. Introduction

Governments of most developed countries aim to substantially reduce energy use to limit the emission of greenhouse gases (such as carbon dioxide). The effectiveness of taxing energy use depends on the substitution elasticity between inputs in production and on technological

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progress. Analysis of past experience may give insight in the potential effectiveness of energy taxation to induce a decrease in energy use.

In this paper it is argued that in assessing the potential impact of increasing the price of energy through taxation, the choice of the estimation period is of crucial importance. Examination of the data indicates that the 1973-1994 period can be divided in two sub-periods. From 1973 to 1986, energy prices went up, while prices have been observed to fall quite substantially in later years, as can be seen from Figure 1.¹

< Insert Figure 1 about here >

This subdivision may be important as the economic consequences of energy price increases and decreases are generally not symmetric. The literature on the potential causes of asymmetric responses to energy price increases and decreases has focused on the importance of irreversibility. If adjustment to changes in relative prices involves adaptation costs, economic agents have an incentive to postpone the adjustment. The incentive to postpone is even stronger when there is uncertainty about the persistence of the change. If adjustments are costly and the future is uncertain, the option value of waiting increases because new information is likely to arrive over time, which may exceed the foregone benefits of adjusting straightaway. This idea has been applied at various levels in the economy. The literature focusing at the sectoral level, initiated by Hamilton (1988), attacks the idea that production factors are able to relocate smoothly from one sector to another. If production factors (mainly capital and labour) are specialised, it may be optimal not to immediately leave adversely affected sectors and to move to positively affected sectors, but to remain unemployed and wait for conditions to improve. At the micro level, firms are likely to postpone irreversible investment expenditures on both energy-saving technologies and their reversal towards energy-intensive technologies (see for example Bernanke, 1983). This means that firms will not respond immediately to energy price increases; but if they have responded, energy prices will have to fall substantially before the investment is reversed.

Empirical studies seem to corroborate this explanation of asymmetric responses. At the micro-economic level there is evidence pointing to the fact that firms and consumers adapt faster (and stronger) to energy price increases than to price decreases (*e.g.* Bacon, 1991; Borenstein *et al.*, 1997; Gately, 1992; Kirchgässner and Kübler, 1992; Mork, 1989; Ryan *et al.*, 1996). At the macro-level, asymmetries may also be important. It has been observed that economic activity is more strongly affected by increases in the energy price than by decreases

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(Dargay and Gately, 1994; Gardner and Joutz, 1996; Mork *et al.*, 1994; Mory, 1993; Smyth, 1993). However, not all price increases will have an equally strong impact on investments in energy-saving technologies. If energy prices increase after a period of low prices, the change is merely a recovery that is unlikely to induce additional investments in energy efficiency. Only “all time highs” will induce new investments in energy efficiency (Hamilton, 1996).

If such an asymmetric response exists, it has important policy implications. Currently, energy prices are relatively low after a period of significant price increases (1973-1986). This means that (part of the) industry has already geared its technology to higher energy prices in the past.² Increasing energy tax rates now (as part of environmental policy) is therefore expected not to have a strong impact on investment behavior and technology choice, and thus result in only modest reductions in energy use. More likely, firms are forced to simply incur the rise in costs. This means that in order to achieve a substantial reduction in energy use, energy prices should be increased considerably with potentially high costs in terms of, for example, international competitiveness. However, in the post-1986 period, energy prices are much lower and also less subject to fluctuations. Given the positive correlation between the *level* of energy prices and their *variance* (*e.g.* Ferderer, 1996), uncertainty is likely to be smaller in the post-1986 period. As this may also affect the responsiveness of Dutch industry to changes in energy prices (and hence to taxation), the impact of uncertainty should be analyzed.

To explore the consequences of irreversibility and uncertainty for the environmental effectiveness of energy taxation in the Netherlands, the mechanisms behind asymmetric responses are elucidated through the use of a simple investment model presented in section 2. On the basis of this model we show in section 3 that, following a period of energy price increases, prices will have to drop substantially before energy-saving technologies are to be replaced by energy-intensive ones. This drop is likely to be larger (i) the higher the adjustment costs, (ii) the faster energy prices are expected to increase over time and (iii) the higher uncertainty about future prices. In turn, this means that energy price recoveries will not have much impact on energy use, suggesting that energy policy in periods of low energy prices will not be very effective. In section 4, an empirical analysis is undertaken for eight sectors of Dutch industry. The results are discussed in section 5, and the conclusions ensue.

¹Sectoral energy prices have been calculated on the basis of the share of the various energy carriers in a sector's energy use.

²On average, the (economic) lifetime of a installed capital is about 15 to 20 years.

2 Implications of investing under uncertainty for responses to energy price changes

In this section, an illustration is provided why asymmetric responses to energy price changes may arise. The main features causing the asymmetric response are the sunk-cost nature of investments in new technologies, exacerbated by the existence of uncertainty about the future. Suppose that there are two alternative technologies available for firms. A given quantity of goods can be produced by either an energy-intensive or a labour-intensive technology. Suppose that inputs for the energy-intensive technology are E_1 units of energy, and L_1 units of labour, while the corresponding inputs for the labour-intensive technology are E_2 and L_2 , respectively. From the assumption it is clear that $E_1 > E_2$ and $L_1 < L_2$. For notational convenience, define $\Delta E = E_1 - E_2$ and $\Delta L = L_2 - L_1$. Furthermore, assume that the adjustment costs (C_A) from switching either from the energy-intensive to labour-intensive technology or vice versa, are the same.³

With respect to the prices of both types of inputs, we assume that the price of labour (W) is constant and known throughout, but that future energy prices (P_E) are uncertain. Since most types of energy currently employed come from depletable resources, we assume a time trend for prices, but disturbances may force the energy price to deviate from its trend path. More specifically, the energy price is assumed to follow a Brownian motion:

$$(1) \quad dP_E = \alpha P_E dt + \sigma P_E dz.$$

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 1. This implies that $E(dP_E) = \alpha P_E dt$ with variance $\sigma^2 P_E^2 dt$ (Dixit and Pindyck, 1994, p. 70-71). Therefore, the expected energy price at time t equals:

