Operational and Investment Response to Energy Prices in the OECD Manufacturing: Evidence from the Vintage Capital Model

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Abstract

This paper analyzes the effect of energy prices on consumption of energy services, separately accounting for operational and investment choices in different sectors. Our model incorporates both the possibility of substitution between production inputs, and the potential for more efficient use of these inputs by choosing more efficient technologies at the time of investment. Vintage representation of capital stock significantly improves the explanatory value of the model at the industry level. The results of policy simulations for the U.K. petrochemical industry (the most energy-intensive industry in the sample) indicate that total own-price elasticity of energy demand is close to one.

JEL: D24, E22, Q41, Q43

Keywords: energy efficiency, energy prices, investment, vintage capital model

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1 Introduction

Empirical analysis of the effect of energy prices on energy use has been so far limited by the ability of econometric models to reflect the adaptation of the capital stock to energy price changes. J.M. Griffin & C.T. Schulman (2005, p.5) describe the problem as follows: "In a properly specified econometric demand model, the stocks of energy-using equipment would be modeled with of a number of investment and depreciation equations for each type of energy using capital. Energy consumption would then depend on the utilization and efficiency characteristics of the stock of equipment. Such an elaborate model could then be simulated to describe the adaptation of the capital stock to energy price shocks. But given the absence of capital stock data needed to reflect the adjustment of the capital stock of energy using equipment, econometricians estimate reduced form single demand equations featuring a distributed lag on price to capture the adaptation of the capital stock."

While the reduced-form econometric models of energy demand are useful in a number of respects they fail in answering some important questions. First, though these models make it possible to obtain and compare short-run and long-run elasticities, they do not describe the *path* to the long run, or the pattern of investment in energy-using capital stock over time (R.S. Pindyck & J.J. Rotemberg 1983). Second, these models can say very little about the *sources* of changes in energy demand and energy productivity (or its reciprocal - energy intensity). Finally, it is difficult to reconcile the conclusions from reduced-form models aiming to study the short-run disequilibria associated with the incomplete adjustment of the capital stock and the long-run equilibria in which the capital stock turns over completely. As Griffin & Schulman (2005, p.5) point out, "trying to do both with such a simple model may accomplish neither objective."

This paper attempts to address this limitation in modelling the effect of energy prices on energy use. Our structural econometric model explicitly incorporates the capital stock, and separately accounts for short-term (operational) and longer-term (investment) choices in different sectors. Specifically, we expand the traditional estimation of energy, materials, and labour responses to input price changes by including vintages for the capital stock. Each vintage of the capital stock has its own energy efficiency, which is a function of input prices at the time of investment, and exogenous technological change. In our vintage capital model, a rational, cost-minimizing firm chooses both the optimal input quantities and the efficiency of new capital stock. The model therefore accounts separately for the flexibility of substitution between input factors to production (labour, energy and materials), and the potential for more efficient use of these inputs by choosing more efficient technologies at the time of investment. In doing so, our model allows for the adaptation of the capital stock in response to energy price shocks.[1]

The distinction between input efficiency and input use presented in this paper is important for both researchers and policy-makers, especially in the context of climate change mitigation. The choice of input efficiency made at the time of investment has long-term implications. Energy-inefficient and capital-intensive power plant or manufacturing belt typically stays in production for many years before it retires from production process. Upgrades to achieve better energy efficiency are not always technologically feasible or too costly to implement. And the costs and benefits of choosing technologies with better energy efficiency vary across manufacturing industries. For example, assuming the same installation costs, the net benefits from installing (more expensive) energy efficient technology will be larger for more energy-intensive (e.g. petrochemical, steel) industries. Understanding firms' investment response to energy provides guidance of decarbonisation trajectories.[2] For example, market based climates policies aimed at reductions in fossil fuel will succeed if firms' investment response to rising energy prices is large.

The model is estimated for five manufacturing industries in 19 OECD countries, between 1990 and 2005, using the translog cost function approach. Compared to earlier models our cost-share equations are non-linear in factor prices because of the composite effect of input substitution and changes in the efficiency of capital stock. This introduces additional complexity for the estimation of the relevant parameters of the model, and provides a better explanation of energy demand at the sector level. The assumption of constant efficiency of capital

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[1] An alternative econometric approach, which allows for adaptation of capital stock to energy prices is the quasi-fixed input demand model (see e.g. ER Berndt, CJ Morrison & GC Watkins 1981, Pindyck & Rotemberg 1983, D.C. Popp 2001, I. Sue Wing 2008). This approach is based on entirely different assumptions about the nature of the adaptation of the capital stock, and should be treated complementary to our model. For comparison of these approaches (and defense of the vintage capital approach), see A. Atkeson & P.J. Kehoe (1999).

[2] Many computational economic models of energy climate change (e.g. U.S. EIA NEMS Industrial Demand Module, OECD ENV-Linkages model, and MIT Integrated Global System Modeling framework) employ capital vintage structure. Validation of energy price response vintage elasticities in these models based on rigorous econometric analysis (attempted in this study) remains an important problem to be solved. The authors thank John Reilly for making this point.

stock is rejected for all sectors.

The results for all industries indicate that energy prices affect both the operational (input substitution) and the investment (energy efficiency of capital stock) components of energy demand. Estimated own-price elasticities of energy demand vary in the range of 0.26 and 1.00, and are in line with previous estimates. Estimated elasticities of energy input efficiency with respect to energy price vary between 0.03 (for pulp and paper industry) to 0.9 (for petrochemical industry). The investment response to energy prices thus varies considerably across manufacturing industries, being significant in some and negligible in others. This result indicates that differences in the estimated investment response to energy prices from previous empirical studies can be, to some extent, attributed to the aggregation problem.

An important finding of this paper is that energy and climate policies aimed at reductions in fossil fuel emissions can result in a substantial reduction of energy use in energy intensive sectors. The results of policy simulations for the U.K. petrochemical industry (the most energy-intensive industry in the sample) indicate that a 17 percent increase in energy prices from a \$30 carbon tax results in a 19.5 percent decline in energy use. That is the total (operational and investment) own-price elasticity of energy demand is close to one.

The rest of this paper is structured as follows. The first section reviews existing literature on the effect of energy prices on energy efficiency. The second section outlines the vintage capital model and resulting stochastic specification. The third section describes the dataset. The fourth section presents the main findings of the research. The fifth section presents the results of policy simulations. The final section concludes, and suggests policy recommendations.

2 Literature Review

The effect of energy prices on energy use is a complex problem, which is still not well quantified. The economic literature identifies several channels through which prices influence energy demand in the short, medium and long-run. In the short-run, the main channel is input substitution, which captures the effect of relative energy prices on the optimal choice of inputs to production. An increase in real energy prices lowers the demand for energy services and their complements (e.g. capital), and raises the demand for substitutes to energy services (e.g. labor). This channel is well studied both theoretically and empirically based on capital-labor-energy-materials (KLEM) input demand model (e.g. E.R. Berndt & D.O. Wood 1975, J.M. Griffin & P.R. Gregory 1976, R.S. Pindyck 1979).[3]

In the medium run, two important channels are the change in the industrial structure of the economy, and improvements in the energy efficiency of the capital stock. The change in the industrial structure of the economy takes place because an increase in the real price of energy services raises the price of intermediate and final goods throughout the economy, leading to a series of price and quantity adjustments, with energy-efficient goods and sectors likely to gain at the expense of energy-intensive ones (S. Sorrell & J. Dimitropoulos 2008, p.637). Although a large number of studies in energy economics have attempted to assess the scope of this channel[4], their findings are still difficult to reconcile. Two recent empirical contributions are studies by G.E. Metcalf (2008) and Sue Wing (2008). Both studies decompose changes in aggregate energy intensity into shifts in the structure of sectoral composition and adjustments in the efficiency of energy use. G. Metcalf (2008) adapts an index number based theoretical approach, and finds that "roughly three-quarters of the improvements in U.S. energy intensity since 1970 results from efficiency improvements" (G.E. Metcalf 2008, p.1). Sue Wing's (2008) structural model attributes most of the changes in the U.S. energy intensity to adjustments of quasi-fixed inputs and disembodied autonomous technological progress. The study concludes that "price-induced substitution of variable inputs generated transitory energy savings, while innovation induced by energy prices had only a minor impact." (Sue Wing 2008, p.21).

In the medium-run, firms also respond to an increase in real energy prices by changing their investment decisions and improving the energy efficiency of their capital stock (achieving smaller energy input requirements per amount of capital used). For example, firms in the commercial sector may insulate their office buildings, and firms in the transport sector may adopt hybrid vehicles to achieve better mileage per gallon. Atkeson & Kehoe (1999) establish a theoretical foundation for this channel by analyzing energy efficiency in the context of a putty-clay model. In their model, each vintage of the capital stock has its own energy efficiency. In the short-run, capital and energy inputs are complements, and energy demand elasticity is small. In the long-run, in response to perma-

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[3] For a summary of subsequent studies on this topic, see e.g. T. Barker, P. Ekins & N. Johnstone (1995), and L. Kilian (2008)

[4] For a survey of these studies, see BW Ang & FQ Zhang (2000).

nent energy price changes, agents invest in capital goods with different energy efficiency. As a result, energy use becomes more responsive to energy prices.[5] Notwithstanding sound theoretical underpinnings, there is little empirical work on the effect of energy prices on the energy efficiency of capital stock.[6] This paper attempts to address this shortcoming in the empirical literature on energy efficiency.

In the long-run, the significant channel is technological change, both exogenous (e.g. resulting from autonomous scientific advances), and energy-price induced.[7] This channel has been studied empirically by Newell, Jaffe & Stavins (1999), D. Popp (2002), Griffin & Schulman (2005), M. Frondel & C.M. Schmidt (2006), and J. Linn (2008). All of these studies use different methodologies and reach different conclusions. Newell, Jaffe & Stavins (1999) develop a product-characteristics model of energy-saving consumer durables. They find that the energy price has little effect on the rate of overall innovation, but it does affect the direction of innovation for some products. Popp (2002) estimates a structural model, using U.S. patent data as an instrument for scientific knowledge, and finds that both energy prices and the quantity of existing knowledge have significant positive effects on innovation in the energy sector. Frondel & Schmidt (2006) compare energy-price elasticities of capital before and after the oil crisis of the early 1970s. The results of their counterfactual analysis indicate a substantial technological change, but its magnitude is unknown because of the change in economic circumstances (Frondel & Schmidt 2006, p.187.). Griffin & Schulman (2005) argue that energy-saving technical change explains asymmetric price responses in econometric energy demand models.[8] Linn (2008) uses U.S. plant-level data to compare the energy intensity of entrants and incumbents. The results of J. Linn's (2008) empirical analysis show that energy prices and technology adoption have a small effect on energy intensity.

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[5] A. Díaz, L.A. Puch & M.D. Guilló (2004) relax some assumptions of Atkeson & Kehoe (1999), and reach similar conclusions.

[6] A notable exception is a study by R.G. Newell, A.B. Jaffe & R.N. Stavins (1999), but their analysis focuses only on three particular products (room air conditioners, central air conditioners, and gas water heaters).

[7] Note the difference between the improvement in energy efficiency of capital stock discussed above and the technological change. The former channel refers to choosing between the pool of available technologies with different intensities of energy use, whereas the latter refers to inventing new energy-saving technologies.

[8] Also see D. Gately & H.G. Huntington (2002), and O.I. Adeyemi & L.C. Hunt (2007).

3 Vintage Capital Model of Energy Demand

We introduce a partial equilibrium vintage capital model that separately accounts for investment and operational (production) decisions in manufacturing sector. The model allows for adaptation of the capital stock in response to energy price shocks and contributes to existing literature on modeling input demands, by providing a unified empirical framework for substitution between input factors to production (labour, energy and materials), and the potential for more efficient use of these inputs by choosing more efficient technologies at the time of investment. The model focuses on production and investment decisions over short- and medium-run. Firms choose between different types of capital from an existing portfolio of *available* technologies, which improve gradually over time. The research and development, and capital-goods producing sectors that account for long-run response to energy prices by extending the range of available technologies (Popp 2002) are not considered in this partial equilibrium model of manufacturing decisions.

We start with the firms' investment. Firms add new capital stock, which comprises of both durable and non-durable inputs, based on a specific production technology. For each capital vintage, firms choose the optimal level of input efficiency of production technology, given autonomous efficiency improvements (M. Webster, S. Paltsev & J. Reilly 2008) and their expectations of future input costs. We assume that firms are forward-looking, and form their expectations based on the input prices at the time of investment. This assumption requires additional explanation, especially in the context of energy prices, as some scholars noted that energy demand responds asymmetrically to energy prices (Gately & Huntington 2002, Adeyemi & Hunt 2007), so time lags could matter. We believe this assumption is justified for the following reasons. First, input prices, and, especially, energy prices are very difficult to forecast, and likely follow a random walk (R.S. Pindyck 1999, R. Alquist & L. Kilian 2010). Second, energy costs are relatively small share of total expenditures for most manufacturing firms, whereas the costs of obtaining accurate information on factors affecting future costs are non-trivial (R.B. Howarth & B. Andersson 1993). Third, recent evidence from rigorous econometric studies based on micro- level data suggest that find that average consumer beliefs are indistinguishable from a no-change forecast (S.T. Anderson, R. Kellogg & J.M. Sallee 2011, H. Allcott, S. Mullainathan & D. Taubinsky 2011), and "researchers are likely justified in assuming a no-change forecast, as is common practice" (Anderson, Kellogg &

Sallee 2011, p.1). Finally, lagged energy prices could matter over very long-term, as new technologies penetrate the market, which is not the focus of this study.

We then consider production decisions, where firms minimize realized input costs to produce the desired output level, given the level of input efficiency of installed production technology. The resulting equations are subsequently used to form stochastic specifications and estimate the input price elasticities of factor substitution and capital stock efficiency.

