An econometric model of production with endogenous improvement in energy efficiency, 1970-1995

Running title: Energy efficiency in production

by Klaus Conrad

Mannheim University

Abstract

The purpose of this paper is to introduce a modification of a standard four input production process where energy is used in an inefficient way due to partly unnecessary waste of energy. In this production process, R&D investment is an additional input in order to improve energy efficiency. It closes the gap between energy purchased and energy used effectively. The more is invested, the less is the waste of energy. With the cost and benefit of R&D investment incorporated in our model of the firm, we analyze the impact of an energy tax on R&D effort, on output and on the waste of energy. The model is implemented empirically by choosing a translog cost function and a set of first-order conditions, using data for the German chemical industry, 1970-1995. In a simulation study based on higher energy prices we found outsourcing as the consequent reaction of the firm - more material is used and less of energy, labor, and capital, given the unchanged output level. There is no indication of a double dividend in terms of environmental improvement as well as higher demand for labor on the industry level calling for a computable general equilibrium approach in order to answer this open question.

Production process, energy demand, energy saving technical change, process R&D expenditures, energy tax

[C 51, D 21, O 31, Q 41, Q 48]

Mannheim University

Department of Economics

Seminargebäude A5

D-68131 Mannheim

Phone: + 49 292 5121

Fax: + 49 292 3185

e-mail: kconrad@rumms.uni-mannheim.de

An econometric model of production with improvement
in energy efficiency, 1970-1995

by Klaus Conrad

Mannheim University

1. Introduction

It is wellknown that results from an environmental policy in response to global climate change are quite sensitive to the assumption on the rate of energy efficiency improvements. However, technical progress is traditionally considered as a non-economic variable in economic policy models. It is exogenous in most policy evaluations as well as in the theory of environmental economics. Everybody agrees that the neglect of induced technological progress may lead to overestimation of the costs of greenhouse gas reduction, but no one knows how technological progress responses to economic incentives. This obviously hampers thinking about schedules of emission mitigation targets and policies of sustainable development in the presence of uncertainty. The omission of induced technological change might lead to underestimation of the net benefits of tighter environmental policies because such a policy can induce major technical advances in abatement technologies.

Most models either neglect the role of technological change, or exogenous Hicks-neutral technical change is introduced (The increased output of other goods and services per unit of input and the increase in emissions reduction per unit of input are the same). One of the few attempts to (partly) endogenize technical change is the approach followed by Jorgenson and Wilcoxen (1990) and later by McKibbin and Wilcoxen (1992). Technological development is partly endogenized by the specification of productivity growth as a function of the prices of all inputs of an industry. In this approach substitution away from polluting inputs can affect the rate of productivity growth. A decrease in an industry's productivity level will raise the price of its output relative to its input prices, i.e. the industry will become less competitive. If the bias of technical change is input of type i using and the price of such a pollution intensive input increases (e.g. by a tax), then cost reduction due to productivity growth will be reduced. Technological development is treated only partially in these models because an autonomous trend is included which interacts with the prices of intermediate inputs. The translog unit cost functions are functions of the prices of all inputs and of time t as an index of technology. There is price induced productivity growth in the model which affects input shares. But technological change is not endogenized in terms of leading to new vintages of durable goods, to new products or to different qualities or major breakthroughs.

Autonomous energy efficiency improvements (AEEI) are more difficult to estimate than those that are induced by price increases. AEEI decouples resource demand and economic output, and so yields resource-saving technical change. Econometric investigations by Jorgenson and Wilcoxen (1990) of the US post-1947 historical record show no evidence for autonomous time trends of this type. Technologically oriented end-use analysts, however, have suggested that non-price efficiency improvements may be induced by changes in public policy like a mandatory doubling of average fuel efficiency of automobiles during the course of ten years. Manne and Richels (1991) introduce those exogenous efficiency improvements, for example. Their production function also allows for the possibility of costless AEEI which reduce the share of energy in GNP over time. A factor for autonomous energy efficiency improvement integrates all non-price

induced changes in energy intensity and therefore represents the efficiency effect of technological, structural and political objectives (e.g. voluntary agreements). This approach emphasizes to show the **effect** of technical change but can not model aspects like innovation, adaptation or diffusion.