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

Now the costs and benefits of switching from the energy-intensive technology to the labour-intensive technology can be determined. The change in technology results in savings on energy expenses, but expenditures on labour increase. Taking into account the adjustment costs C_A , the value of switching to labour-intensive (and hence energy-saving) technology equals:

$$(3) \quad \Omega^{ES}(P_E) = \int_0^{\infty} E(P_E) \Delta E e^{-rt} dt - \frac{W \Delta L}{r} - C_A = \frac{P_E \Delta E}{r - \alpha} - \left(\frac{W \Delta L}{r} + C_A \right),$$

³Note that this assumption seems unnecessarily restrictive. However, dropping it would have clear-cut consequences for the qualitative results derived in this section. If adjustment costs from energy-intensive to energy-saving technologies are higher than the reversal (which seems plausible because of, for instance, uncertainty with respect to the performance of new technologies and maybe also because

where r is the (exogenously determined) discount rate.⁴

After implementing the labour-intensive technology, the firm may decide to reverse its investment if the price of energy is sufficiently low (see below). For a certain energy price level P_E , the value of this reversal option equals:

$$(4) \quad \Omega^{EI}(P_E) = \frac{W\Delta L}{r} - \int_0^{\infty} E(P_E)\Delta E e^{-rt} dt - C_A = \frac{W\Delta L}{r} - \left(\frac{P_E \Delta E}{r - \alpha} + C_A \right),$$

What energy price is sufficiently high to induce the firm to switch towards the energy-saving (*i.e.* labour-intensive) 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. Given the uncertainty that the firm faces, postponing the decision reduces the probability of investing while such an investment turns out to be unprofitable. In mathematical terms, the firm maximizes:

$$(5) \quad F^{ES}(P_E) = \max \left\{ \Omega^{ES}(P_E), \frac{1}{1+rdt} E(F^{ES}(P_E) + dF^{ES}(P_E)) \right\}.$$

The value $\Omega^{ES}(P_E)$ is labeled 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 the brackets) is usually referred to as the “continuation value”. The firm's optimal decision maximizes the net present value of the investment option F^{ES} . As soon as the termination value exceeds the continuation value, the investment is undertaken. The energy price for which this is just the case will be referred to as the critical energy price P_E^{ES*} .

Applying Ito calculus, the following differential equation is obtained:

$$(6) \quad rF^{ES} dt = E \left[F_P^{ES} dP_E + \frac{1}{2} F_{PP}^{ES} (dP_E)^2 \right] = \left[F_P^{ES} \alpha P_E + \frac{1}{2} F_{PP}^{ES} \sigma^2 P_E^2 \right] dt.$$

Try $F^{ES} = AP_E^\beta$. Solving the differential equation, two roots can be found:

$$(7) \quad \beta = \left(\frac{1}{2} - \frac{\alpha}{\sigma^2} \right) \pm \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2} \right)^2 + \frac{2r}{\sigma^2}}.$$

This term 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 environmental regulations requiring emission cleaning activities), the conclusions of this section will only be strengthened.

⁴The 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

of the form $F^{ES}(P_E) = A_1 P_E^{\beta_1} + A_2 P_E^{\beta_2}$ 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. 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: $F^{ES} = \Omega^{ES}$: given the fact the investment is undertaken, waiting apparently no longer has a positive net value (see equation 5). In the second place, optimality requires that the option value function F^{ES} and the termination value function Ω^{ES} meet tangently at the critical price level: $F_P^{ES} = \Omega_P^{ES}$. Using these two additional conditions, it can be found that

$$(8) \quad P_E^{ES*} = \left(\frac{\beta_1}{\beta_1 - 1} \right) \left(\frac{r - \alpha}{\Delta E} \right) \left[\frac{W\Delta L}{r} + C_A \right].$$

Note that according to the NPV rule, the investments would be carried out as soon as:

$$(9) \quad \frac{P_E \Delta E}{r - \alpha} > \frac{W\Delta L}{r} + C_A.$$

The critical value under uncertainty, irreversibility and flexibility with respect to the timing of the investment decision exceeds the NPV's critical value because $\frac{\beta_1}{\beta_1 - 1} > 1$ as $\beta_1 > 1$.

After the switch towards the energy-saving technology, the energy price may fall such that the firm may decide to reverse its decision and to re-install an energy-intensive (but labour-saving) technology. In each period, it weighs the benefits of reversing now and the benefits of postponing the switch:

$$(10) \quad F^{EI}(P_E) = \max \left\{ \Omega^{EI}(P_E), \frac{1}{1 + rdt} \mathbb{E}(F^{EI} + dF^{EI}) \right\}.$$

Hence,

$$(11) \quad rF^{EI} dt = - \left[F_P^{EI} \alpha P_E + \frac{1}{2} F_{PP}^{EI} \sigma^2 P_E^2 \right] dt.$$

Again, try $F^{EI} = AP_E^\beta$. Then,

$$(12) \quad \beta = \left(\frac{1}{2} - \frac{\alpha}{\sigma^2} \right) \pm \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2} \right)^2 - \frac{2r}{\sigma^2}}.$$

This time only the negative root (β_2) plays a role: the lower the energy price, the higher the likelihood that the reversal will be profitable and hence the higher the value of the reversal option. Using $F^{EI} = \Omega^{EI}$ and $F_P^{EI} = \Omega_P^{EI}$, it can be found that

coefficient between market risk and the riskiness of the energy price (see Dixit and Pindyck, 1994, p.

$$(13) \quad P_E^{EI*} = \left(\frac{\beta_2}{\beta_2 - 1} \right) \left(\frac{r - \alpha}{\Delta E} \right) \left[\frac{W\Delta L}{r} - C_A \right].$$

Note that, because $\beta_2 < 0$, $0 < \frac{\beta_2}{\beta_2 - 1} < 1$ and hence the calculated critical value is lower than the value indicated by the NPV approach.

3 Predictions of the theory

The analysis presented above implies that there is an asymmetry in the response to energy price increases and decreases. The existence of adjustment costs, high expected rates of energy price increases and uncertainty about future prices drive a wedge between the critical energy price for a switch towards labour-intensive technologies, and the critical price for its reversal. Hence, in response to a price increase, investments will be undertaken. But a subsequent (moderate) drop in energy prices will not induce the reversal towards the energy-intensive technology.