3.1 Investment Choice of Input Efficiency

We assume that the manufacturing industries in OECD countries operate in perfectly competitive product and factor markets, that is, take input prices as given. We can therefore view each manufacturing sector as consisting of a single firm that has certain production technology, or, equivalently, as consisting of many firms whose aggregate technology is represented by our model (Pindyck & Rotemberg 1983). At any time t the firm i is fully flexible in its choice of labor ($x^l_{i,t}$), energy ($x^e_{i,t}$), and materials ($x^m_{i,t}$) inputs. The capital stock ($x^k_{i,t}$) has vintage representation, and each vintage has its own technological efficiency with respect to each input to the production function. The investment in factor efficiency of a capital vintage is sunk. New capacity with a different production technology can be added, but all old vintages must depreciate before adjustment is complete (i.e. there is no pre-retirement of capital stock). The production technology is thus inflexible in terms of the capital efficiency requirements.[9]

We assume that the efficiency of a vintage of capital stock, k, in period q with respect to other inputs, labor, l, energy, e, and materials, m, is represented by an index $\gamma^j_{i,q}$. The index $\gamma^j_{i,q}$ measures the amount of labor, energy and materials inputs required to produce input service, i.e. output of useful work (however measured).[10] While firms make technology choices in period q, there is a lag between the firm's investment decision and plant commissioning. The technology is installed and becomes fully functional in period $q + 1$. Firms'

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[9] This assumption is consistent with "putty-clay" production technology models. For discussion of this assumption see Atkeson & Kehoe (1999). Other studies that adopt putty-clay models of energy use are R.G. Hawkins (1978), A.B. Abel (1983), C.S. Struckmeyer (1986), C.S. Struckmeyer (1987), and C. Wei (2003).

[10] For example, if average internal temperature is taken as the appropriate measure of useful work from manufacturing heating system, labor efficiency of capital stock will depend on the degree of thermal system's automation, energy efficiency of capital stock will depend upon the thermal efficiency of the boiler, whereas materials' efficiency of capital stock will depend upon the quality of thermal insulation.

production decisions in period q are thus made based on production technology installed in period $q-1$.

The quantity of input $j = l, e, m$ in period q, $x^j_{i,q}$, and the index of input efficiency of capital vintage, $\gamma^j_{i,q-1}$, determine the input service to production function, $\widetilde{x}^j_{i,q}$:

$$\widetilde{x}^j_{i,q} = \frac{x^j_{i,q}}{\gamma^j_{i,q-1}}, \quad \gamma^j_{i,q} > 0 \ . \tag{1}$$

Similarly, the relationship between the price of input in period q, $w^j_{i,q}$ and the price of service $\widetilde{w}^j_{i,q}$ is given by

$$\widetilde{w}^j_{i,q} = w^j_{i,q} \gamma^j_{i,q-1}. \tag{2}$$

Equations (1) and (2) imply that the lower is the value of the index of input efficiency of capital vintage, $\gamma^j_{i,q-1}$, the more services capital vintage $x^k_{i,q}$ can produce from a given input $j = l, e, m$, and the lower is the price of that service. As the vintage of capital stock cannot produce more services with respect to itself, we assume that the value of the index of capital efficiency of capital stock is equal to one for all capital vintages,

$$\gamma^k_{i,t} = 1. \tag{3}$$

The input efficiency that firms choose for energy, labour and materials is a function of input prices and exogenous technological change:

$$\gamma^j_{i,q} = (1-\zeta)^q \left(\frac{w^j_{i,q}}{\overline{w}^j} \right)^{-\phi^j}, \ j = l, e, m, \tag{4}$$

where $\overline{w}$ is the average price of input j across countries and all time periods[11], ϕ^j is the elasticity of input's j efficiency with respect to input price changes, and ζ is the rate of exogenous Hicks-neutral technological change[12]. In Appendix

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[11] We have chosen the OECD average input price across countries and all time periods to reflect the effects of globalization and industry migration. We also considered the input price based on the country average across time: $\overline{w}^j_i = \sum_{t=1}^{T} w^j_{i,t}/T$. Estimation results were not different.

[12] While there is some evidence that technological change can be non-neutral (DW Jorgenson & BM Fraumeni 1981), allowing for the possibility of exogenous technological change to differ across inputs is precluded by the numerical complexity of the model. Given this, our estimates for exogenous technological change should be interpreted with caution.

A we show that this is the profit maximizing (cost minimizing) choice of a firm that faces a technology cost function.

Let z be the first capital vintage observable to an econometrician. Then, for all observed capital vintages $q \geq z$ we can derive the index of input efficiency of capital stock $\gamma_{i,t}^{j}$ as a sum of historic vintage efficiencies weighted by each vintage's q contribution to capital stock x_t^k :

$$\gamma_{i,t}^{j} = \sum_{q=z}^{t} (1-\zeta)^q \left(\frac{w_{i,q}^{j}}{\overline{w}^{j}} \right)^{-\phi^j} \frac{I_{i,q}\,(1-\delta)^{t-q}}{x_{i,t}^{k}}, \; j = l, e, m, \tag{5}$$

where $I_{i,q}$ is the vintage investment in period q, and δ is the rate of economic depreciation of capital stock.[13]

Because we do not know the values of the index of input efficiency of capital stock for vintages outside the observation sample, we have to assume that they are the same as in the first period of the observed sample. Under this assumption the index of input efficiency of capital stock with respect to energy, labour and materials for all observations becomes

$$\gamma_{i,t}^{j} = (1-\delta)^t \, x_{i,0}^{k} \left(\frac{w_{i,0}^{j}}{\overline{w}^{j}} \right)^{-\phi^j} + \sum_{q=1}^{t} (1-\zeta)^q \left(\frac{w_{i,q}^{j}}{\overline{w}^{j}} \right)^{-\phi^j} \frac{I_{i,q}\,(1-\delta)^{t-q}}{x_{i,t}^{k}}, \; j = l, e, m, \tag{6}$$

where the first term on the right hand side is the value of the index of input efficiency of capital stock in the first period of observation sample.[14]

3.2 Production Choice of Input Factors

We assume that firms minimize the costs of their inputs to deliver the output Y:

$$\min \sum_{j=k,l,e,m} w_{i,t}^{j} x_{i,t}^{j} \; s.t. \; f(\widetilde{x}_{i,t}^{k}, \widetilde{x}_{i,t}^{l}, \widetilde{x}_{i,t}^{e}, \widetilde{x}_{i,t}^{m}) = Y_{i,t}, \tag{7}$$

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[13] Interpretation of the index of input efficiency of capital stock becomes difficult if vintage investment is negative. Almost all observations in our dataset corresponded to positive vintage investment. To avoid confusion with interpretation of the index of input efficiency of capital stock, we set its value equal to the previous period in rare cases of negative vintage investment.

[14] We attempted to estimate the joint efficiency of all unobserved capital stock vintages as a free parameter, but were unable to obtain estimates of reasonable magnitude because of flatness in the estimated non-linear likelihood function. Estimates of other parameters did not change significantly in either signs or magnitudes after imposing this restriction.

where $f(\cdot)$ is a continuous, twice differentiable production function relating the flow of gross output $Y_{i,t}$ to the services of four inputs - capital $\left(\widetilde{x}^k\right)$, labor $\left(\widetilde{x}^l\right)$, energy $(\widetilde{x}^e)$, and all other intermediate materials $(\widetilde{x}^m)$.

Let $\widetilde{x}^*_{i,t}(Y_{i,t}, \widetilde{w}^k_{i,t}, \widetilde{w}^l_{i,t}, \widetilde{w}^e_{i,t}, \widetilde{w}^m_{i,t})$ be the set of optimal input services, and $C(Y_{i,t}, \widetilde{w}^k_{i,t}, \widetilde{w}^l_{i,t}, \widetilde{w}^e_{i,t}, \widetilde{w}^m_{i,t})$ be the expenditure function which corresponds to the production function. Following the economic literature on input demand starting from L.R. Christensen, D.W. Jorgenson & L.J. Lau (1973) and Berndt & Wood (1975), we assume that the expenditure function can be approximated by the translog model:

$$\log C_{i,t} = \alpha_0 + \alpha_Y \log Y_{i,t} + \sum_j \alpha_{ij} \log \widetilde{w}^j_{i,t} + \frac{1}{2}\beta_{YY} \left(\log Y_{i,t}\right)^2 +$$
$$\frac{1}{2}\sum_j \sum_k \beta_{jk} \log \widetilde{w}^j_{i,t} \log \widetilde{w}^j_{i,t} + \sum_j \beta_{Yj} \log Y_{i,t} \log \widetilde{w}^j_{i,t} + \lambda t. \tag{8}$$

Differentiating (8) with respect to the logarithm of the prices of efficient inputs, and applying Shephard's lemma yields four factor input cost share equations

$$S^j_{i,t} = \alpha_{ij} + \beta_{Yj} \log Y_{i,t} + \sum_j \beta_j \log \widetilde{w}^j_{i,t}, \tag{9}$$

where $S^j_{i,t} = \frac{\partial C}{\partial \widetilde{w}^j_{i,t}} \cdot \frac{\widetilde{w}^j_{i,t}}{C} = \frac{\widetilde{w}^j_{i,t}\widetilde{x}^*_{i,t}}{C} = \frac{w^j_{i,t}x^*_{i,t}}{C}$ is the share of each input j in firms' total cost.

3.3 Estimation of Vintage Capital Model

Combining equations (2), (6) and (9), and adding stochastic error term, ε^j_{it}, yields a system of four equations to be estimated:

$$S^j_{i,t} = \alpha_{ij} + \beta_{Yj} \log Y_{i,t} + \tag{10}$$
$$\sum_j \beta_j \log \left(w^j_{i,t} \left[\psi \left(1-\delta\right)^{t-1} + \sum_{q=1}^{t-1} \left(\frac{w^j_{i,l}}{\overline{w}^j}\right)^{-\phi^j} \left(1-\zeta\right)^q \sigma_{i,q} \right] \right) + \varepsilon^j_{it},$$

where α_{ij} are country-specific fixed effects, $\sigma_{i,q}$ is the last term in equation

(5), and $\psi = x_0^k \left(\frac{w_{i,0}^j}{\overline{w}^j}\right)^{-\phi^j}$.[15] To avoid the problem of endogeneity of input prices at individual industry level, we use average estimates for input prices in the entire manufacturing sector. An alternative approach of instrumental variables estimation is confounded by a general difficulty of finding good instruments (W.E. Diewert & K.J. Fox 2008). And the small sample bias from a set of popularly instrumental variables (lagged prices, population, taxes, government purchases) is not necessarily smaller than that obtained from actual prices (Griffin & Gregory 1976, W.A. Barnett, J. Geweke & M. Wolfe 1991, C. Burnside 1996). [16]

The system of equations (10) is a non-linear problem, where the parameters ϕ^j and ζ should be evaluated at each data point across time-series dimension. This makes traditional estimation approaches, such as e.g. iterated feasible generalized non-linear least squares (IFGNLS), non-applicable as they exhaust the degrees of freedom in panels with short individual dimension N. Instead, following Popp (2001) and Sue Wing (2008), we treat the system of equations (10) as a *conditionally linear* problem. Conditional on realization of unknown parameters ϕ^j and ζ, the system of equations (10) becomes a seemingly unrelated regression, which is efficiently estimated by full information maximum likelihood (FIML).

The values of parameters ζ and ϕ^j are chosen to maximize the value of the model's goodness-of-fit criterion, and are obtained by multidimensional grid search using simulated annealing algorithm (W.L. Goffe, G.D. Ferrier & J. Rogers 1994). To minimize the computational burden of a multidimensional grid search, based on earlier empirical findings (e.g. Jorgenson & Fraumeni 1981, B.H. Baltagi & J.M. Griffin 1988, Newell, Jaffe & Stavins 1999, Sue Wing 2008, Webster, Paltsev & Reilly 2008), we set the estimation bounds for the exogenous technological change parameter, ζ, to vary between -0.03 and 0.05, and the elasticity of input efficiency of capital stock with respect to input price changes, ϕ^j, - between 0 and 1.5.[17] Because the share equations in the model (10) add to one, only 3 share equations are estimated.

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[15] Our econometric approach described by equation (10) is similar to R. Haas & L. Schipper (1998), who advocate calculating an index of energy efficiency, and using it directly in econometric specification for energy demand. The index of Haas & Schipper (1998) though is obtained through factor decomposition, and is thus purely exogenous.

[16] Endogeneity problem remains if total output of a manufacturing industry affects input prices, and output is correlated across manufacturing industries. This is highly unlikely for any country in the sample, including the U.S.

[17] We have examined the model sensitivity to relaxing the range of estimation bounds, and the results turned out to be robust (no corner solutions).

While the system (10) forms our basic empirical model we also estimate a restricted model, assuming that the input efficiency of capital stock does not change, so $\gamma_{i,t}^{j}$ is set to 1 (or both ζ and ϕ^{j} are set to zero). Under this restriction the model becomes a conventional translog model of input demand of Berndt & Wood (1975) and Griffin & Gregory (1976).[18] We then use the likelihood-ratio test to evaluate the significance of input efficiencies of capital stock in the models of energy demand.

To quantify operational response to current price changes holding all previous prices constant, we compute own-price and cross-price elasticities of substitution.[19] These elasticities are given by

$$\eta_{jj} = \frac{\partial \ln x_{i,t}^{j}}{\partial \ln w_{i,t}^{j}} = \frac{\beta_{jj} + \left(S_{i,t}^{j}\right)^{2} - S_{i,t}^{j}}{S_{i,t}^{j}},\ j = k, l, e, m. \tag{11}$$

and

$$\eta_{pj} = \frac{\partial \ln x_{i,t}^{j}}{\partial \ln w_{i,t}^{p}} = \frac{\beta_{pj} + S_{i,t}^{p} S_{i,t}^{j}}{S_{i,t}^{j}},\ p, j = k, l, e, m,\ p \neq j. \tag{12}$$

Estimated elasticities have a standard economic interpretation and capture several separate substitution effects, including within-firm input substitution and within-industry compositional changes.[20] Because we include country-specific fixed effects, and identify coefficients, β, based on within-country variation over time, the operational response elasticities, η_{jj}, and, η_{pj}, capture short-run equilibrium effects. On the contrary, investment elasticities of input efficiency of capital stock with respect to input price changes, ϕ^{j}, and exogenous technological change, ζ,incorporate the dynamics of the capital stock and capture medium- and long-run equilibrium effects.