An alternative approach to endogenize technical change is the use of capital vintages involving different technologies. The differentiation of technologies can have effects on the form of the production function, on the input structure, or on flexibility (different elasticities of substitution for the vintages). With new vintages substitution possibilities among production factors are higher than with old vintages. In Bergman (1990) the "old" production units in steel or pulp and paper industries are assumed to have zero elasticities of substitution, whereas the elasticity of substitution of "new" production units in these industries is positive.

A further methodological approach to take into account the vintage concept is to replace capital K in a variable cost function by Solow's (1959) expression for an effective capital stock. In his 1959 article, Solow criticized the disembodied nature of technical change in aggregate production functions. He emphasized the fact that most improvements in technology need to be embodied in net capital formation, or in the replacement of old-fashioned equipment, before they can be made effective. Solow proposed to distinguish capital equipment of different vintages and formulated a Cobb-Douglas function for output produced with capital of a given vintage. Technical change is represented by a rate of embodied technical change as well as of disembodied technical change. His measure of effective capital incorporates the assumption that all technical progress is embodied in the improving quality of successive vintages of capital investment.

If technical progress is unembodied in capital plant and equipment, then its effects do not depend in any way on the rate of investment in capital plant and equipment. An alternative notion is that technical progress is entirely embodied in the design and operating characteristics of new capital plant and equipment. According to this view, the energy saving effects of embodied technical progress depend critically on the rate at which new investment goods diffuse into the economy, i.e. on the vintage composition of the capital stock. For policy measures the nature of technical progress matters. If technical progress is embodied, tax credits for investments in new energy-efficient equipment provide an incentive to realize its effects more quickly than if technical change were unembodied. However, under embodied technical change energy savings can be realized only by changing the energy using characteristics of the long-lived capital stock, whereas under unembodied technical change the effectiveness of the entire capital stock is augmented regardless of its vintage composition. One example of unembodied technical change is learning by doing in which workers learn how to produce more efficiently. However, if technical progress were embodied, it augments only the most recent vintage of investment, and not any of the earlier vintages of surviving capital.

More recent approaches to endogenize technological change are based on expanding product variety, or improving the quality of (intermediate) products, or models based on human capital accumulation. The first group of these models treat R&D activity like other production activities which convert primary inputs into knowledge (Romer (1990), Grossman and Helpman (1991)). The total amount of knowledge or, equivalently, the level of technology enforces growth, increases the number of new intermediate products or the variety of technologies. In the second group of models (e.g. Aghion and Howitt (1992)), technological progress increases the productivity of the intermediate good in the production of the final good. Here, innovation produced by the research sector improves the quality of the

intermediate good which replaces the older one. In these models the outcome of an innovation is uncertain and the number of researchers is endogenous. The third group focuses on endogenous growth by pointing out that capital accumulation and growth will be more rapid in countries that are better endowed of physical and human capital (Lucas (1988)). In the literature on environmental policy and economic growth, Bovenberg and Smulders (1996) have build an endogenous growth model in this spirit which describes endogenous technical advances in environmentally friendly technologies. In their model there is an environmental R&D sector which produces environmental technology capital in order to raise total factor productivity.

The model we present in this paper belongs in its spirit to the second group because it focuses on the improvement of the use of energy as an intermediate good in the production process. Depending on the price of energy, part of energy is wasted in the production process. If a tax on energy or on carbon dioxide increases the price of energy, firms invest in energy saving process R&D in order to improve the efficiency of the energy input. Since we want to estimate our model econometrically because we are interested in the impact of higher energy taxation on energy efficiency, we propose a less sophisticated model than some of those found in the theoretical literature. After presenting our approach of an endogenous energy efficiency index in section 2, we determine in section 3 the response of the firm to higher energy prices using a comparative statics analysis. In section 4 we implement this model empirically by using time series data of the German chemicals industry. In section 5 we discuss the results and carry out a simulation study in order to quantify the impact of a energy tax on energy efficiency. Section 6 concludes the paper.