This point is illustrated in Figure 2, where critical energy price lines are drawn for various time trends and for two levels of uncertainty ($\sigma = 0.01$ and $\sigma = 0.05$). From Figure 2 it is clear that there is a gap (an area between the two critical energy price levels) where prices can fluctuate without firms adapting their production technologies. Expectations about future price developments play an important role in deciding whether or not to invest in energy-saving technology. Indeed, the critical price lines demonstrate that a higher (expected) price trend induces the firm to invest sooner (although the reduction is not substantial), but more importantly that the energy price should be much lower before the firm will start contemplating to reverse its decision. The reason is that high trend values compensate for stochastic drops in the energy price. The reversal will thus only take place if the actual energy price is quite low: only then can it be expected to stay at a low level for a substantial period of time (see equation 1). Furthermore, the higher the uncertainty with respect to future prices, the longer a firm will postpone investing: the higher the uncertainty, the larger the inertia gap.

< Insert Figure 2 about here >

This idea can also be illustrated in another way. Suppose that there are many firms in the industry; one hundred to be precise. Suppose that the change in labour use is identical for all firms and is equal to one unit, but that some firms are more energy-inefficient than others: some firms can only reduce energy consumption with half a unit while others can reduce it

with 1.5 unit. Assume that all firms are uniformly distributed between $\Delta E=0.5$ and $\Delta E=1.5$. That means that as the energy price increases, some firms will decide to undertake the energy-saving investments, but others will want to wait. This situation is plotted in Figure 3, where the number of firms using energy-saving technologies (N_{ES}) is plotted on the vertical axis against the energy price level on the horizontal axis. In the numerical example with a low trend and low uncertainty ($\alpha = 0.03, \sigma = 0.03$), the critical energy price ($P_E^{ES^*}$) for the firm that can achieve the highest savings in energy use, is about 0.7. If the energy price increases above that critical level, an increasing number of firms will implement the energy-saving technology. If the price continues to increase up to 2.0, all firms eventually switch towards the energy-saving (labour-intensive) option. However, for a subsequent decrease in energy prices, at first none of the firms react and only after the energy price has fallen sufficiently (to less than 1.4 in this numerical example), firms reverse their investments and N_{ES} falls. Suppose that the price of energy did not fall all the way to the point where all firms would have reversed their investments, but only to intermediate price levels. Then only few (or even maybe none) of the firms would have adapted their technologies yet and a subsequent price recovery would again not evoke any responses. This would mean that after a period of price increases followed by price decreases, energy policy would be less effective in inducing investments in energy-saving technologies. The switching functions have also been drawn for the case of a higher trend ($\alpha = 0.07, \sigma = 0.01$) and for a higher level of uncertainty ($\alpha = 0.03, \sigma = 0.05$). The inertia gap is again larger the higher the uncertainty of the energy price level and the higher the expected rate of energy price increase.

< Insert Figure 3 about here >

From these two figures it is clear that the asymmetry in the response to energy price changes will increase with α and σ . If the upper critical level (*i.e.*, switch towards labour-intensive technology) has just been attained, the firm will undertake the investment. However, to reverse that decision, the energy price should drop substantially. For a large range of price decreases, nothing will happen in terms of energy use. The size of the inertia gap is larger (i) the higher the expected rate of price increase and (ii) the more uncertainty about future price levels. Of course, adaptation costs (C_A) also play a role: the higher these costs, the larger the inertia gap.

4 Empirical model

The theory presented in sections 2 and 3 has clear implications for energy policy in periods of relatively low energy prices that we would like to test empirically. Concerning the empirical analysis, we focus on the sectoral level because of the lack of time-series data at the firm level. Two main hypotheses can be formulated on the basis of the previous section. In the first place, theory predicts that at the sectoral level, more substitution will take place in periods where energy price increases result in “all time highs” than in periods of low prices, where increases will be mere price recoveries. Changes in the technology used by individual firms will show up in the sectoral data as input substitution. Therefore, substitution elasticities are expected to be higher in energy price booms than in slumps. In the second place, new technologies may result in efficiency gains. Little investments aimed at increasing energy performance are expected to take place in periods of low energy prices, and therefore technological progress is likely to be lower especially in energy-saving technologies.

Therefore, the prediction would be that in the post-1986 period (characterized by relatively low energy prices) neither the substitution elasticities between the various inputs nor the rates of technological progress would be substantial, implying that energy taxation may not be an effective instrument in the post-1986 period. However, there are two mitigating forces. The size of the “inertia price region” is smaller the lower the expected rate of energy price increases, and also the smaller the uncertainty about future energy prices. In the post-1986 period energy prices have recovered only slowly, and there are even periods where energy prices were observed to fall. Concerning uncertainty with respect to future levels of energy prices, the energy price *level* is often positively correlated with the *variance* of energy prices: relatively high prices are generally more volatile than relatively low prices (Ferderer, 1996). This implies that the size of the inertia gap is expected to be smaller in the post-1986 period than in the pre-1986 period, and hence that the production structure of the Dutch economy would be *more* sensitive to changes in the relative prices of the various inputs.

We aim to test the degree of substitutability of the various inputs (energy, labour and capital) and to analyze the type of technological progress (labour-saving, capital-saving or energy-saving) in response to changes in the relative prices of the various inputs. Figure 4 shows the energy-capital ratio for the sectors in our panel. In general, the energy-capital ratio declines until the mid-eighties. This decline may be caused by either input substitution or by energy-saving technological progress (or both).

< Insert Figure 4 about here >

From Figure 5 we can observe that the energy-labour ratio tends to increase for most of the sectors of industry our panel. Possibly, labour-saving technological progress dominates.

< Insert Figure 5 about here >

In order to allow for different substitution elasticities, nested CES functions will be estimated. The production functions of the various sectors are assumed to have a similar structure, where capital and energy are combined at the first level to produce an “intermediate output” (which will be referred to as Z), which is then combined with labour at the second level:

$$(14) \quad Q = \left[B_Z^{-\rho_2} \left[(A_K K)^{-\rho_1} + (A_E E)^{-\rho_1} \right]^{\rho_2/\rho_1} + (B_L L)^{-\rho_2} \right]^{-1/\rho_2}$$

In this equation the ρ 's are the substitution parameters; the elasticity of substitution at level i (σ_i) then equals $1/(1+\rho_i)$. The nature of technological change can be derived from the changes over time of the parameters A_K , A_E , B_Z , and B_L . Changes over time of B_L , for example, reflect labour-augmenting technological progress. Because of the two-level structure of the production function, there is also a parameter that measures the efficiency with which the composite input is used (B_Z).