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[18] While translog models with distributed lags or exogenous time trend in share equations are less restrictive than conventional translog model, the cannot be nested in the vintage capital model, correspondingly there are no formal statistical tests comparing the the goodness of fit of these models. Comparing the results from these models to those from vintage capital model is, therefore, beyond the scope of this paper.

[19] We have also estimated Allen's and Morishima's partial elasticities of substitution. Because these elasticities have less straightforward interpretation (M. Frondel 2004), and can be directly inferred from estimated cross-price elasticities, their estimates are not reported.

[20] Sorting out between these effects is however beyond the scope of this paper.

4 Data

The vintage capital model is estimated using panel data from 19 OECD countries between 1990 and 2005 separately for five manufacturing industries - food, beverages and tobacco (ISIC sectors 15 and 16), pulp, paper products, paper, and publishing (ISIC sectors 21 and 22), chemical, rubber, plastics, and fuel products (ISIC sectors 23, 24, and 25), basic metals, and fabricated metal products (ISIC sectors 27 and 28), and electrical and optical equipment (ISIC sectors 30, 31, 32, and 33).[21] The use of disaggregated data reduces measurement error and improves the quality of the estimates, as different sectors use energy for different purposes, which affects their ability to substitute between energy and other inputs.[22] Due to data limitations the analysis was not possible at a less aggregate level.

The main data source for empirical analysis is the EU KLEMS database, which is constructed based on the methodology of D.W. Jorgenson, F.M. Gollop & B.M. Fraumeni (1987) and D.W. Jorgenson, M.S. Ho & K.J. Stiroh (2005).[23] The EU KLEMS database comprises data on production inputs, labor and capital input prices[24], and output at the industry level for the European Union, the United States, Korea, and Japan. The relatively small number of available observations makes it necessary to assume that each country's manufacturing industry has the same production function. Though being restrictive, this is a standard assumption made in inter-country studies of energy demand. To best of authors' knowledge there is no study addressing this issue, and doing so is beyond the scope of this paper. We however exclude non-manufacturing industries (e.g. agriculture, commerce and transportation), where the assumptions of identical production functions and rational cost minimizing firms are less likely to be satisfied.[25] A full list of variables, countries and the descriptive statistics

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[21] To preserve space in the text these industries are further referred to as food processing, pulp and paper products, petrochemical, metals, and electrical industries.

[22] For example, manufacturing of steel and aluminum is based on high temperature heating and electrochemical processes that have few (if any) available substitutes for energy. On the other hand, energy- and / or capital- intensive processes can be substituted for labor intensive processes in light manufacturing industries.

[23] For more details, see M.P. Timmer, M. O Mahony & B. van Ark (2007).

[24] Data on the price of capital services were not available for some countries. For these countries following AA Andrikopoulos, JA Brox & C. Paraskevopoulos (1989) and W.G. Cho, K. Nam & J.A. Pagán (2004) we computed the capital input prices (available from IMF International Financial Statistics Database) as a sum of the nominal interest rate on short-term government papers, and the capital depreciation rate.

[25] This is because manufacturing industries are globally interconnected, internationally competitive, less distorted by national policies, and have large cross-border flows of know-how. In a separate paper we estimate the vintage capital model for non-manufacturing industries.

for the final dataset are shown in Tables 4-10 (Appendix B).

In our dataset we only have data for capital stock $x^k_{i,t}$ and do not observe actual investment. Following a large number of empirical studies on investment behavior (for a survey see D.W. Jorgenson 1971) we assume a geometric mortality distribution, (e.g. replacement is proportional to actual capital stock) and a time-invariant rate of economic depreciation. Under these assumptions vintage investment in period q is given by

$$I_{i,q} = x^k_{i,q} - (1-\delta)x^k_{i,q-1}. \tag{13}$$

Based on the estimates from Timmer, O Mahony & van Ark (2007, Appendix 1) we set economic depreciation rates as 11 percent in the food processing industry, and 10 percent in all other industries.

The EU KLEMS dataset does not include information on energy and materials input prices. We obtain the end-use energy price data from the International Energy Agency database, and construct the average energy price for the manufacturing sector by weighting energy carriers' prices by the consumption of each energy carrier in the manufacturing sector.[26] We construct the price of materials by weighting international commodity prices (from the IMF International Financial Statistics database) by sector consumption of each commodity (from UNIDO Industrial production database). The data series for labor, energy, and material costs, and for the values of output and capital stock, are all deflated to their real values based on the industry deflators, using 1995 as a base year, and converted into United States dollars at nominal exchange rates.[27]

Figure 1 shows the average energy prices in the manufacturing sector across OECD countries in 2000. The highest energy prices are in Italy, Ireland, Japan and Sweden, and the lowest are in Australia, Netherlands, Greece, and the United States. These differences in energy prices across OECD countries are because of variation in energy taxes, the types of fuels used in the production process, and local distribution costs. Variation in industrial energy prices across the manufacturing industry in the OECD is relatively small compared to other sectors, such as commerce or transportation (IEA International Energy Agency 2008). This may reflect constraints on national energy tax policies, which are

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[26] Specifically, we consider the following energy products - oil and petrolium products (high- and low-sulphur fuel oil, light fuel oil, automotive diesel, and gasoline), natural gas, coal, and electricity. Consumption of each product is measured in British thermal units (BTUs). More details are available in the technical appendix, available from authors upon request.

[27] We have also estimated the model using dollar conversion at purchasing power parity exchange rates. The results were of comparable magnitude to those reported below.

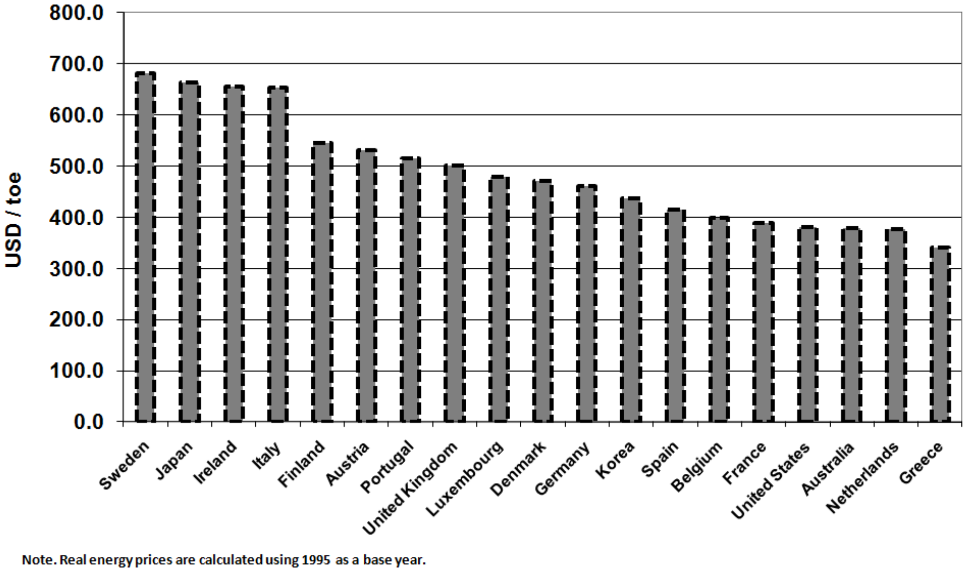

Figure 1: Average Real Energy Prices in OECD Manufacturing Sector in 2005.

major drivers of international energy price differences[28], posed by countries' concerns to maintain their international competitiveness in manufacturing sector (D. Brack, M. Grubb & C. Windram 2000).

5 Results of Estimation of the Vintage Capital Model

The empirical estimates of stochastic specification (10) applied separately to each of the five industries over the period 1990 - 2005 across 19 OECD countries are presented in Tables 11-15 (Appendix B). We present the results for both the vintage capital model, and the standard translog model of energy demand, in which the indices of input efficiency of capital stock are set to 1. Tables 1, 2 and 3 present estimated own-price elasticities of input demand, cross-price elasticities of energy demand, and own-price elasticities of input efficiency of capital

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[28] For example, in transportation sector international energy price differences are almost entirely due to gasoline tax, which accounts for nearly 60 percent of final energy price in Sweden, Germany and the United Kingdom, compared to just 13 percent in the United States (International Energy Agency 2008).

stock from the vintage capital model. Tables 16-20, Appendix B, demonstrate the variation of estimated elasticities across countries. Estimated cross-price elasticities of other input demands are presented in Tables 21-23, Appendix B. Figures 5-9, Appendix C, show the values of the calculated indices of input efficiency of capital stock.

Table 1: Estimated Own-Price Elasticities of Input Demand in OECD Manufacturing Sectors

Sector	η_{LL}		η_{KK}		η_{EE}		η_{MM}	
	VCM	TL	VCM	TL	VCM	TL	VCM	TL
Chemical, Rubber, Plastics and Fuel Products	-0.46***	-0.82***	-0.71***	-0.77***	-0.41***	-0.57***	-0.43***	-0.36***
	(0.05)	(0.04)	(0.08)	(0.06)	(0.11)	(0.10)	(0.03)	(0.03)
Electrical and Optical Equipment	-0.62***	-0.49***	-0.58***	-0.81***	-0.26***	-0.26***	-0.45***	-0.49***
	(0.03)	(0.03)	(0.09)	(0.08)	(0.09)	(0.09)	(0.03)	(0.03)
Food Products, Beverages, and Tobacco	-0.55***	-0.56***	-1.08***	-1.08***	-0.37***	-0.40***	-0.31***	-0.30***
	(0.03)	(0.03)	(0.03)	(0.02)	(0.12)	(0.12)	(0.01)	(0.01)
Basic Metals and Fabricated Metal Products	-0.31***	-0.41***	-0.78***	-0.84***	-1.00***	-0.93***	-0.44***	-0.40***
	(0.05)	(0.05)	(0.02)	(0.03)	(0.10)	(0.08)	(0.03)	(0.03)
Pulp, Paper, Paper Products, Printing and Publishing	-0.38***	-0.44***	-0.41***	-0.94***	-0.43***	-0.41***	-0.33***	-0.34***
	(0.03)	(0.03)	(0.08)	(0.07)	(0.15)	(0.15)	(0.05)	(0.05)

Note. VCM - Vintage Capital Model, TL - Translog Model. All Elasticities are Calculated at Sample Means.
Standard errors (in parentheses) are based on covariance calculations of elasticity formula (11) . *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The regression results show that the vintage capital model generally provides a better explanation of energy demand. The R-squared are higher for the vintage capital model (Tables 11-15, Appendix B). The likelihood ratio test indicates that the translog restriction of input efficiencies of capital stock being equal to 1 is rejected at the 1 percent level of significance for four out of five industry estimates. However, for the food processing industry the translog model can be rejected only at a 10 percent level of significance.

Overall, the estimates of own-price and cross-price elasticities of input demand are consistent with their economic interpretation. Table 1 demonstrates that all of the estimated own-price elasticities of input demands across different sectors have the expected signs and reasonable magnitudes.[29] The vintage capital model and the translog model yield comparable estimates for the input demand elasticities in four out of five industries, with an exception of elasticities of capital demand. The estimated elasticities of capital demand based on the translog model are higher, except in the food processing industry. The estimated elasticities of input demand based on the translog model are also higher for the petrochemical industry. The results from both the vintage capital model

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[29] Estimated elasticities did not have the expected sign in some countries (see Tables 16-20, Appendix B, for details). However, in almost all cases, they were not statistically different from zero.

and the translog model indicate that long-run energy demand is inelastic in all sectors, except for the metals industry, where the long-run energy demand is close to unit-elastic.

Table 2: Estimated Cross-Price Elasticities of Energy Demand in OECD Manufacturing Sectors

Sector	η_{LE}		η_{KE}		η_{ME}	
	VCM	**TL**	**VCM**	**TL**	**VCM**	**TL**
Chemical, Rubber, Plastics and Fuel Products	0.39***	0.39***	0.16	0.09	0.07**	0.14***
	(0.05)	(0.05)	(0.11)	(0.10)	(0.03)	(0.03)
Electrical and Optical Equipment	0.24***	0.25***	0.12	0.05	-0.13***	-0.12***
	(0.03)	(0.03)	(0.13)	(0.14)	(0.03)	(0.03)
Food Products, Beverages, and Tobacco	0.02	0.04*	0.10	0.09	-0.01	-0.01
	(0.03)	(0.02)	(0.06)	(0.06)	(0.01)	(0.01)
Basic Metals and Fabricated Metal Products	0.15**	0.16***	-0.10*	-0.15**	0.03	0.03
	(0.05)	(0.05)	(0.05)	(0.05)	(0.02)	(0.02)
Pulp, Paper, Paper Products, Printing and Publishing	0.07**	0.03	-0.001	0.05	-0.005	-0.001
	(0.03)	(0.03)	(0.12)	(0.13)	(0.04)	(0.04)

Note. VCM - Vintage Capital Model, TL - Translog Model. All Elasticities are Calculated at Sample Means.
Standard errors (in parentheses) are based on covariance calculations of elasticity formula (12) . *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2 shows estimated cross-price elasticities of labor, capital, and materials demand with respect to energy price. As expected, labor is a substitute for energy across all industries. Capital and energy inputs are substitutes in the petrochemical, electrical, and food processing industries. Capital and energy are complements in the metals industry. The vintage capital model suggests that capital and energy are also complements in the pulp and paper industry. Estimated cross-price elasticities for capital and energy, however, are not statistically different from zero. The translog model indicates that capital and energy are substitutes in the pulp and paper products industry. Materials and energy inputs are substitutes in the energy-intensive petrochemical industry, and are complements in the materials-intensive electrical industry. Estimated cross-price elasticities for materials with respect to energy price are close to zero, and not statistically significant in food processing, metals, or the pulp and paper products industries. These results indicate that estimated differences in cross-price elasticities of input demand from previous empirical studies (P. Thompson & T.G. Taylor 1995) can be, in part, attributed to aggregation across different industry samples.