2. A model with inefficient use of energy

We consider a production technology which produces a good of quantity x with the $KLEM$ inputs, capital (K), labor (L), gross energy (GE) and material (M):

$$(1) \quad x = F(K, L, GE, M).$$

By gross energy we mean energy input with a byproduct "waste of energy" which reduces the efficiency of the production process. In the theory of production the assumption is made that production is characterized by points on the production frontier. The assumption of free disposal of waste takes care of inefficiency in energy use. We argue that awareness for energy conservation should be raised in order to

achieve production close to the production possibility frontier. We distinguish between gross energy and net energy (E) input where

(2) $E = (1-\alpha)\,GE\ ,\ \ 0 \leq \alpha \leq 1\ ,\ \ and\ \ WE = \alpha \cdot GE$

with WE as gross waste and " as the waste coefficient or coefficient of energy inefficiency. Therefore, the function in (1) is not a production function because it does not characterize efficient production.

The net energy input has to be the appropriate argument in F (q) for F to be a production function:

(3) $x = f(K,L,E,M)$

To improve energy efficiency, i.e. to reduce the waste coefficient, is costly because it requires time and effort, and hence causes cost of labor and material. We denote with e the effort to reduce the waste of energy and assume " (e) to be a function of this effort $(\alpha'(e) < 0, \alpha''(e) > 0)$. For the empirical implementation, e will be the intensity of R&D activities to improve energy efficiency. We also include e as an argument in the production function in order to represent the aspect that a higher effort (R&D level) in avoiding waste of energy will reduce productivity in terms of less output with given levels of $KLEM$ inputs. Using (2) and (3), we cast the standard cost minimizing problem

$$\min_{K,L,GE,M} PK \cdot K + PL \cdot L + (PGE + t_g)\,GE + PM \cdot M \qquad s.t. \quad x = F(K,L,GE,M)$$

in such a way that the net quantity of energy E and not of gross energy GE is the input the firm focuses on

(4)

$$\min_{K,L,E,M,e} \quad PK \cdot K + PL \cdot L + \frac{PGE + t_E}{1 - \alpha(e)} \cdot E + PM \cdot M \qquad s.t. \quad x = f(K, L, E, M, e)$$

with $f_e < 0$. *PK, PL, PGE, PM* are the prices of capital, labor, gross energy and material and t_E is the tax rate on energy. We include the tax rate t_E as a reminder that it can be used as a policy instrument to raise energy efficiency.

Next we define the price of energy to be

$$PE(e; t_E) = \frac{PGE + t_E}{1 - \alpha(e)}$$

(5)

with

$$PE_e = \frac{\alpha'}{(1 - \alpha)^2} \quad (PGE + t_E) < 0$$

(6)

i.e. effort *e* reduces the price for the efficient energy input. Since the cost function, dual to the production function, is more convenient for the analysis we have in mind, we state the problem as one of profit maximization under perfect competition by using a cost function:

$$\max_{x,e} \Pi = p \cdot x - C(x, PK, PL, PE(e,t_g), PM, e)$$
(7)

with PE as defined in (5). The decline in output from the GE-reducing effect of effort e is now expressed in terms of $C_e > 0$ and $C_{ee} > 0$. An environmentally friendly production process with emphasis on energy conservation increases the cost for producing x. The benefit is a lower price PE due to energy efficiency of the input energy.

The FOC with respect to x is:

$$p - C_x(x, PK, PL, PE, PM, e) = 0$$
(8)
,

and the FOC with respect to e is:

$$-E \cdot PE_e - C_e = 0$$
(9)

because of Shephard's Lemma $(E = C_{PE})$. According to (9), the level of e is optimal if marginal savings in the cost of energy justifies exactly the increase in the cost of producing output x with a more energy efficient technology. PE_e is negative because an increase in effort reduces waste of energy and raises net energy.

3. Comparative Statics

In order to determine the effect of a change in the energy tax t_E on production, effort and energy wasted, we totally differentiate equations (8) (i.e. $\Pi_x = 0$) and (9) (i.e. $\Pi_e = 0$):

$$\Pi_{xx}\, dx + \Pi_{xe}\, de = -\Pi_{x\,t_s}\, dt_E \tag{10}$$

$$\Pi_{ex}\, dx + \Pi_{ee}\, de = -\Pi_{e\,t_s}\, dt_E \tag{11}$$

To obtain unambiguous qualitative results and to simplify the analysis it is convenient to find an assumption which implies $\Pi_{xe} = \Pi_{ex} = 0$. Such an assumption is a homothetic production function. The comparative statics analysis shows that the elasticity of output with respect to the energy tax is