At the first level, energy and capital are combined into the intermediate output Z in a profit-maximizing way. The optimization problem is:

$$(15) \quad \max_{K,E} P_Z Z - RK - P_E E$$

subject to

$$(16) \quad Z = \left((A_K K)^{-\rho_1} + (A_E E)^{-\rho_1} \right)^{-1/\rho_1},$$

In (15), R is the price of capital and P_Z the price of the intermediate output. Rewriting the decision problem, the following Lagrangean can be derived:

$$(17) \quad \Lambda = P_Z Z - RK - P_E E - \lambda \left[Z - \left[(A_K K)^{-\rho_1} + (A_E E)^{-\rho_1} \right]^{1/\rho_1} \right]$$

where λ is the Langrange multiplier.

Similarly, we assume profit maximization at the second level, which results in the following optimization problem:

$$(18) \quad \max_{L,Z} PQ - WL - P_Z Z$$

subject to

$$(19) \quad Q = \left((B_Z Z)^{-\rho_2} + (B_L L)^{-\rho_2} \right)^{-1/\rho_2}.$$

In equation (18), P is the price of output. The first-order conditions of these two optimization problems yield the standard result that the value marginal productivity of each input should be equal to its marginal cost. In the case of labour, this is fairly straightforward:

$$(20) \quad P \frac{\partial Q}{\partial L} = PB_L^{-\rho_2} \left(\frac{Q}{L} \right)^{1+\rho_2} = W$$

and hence

$$(21) \quad \frac{Q}{L} = B_L^{\rho_2/(1+\rho_2)} \left(\frac{W}{P} \right)^{1/(1+\rho_2)}.$$

The value marginal productivities of capital and energy should also equal their respective marginal costs, being the respective input prices:

$$(22) \quad P \frac{\partial Q}{\partial K} = P \frac{\partial Q}{\partial Z} \frac{\partial Z}{\partial K} = PB_Z^{-\rho_2} \left(\frac{Q}{Z} \right)^{1+\rho_2} A_K^{-\rho_1} \left(\frac{Z}{K} \right)^{1+\rho_1} = R$$

$$(23) \quad P \frac{\partial Q}{\partial E} = P \frac{\partial Q}{\partial Z} \frac{\partial Z}{\partial E} = PB_Z^{-\rho_2} \left(\frac{Q}{Z} \right)^{1+\rho_2} A_E^{-\rho_1} \left(\frac{Z}{E} \right)^{1+\rho_1} = P_E$$

On these two equations, the following optimal capital-energy ratio can be derived:

$$(24) \quad \frac{E}{K} = \left(\frac{R}{P_E} \right)^{1/(1+\rho_1)} \left(\frac{A_K}{A_E} \right)^{\rho_1/(1+\rho_1)} = \left(\frac{R}{P_E} \right)^{\sigma_1} \left(\frac{A_K}{A_E} \right)^{1-\sigma_1}.$$

By log-differentiating equations (21) and (24), the various rates of technological progress can be derived:

$$(25) \quad dq - dl = \sigma_2(dw - dp) + (1 - \sigma_2)db_l$$

$$(26) \quad de - dk = \sigma_1(dr - dp_e) + (1 - \sigma_1)(da_k - da_e)$$

Estimating equation (25) yields σ_2 , and the rate of growth of labour-augmenting technological progress. Equation (26) will yield information on σ_1 and on the difference between da_k and da_e . Next, we derive an equation for the rate of growth of the labour-capital ratio by equating the ratio of the cost of capital and labour to the ratio of their respective marginal productivities:

$$(27) \quad \frac{R}{W} = B_Z^{-\rho_2} \left(\frac{Q}{Z} \right)^{1+\rho_2} A_K^{-\rho_1} \left(\frac{Z}{K} \right)^{1+\rho_1} B_L^{\rho_2} \left(\frac{Q}{L} \right)^{-(1+\rho_2)} = \left(\frac{B_Z}{B_L} \right)^{-\rho_2} A_K^{-\rho_1} \left(\frac{Z}{L} \right)^{\rho_1-\rho_2} \left(\frac{L}{K} \right)^{1+\rho_1}$$

Noting that $\rho_1 - \rho_2 \equiv \frac{\sigma_2 - \sigma_1}{\sigma_2 \sigma_1}$, we find that

$$(28) \quad \frac{L}{K} = \left(\frac{R}{W} \right)^{\sigma_1} \left(\frac{B_Z}{B_L} \right)^{\sigma_1(1-\sigma_2)/\sigma_2} A_K^{1-\sigma_1} \left(\frac{Z}{L} \right)^{(\sigma_1-\sigma_2)/\sigma_2}.$$

Rewriting this equation in growth rates, the following equation can be derived:

(29)

$$dl - dk = \sigma_1(dr - dw) + \frac{\sigma_1 - \sigma_2}{\sigma_2}(dz - dl) + \frac{\sigma_1(1 - \sigma_2)}{\sigma_2}(db_z - db_l) + (1 - \sigma_1)da_k.$$

Two problems arise with the estimation of this equation. In the first place, we cannot estimate this equation directly because Z (and hence dz) is not directly observable. As is shown in Appendix A, this data problem can be addressed using standard index theory.

In the second place, the estimation model (25), (26) and (29), is underidentified. In equations (26) and (29), the intercepts reflect more than one type of technological progress. This can be elucidated by presenting the regression equations:

$$(30) \quad dq - dl = \sigma_2(dw - dp) + (1 - \sigma_2)c_1$$

$$(31) \quad de - dk = \sigma_1(dr - dp_e) + (1 - \sigma_1)c_2$$

$$(32) \quad dl - dk = \sigma_1(dr - dw) + \frac{\sigma_1 - \sigma_2}{\sigma_2}(dz - dl) + c_3$$

where each equation has a constant term:

$$(33) \quad c_1 \equiv db_l,$$

$$(34) \quad c_2 \equiv da_k - da_e, \text{ and}$$

$$(35) \quad c_3 \equiv \frac{\sigma_1(1 - \sigma_2)}{\sigma_2}(db_z - db_l) + (1 - \sigma_1)da_k$$

respectively. Concerning the substitution elasticities, we can identify σ_1 and σ_2 respectively from equations (31) and (30) while c_1 gives us the rate of labour-augmenting technological progress (db_l). The intercept of equation (31) yields information on the *difference* between da_k and da_e , but not the actual *levels* of the rates of these two types of technological progress (see equation 34). The interpretation of the intercept of equation (32) is even more complex, as is clear from (35): this intercept captures both the difference in labour-saving technological progress and technological progress that enhances the intermediate input, and capital-augmenting technological progress.