Table 3 illustrates the estimated elasticities of input efficiency with respect to input prices, the estimated rate of exogenous technological change, and real input price changes in the OECD manufacturing sector between 1990 and 2005. Estimated elasticities have reasonable magnitudes, and vary significantly across sectors. The estimated elasticity of labor input efficiency with respect to labor prices varies from 0.3 to 0.9 with the highest investment response in the electrical, petrochemical and metals industries. The estimated elasticity of energy input efficiency with respect to energy prices ranges between 0.3 and 0.9 in the petrochemical, food processing and metals industries, and is close to zero in the pulp and paper products and electrical industries. These results are comparable to previous studies, which conclude that estimated elasticities of energy input efficiency with respect to energy prices exhibit significant heterogeneity and range between 0.1 (Linn 2008) to 0.37 (Popp 2001, Table 5, p. 236) to 1.22 (Sue Wing 2008, Table 4, pp. 39-40.).[30]

Table 3: Elasticities of Input Efficiency with Respect to Input Prices, Real Input Price Changes, and the Rate of Exogenous Technological Change in OECD Manufacturing Sectors, 1990-2005

Sector	**Elasticities of Input Efficiency wrt. Input Price, ϕ^j**			**Exogenous Technological Change, ζ**
	Labor	**Energy**	**Materials**	
Chemical, Rubber, Plastics and Fuel Products	0.71	0.89	0.01	0.032
Electrical and Optical Equipment	0.88	0.05	0.04	0.027
Food Products, Beverages, and Tobacco	0.30	0.72	0.03	-0.017
Basic Metals and Fabricated Metal Products	0.77	0.30	0.90	-0.002
Pulp, Paper, Paper Products, Printing and Publishing	0.41	0.03	0.42	0.045
Change in Input Prices in OECD Manufacturing, 1990-2005	22.33	16.4	-6.29	

The estimated elasticity of materials efficiency with respect to materials prices varies from 0.4 to 0.9 in the pulp and paper products and metals industries, and is close to zero in the petrochemical, electrical and food processing industries. Table 3 shows that the real price of materials has fallen in all sectors. Weak investment response to falling materials prices in petrochemical, electrical and food processing industries can be supportive to the hypothesis of asymmetric demand response to input prices (see e.g. S. Borenstein, A.C. Cameron & R. Gilbert 1997, S. Peltzman 2000, Gately & Huntington 2002). The parameter ζ is positive in the petrochemical, electrical, and pulp and paper products industries, indicating that autonomous technological change increases the input efficiency of capital stock.[31] The parameter ζ is negative in the food processing and metals industries, indicating that autonomous technological change increases the input

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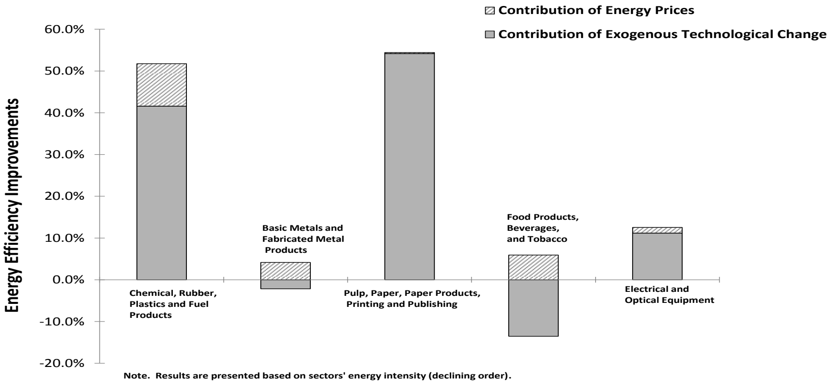
[30] More detailed comparison of estimated elasticities to quoted studies is difficult, because all those studies use different econometric methodologies and datasets.

[31] 3 to 4 percent estimates of annual exogenous technological change in the petrochemical and pulp and paper products industries are higher than estimated rates of autonomous energy efficiency improvements at the economy level (0.5 to 2.5 percent) found in earlier studies. The determinants of technological change at the industry level can be inferred from a rigorous

intensity of capital stock. These results are comparable to Sue Wing's (2008) estimates of energy efficiency elasticities with respect to autonomous technology improvements in the range of -0.03 to 0.08.[32]



Note. Results are presented based on sectors' energy intensity (declining order).

Figure 2: Contribution of Energy Prices and Exogenous Technological Change to Energy Input Efficiency in OECD Manufacturing Industries, 1990-2005.

Figure 2 shows the estimated effect of energy prices and the exogenous technological change on the efficiency of energy input in OECD manufacturing industries. Between 1990 and 2005 the energy efficiency of capital stock has increased in all sectors, except for the food processing industry, where it has fallen by 7.5 percent. The increase in energy efficiency varies from 2 percent in the metals industry to more than 50 percent in the petrochemical and pulp and paper products industries. In less energy-intensive sectors (see Tables 6 - 10, Appendix B), such as pulp and paper products, and the electrical industry, more than 90 percent of energy efficiency improvements are attributable to exogenous technological change. In more energy-intensive industries the relative effect of exogenous technological change is also high but the contribution of energy prices

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econometric analysis using a detailed engineering description of production activities and of the innovations to them (R.J. Kopp & V.K. Smith 1985), and are beyond the scope of this paper. Also see footnote 9.

[32] The opposite sign is used here as Sue Wing (2008) reports the estimates of energy *intensity* elasticities with respect to autonomous technology improvements.

is larger. In the petrochemical industry, energy prices account for 20 percent (or 10 percent out of an overall 50 percent) of total improvements in energy efficiency. These results are consistent with J. Greenwood, Z. Hercowitz & P. Krusell (1997), who find that investment-specific technological change accounts for the major part of efficiency growth. In the metals industry, energy prices account for all improvements in energy efficiency, offsetting the negative effect of exogenous technological change.

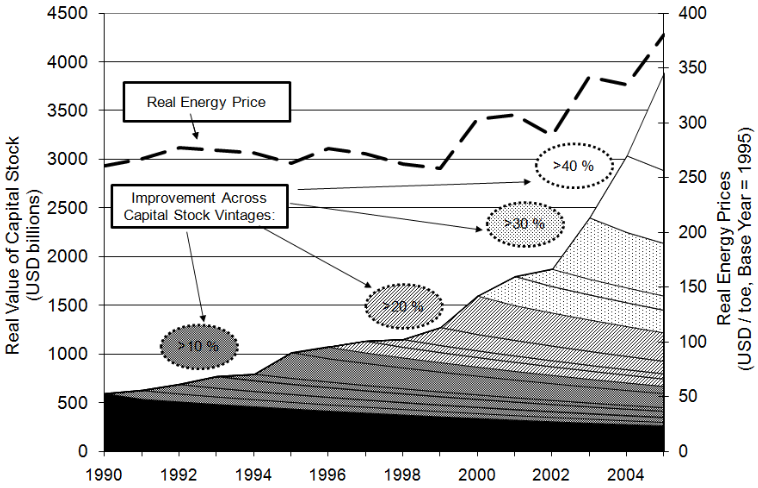

Figure 3: Real Energy Prices and Energy Efficiency Improvements in the U.S. Petrochemical Industry

Figure 3 illustrates the effect of energy prices on energy input efficiency across capital vintages, based on a special case of the petrochemical sector in the United States in 1990-2005. The capital stock (whose real value is shown on the left hand-side of vertical axis of Figure 3) is split into vintages that add up to fifteen in 2005, and the value of each vintage depreciates by 10 percent each year. The first vintage (shown in black) also includes all capital stock before 1990. The value of the index of energy input efficiency for this vintage is close to 1 (Figure 5, Appendix C). The percentages in the bubbles refer to estimated cumulative improvements in energy efficiency relative to 1990. Figure 3 shows that, according to the vintage capital model, the energy efficiency of capital stock in the U.S. manufacturing sector has improved by 52 percent between 1990 and 2005. Real energy prices did not change significantly before 2000, and most improvements in the energy efficiency were driven by exogenous energy-saving technological change. The major price-induced improvement in energy efficiency came between 2000 and 2005, following a sharp rise in real energy prices (shown on the right hand-side of vertical axis of Figure 3).

6 Simulated Effects of Greenhouse Gas Emissions Tax

The results of the vintage capital model indicate that energy-price induced improvements in capital stock are significant in determining the future energy efficiency of production in three out of five industries analyzed in this study. These findings imply that energy and climate policies that provide incentives for early investment in energy efficient capital stock may reduce future energy (including fossil fuel) input consumption. To illustrate the outcome of such policies we use the vintage capital model predictions to evaluate the effect of a greenhouse gas emissions tax on energy consumption. Specifically, we simulate the effect of the greenhouse gas (carbon dioxide, CO_2) emissions tax implemented in 2005 in the special case of U.K. petrochemical industry, where (as shown in Tables 2 and 3, and Figure 2 above), both operational and price-induced investment responses are non-trivial.

We assume that all input prices, except for the energy price, and output remain at their 2005 levels (e.g. $\Delta Y_{i,t} = \Delta w_{i,t}^{j=k,l,m} = 0, t > 2005$). The capital stock remains constant, and the vintage investment offsets capital stock depreciation (e.g. $x_{i,t>2005}^{k} = x_{i,2005}^{k}$, $\Delta I_{i,l>2005} = (1-\delta)\, x_{i,2005}^{k}$). Based on the results of the vintage capital model (see Table 3 and Table 16, Appendix B) we assume the rate of exogenous technological change, $\zeta = 0.032$, the elasticity of energy input efficiency with repect to energy price, $\phi^{e} = 0.89$, and the own-price elasticity of energy demand for the U.K. petrochemical industry, $\eta_{ee} = -0.58$. Because EU KLEMS dataset does not have data on sector energy consumption we obtain this data from the U.K. Department of Energy and Climate Change publication *Energy Consumption in the United Kingdom.*

Figure 4 illustrates the simulation results. In the baseline scenario, we assume there is no greenhouse gas emission tax, and the energy price does not change. The change in the energy input consumption in the baseline scenario is determined by two factors. The first factor is the improvement in the energy efficiency of capital stock due to exogenous technological change. To quantify

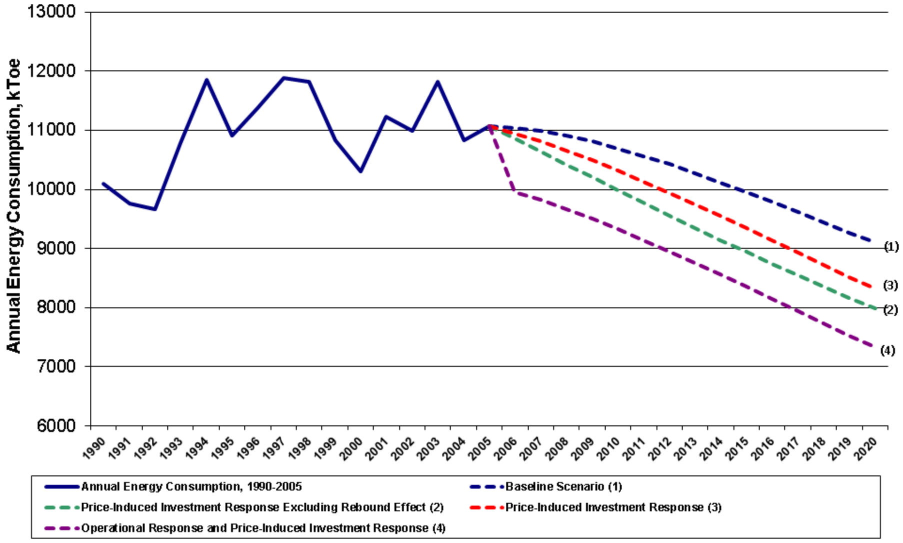

Figure 4: Simulated Effect of \$30 Carbon Tax on Energy Consumption in the U.K. Petrochemical Industry

this effect we use the assumptions above to compute an index of the energy efficiency of capital stock for the simulation sample based on equation (6). The second factor is the change in the share of energy services due to the substitution effect between labor, energy, and materials services. We compute the change in the share of energy services using the results from regression (10) for the manufacturing sector (see Table 11, Appendix B), and convert this change into energy units (*toe*). In formal terms, expected energy consumption in the baseline scenario is calculated as

$$x^e_{i,t} = x^e_{i,0}\gamma^e_t + \left(S^e_{i,t-1} + \Delta S^e_{i,t}\right)\frac{C}{w^e_{i,t}},\ t_0 = 2005, \tag{14}$$

where $\Delta S^e_{i,t}$ is derived from the system of cost share equations (9):

$$\Delta S^e_{i,t} = \sum_{j=k,l,e,m} \beta_j \Delta \log\left(w^j_{i,t}\gamma^j_{i,t}\right) = \sum_{j=l,e,m} \beta_j \Delta \log \gamma^j_{i,t}, \tag{15}$$

because $w^j_{i,t}$ do not change. Our calculations show that in the baseline scenario energy input consumption declines by 22 percent by 2020.