$$\frac{d \ln x}{d \ln t_E} = -\frac{t_E \cdot GE}{p \cdot x}\, \frac{\eta_{E,x}}{\eta_{MC,x}} < 0 \tag{12}$$

where the elasticities 0 of energy or marginal cost with respect to output are positive. The higher the energy tax in relation to revenue, the

higher the negative impact on output from the tax. Furthermore, the change in effort e with respect to a change in the energy tax is

$$\frac{de}{dt_E} = \frac{GE \left(\varepsilon_{E,e} + \varepsilon_{E,PE} \cdot \varepsilon_{PE,e} \right) + WE \cdot \frac{\varepsilon_{\alpha,e}}{1-\alpha}}{e \cdot \Pi_{ee}} > 0$$

(13)

where $\Pi_{ee} < 0$ due to the strict concavity assumption of the profit function in e and x. As we expect $\frac{de}{dt_E} > 0$, the numerator in (13) should turn out to be negative. First of all, all elasticities ε are negative. The elasticity of energy input with respect to effort e, $\varepsilon_{E,e}$, is negative by assumption because we assume that effort to reduce energy inefficiency is energy saving. $\varepsilon_{E,PE}$ is negative since it is a price elasticity of input demand; the elasticity of the price of energy with respect to e, i.e. $\varepsilon_{PE,e}$, is negative because of $PE_e < 0$ (see (6)), and the elasticity of the inefficiency coefficient $\alpha(e)$ with respect to e is negative as $\alpha' < 0$. We will assume that the product of the two elasticities, which is a positive figure, will not dominate the two negative effects in the numerator; i.e. the effect of e on energy demand via the price PE is weaker than the sum of the direct effects of e on energy saving productivity as well as on lowering the inefficiency coefficient. This seems to be a reasonable assumption and it justifies the positive sign in (13).

It is of interest to decompose the impact of the energy tax on reducing to waste energy. By differentiating the equation for WE,

$$WE = \frac{\alpha(e)}{1-\alpha(e)} E\left(x, PE\left(e, t_E\right), e\right)$$

totally, the following five aspects are captured by our model:

$$\frac{d\ln WE}{d\ln t_E} = \frac{\varepsilon_{\alpha,e}}{1-\alpha}\frac{d\ln e}{d\ln t_E} + \eta_{E,x}\frac{d\ln x}{d\ln t_E} + \varepsilon_{E,PE}\left(\frac{\partial\ln PE}{\partial\ln t_E} + \varepsilon_{PE,e}\frac{d\ln e}{d\ln t_E}\right) + \varepsilon_{E,e}\frac{d\ln e}{d\ln t_E}.$$

The first term is negative and represents the effect of a higher tax on e (positive) which in turn lowers the waste coefficient " . The second term (also negative) captures the reduction in energy wasted due to a lower production level. The third term (negative) represents the demand effect on E because t_E increases the price of efficiently used energy E . The fourth term (the only positive one) shows an

offsetting effect of t_E on E because an energy tax raises effort, effort in turn lowers PE via $\alpha'(e) < 0$, which then raises the demand for E . The fifth term (negative) finally shows the benefit of a tax in terms of an energy saving bias of the effort. The model therefore captures all relevant aspects for an energy conservation policy which aims at reducing inefficiency in energy intensive industries. Although this approach looks like having endogenized technical change, it can not be used to make predictions or to recommend the introduction of certain technologies. However, an econometric estimation of the model may help us with our search for endogenizing technological change.

4. Empirical implementation

For implementing our approach towards endogenizing technical change we measure effort e by the capital stock of R&D investment in energy saving process innovation. For that purpose we split up R&D expenditure of an industry in expenditure on product innovation and in those for process innovation. The latter will be split again, this time in R&D investment in energy saving innovations, RDE , and in non-energy saving innovation, $RDNE$, which means expenditures to reduce the cost of the production process. The stock of R&D capital ($KRDE$) to achieve an energy saving production process is calculated by using cumulative R&D expenditures as a proxy of knowledge. The stock of R&D capital ($KRDNE$) to achieve a reduction in the cost of production is calculated in a similar way. As a case study we choose the chemicals industry.