This implies that we can not identify the growth rates of the capital-augmenting and energy-augmenting technological progress (see Chang, 1994, p. 23). Only if either $\sigma_1 = 0$ or $\sigma_2 = 1$, the first term in c_3 drops out and the rate of capital-augmenting technological progress is known, and hence, from c_2 , the rate of energy-augmenting technological progress as well.

5 Results

We have gathered data on a balanced panel of eight sectors of industry for the Dutch economy. These sectors are agriculture, food and beverages, textiles and clothing, paper industry, basic metal industry, building materials, chemical industry and construction. These sectors are chosen on the basis of data availability for a longer time period. Data on energy use and energy prices are not (yet) available for the period before 1973 and after 1994 (at least not measured in a consistent way with the 1973-1994 period), so we restricted the time period to the period 1973-1994.⁵

Table 1 Summary of the parameters found for the various estimation periods

Period	σ_1	σ_2	db_l	da_k	da_e
1974-1994	0.000492*	0.488788	0.025149	-0.000529	0.023600
1974-1986	0.000634	0.504730	0.030439	-0.000895	0.041803
1986-1994	-0.000354*	0.457320	0.014774	0.000049*	-0.003842*

* Not significantly different from zero at 5%.

Applying iterative weighted least squares analysis while assuming common effects,⁶ we estimated the model consisting of equations (30)-(32) for three different periods: the entire sample period, and the sub-periods of price increases (1974-1986) and of price decreases (1986-1994). The actual results of the regression are presented in Appendix B; the most important results are summarized in Table 1.

As has been stated above, the nature of technological progress cannot be identified unless the substitution elasticities have certain values. The elasticity of substitution between capital and energy (σ_1) is found to be very close to zero or even insignificant, and hence the identification problem disappears: coefficient c_3 captures exclusively capital-augmenting technological progress, which means we can calculate the rate of energy-augmenting technological progress from c_2 .

⁵There are three main sources of the data: volumes and prices of value added and labour are taken from the P-series of the National Accounts 1997 of CBS Statistics Netherlands (CBS, 1998). Data on the stock of capital in 1990-prices are provided by the CPB, Netherlands Bureau for Economic Policy Analysis. Data on the use of energy and the price of energy are based on the publication *De Nederlandse Energiehuishouding* (CBS, various issues). Some data series had to be constructed; the methodology applied is described in Appendix A.

⁶That is, no sector specific dummies have been included. Apart from running common effects panel estimations, we also ran fixed effects estimation regressions (thus allowing for sector-specific results). As can be seen from Appendix C, the general results of the common effects estimations are consistent with the results of the fixed effects analysis (presented in detail in Appendix B).

Concerning the entire sample period, capital and energy are found to be complements while intermediate output and labour are found to be substitutes (the elasticity of substitution is less than 1). Furthermore, over this period technological change has been fairly substantial for labour and energy. The capital-augmenting technology parameter is very close to zero, but this is probably caused by the complementarity of capital and energy.⁷ On the basis of this regression one may conclude that energy pricing policies are expected to be fairly effective: input substitution and technological progress are fairly large.

However, subdivision of the entire sample period in a period of general price increases (1974-1986) and decreases (1986-1994) contradicts this conclusion: the coefficient estimates differ substantially between the two sub-periods discerned. In the period of increasing prices, the elasticity of substitution between capital and energy is low but significantly different from zero, while it became insignificant in the period of price decreases. Furthermore, in the first period technical progress in labour was slightly above 3% and in energy use even over 4%. In the period of price decreases, labour-augmenting technological progress fell to less than 1.5% and energy-augmenting technical progress even fell to zero. This suggests that indeed the two periods differ: an asymmetry exists between periods of high and increasing energy prices (where technological progress and the elasticity of substitution are fairly substantial) and periods of low energy prices (where both technological progress and substitution elasticities are low). This implies that it is very likely that an increase in the price of energy through taxation is not going to generate a substantial reduction in energy use. That means that estimating the effectiveness of energy taxation on the basis of the entire post-1973 period is likely to yield an overestimation of the true effectiveness.

6 Conclusions

This paper aims to shed light on the effectiveness of environmental policy in periods of high and low energy prices. It is argued that while firms are likely to invest in energy-saving technologies when energy prices hit all-time highs, they are unlikely to reverse the investment in periods of lower energy prices. This implies that in periods of relatively low energy prices, small increases in energy taxation will not induce any changes in the production structure. Therefore, energy taxes are not expected to be a strong instrument of environmental policy in periods of low energy prices. In assessing the environmental effectiveness of energy taxation, only the period of relatively low and stable energy prices should be used. Using a time series that includes periods where the energy price was found to hit all-time highs, the firms'

⁷Another explanation may be the continuous reductions in labour time, implying a lower utilization rate of capital.

possibilities to adapt will be overestimated. However, looking at the post-1986 experience, in that period energy prices are fairly low and have a low variance. This means that the size of the inertia gap is lower in that period, so that taxation for environmental purposes may be effective after all.

On the basis of a panel analysis of eight Dutch industrial sectors, we conclude that there are marked differences in the substitution elasticities and technological progress parameters between the period of high and increasing prices (1974-1986) and the period of relatively low and stable prices (1986-1994). In the latter period, capital and energy are found to be complements while the elasticity of substitution between labour and the capital-energy composite input also turns out to be lower than in the pre-1986 period. Furthermore, when prices generally increased, energy-saving technological progress was over 4% while it is insignificant in the post-1986 period.

These results suggest that energy taxation is not likely to be a very effective instrument in periods of relatively low energy prices, as is currently the case. If the Dutch government decides to increase the price of energy through taxation, the subsequent reduction in energy use will not be substantial while firms will have to incur the higher costs, with potentially harmful consequences for international competitiveness.