In the counterfactual scenario, we assume there is \$30 tax per ton of emitted greenhouse gas. Using the data for the UK petrochemical industry, we find that one ton of the fuel mix emits 2.4 tons of the CO_2 (computation details are available in Table 24, Appendix B).[33] Then, a \$30 tax per ton of greenhouse gas corresponds to \$73 per *toe*, or (given that the average real energy price in the U.K. petrochemical industry in 2005 was \$433 per *toe*) to a 17 percent increase in energy input price. We assume that energy-using capital stock in manufacturing sectors is idiosyncratic in fuel mix, so no interfuel substitution is possible.[34]

The change in energy input consumption in the counterfactual scenario relative to the baseline scenario depends on two factors. The first factor is a price-induced change in the energy efficiency of the capital stock (or the price-induced investment response). We first perform the same calculations as in the baseline scenario, now assuming a 17 percent increase in the energy input price. Our calculations show that the price-induced investment response results in 12 percent less energy consumption relative to that in the baseline scenario by 2020. This analysis, however, does not include the "rebound effect".[35] To quantify the rebound effect from the vintage capital model, we first calculate an increase in the share of energy service consumption, $S^e_{i,t}$, due to greenhouse gas tax induced improvements in energy efficiency of capital stock (holding other factors constant):

$$\Delta S^e_{i,t} = \sum_{j=k,l,e,m} \beta_j \Delta \log\left(w^j_{i,t}\gamma^j_{i,t}\right) = \beta_e \Delta \log(w^e_{i,t}) + \sum_{j=l,e,m} \beta_j \Delta \log \gamma^j_{i,t}, \quad (16)$$

and convert this change into level terms as in equation (14). The rebound effect is the difference in price-induced energy consumption, with and without

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[33] The data on fuel mix composition in the U.K. petrochemical industry is obtained from the U.K. Department of Energy and Environment database. The greenhouse emission coefficients per type of fuel (in million of British Thermal Units, BTU) are obtained from the US Department of Energy Voluntary Reporting of Greenhouse Gases Program website (http://www.eia.doe.gov/oiaf/1605/coefficients.html) and converted to tons of oil equivalent (*toe*, 1 *toe* $\approx$ 40 x 10^6 BTU).

[34] J. Steinbuks (2011) estimated econometric model of interfuel substitution for 15 energy-intensive UK manufacturing sectors between 1990 aand 2005, and found very small cross-price elasticities of fuel demand in both the short- and the long- run. This finding is consistent with earlier studies of interfuel substitution in manufacturing based on disaggregated data (A.D. Woodland 1993, T.B. Bjorner & H.H. Jensen 2002).

[35] In this context the "rebound effect" is defined as a direct increase in demand for an energy service whose supply has increased as a result of improvements in technical efficiency in the use of energy (. J.D. Khazzoom 1980, L. Greening, D.L. Greene & C. Difiglio 2000, Sorrell & Dimitropoulos 2008)

adjustments for changes in the share of energy service relative to the baseline scenario.[36] Our calculations show a medium-run cumulative rebound effect of 29 percent.[37] In the presence of the rebound effect, energy efficiency improvements result in 9 percent less energy consumption relative to the baseline scenario by 2020.

The second factor is the change in energy demand due to input substitution (or the operational response). Because prices of other inputs are assumed constant, the decline in energy demand depends solely on the own-price elasticity of energy demand. Our calculations show that the operational response to the greenhouse gas emissions tax results in 11 percent less energy consumption than in the baseline scenario by 2020.

Bringing all effects together, expected energy consumption allowing for operational and investment responses to energy prices is calculated as

$$x_{i,t}^{e} = x_{i,0}^{e} \left(\frac{\gamma_t^e}{1 + \frac{\Delta w_{i,t}^e}{w_{i,t}^e} \eta_{ee}} \right) + \left(S_{i,t-1}^{e} + \Delta S_{i,t}^{e} \right) \frac{C}{w_{i,t}^{e}}, \; t_0 = 2005. \qquad (17)$$

Our computations show that a 17 percent increase in the energy input price due to the greenhouse gas tax lowers energy consumption by 19.5 percent relative to the baseline scenario, or energy demand is approximately unit-elastic. Price-induced efficiency improvements lower medium-run energy consumption by 12 percent relative to the baseline scenario. However, 29 percent of these price-induced efficiency improvements (or 3.5 percent of energy consumption in the baseline scenario) are reverted due to the rebound effect. The remaining 11 percent decline in medium-run energy consumption relative to the baseline scenario is due to a reduction in medium-run energy demand. These results indicate that energy and climate policies that increase energy costs result in significant reductions in energy use in the medium- and long-run.

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[36] Note there is also the rebound effect from improvements in energy efficiency of capital stock due to exogenous technological change. This effect is the same in both scenarios, and therefore is not calculated separately.

[37] In a comprehensive survey of different approaches to measurement of the rebound effect S. Sorrell (2007) argues that a plausible range for long-run rebound effect is between 5 and 30 percent. Unfortunately, econometric evidence for the rebound effect in manufacturing industries is almost non-existent (Sorrell 2007, p. 30.).

7 Concluding Remarks

We have expanded the traditional estimation of energy, materials, and labour responses to input price changes by including vintages for the capital stock. The model allows for both substitution across production inputs (labour, energy and materials), and more efficient use of these inputs by choosing more efficient technologies at the time of investment.

In order to test the model, we develop a new dataset for 19 OECD countries and 5 manufacturing industries over the period 1990-2005. At the industry level, the explanatory value of the model with vintage capital stock is significantly improved. The conventional translog model of energy demand is rejected for all industries apart from one. Estimated own-price elasticities of energy demand vary between 0.26 and 1.00 and are in line with previous estimates from the economic literature. Estimated elasticities of energy input efficiency with respect to energy price vary between 0.03 and 0.9. The investment response to energy prices thus varies significantly across manufacturing industries, being significant in some and negligible in others. This result indicates that differences in estimated investment response to energy prices from previous empirical studies can be, to some extent, attributed to the aggregation problem.

An important finding of this paper is that energy and climate policies aimed at reductions in fossil fuel emissions can result in substantial reductions in energy use in energy intensive sectors. The results of policy simulations for the U.K. petrochemical industry (the most energy-intensive industry in the sample) indicate that a 17 percent increase in energy prices from $30 greenhouse gas emissions tax results in a 19.5 percent decline in energy use. That is total (operational and investment) own-price elasticity of energy demand is close to one.

In further work it will be interesting to address data-driven limitations of this study, and explore the robustness of our results by: (1) expanding the observation period beyond 1990-2005; (2) extending the analysis to larger number of industries; and (3) including non-OECD countries in the data set.

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A Derivation of Firm's Investment Choice of Capital Vintage Efficiency

The firm's choice of production technology depends on the input cost savings from new technology and the costs of setting up new technology. For simplicity, let us assume that the index of input efficiency of capital vintage in time $q-1$ is equal to one. If in period q the firm installs the same technology, based on equation (1) the cost of input services to the production function in period $q+1$, $F^j_{i,q+1}$, will be given by

$$F^j_{i,q+1} = E\left(w^j_{i,q+1}\widetilde{x}^j_{i,q+1}\right) = E\left(w^j_{i,q+1}x^j_{i,q+1}\right), \tag{18}$$

where $E(\cdot)$ denotes the expectations operator.

If in period q, the firm installs more efficient technology with the index of input efficiency of capital vintage $\gamma^j_{i,q}$, based on equation (1) the cost of input services to the production function in period $q+1$, $F'^j_{i,q+1}$, will be given by:

$$F'^j_{i,q+1} = E\left(w^j_{i,q+1}\widetilde{x}^j_{i,q+1}\right) = \frac{1}{\gamma^j_{i,q}}E\left(w^j_{i,q+1}x^j_{i,q+1}\right) < F^j_{i,q+1}. \tag{19}$$

Based on the standard assumptions of the theory of the firm, we assume that the unit cost of installing technology with the index of input efficiency of capital vintage $\gamma^j_{i,q}$ can be represented by a continuous, twice-differentiable, and convex cost function $g\left(\gamma^j_{i,q}\right)$.

Given the assumptions above, the firm's i input cost savings from installing more efficient technology γ using x units of input j in period $q+1$ are

$$\pi^j_{i,t} = \left(1 - \frac{1}{\gamma^j_{i,q}}\right)E\left(w^j_{i,q+1}x^j_{i,q+1}\right) - g\left(\gamma^j_{i,q}\right)E\left(x^j_{i,q+1}\right). \tag{20}$$

Applying first order conditions to equation (20), setting them to zero, and solving the resulting equation yields a firm's optimal index of input efficiency of capital vintage $\gamma^{*j}_{i,q}$:

$$\gamma^{*j}_{i,q} = \arg\max_{\gamma^j_{i,q}}\left[\frac{E\left(w^j_{i,q+1}x^j_{i,q+1}\right)}{g'\left(\gamma^j_{i,q}\right)\left(\gamma^j_{i,q}\right)^2 E\left(x^j_{i,q+1}\right)}\right]. \tag{21}$$

To obtain a closed-form solution for $\gamma^{*j}_{i,q}$ one can use in an empirical specification, we assume that input quantities are deterministic functions of input prices:

$$E\left(x_{i,q}^{j}\right)=\xi\left(w_{i,q}^{j}\right), \tag{22}$$

and that the input prices exhibit a random walk[38], so that current input prices are the best predictors of future input costs:

$$E\left(w_{i,q+1}^{j}\right)=w_{i,q}^{j}, \tag{23}$$

and the cost of installing technology with the index of input efficiency of capital vintage $\gamma_{i,q}^{j}$ is given by:

$$g\left(\gamma_{i,q}^{j}\right)=\frac{h}{\varphi}\left(\gamma_{i,q}^{j}\right)^{\varphi}, \tag{24}$$

where h and φ are positive constants determining the curvature of the cost function. Using equations (22), (23), and (24) in equation (21) yields the closed form solution for a firm's investment choice of input efficiency of capital vintage $\gamma_{i,q}^{j}$:

$$\gamma_{i,q}^{*j}=\left(\frac{w_{i,q}^{j}}{h}\right)^{\frac{1}{\varphi+1}}. \tag{25}$$

Let $h=\overline{w}^{j}$, where $\overline{w}^{j}=\frac{\sum_{i=1}^{n}\sum_{t=1}^{T}w_{i,t}^{j}}{nT}$ is the average price of input j across countries and all time periods.[39]

Then equation (25) becomes:

$$\gamma_{i,q}^{*j}=\left(\frac{w_{i,q}^{j}}{\overline{w}^{j}}\right)^{-\phi^{j}}, \tag{26}$$

where $\phi^{j}=-\frac{1}{\varphi+1}=\frac{\partial\gamma_{i,q}^{j}}{\partial w_{i,q}^{j}}\frac{w_{i,q}^{j}}{\gamma_{i,q}^{j}}$ is the elasticity of input efficiency of capital stock with respect to input price changes. Equation (26) implies that higher input prices result in a greater input efficiency of capital stock (a smaller value of $\gamma_{i,q}^{j}$, implying that smaller input quantities are required to produce

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[38] This assumption is consistent with evidence found in empirical studies (see e.g. O. Ashenfelter & D. Card 1982, Pindyck 1999).

[39] Note that because $\overline{w}^{j}$ is a constant, the cost of installing new technology given by equation (24) does not really depend on input prices. It is just a (somewhat arbitrary chosen) scaling factor.

the same amount of output, holding the capital stock constant). This result is consistent with theoretical works showing that firms respond to input price changes by choosing more efficient technologies for the production process (see e.g. Khazzoom 1980, K. Train 1986).

B Tables

Table 4: List of Variables

Variable	Desctiption	Units
S_L	Share of Labor in the Total Cost	Percent
S_K	Share of Capital in the Total Cost	Percent
S_E	Share of Energy in the Total Cost	Percent
S_M	Share of Materials in the Total Cost	Percent
Y	Real Sector Output	Real USD million
w_L	Real Average Wage	Real USD / hour
w_K	Rate of Return on Capital	Percent
w_E	Real Average Price of Energy	Real USD / toe
w_M	Real Average Price of Materials	Real USD / metric ton
INT	Sector Energy Intensity	Toe / real USD thousand

Table 5: List of Countries

Country ID	Country	Data Availability
1	Australia	1990-2005
2	Austria	1990-2005
3	Belgium	1990-2005
4	Denmark	1990-2005
5	Finland	1990-2005
6	France	1990-2005
7	Germany	1990-2005
8	Greece	1990-2005
9	Ireland	1990-2005
10	Italy	1990-2005
11	Japan	1990-2005
12	Korea	1990-2005
13	Luxembourg	1990-2005
14	Netherlands	1990-2005
15	Portugal	1990-2005
16	Spain	1990-2005
17	Sweden	1990-2005
18	United Kingdom	1990-2005
19	United States	1990-2005

Table 6: Descriptive Statistics (1995): Chemical, Rubber, Plastics and Fuel Products

Country	S_L	S_K	S_E	S_M	Y	w_L	w_K	w_E	w_M	INT
Australia	0.18	0.12	0.23	0.46	22689	15.0	0.13	332.7	842.1	0.59
Austria	0.25	0.16	0.10	0.49	14163	23.7	0.11	406.7	1153.1	0.22
Belgium	0.20	0.15	0.15	0.49	42620	32.7	0.11	327.5	1221.2	0.39
Denmark	0.25	0.16	0.17	0.42	10480	26.4	0.12	354.5	1048.7	0.42
Finland	0.18	0.17	0.25	0.40	10145	25.2	0.13	411.4	1064.0	0.52
France	0.19	0.14	0.19	0.48	143280	26.5	0.12	314.2	1219.7	0.50
Germany	0.30	0.13	0.16	0.41	238281	32.1	0.10	432.9	1394.4	0.30
Greece	0.19	0.11	0.38	0.32	7076	7.6	0.21	354.2	1182.9	0.95
Ireland	0.12	0.46	0.04	0.39	12382	14.8	0.12	372.6	1709.9	0.08
Italy	0.16	0.15	0.20	0.49	118146	17.4	0.18	405.4	1296.2	0.44
Japan	0.17	0.29	0.07	0.47	527805	26.2	0.07	729.3	1162.5	0.08
Korea	0.15	0.15	0.29	0.40	89309	6.4	0.16	277.5	1077.9	0.92
Luxembourg	0.21	0.21	0.02	0.56	1482	29.3	0.11	360.6	1709.5	0.06
Netherlands	0.14	0.18	0.22	0.47	52757	26.1	0.11	333.8	1281.0	0.57
Portugal	0.14	0.13	0.28	0.45	8168	6.0	0.16	308.8	1134.9	0.81
Spain	0.19	0.16	0.25	0.40	59174	16.3	0.13	318.6	1226.9	0.63
Sweden	0.19	0.27	0.19	0.35	17789	22.1	0.15	327.7	947.8	0.48
United Kingdom	0.24	0.16	0.16	0.44	110267	18.3	0.13	296.8	1036.1	0.48
United States	0.23	0.20	0.23	0.33	650382	24.3	0.11	262.8	1313.4	0.72
OECD-19	0.19	0.18	0.19	0.43	112442	20.9	0.13	364.6	1211.7	0.48