For the econometric analysis we replace the cost function in (7) by

$$\max_{x, KRDE, KRDNE} \Pi = p \cdot x - C(x, PK, PL, PE(KRDE, t_E), PM) \cdot KRDNE^{-\alpha_{RD}}$$

(14)
$$- PKRD \cdot (KRDE + KRDNE)$$

There is Hicks-neutral technical change with respect to non-energy R&D capital, and *PKRD* is the user cost of capital per unit of both types of R&D capital stocks. The FOC (9) can be rewritten as

15. $-E \cdot PE_{KRDE} - PKRD = 0$

For our econometric analysis it is preferable to approximate $(1 - \alpha(KRDE))^{-1}$ in $PE(KRDE, t_E)$ by $\exp\left(\dfrac{p}{KRDE}\right)$. Therefore, *PE* is

$$PE(KRDE, t_E) = \exp\left(\frac{p}{KRDE}\right) \cdot (PGE + t_E)$$

(16)

Equivalently, *E* is

$$E = \exp\left(-\frac{\rho}{KRDE}\right) \cdot GE \quad \text{with} \quad \exp\left(-\frac{\rho}{KRDE}\right) \le 1$$

(17)

The parameter $\rho > 0$ captures how rapidly maximum energy efficiency $(\rho = 0)$ is approached as *KRDE* increases. The functional form for the relationship between *KRDE* and energy efficiency approximates the fact that as one spends more and more R&D expenditure for an energy efficient process, there is a limit to the amount of energy savings that can result. Expenditures on energy have to satisfy the identity

$$PE(\cdot) \cdot E(\cdot) = (PGE + t_E) \cdot GE.$$

With this exponential specification the FOC (15) yields

$$KRDE^2 = \rho \, \frac{(PGE + t_E) \cdot GE}{PKRD}$$

(18)

where $PKRD = PRD(r + \delta)$ with *PRD* as the price of R&D expenditure and *r* as the rate of return (interest rate for government bonds).

As a specification of a cost function we choose the translog specification of a homothetic production technology. With restrictions imposed on the parameters from symmetry of the β 's and from linear homogeneity in prices the translog cost function is:

$$\ln C = \alpha_0 + \ln PK + \alpha_x \ln x + \alpha_L \ln \overline{PL} + \alpha_M \ln \overline{PM} - \alpha_{RD} \cdot \ln KRDNE$$

$$+ \alpha_E \left(\ln \overline{PGE} + \rho \cdot KRDE^{-1} \right) + \frac{1}{2} \left(\beta_{LL} \ln^2 \overline{PL} + \beta_{MM} \ln^2 \overline{PM} \right.$$

$$+ \beta_{EE} \left(\ln^2 \overline{PGE} + \ln \overline{PGE} \cdot \rho \cdot KRDE^{-1} + \rho^2 \cdot KRDE^{-2} \right) \bigg)$$

$$+ \beta_{LM} \ln \overline{PL} \cdot \ln \overline{PM} + \beta_{LE} \left(\ln \overline{PL} \cdot \ln \overline{PGE} + \rho \cdot KRDE^{-1} \cdot \ln \overline{PL} \right)$$

(19) $$+ \beta_{ME} \left(\ln \overline{PM} \cdot \ln \overline{PGE} + \rho \cdot KRDE^{-1} \cdot \ln \overline{PM} \right)$$

where $\overline{PL} = \dfrac{PL}{PK}$, $\overline{PM} = \dfrac{PM}{PK}$ and $\overline{PGE} = \dfrac{PGE + t_E}{PK}$. PE in the cost function has been replaced by $PE(\cdot)$ as in (16). Since (8) can

be written as $\dfrac{p \cdot x}{C} = \dfrac{\partial \ln C}{\partial \ln x}$, using this cost function specification, (8) becomes

(8') $$\frac{p \cdot x}{C} = \alpha_x$$

From Shephard's Lemma we obtain the cost-shares as logarithmic derivatives of the cost function:

$$\frac{PL \cdot L}{C} = \alpha_L + \beta_{LL} \ln \overline{PL} + \beta_{LM} \ln \overline{PM} + \beta_{LE}\left(\ln \overline{PGE} + \frac{P}{KRDE}\right)$$

(20)

$$\frac{(PGE + t_E) \cdot GE}{C} = \alpha_E + \beta_{EE}\left(\ln \overline{PGE} + \frac{P}{KRDE}\right) + \beta_{LE} \ln \overline{PL} + \beta_{ME} \ln \overline{PM}$$