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Appendix A Data construction

Concerning the data used in this paper, three series had to be constructed: the prices and quantities of intermediate output from the first level Z and the user cost of capital. The intermediate (composite) output in constant prices can be calculated as the nominal composite output divided by its price index. The value of the composite output in nominal terms equals nominal capital expenditures plus nominal energy expenditures:

$$(A.1) \quad P_Z Z \equiv RK + P_E E .$$

If we re-scale the prices such that in the base-year $P_E=R=1$, K and E can be calculated in base-year prices. Then composite output Z is simply $Z=K+E$. This means that we can calculate the price index of this combined output Z as a weighted average of the price indices of the constituent parts:

$$(A.2) \quad P_Z = \left(\frac{K}{K+E} \right) R + \left(\frac{E}{K+E} \right) P_E .$$

Dividing expressions (A.1) and (A.2) yields the volume of input Z .

The (nominal) user cost of capital is not calculated in the usual way.⁸ Here, we made use of data on the stock of capital (measured in 1990-prices) kindly provided by CPB, Netherlands Bureau for Economic Policy Analysis. We constructed capital income resulting from production as the gross operating surplus corrected for wage income of self-employed, were self-employed earn the same wage rate as employees. The nominal rental price of capital is now simply calculated as capital income (in current prices) divided by the stock of capital in 1990-prices.

Finally, given data on the volume of labour input (L), capital input (K) and energy input (E), and their respective prices (W , R and P_E), we can construct gross output in nominal terms as value added in nominal terms plus the value of the energy input: $PQ = WL + RK + P_E E$, where $WL+RK$ equals nominal value added.

⁸The most simple Jorgenson type of user cost of capital is $R = P_i(i - \Delta \log P_i + \delta)$, where P_i is the purchase price of a unit of capital, i is the (nominal) interest rate, and δ is the (constant) rate of depreciation.

Appendix B Common-effects estimation results

The regression results for the three estimation periods (1974-1994, 1974-1986 and 1986-1994) are presented below.

Table B.1 Estimation results for the entire sample period (1974-1994)

	Coefficient	Std. Error	t-Statistic	Prob.
σ_2	0.488788	0.064726	7.551644	0.0000
db_1	0.025149	0.006198	4.057429	0.0001
σ_1	0.000492	0.000314	1.566003	0.1180
$da_k - da_e$	-0.024129	0.006071	-3.974491	0.0001
C_3	-0.000529	0.000112	-4.724527	0.0000
S.E. of regression	0.053435	Mean dependent var		0.030893
Durbin-Watson stat	1.989492	S.D. dependent var		0.042262
		Sum squared resid		0.054251

Table B.2 Estimation results for the period of price increases (1974-1986)

	Coefficient	Std. Error	t-Statistic	Prob.
σ_2	0.504730	0.080529	6.267654	0.0000
db_1	0.030439	0.008632	3.526160	0.0005
σ_1	0.000634	0.000311	2.038500	0.0424
$da_k - da_e$	-0.042698	0.007087	-6.025124	0.0000
C_3	-0.000895	0.000137	-6.541281	0.0000
S.E. of regression	0.049564	Mean dependent var		0.037877
Durbin-Watson stat	1.855769	S.D. dependent var		0.043813
		Sum squared resid		0.027023

Table B.3 Estimation results for the period of price decreases (1986-1994)

	Coefficient	Std. Error	t-Statistic	Prob.
σ_2	0.457320	0.088029	5.195075	0.0000
db_1	0.014774	0.007634	1.935264	0.0543
σ_1	-0.000354	0.000720	-0.491649	0.6235
$da_k - da_e$	0.003891	0.007522	0.517297	0.6055
C_3	4.88E-05	0.000124	0.394853	0.6934
S.E. of regression	0.061174	Mean dependent var		0.025270
Durbin-Watson stat	2.094879	S.D. dependent var		0.040900
		Sum squared resid		0.026196

Appendix C Fixed effects estimation results for the technical progress parameters

Apart from the common-effects estimations that are presented in the main text, we also ran fixed-effect regressions where the technological progress parameters are allowed to differ (the elasticities of substitution are still assumed to be the same across all sectors of industry). Table C.1 presents the results with respect to the common elasticities of substitution. These results are very similar to the ones derived from common effects estimation.

Table C.1 Results from fixed effects estimations

Period	σ_1	σ_2
1974-1994	0.000478*	0.447070
1974-1986	0.000630	0.478026
1986-1994	-0.000360*	0.402200

* Not significantly different from zero at 5%.

The technological progress parameters differ across sectors. For the whole sample period only three or four out of eight sectors produce significant coefficients with respect to energy saving and capital saving as can be seen from Table C.2.

Table C.2 Results from fixed effects estimations for the period 1974-1994

Period	db_l	da_k	da_e
Agriculture	0.017227*	-0.000105*	0.00509*
Food and beverages	0.039362	-0.000624	0.028606
Textiles and clothing	0.035026	-0.000523	0.038628
Paper industry	0.037968*	-0.000583	0.034521
Basic metal industry	0.017785*	-0.000978	0.032746*
Building materials	0.015242*	-0.003342*	0.012503*
Chemical industry	0.045138*	-0.001603*	0.010099*
Construction	0.006291*	-0.001002*	0.035350*

* Not significantly different from zero at 5%.

For the sub-periods we find results (not reported here) which are very similar to the common effects results in Section 4. For the first sub-period the same sectors produce significant coefficients with respect to technological progress. For the second sub-period all technology parameters are insignificant, except one: In the period 1986-1994 we find labor-augmenting technological progress in the food and beverages industry of 4.7%.

Figure 1 Energy prices (1990=100) for eight sectors of industry of the Dutch economy for the period 1973-1994.