Table 7: Descriptive Statistics (1995): Electrical and Optical Equipment

Country	S_L	S_K	S_E	S_M	Y	w_L	w_K	w_E	w_M	INT
Australia	0.32	0.10	0.02	0.56	7667	15.0	0.13	332.7	842.1	0.06
Austria	0.38	0.11	0.01	0.50	12074	23.7	0.11	406.7	1153.1	0.03
Belgium	0.34	0.12	0.01	0.54	10979	32.7	0.11	327.5	1221.2	0.02
Denmark	0.32	0.12	0.01	0.55	6490	26.4	0.12	354.5	1048.7	0.02
Finland	0.21	0.15	0.01	0.64	11699	25.2	0.13	411.4	1064.0	0.01
France	0.28	0.10	0.02	0.60	83511	26.5	0.12	314.2	1219.7	0.04
Germany	0.43	0.05	0.02	0.50	171027	32.1	0.10	432.9	1394.4	0.03
Greece	0.23	0.14	0.03	0.61	1276	7.6	0.21	354.2	1182.9	0.07
Ireland	0.13	0.20	0.00	0.67	12896	14.8	0.12	372.6	1709.9	0.01
Italy	0.29	0.09	0.02	0.59	61458	17.4	0.18	405.4	1296.2	0.05
Japan	0.27	0.18	0.02	0.54	559964	26.2	0.07	729.3	1162.5	0.02
Korea	0.19	0.13	0.02	0.66	85829	6.4	0.16	277.5	1077.9	0.06
Luxembourg	0.36	0.12	0.01	0.51	200	29.3	0.11	360.6	1709.5	0.03
Netherlands	0.33	0.07	0.01	0.59	20742	26.1	0.11	333.8	1281.0	0.02
Portugal	0.17	0.10	0.01	0.72	4934	6.0	0.16	308.8	1134.9	0.02
Spain	0.28	0.14	0.02	0.56	23726	16.3	0.13	318.6	1226.9	0.05
Sweden	0.27	0.12	0.01	0.60	18037	22.1	0.15	327.7	947.8	0.01
United Kingdom	0.27	0.14	0.01	0.58	74476	18.3	0.13	296.8	1036.1	0.04
United States	0.36	0.18	0.01	0.45	542450	24.3	0.11	262.8	1313.4	0.04
OECD-19	0.29	0.12	0.01	0.58	89970	20.9	0.13	364.6	1211.7	0.03

Table 8: Descriptive Statistics (1995): Food Products, Beverages, and Tobacco

Country	S_L	S_K	S_E	S_M	Y	w_L	w_K	w_E	w_M	INT
Australia	0.18	0.13	0.02	0.66	34496	15.0	0.13	332.7	842.1	0.06
Austria	0.24	0.13	0.02	0.61	16313	23.7	0.11	406.7	1153.1	0.05
Belgium	0.17	0.10	0.02	0.71	31772	32.7	0.11	327.5	1221.2	0.06
Denmark	0.17	0.08	0.02	0.73	20852	26.4	0.12	354.5	1048.7	0.05
Finland	0.18	0.12	0.02	0.68	11059	25.2	0.13	411.4	1064.0	0.04
France	0.17	0.09	0.02	0.71	137949	26.5	0.12	314.2	1219.7	0.07
Germany	0.23	0.11	0.03	0.63	170822	32.1	0.10	432.9	1394.4	0.07
Greece	0.16	0.08	0.02	0.74	13943	7.6	0.21	354.2	1182.9	0.05
Ireland	0.14	0.17	0.02	0.67	15120	14.8	0.12	372.6	1709.9	0.04
Italy	0.19	0.06	0.02	0.73	96923	17.4	0.18	405.4	1296.2	0.05
Japan	0.22	0.25	0.02	0.52	376455	26.2	0.07	729.3	1162.5	0.02
Korea	0.14	0.08	0.02	0.77	49716	6.4	0.16	277.5	1077.9	0.06
Luxembourg	0.24	0.16	0.02	0.58	639	29.3	0.11	360.6	1709.5	0.05
Netherlands	0.13	0.11	0.01	0.74	55076	26.1	0.11	333.8	1281.0	0.04
Portugal	0.11	0.09	0.01	0.79	13024	6.0	0.16	308.8	1134.9	0.04
Spain	0.16	0.11	0.01	0.72	76792	16.3	0.13	318.6	1226.9	0.04
Sweden	0.18	0.11	0.02	0.70	16001	22.1	0.15	327.7	947.8	0.04
United Kingdom	0.21	0.12	0.02	0.65	96897	18.3	0.13	296.8	1036.1	0.07
United States	0.19	0.18	0.02	0.61	457682	24.3	0.11	262.8	1313.4	0.05
OECD-19	0.18	0.12	0.02	0.68	89028	20.9	0.13	364.6	1211.7	0.05

Table 9: Descriptive Statistics (1995): Basic Metals and Fabricated Metal Products

Country	S_L	S_K	S_E	S_M	Y	w_L	w_K	w_E	w_M	INT
Australia	0.19	0.16	0.05	0.59	30715	15.0	0.13	332.7	842.1	0.15
Austria	0.31	0.13	0.05	0.51	16236	23.7	0.11	406.7	1153.1	0.11
Belgium	0.24	0.09	0.06	0.60	26954	32.7	0.11	327.5	1221.2	0.17
Denmark	0.35	0.10	0.02	0.52	6980	26.4	0.12	354.5	1048.7	0.06
Finland	0.18	0.14	0.04	0.64	11477	25.2	0.13	411.4	1064.0	0.10
France	0.30	0.12	0.04	0.54	95603	26.5	0.12	314.2	1219.7	0.11
Germany	0.38	0.05	0.06	0.51	181713	32.1	0.10	432.9	1394.4	0.11
Greece	0.25	0.06	0.11	0.58	4340	7.6	0.21	354.2	1182.9	0.28
Ireland	0.33	0.13	0.05	0.49	1576	14.8	0.12	372.6	1709.9	0.11
Italy	0.24	0.13	0.04	0.59	108906	17.4	0.18	405.4	1296.2	0.10
Japan	0.23	0.16	0.04	0.57	466726	26.2	0.07	729.3	1162.5	0.05
Korea	0.15	0.11	0.06	0.68	77413	6.4	0.16	277.5	1077.9	0.20
Luxembourg	0.23	0.02	0.08	0.66	3088	29.3	0.11	360.6	1709.5	0.21
Netherlands	0.30	0.14	0.03	0.53	21877	26.1	0.11	333.8	1281.0	0.07
Portugal	0.28	0.09	0.04	0.60	5336	6.0	0.16	308.8	1134.9	0.13
Spain	0.26	0.17	0.05	0.52	45777	16.3	0.13	318.6	1226.9	0.12
Sweden	0.22	0.18	0.04	0.55	20544	22.1	0.15	327.7	947.8	0.10
United Kingdom	0.32	0.09	0.05	0.54	67240	18.3	0.13	296.8	1036.1	0.14
United States	0.31	0.14	0.04	0.52	366766	24.3	0.11	262.8	1313.4	0.12
OECD-19	0.27	0.12	0.05	0.57	82067	20.9	0.13	364.6	1211.7	0.13

Table 10: Descriptive Statistics (1995): Pulp, Paper, Paper Products, Printing and Publishing

Country	S_L	S_K	S_E	S_M	**Y**	w_L	w_K	w_E	w_M	**INT**
Australia	0.35	0.16	0.03	0.46	15502	15.0	0.13	332.7	842.1	0.06
Austria	0.28	0.15	0.03	0.54	10422	23.7	0.11	406.7	1153.1	0.07
Belgium	0.27	0.14	0.03	0.56	11929	32.7	0.11	327.5	1221.2	0.08
Denmark	0.38	0.11	0.01	0.49	6767	26.4	0.12	354.5	1048.7	0.03
Finland	0.18	0.22	0.08	0.52	22378	25.2	0.13	411.4	1064.0	0.17
France	0.31	0.10	0.03	0.56	60939	26.5	0.12	314.2	1219.7	0.07
Germany	0.38	0.12	0.04	0.46	97837	32.1	0.10	432.9	1394.4	0.08
Greece	0.35	0.05	0.07	0.52	2511	7.6	0.21	354.2	1182.9	0.17
Ireland	0.19	0.25	0.01	0.55	5482	14.8	0.12	372.6	1709.9	0.03
Italy	0.29	0.12	0.03	0.57	42764	17.4	0.18	405.4	1296.2	0.07
Japan	0.33	0.17	0.03	0.47	231808	26.2	0.07	729.3	1162.5	0.03
Korea	0.28	0.10	0.04	0.57	22281	6.4	0.16	277.5	1077.9	0.12
Luxembourg	0.32	0.15	0.01	0.52	371	29.3	0.11	360.6	1709.5	0.03
Netherlands	0.33	0.15	0.02	0.50	20733	26.1	0.11	333.8	1281.0	0.05
Portugal	0.19	0.24	0.05	0.52	5241	6.0	0.16	308.8	1134.9	0.15
Spain	0.26	0.16	0.03	0.56	26319	16.3	0.13	318.6	1226.9	0.08
Sweden	0.23	0.24	0.04	0.48	22928	22.1	0.15	327.7	947.8	0.11
United Kingdom	0.36	0.14	0.02	0.49	62542	18.3	0.13	296.8	1036.1	0.04
United States	0.39	0.16	0.03	0.43	359368	24.3	0.11	262.8	1313.4	0.08
OECD-19	0.30	0.15	0.03	0.51	54112	20.9	0.13	364.6	1211.7	0.08

Table 11: Parameter Estimates of Total Cost Function: Chemical, Rubber, Plastics and Fuel Products

	Vintage Capital Model		**Translog Model**	
	est. coefficient	**standard error**	**est. coefficient**	**standard error**
Labor Share Equation: constant	0.454***	0.077	0.576***	0.088
Labor Share Equation: Output	-0.053***	0.005	-0.048***	0.007
Labor Share Equation: Wage	0.058***	0.010	-0.001	0.008
Labor Share Equation: Return on Capital	-0.015***	0.006	0.012**	0.005
Labor Share Equation: Energy Price	0.026***	0.009	0.030***	0.009
Labor Share Equation: Materials Price	0.020***	0.007	0.023***	0.009
Capital Share Equation: constant	-1.320***	0.134	-1.566***	0.131
Capital Share Equation: Output	0.128***	0.009	0.163***	0.011
Capital Share Equation: Wage	-0.143***	0.017	-0.111***	0.012
Capital Share Equation: Return on Capital	0.017*	0.010	0.008	0.008
Capital Share Equation: Energy Price	-0.009	0.015	-0.020	0.013
Capital Share Equation: Materials Price	0.048***	0.012	0.013	0.013
Energy Share Equation: constant	0.906***	0.192	0.762***	0.196
Energy Share Equation: Output	0.008	0.013	0.013	0.016
Energy Share Equation: Wage	-0.013	0.024	0.026	0.018
Energy Share Equation: Return on Capital	0.033**	0.014	0.005	0.012
Energy Share Equation: Energy Price	0.043**	0.021	0.024	0.019
Energy Share Equation: Materials Price	-0.130***	0.017	-0.128***	0.019
Materials Share Equation: constant	0.960***	0.138	1.228***	0.132
Materials Share Equation: Output	-0.082***	0.010	-0.128***	0.011
Materials Share Equation: Wage	0.097***	0.017	0.086***	0.012
Materials Share Equation: Return on Capital	-0.035***	0.010	-0.025***	0.008
Materials Share Equation: Energy Price	-0.060***	0.015	-0.033**	0.013
Materials Share Equation: Materials Price	0.061***	0.012	0.091***	0.013
Number of observations	285		285	
Labor Share Equation: R^2	0.93		0.91	
Capital Share Equation: R^2	0.94		0.95	
Energy Share Equation: R^2	0.89		0.88	
Materials Share Equation: R^2	0.89		0.90	
LR Test: $\phi_L=\phi_E=\phi_M=\zeta=0$, χ^2 (pval)	71.88 (0.00)			
note: *** p<0.01, ** p<0.05, * p<0.1				

Note. Estimates for country-specific fixed effects are not reported in Tables 11-15, and are available upon request.