(21)

$$\frac{PM \cdot M}{C} = \alpha_M + \beta_{MM} \ln \overline{PM} + \beta_{LM} \ln \overline{PL} + \beta_{ME}\left(\ln \overline{PGE} + \frac{P}{KRDE}\right)$$

(22)

We have omitted the equation for the cost share of capital because cost shares add up to one and error terms to zero. Therefore the parameters of the cost share of capital can be derived from the parameter restrictions:

$$\alpha_L + \alpha_E + \alpha_M + \alpha_K = 1, \ \beta_{LL} + \beta_{LE} + \beta_{LM} + \beta_{LK} = 0 \qquad etc.$$

Finally, the FOC with respect to *KRDNE* is

23. $$\frac{PKRD \cdot KRDNE}{C} = -\frac{\partial \ln C}{\partial \ln KRDNE} = \alpha_{RD}$$

We have estimated the parameters of the system (19), (8'), (18) and (20) - (23) using the maximum likelihood method.

5. Results from estimation and simulation

Yearly data on prices and quantities and on R&D expenditures have been collected for the chemical industry for the years 1970-1995. Between 21% and 26% of total R&D expenditure are spent for process innovation. As there are no data on R&D investment in energy saving innovations, we used the share of abatement expenditure for reducing air pollution in total environmental abatement expenditure of the chemical industry. This percentage was 27% in 1970, 46% in 1985 and about 33% after 1993. Since efforts to reduce emissions from burning fossil fuel could be equivalent to investments in energy saving innovation we consider these percentage figures as a reasonable proxy. The R&D capital stocks were constructed by the perpetual inventory method with an assumed depreciation rate of 15 percent. In Table 1 we present the parameter estimates of our system of equations and the level of the R&D stock for some selected years. The

efficiency factor in $E = \exp\left(-\frac{0.162}{KRDE}\right) \cdot GE$ is 86 percent in 1970 and improves up to 94 percent in the nineties. The effective price of

energy, $PE = \exp\left(\frac{0.162}{KRDE}\right) \cdot (PGE + t_E)$ is therefore 115 percent higher than the market price $PGE + t_E$ and drops to 106 percent

above this price. The elasticity of costs with respect to the stock of non-energy process innovation is $\alpha_{RD} = -0.007$.

For an interpretation of the β-parameters we could employ the Allen-Hicks partial elasticity of substitution expressed by

$\sigma_{ij} = (\beta_{ij} + s_i \cdot s_j) / s_i s_j$ $(i \neq j)$ and $\sigma_{ii} = \left[b_{ii} + s_i (s_i - 1) \right] / s_i^2$ where s_i are the cost shares (e.g. $s_L = PL \cdot L / C$). Here we

present price elasticities of the inputs which can be calculated by multiplying σ_{ij} by the cost shares, i.e. $\varepsilon_{ij} = s_j \cdot \sigma_{ij}$. With

$s_E = 0.07$, $s_L = 0.24$, $s_M = 0.6$ and $s_K = 0.09$ as mean of the cost shares, the matrix of input price elasticities i

$$
\begin{pmatrix}
\varepsilon_{LL} & \varepsilon_{LK} & \varepsilon_{LE} & \varepsilon_{LM} \\
\varepsilon_{KL} & \varepsilon_{KK} & \varepsilon_{KE} & \varepsilon_{KM} \\
\varepsilon_{EL} & \varepsilon_{EK} & \varepsilon_{EE} & \varepsilon_{EM} \\
\varepsilon_{ML} & \varepsilon_{MK} & \varepsilon_{ME} & \varepsilon_{MM}
\end{pmatrix}
=
\begin{pmatrix}
-.35 & .8 & -.04 & .31 \\
.21 & .0 & -.11 & -.10 \\
-.13 & -.14 & -.63 & .90 \\
.12 & -.02 & .10 & -.20
\end{pmatrix}.
$$

Labor and energy are more price elastic than capital and material. Substitutional relations are as expected: material and energy are substitutes as are material and labor, and labor and capital. Also the complementary relations are as expected: capital and material are complements as are energy and capital. However, in view of the double dividend discussion of raising the price of energy and reducing non-wage labor costs in order to improve the state of the environment and of unemployment, the complementary relationship between energy and labor is somewhat surprising.