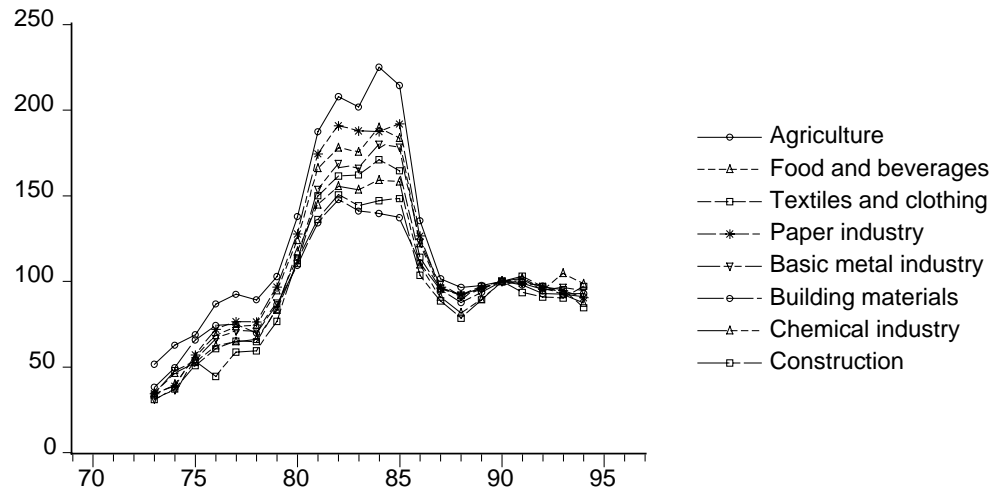
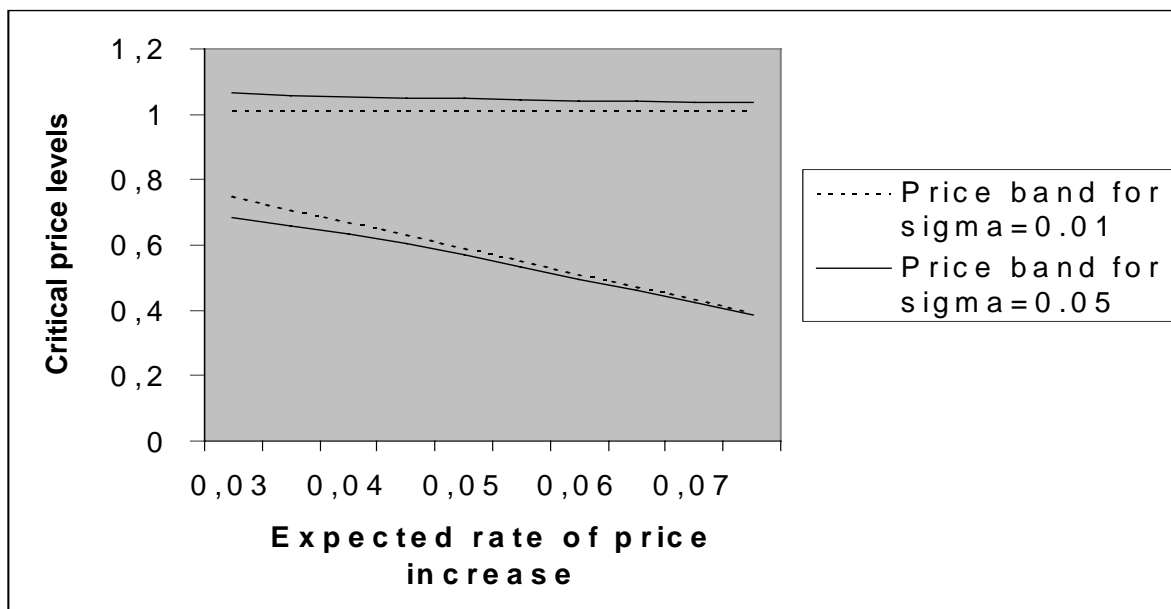
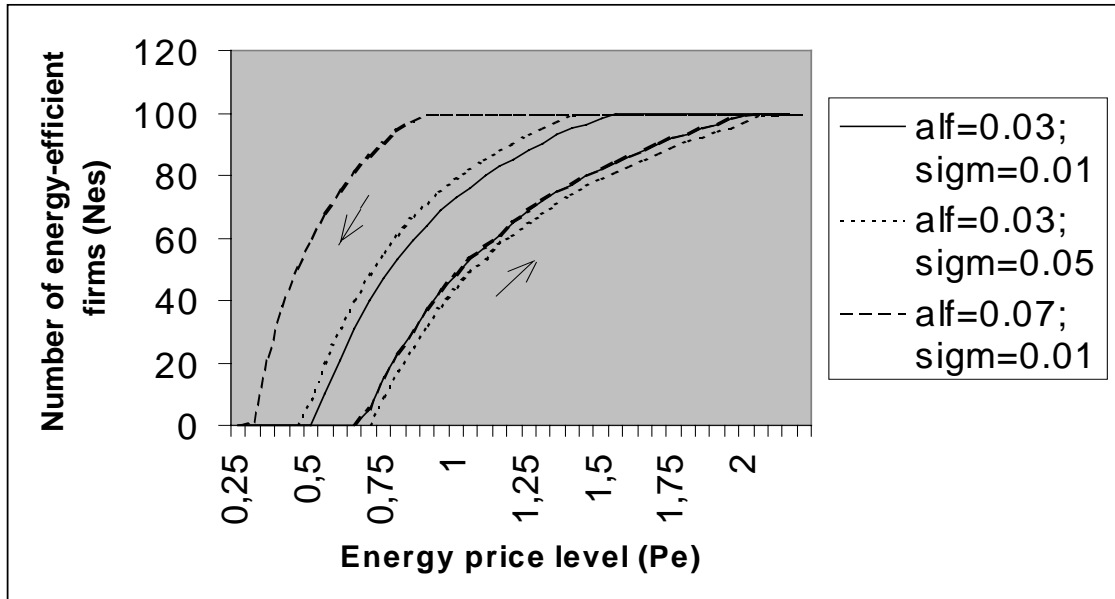


Figure 2 *Inertia price gaps as a function of the expected rate of energy price increases, for two different levels of uncertainty ($\sigma = 0.01$ and $\sigma = 0.05$).*



Parameter values: $\Delta E = 1, \Delta L = 1, r = 0.125, W = 1, C_A = 0.1$.

Figure 3 The number of firms applying energy-saving technologies as a function of the energy price level for different combinations of expected rates of energy price increases and variances ($\alpha=0.03, \sigma=0.01$; $\alpha=0.07, \sigma=0.01$; and $\alpha=0.03, \sigma=0.05$) for a price increase and subsequent decrease.



Parameter values: $\Delta E = 1, \Delta L = 1, r = 0.125, W = 1, C_A = 0.1$.