Table 12: Parameter Estimates of Total Cost Function: Electrical and Optical Equipment

	Vintage Capital Model		**Translog Model**	
	est. coefficient	**standard error**	**est. coefficient**	**standard error**
Labor Share Equation: constant	0.952***	0.091	1.211***	0.095
Labor Share Equation: Output	-0.079***	0.005	-0.089***	0.006
Labor Share Equation: Wage	0.057***	0.010	0.033***	0.009
Labor Share Equation: Return on Capital	-0.001	0.008	0.017**	0.007
Labor Share Equation: Energy Price	0.061***	0.012	0.050***	0.012
Labor Share Equation: Materials Price	-0.009	0.012	-0.0003	0.013
Capital Share Equation: constant	-0.604***	0.113	-0.748***	0.120
Capital Share Equation: Output	0.060***	0.006	0.065***	0.008
Capital Share Equation: Wage	-0.103***	0.013	-0.060***	0.011
Capital Share Equation: Return on Capital	0.008	0.010	-0.006	0.009
Capital Share Equation: Energy Price	0.005	0.015	-0.001	0.016
Capital Share Equation: Materials Price	0.047***	0.015	0.037**	0.016
Energy Share Equation: constant	0.029**	0.012	0.046***	0.012
Energy Share Equation: Output	-0.002**	0.001	-0.004***	0.001
Energy Share Equation: Wage	-0.001	0.001	0.003***	0.001
Energy Share Equation: Return on Capital	-0.002**	0.001	-0.004***	0.001
Energy Share Equation: Energy Price	0.008***	0.002	0.005***	0.002
Energy Share Equation: Materials Price	-0.006***	0.002	-0.005***	0.002
Materials Share Equation: constant	0.623***	0.124	0.490***	0.128
Materials Share Equation: Output	0.021***	0.007	0.028***	0.008
Materials Share Equation: Wage	0.046***	0.014	0.024**	0.012
Materials Share Equation: Return on Capital	-0.005	0.011	-0.008	0.010
Materials Share Equation: Energy Price	-0.074***	0.016	-0.054***	0.017
Materials Share Equation: Materials Price	-0.032**	0.016	-0.032*	0.017
Number of observations			285	
Labor Share Equation: R^2	0.92		0.92	
Capital Share Equation: R^2	0.74		0.71	
Energy Share Equation: R^2	0.75		0.76	
Materials Share Equation: R^2	0.85		0.84	
LR Test: $\phi_L=\phi_E=\phi_M=\zeta=0$, χ^2 (pval)		41.98 (0.00)		
note: *** p<0.01, ** p<0.05, * p<0.1				

Table 13: Parameter Estimates of Total Cost Function: Food Products, Beverages, and Tobacco

	Vintage Capital Model		Translog Model	
	est. coefficient	standard error	est. coefficient	standard error
Labor Share Equation: constant	0.733***	0.084	0.660***	0.081
Labor Share Equation: Output	-0.062***	0.008	-0.061***	0.008
Labor Share Equation: Wage	0.047***	0.007	0.044***	0.006
Labor Share Equation: Return on Capital	-0.008***	0.003	-0.018***	0.003
Labor Share Equation: Energy Price	-0.001	0.006	0.003	0.005
Labor Share Equation: Materials Price	0.017***	0.007	0.019***	0.007
Capital Share Equation: constant	0.047	0.118	0.039	0.113
Capital Share Equation: Output	0.011	0.011	0.016	0.011
Capital Share Equation: Wage	0.019**	0.009	0.016**	0.008
Capital Share Equation: Return on Capital	-0.023***	0.004	-0.023***	0.003
Capital Share Equation: Energy Price	0.009	0.008	0.008	0.007
Capital Share Equation: Materials Price	-0.026***	0.009	-0.032***	0.009
Energy Share Equation: constant	0.140***	0.030	0.129***	0.030
Energy Share Equation: Output	-0.015***	0.003	-0.012***	0.003
Energy Share Equation: Wage	0.007***	0.002	0.006***	0.002
Energy Share Equation: Return on Capital	0.003***	0.001	0.0003	0.001
Energy Share Equation: Energy Price	0.012***	0.002	0.012***	0.002
Energy Share Equation: Materials Price	-0.003	0.002	-0.005*	0.002
Materials Share Equation: constant	0.080	0.118	0.172	0.116
Materials Share Equation: Output	0.065***	0.011	0.057***	0.011
Materials Share Equation: Wage	-0.072***	0.009	-0.066***	0.008
Materials Share Equation: Return on Capital	0.028***	0.004	0.041***	0.004
Materials Share Equation: Energy Price	-0.019**	0.008	-0.023***	0.007
Materials Share Equation: Materials Price	0.012	0.009	0.018*	0.009
Number of observations	285		285	
Labor Share Equation: R^2	0.94		0.94	
Capital Share Equation: R^2	0.92		0.92	
Energy Share Equation: R^2	0.73		0.72	
Materials Share Equation: R^2	0.96		0.96	
LR Test: $\phi_L=\phi_E=\phi_M=\zeta=0$, χ^2 (pval)	19.19 (0.08)			
note: *** p<0.01, ** p<0.05, * p<0.1				

Table 14: Parameter Estimates of Total Cost Function: Basic Metals and Fabricated Metal Products

	Vintage Capital Model		**Translog Model**	
	est. coefficient	**standard error**	**est. coefficient**	**standard error**
Labor Share Equation: constant	1.557***	0.107	1.651***	0.129
Labor Share Equation: Output	-0.122***	0.013	-0.119***	0.013
Labor Share Equation: Wage	0.107***	0.011	0.080***	0.011
Labor Share Equation: Return on Capital	0.014***	0.005	0.028***	0.007
Labor Share Equation: Energy Price	0.026**	0.010	0.028***	0.010
Labor Share Equation: Materials Price	-0.017	0.013	-0.024**	0.012
Capital Share Equation: constant	-0.661***	0.095	-0.760***	0.113
Capital Share Equation: Output	0.087***	0.012	0.096***	0.011
Capital Share Equation: Wage	-0.095***	0.009	-0.078***	0.009
Capital Share Equation: Return on Capital	0.010**	0.004	0.004	0.006
Capital Share Equation: Energy Price	-0.014	0.009	-0.019**	0.009
Capital Share Equation: Materials Price	0.014	0.011	0.009	0.011
Energy Share Equation: constant	0.109**	0.049	0.109**	0.055
Energy Share Equation: Output	-0.011*	0.006	-0.006	0.005
Energy Share Equation: Wage	0.015***	0.005	0.009**	0.005
Energy Share Equation: Return on Capital	-0.006***	0.002	-0.003	0.003
Energy Share Equation: Energy Price	-0.002	0.005	0.001	0.004
Energy Share Equation: Materials Price	0.002	0.006	-0.005	0.005
Materials Share Equation: constant	-0.005	0.134	-0.00005	0.146
Materials Share Equation: Output	0.046***	0.016	0.029	0.014
Materials Share Equation: Wage	-0.027**	0.013	-0.011	0.012
Materials Share Equation: Return on Capital	-0.019***	0.006	-0.028	0.008
Materials Share Equation: Energy Price	-0.009	0.013	-0.010	0.012
Materials Share Equation: Materials Price	0.0003	0.016	0.020	0.014
Number of observations	285		285	
Labor Share Equation: R^2	0.93		0.92	
Capital Share Equation: R^2	0.85		0.82	
Energy Share Equation: R^2	0.75		0.73	
Materials Share Equation: R^2	0.88		0.88	
LR Test: $\phi_L=\phi_E=\phi_M=\zeta=0$, χ^2 (pval)		83.31 (0.00)		
note: *** p<0.01, ** p<0.05, * p<0.1				

Table 15: Parameter Estimates of Total Cost Function: Pulp, Paper, Paper Products, Printing and Publishing

	Vintage Capital Model		**Translog Model**	
	est. coefficient	**standard error**	**est. coefficient**	**standard error**
Labor Share Equation: constant	0.784***	0.110	0.955***	0.110
Labor Share Equation: Output	-0.049***	0.007	-0.055***	0.008
Labor Share Equation: Wage	0.090***	0.013	0.074***	0.012
Labor Share Equation: Return on Capital	-0.022***	0.007	0.012**	0.006
Labor Share Equation: Energy Price	0.009	0.011	-0.000	0.010
Labor Share Equation: Materials Price	-0.014	0.012	-0.006	0.013
Capital Share Equation: constant	-0.906***	0.163	-1.287***	0.176
Capital Share Equation: Output	0.162***	0.010	0.173***	0.013
Capital Share Equation: Wage	-0.154***	0.020	-0.105***	0.020
Capital Share Equation: Return on Capital	0.060***	0.010	-0.015	0.009
Capital Share Equation: Energy Price	-0.005	0.016	0.003	0.017
Capital Share Equation: Materials Price	-0.054***	0.018	-0.062***	0.020
Energy Share Equation: constant	0.124***	0.042	0.137***	0.040
Energy Share Equation: Output	-0.008***	0.003	-0.010***	0.003
Energy Share Equation: Wage	0.009*	0.005	0.006	0.004
Energy Share Equation: Return on Capital	-0.003	0.003	0.001	0.002
Energy Share Equation: Energy Price	0.014***	0.004	0.015***	0.004
Energy Share Equation: Materials Price	-0.015***	0.005	-0.012***	0.005
Materials Share Equation: constant	0.997***	0.184	1.196***	0.183
Materials Share Equation: Output	-0.104***	0.012	-0.108***	0.013
Materials Share Equation: Wage	0.055**	0.022	0.024	0.020
Materials Share Equation: Return on Capital	-0.035***	0.012	0.002	0.010
Materials Share Equation: Energy Price	-0.019	0.018	-0.017	0.017
Materials Share Equation: Materials Price	0.083***	0.020	0.080***	0.021
Number of observations	285		285	
Labor Share Equation: R^2	0.92		0.91	
Capital Share Equation: R^2	0.88		0.85	
Energy Share Equation: R^2	0.85		0.85	
Materials Share Equation: R^2	0.78		0.77	
LR Test: $\phi_L=\phi_E=\phi_M=\zeta=0$, χ^2 (pval)	86.67 (0.00)			
note: *** p<0.01, ** p<0.05, * p<0.1				

Table 16: Estimated Energy Demand Elasticities by Country: Chemical, Rubber, Plastics and Fuel Products

Country	**Model I (Vintage Capital)**								**Model II (Translog)**							
	η_{EE}		η_{LE}		η_{KE}		η_{ME}		η_{EE}		η_{LE}		η_{KE}		η_{ME}	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Australia	-0.56	0.02	0.43	0.06	0.21	0.05	0.13	0.04	-0.63	0.04	0.45	0.06	0.13	0.05	0.20	0.05
Austria	-0.39	0.15	0.21	0.04	0.04	0.03	-0.02	0.04	-0.62	0.06	0.23	0.03	-0.03	0.02	0.04	0.04
Belgium	-0.57	0.03	0.37	0.11	0.16	0.07	0.09	0.07	-0.66	0.05	0.39	0.11	0.08	0.06	0.15	0.07
Denmark	-0.58	0.01	0.31	0.04	0.15	0.03	0.05	0.03	-0.68	0.01	0.33	0.04	0.08	0.03	0.12	0.03
Finland	-0.55	0.02	0.47	0.06	0.26	0.04	0.15	0.03	-0.61	0.03	0.50	0.06	0.19	0.03	0.22	0.04
France	-0.58	0.01	0.38	0.05	0.16	0.03	0.10	0.03	-0.66	0.02	0.41	0.05	0.07	0.03	0.16	0.03
Germany	-0.58	0.01	0.28	0.05	0.13	0.04	0.04	0.03	-0.68	0.02	0.30	0.05	0.04	0.05	0.11	0.04
Greece	-0.47	0.03	0.58	0.05	0.34	0.03	0.22	0.02	-0.51	0.03	0.60	0.05	0.23	0.04	0.32	0.03
Ireland	0.98	1.08	0.28	0.04	0.01	0.01	-0.17	0.07	0.12	0.60	0.32	0.05	-0.01	0.01	-0.08	0.05
Italy	-0.58	0.01	0.38	0.04	0.15	0.02	0.10	0.03	-0.67	0.02	0.40	0.04	0.06	0.02	0.15	0.03
Japan	-0.38	0.05	0.25	0.02	0.05	0.01	-0.04	0.01	-0.62	0.03	0.28	0.03	0.01	0.01	0.01	0.01
Korea	-0.54	0.03	0.53	0.08	0.26	0.05	0.17	0.04	-0.60	0.04	0.56	0.09	0.18	0.05	0.24	0.05
Luxembourg	1.02	0.31	0.14	0.02	-0.03	0.01	-0.08	0.01	0.14	0.17	0.16	0.02	-0.09	0.02	-0.04	0.01
Netherlands	-0.57	0.01	0.47	0.07	0.20	0.03	0.13	0.03	-0.65	0.02	0.50	0.07	0.13	0.03	0.19	0.03
Portugal	-0.52	0.03	0.56	0.07	0.26	0.04	0.21	0.05	-0.58	0.04	0.59	0.07	0.15	0.03	0.27	0.05
Spain	-0.56	0.03	0.43	0.07	0.23	0.05	0.13	0.04	-0.63	0.04	0.45	0.07	0.15	0.04	0.20	0.05
Sweden	-0.57	0.02	0.39	0.06	0.21	0.05	0.05	0.03	-0.65	0.03	0.41	0.06	0.17	0.04	0.14	0.04
United Kingdom	-0.58	0.01	0.30	0.04	0.13	0.03	0.05	0.03	-0.68	0.02	0.31	0.04	0.04	0.03	0.12	0.03
United States	-0.58	0.01	0.37	0.04	0.21	0.03	0.05	0.03	-0.65	0.02	0.38	0.04	0.16	0.03	0.14	0.03

Table 17: Estimated Energy Demand Elasticities by Country: Electrical and Optical Equipment