Insert Table 1

We finally have simulated the impact of a higher price for energy on improvement in energy efficiency. We raised the tax t_E such that the price for energy increased by 5 percent per year beginning in 1981. The energy price in 1995 is therefore twice as high as in the base case. This has an effect on cost C and output x according to (19) and (8'), on energy demand GE (21), and on the stock $KRDE$ of R&D capital for energy saving process innovation. This variable then improves energy efficiency in (17). The base case has been generated with the estimated system which has also been used to simulate the energy tax effect. In the tax simulation we keep output x constant and changed the output price according to the revenue-cost share (8'). We therefore have isolated the substitution effects from the output effect. In Table 2 we present the percentage changes of some variables and of the efficiency index.

Insert   Table   2

The energy tax has increased cost by 5.18 percent in 1995. Under our assumption of an exogenous output level x prices have increased by the same percentage figure. Since $PGE + t_E$ is more than twice as high in 1995 than in 1981, the cost share s_E of energy increased although gross energy demand declined by 36.9 percent in 1995 compared to the base case. Energy input E itself declined by only 35.9 percent because one percent of the decline of 36.9 percent has been compensated by improvement in energy efficiency (see + 1.01 in the last column). This effect is disappointingly low. The reason is our econometric finding which describes a production process with outsourcing as the main reaction on higher energy prices. Such a process is characterized by a reduction in the complements of energy, namely labor and capital, and by an increase in material. Material is required if energy is recycled in terms of waste heat used to substitute heat produced with energy. Material demand is increased if energy intensive activities are outsourced like clay and glass, transportation services, printing and publishing, fabricated metal, instruments, petroleum and coal products, rubber and plastics. Years ago big chemical plants produced electricity on the plant location. Nowadays they sign an agreement with producers of the machinery industry to set up as an independent company power plants on the ground of the firm. Although this is energy input, the delivery comes from the machinery industry; i.e. from material. As can be seen from the Table, a decline in energy, labor and in capital parallels outsourcing. Finally, higher costs enhance non-energy R&D capital by 5.18 percent in order to reduce the cost of production (see (23) and the column for *KRDNE*). The higher costs of energy induce more R&D capital to improve energy efficiency (see (18) and + 14.53% in11[th] column), which in turn improves energy efficiency by 1.01%.

6. Summary and conclusion

The objective of this paper was to develop a simple model of production where energy is used inefficiently due to waste of energy. More effort in terms of R&D investment in process innovation could, however, reduce the gap between gross energy and net energy. Whereas factor augmenting technical change increases energy input by a certain percentage per year or, equivalently, reduces the user cost of energy by that percentage, our interpretation is that technical process closes the gap between energy purchased and energy used effectively. The more is invested in energy saving process R&D, the better is the utilization of purchased gross energy and the less is the waste of energy. In terms of prices our approach implies that the effective price of a unit of energy used in the production process is higher than the price of that unit purchased on the market because part of that unit is wasted due to inefficiencies. The benefit of R&D investment

is that the higher user cost of energy becomes closer to the purchase price of energy.

We have chosen a *KLEM* cost function approach for incorporating the cost and benefit of R&D investment in process innovation. In a comparative statics analysis we introduced an energy tax as an incentive to raise energy efficiency. We have derived its impact on R&D effort, on output and on the waste of energy. We then have implemented our model empirically by choosing a translog cost function for deriving a system of first-order conditions. We estimated the unknown parameters of relative price responses, the efficiency parameter for the use of energy, and the parameter for cost reducing R&D investment in process innovation using data for the German chemical industry. We found out that labor and capital are substitutes as are labor and material, but that energy and labor are complements as are energy and capital. The implication of these relations are that a higher tax on energy will not yield a double dividend for the chemical industry in terms of more employment in that industry together with a better quality of the environment or the savings of natural resources. As shown by our simulation result, the effect of a higher energy tax will be outsourcing by increasing material input and by reducing the other three inputs labor, energy and capital. However, if one wants to know the effect of outsourcing on total employment in the economy, a computable general equilibrium analysis is required in order to embed the partial equilibrium outcome in a general equilibrium framework.

References

Aghion, P. and P. Howitt (1992), A Model of Growth through Creative Destruction, *Econometrica*, 60, 2, 323-351.

Assouline, M. (1998), Endogenous Technical Change – A Survey, Working paper, ERASME, Paris.