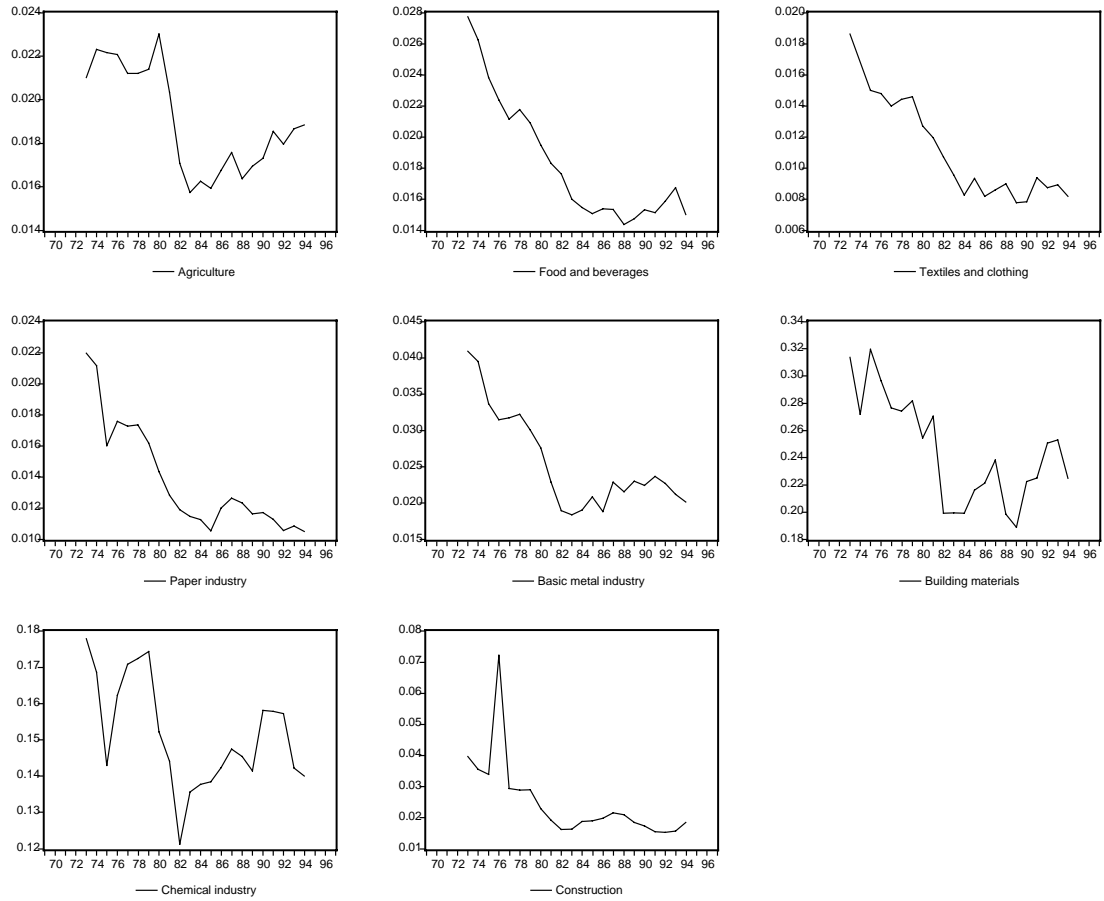


Figure 4 Energy-capital ratio for the sectors of industry in our panel.

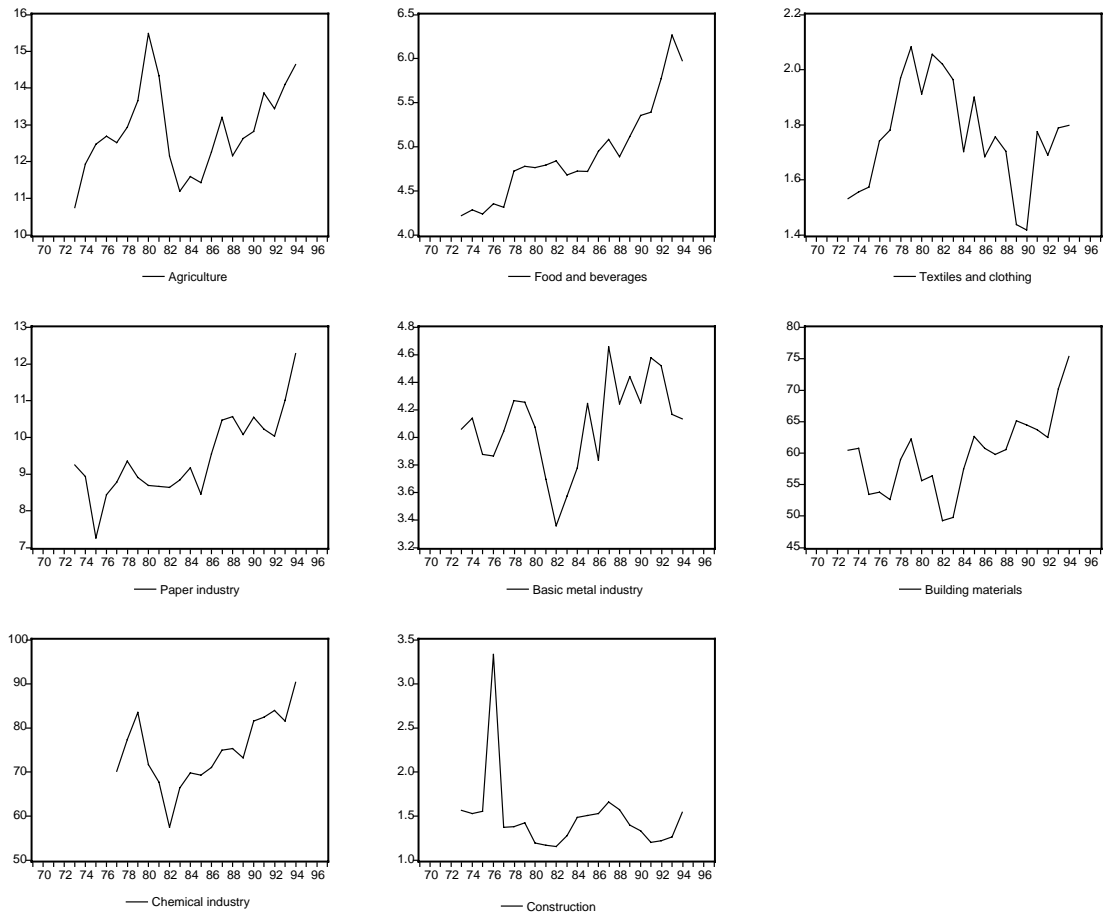


Figure 5 Energy-labour ratio for the sectors of industry in our panel.