Bergman, L. (1990), Energy and Environmental Constraints on Growth: A CGE Modeling Approach, *Journal of Policy Modeling*, 12(4), 671-691.

Bovenberg, A.L. and S.A. Smulders (1996), Transitional Impacts of Environmental Policy in an Endogenous Growth Model, *International Economic Review*, 37, 4, 861-893.

Capros, P., G. Georgakopoulos, S. Proost, D, Van Regemorter, K Conrad, T. Schmidt (1997), The GEM-E3 Model for the European Union, Reference Manual.

Conrad, K., and I. Henseler-Unger (1986), Applied General Equilibrium Modeling for Longterm Energy Policy in the Fed. Rep. of Germany, *Journal of Policy Modeling* 8 (4), 531-549.

Conrad, K. and M. Ehrlich (1993), The Impact of Embodied and Disembodied Technical Progress on Productivity Gaps - An AGE Analysis for Germany and Spain, *Journal of Productivity Analysis*, 4, 317-335.

Grossman, G.M. and E. Helpman (1991), Innovation and Growth in the Global Economy, *MIT Press*, Cambridge (USA).

Jorgenson, D. W. and P. J. Wilcoxen (1990a), Environmental regulation and U.S. economic growth, *The Rand Journal of Economics*, 21, 314-340.

Lucas, R.E. (1988), On the Mechanics of Economic Development, *Journal of Monetary Economics*, 22, 3-42.

Manne, A. S. and R. G. Richels (1991), Global CO_2 Emission Reductions - the Impact of Rising Energy Costs, *The Energy Journal*, 12, 87-108.

Mc Kibbin, W.J. and P.J. Wilcoxen (1992), The Global Costs of Policies to Reduce Greenhouse Gas Emissions, Brookings Discussion Papers, No. 97, The Brookings Institution, Oct.

Romer, P.M. (1990), Endogenous Technical Change, *Journal of Political Economy* , 98, 71-102.

Solow, R. M. (1959), Investment and Technical Progress. In K. J. Arrow et. al. [eds.], *Mathematica l Methods in the Social Sciences* .

Table 1: Parameter estimates and energy efficiency

Parameters	Coefficients	t-statistic	year	*KRDE* in 1985 prices	Efficiency
α_x	1.04	168	1970	1.14	0.867
γ	0.024	3.41	1972	1.15	0.868
α_I	0.23	59	1974	1.37	0.888
	0.61	86	1976	1.55	0.900

α_M	0.08	50	1978	1.76	0.912
α_E	0.07	-	1980	1.73	0.910
α_K	0.097	31	1982	1.83	0.915
β_{LL}	0.021	16.3	1984	1.96	0.920
β_{EE}	0.11	12	1986	2.50	0.937
β_{MM}	0.162	3.6	1988	2.88	0.945
ρ	-0.068	5.15	1990	2.91	0.946
β_{LM}	-0.026	-24.7	1991	2.91	0.946
β_{LE}	0.021	3.59	1992	2.83	0.944
β_{ME}	0.007	-24.9	1993	2.66	0.940
α_{RD}	-0.003	-	1994	2.53	0.938
β_{KL}	0.082	-	1995	2.43	0.935
β_{KK}	-0.016	-			
β_{KE}	-0.063	-			
β_{KM}					

Table 2: The impact of a five percent higher energy price per year

year	price p and cost C in %	cost share s_E of energy	change of energy GE in %	cost share s_L of labor	change of labor L in %	cost share s_M of material
1981	+0.41	+0.001	-3.21	-0.001	-0.18	+0.001
1985	+2.10	+0.005	-15.05	-0.006	-0.70	+0.005
1990	+3.43	+0.01	-26.5	-0.013	-1.47	+0.01
1995	+5.18	+0.016	-36.9	-0.019	-1.80	+0.016

year	change of material M in %	cost share s_K of capital	change of capital K in %	change of $KRDNE$ in %	change of $KRDE$ in %	energy efficiency $\exp(-p/KRDE)$ in %
1981	+0.58	-0.001	-0.55	+0.41	+0.81	+0.06
1985	+2.96	-0.004	-3.86	+2.10	+4.13	+0.25
1990	+5.33	-0.008	-4.73	+3.43	+9.41	+0.70
1995	+8.12	-0.012	-8.33	+5.18	+14.53	+1.01

Endnotes