Country	**Model I (Vintage Capital)**								**Model II (Translog)**							
	η_{EE}		η_{LE}		η_{KE}		η_{ME}		η_{EE}		η_{LE}		η_{KE}		η_{ME}	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Australia	-0.50	0.06	0.21	0.02	0.11	0.02	-0.14	0.013	-0.51	0.06	0.21	0.02	0.05	0.01	-0.12	0.012
Austria	-0.27	0.08	0.19	0.03	0.12	0.02	-0.14	0.010	-0.27	0.08	0.19	0.03	0.05	0.01	-0.13	0.009
Belgium	-0.24	0.20	0.19	0.02	0.13	0.02	-0.14	0.010	-0.24	0.20	0.19	0.02	0.06	0.01	-0.13	0.010
Denmark	-0.19	0.12	0.20	0.03	0.13	0.05	-0.13	0.009	-0.19	0.12	0.21	0.03	0.05	0.02	-0.12	0.008
Finland	0.57	0.62	0.30	0.07	0.07	0.02	-0.14	0.015	0.56	0.62	0.30	0.07	0.03	0.01	-0.13	0.014
France	-0.44	0.07	0.23	0.02	0.15	0.01	-0.12	0.004	-0.44	0.07	0.23	0.02	0.06	0.01	-0.11	0.004
Germany	-0.44	0.07	0.17	0.01	0.18	0.05	-0.14	0.009	-0.45	0.07	0.17	0.01	0.07	0.02	-0.13	0.008
Greece	-0.67	0.01	0.26	0.02	0.13	0.02	-0.11	0.004	-0.67	0.01	0.27	0.02	0.06	0.01	-0.10	0.004
Ireland	0.56	0.52	0.48	0.14	0.08	0.01	-0.11	0.005	0.55	0.52	0.48	0.14	0.03	0.01	-0.10	0.004
Italy	-0.58	0.12	0.22	0.02	0.14	0.01	-0.12	0.011	-0.58	0.12	0.23	0.02	0.07	0.01	-0.11	0.010
Japan	-0.51	0.05	0.24	0.01	0.10	0.01	-0.13	0.004	-0.51	0.05	0.24	0.01	0.05	0.01	-0.12	0.004
Korea	-0.59	0.12	0.39	0.05	0.13	0.02	-0.09	0.005	-0.59	0.12	0.39	0.05	0.06	0.01	-0.09	0.005
Luxembourg	-0.33	0.06	0.18	0.01	0.11	0.01	-0.15	0.009	-0.34	0.06	0.18	0.01	0.05	0.01	-0.14	0.009
Netherlands	-0.30	0.13	0.18	0.01	0.09	0.26	-0.13	0.007	-0.31	0.13	0.18	0.01	0.04	0.09	-0.11	0.007
Portugal	-0.20	0.29	0.32	0.03	0.21	0.07	-0.10	0.009	-0.20	0.29	0.33	0.03	0.08	0.03	-0.09	0.008
Spain	-0.56	0.05	0.25	0.02	0.14	0.03	-0.11	0.010	-0.56	0.05	0.25	0.02	0.06	0.01	-0.10	0.009
Sweden	0.38	0.23	0.22	0.03	0.10	0.18	-0.13	0.014	0.37	0.23	0.22	0.03	0.04	0.06	-0.12	0.013
United Kingdom	-0.36	0.08	0.21	0.02	0.14	0.04	-0.13	0.009	-0.37	0.08	0.22	0.02	0.06	0.01	-0.12	0.009
United States	-0.38	0.06	0.17	0.01	0.09	0.01	-0.18	0.010	-0.38	0.06	0.17	0.01	0.04	0.00	-0.16	0.009

Table 18: Estimated Energy Demand Elasticities by Country: Food Products, Beverages, and Tobacco

Country	Model I (Vintage Capital)								Model II (Translog)							
	η_{EE}		η_{LE}		η_{KE}		η_{ME}		η_{EE}		η_{LE}		η_{KE}		η_{ME}	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Australia	-0.44	0.08	0.02	0.003	0.09	0.004	-0.006	0.003	-0.46	0.07	0.04	0.003	0.08	0.004	-0.012	0.003
Austria	-0.51	0.08	0.02	0.006	0.11	0.011	-0.004	0.004	-0.52	0.08	0.04	0.005	0.10	0.010	-0.010	0.004
Belgium	-0.46	0.07	0.02	0.003	0.11	0.008	-0.004	0.003	-0.48	0.06	0.04	0.003	0.10	0.007	-0.009	0.003
Denmark	-0.40	0.05	0.02	0.002	0.14	0.014	-0.006	0.002	-0.42	0.05	0.04	0.001	0.12	0.012	-0.011	0.001
Finland	-0.36	0.13	0.01	0.004	0.11	0.015	-0.007	0.003	-0.39	0.12	0.04	0.003	0.10	0.013	-0.013	0.003
France	-0.52	0.03	0.02	0.002	0.12	0.007	-0.001	0.002	-0.54	0.03	0.04	0.001	0.11	0.006	-0.006	0.002
Germany	-0.62	0.04	0.03	0.005	0.12	0.010	0.005	0.005	-0.63	0.04	0.05	0.005	0.11	0.010	-0.001	0.005
Greece	-0.42	0.04	0.02	0.002	0.13	0.007	-0.005	0.001	-0.45	0.04	0.04	0.001	0.11	0.006	-0.010	0.001
Ireland	-0.30	0.13	0.01	0.003	0.07	0.010	-0.011	0.004	-0.33	0.12	0.04	0.003	0.06	0.009	-0.016	0.004
Italy	-0.52	0.11	0.02	0.007	0.15	0.012	0.001	0.007	-0.54	0.11	0.04	0.008	0.13	0.011	-0.004	0.007
Japan	-0.08	0.06	0.01	0.001	0.05	0.004	-0.024	0.002	-0.12	0.06	0.03	0.001	0.04	0.003	-0.031	0.002
Korea	-0.39	0.08	0.01	0.003	0.12	0.020	-0.004	0.002	-0.41	0.07	0.05	0.004	0.11	0.017	-0.009	0.002
Luxembourg	-0.53	0.07	0.02	0.004	0.09	0.009	-0.005	0.004	-0.55	0.06	0.04	0.003	0.08	0.008	-0.011	0.004
Netherlands	-0.22	0.10	0.01	0.002	0.10	0.010	-0.010	0.002	-0.25	0.10	0.04	0.002	0.09	0.009	-0.015	0.002
Portugal	-0.25	0.27	0.01	0.009	0.11	0.031	-0.005	0.010	-0.28	0.26	0.05	0.012	0.10	0.028	-0.010	0.010
Spain	-0.14	0.11	0.01	0.003	0.10	0.008	-0.012	0.002	-0.18	0.11	0.03	0.002	0.09	0.008	-0.016	0.002
Sweden	-0.29	0.07	0.01	0.002	0.09	0.013	-0.011	0.002	-0.32	0.07	0.03	0.002	0.08	0.011	-0.017	0.002
United Kingdom	-0.44	0.08	0.02	0.004	0.09	0.008	-0.009	0.004	-0.46	0.08	0.04	0.004	0.08	0.007	-0.015	0.004
United States	-0.24	0.04	0.01	0.001	0.07	0.004	-0.015	0.001	-0.28	0.04	0.03	0.001	0.06	0.003	-0.021	0.001

Table 19: Estimated Energy Demand Elasticities by Country: Basic Metals and Fabricated Metal Products

Country	Model I (Vintage Capital)								Model II (Translog)							
	η_{EE}		η_{LE}		η_{KE}		η_{ME}		η_{EE}		η_{LE}		η_{KE}		η_{ME}	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Australia	-0.98	0.01	0.19	0.012	-0.04	0.010	0.04	0.006	-0.92	0.00	0.19	0.012	-0.07	0.014	0.04	0.006
Austria	-0.99	0.01	0.14	0.012	-0.05	0.024	0.03	0.005	-0.93	0.00	0.15	0.012	-0.09	0.033	0.03	0.005
Belgium	-0.97	0.02	0.17	0.011	-0.10	0.025	0.05	0.011	-0.92	0.01	0.18	0.011	-0.16	0.032	0.05	0.011
Denmark	-1.05	0.01	0.10	0.003	-0.12	0.023	0.01	0.003	-0.93	0.00	0.10	0.004	-0.17	0.031	0.01	0.003
Finland	-0.99	0.01	0.17	0.011	-0.08	0.017	0.04	0.006	-0.93	0.00	0.18	0.012	-0.12	0.022	0.04	0.006
France	-1.02	0.01	0.12	0.004	-0.09	0.015	0.02	0.004	-0.93	0.00	0.13	0.005	-0.14	0.019	0.02	0.004
Germany	-0.97	0.01	0.13	0.011	-0.15	0.072	0.04	0.007	-0.92	0.01	0.14	0.011	-0.22	0.096	0.04	0.007
Greece	-0.92	0.01	0.20	0.013	-0.18	0.063	0.09	0.007	-0.89	0.01	0.20	0.013	-0.28	0.083	0.08	0.007
Ireland	-0.98	0.02	0.14	0.016	-0.03	0.026	0.04	0.013	-0.92	0.01	0.14	0.016	-0.06	0.030	0.03	0.013
Italy	-1.00	0.01	0.14	0.006	-0.09	0.019	0.03	0.005	-0.93	0.00	0.15	0.006	-0.13	0.027	0.03	0.005
Japan	-1.00	0.01	0.16	0.010	-0.05	0.005	0.03	0.003	-0.93	0.00	0.17	0.011	-0.08	0.007	0.03	0.003
Korea	-0.97	0.02	0.26	0.025	-0.05	0.017	0.05	0.015	-0.92	0.01	0.28	0.026	-0.09	0.018	0.05	0.015
Luxembourg	-0.97	0.02	0.18	0.013	-0.26	0.147	0.05	0.015	-0.92	0.01	0.19	0.013	-0.37	0.200	0.05	0.015
Netherlands	-1.03	0.01	0.12	0.005	-0.09	0.021	0.01	0.003	-0.93	0.00	0.12	0.006	-0.13	0.028	0.01	0.003
Portugal	-1.02	0.03	0.14	0.007	-0.10	0.023	0.02	0.009	-0.93	0.00	0.14	0.008	-0.15	0.028	0.02	0.009
Spain	-1.00	0.01	0.15	0.015	-0.05	0.016	0.03	0.005	-0.93	0.00	0.15	0.016	-0.09	0.021	0.03	0.005
Sweden	-1.00	0.01	0.15	0.010	-0.05	0.007	0.03	0.006	-0.93	0.00	0.15	0.010	-0.09	0.011	0.03	0.006
United Kingdom	-0.99	0.01	0.12	0.009	-0.40	0.729	0.03	0.009	-0.93	0.01	0.13	0.009	-0.55	0.980	0.03	0.009
United States	-1.01	0.01	0.12	0.006	-0.05	0.010	0.02	0.005	-0.93	0.00	0.13	0.007	-0.09	0.015	0.02	0.005

Table 20: Estimated Energy Demand Elasticities by Country: Pulp, Paper, Paper Products, Printing and Publishing

Country	**Model I (Vintage Capital)**								**Model II (Translog)**							
	η_{EE}		η_{LE}		η_{KE}		η_{ME}		η_{EE}		η_{LE}		η_{KE}		η_{ME}	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Australia	-0.45	0.04	0.05	0.003	-0.0010	0.006	-0.016	0.003	-0.43	0.04	0.03	0.002	0.04	0.003	-0.01	0.003
Austria	-0.57	0.04	0.07	0.006	0.0012	0.013	0.001	0.004	-0.56	0.05	0.04	0.005	0.06	0.009	0.00	0.004
Belgium	-0.53	0.05	0.06	0.004	0.0002	0.007	-0.003	0.003	-0.51	0.05	0.03	0.004	0.05	0.004	0.00	0.003
Denmark	-0.21	0.15	0.04	0.005	-0.0284	0.009	-0.020	0.004	-0.18	0.15	0.02	0.004	0.04	0.006	-0.02	0.004
Finland	-0.74	0.01	0.12	0.018	0.0523	0.022	0.045	0.014	-0.74	0.01	0.08	0.014	0.10	0.013	0.05	0.014
France	-0.46	0.04	0.06	0.002	-0.0211	0.003	-0.008	0.002	-0.43	0.04	0.03	0.002	0.05	0.004	0.00	0.002
Germany	-0.65	0.04	0.07	0.010	0.0165	0.010	0.005	0.009	-0.64	0.05	0.05	0.009	0.07	0.010	0.01	0.009
Greece	-0.71	0.02	0.09	0.008	-0.0387	0.049	0.024	0.008	-0.70	0.02	0.06	0.007	0.12	0.027	0.03	0.008
Ireland	0.59	0.71	0.06	0.008	-0.0024	0.005	-0.042	0.026	0.66	0.74	0.01	0.007	0.02	0.010	-0.04	0.025
Italy	-0.59	0.07	0.07	0.010	-0.0043	0.011	0.004	0.009	-0.57	0.08	0.04	0.008	0.06	0.007	0.01	0.009
Japan	-0.51	0.06	0.06	0.004	0.0038	0.006	-0.010	0.003	-0.49	0.06	0.03	0.004	0.05	0.004	-0.01	0.003
Korea	-0.65	0.06	0.08	0.012	-0.0159	0.023	0.017	0.011	-0.64	0.06	0.05	0.010	0.08	0.021	0.02	0.011
Luxembourg	-0.33	0.14	0.05	0.005	-0.0143	0.006	-0.014	0.005	-0.31	0.15	0.02	0.004	0.04	0.006	-0.01	0.005
Netherlands	-0.27	0.08	0.05	0.003	-0.0106	0.004	-0.019	0.002	-0.24	0.08	0.02	0.003	0.04	0.002	-0.02	0.002
Portugal	-0.59	0.17	0.09	0.021	0.0237	0.020	0.011	0.019	-0.57	0.17	0.05	0.020	0.06	0.020	0.01	0.019
Spain	-0.52	0.04	0.06	0.004	-0.0004	0.007	-0.005	0.003	-0.51	0.04	0.03	0.003	0.05	0.003	0.00	0.003
Sweden	-0.68	0.02	0.09	0.006	0.0264	0.004	0.015	0.008	-0.67	0.03	0.05	0.007	0.07	0.009	0.02	0.008
United Kingdom	-0.12	0.11	0.04	0.003	-0.0215	0.005	-0.025	0.003	-0.08	0.11	0.02	0.003	0.04	0.005	-0.02	0.003
United States	-0.43	0.04	0.05	0.003	-0.0020	0.004	-0.027	0.007	-0.40	0.04	0.03	0.002	0.04	0.003	-0.02	0.007

Table 21: Estimated Cross-Price Elasticities of Labor Demand in OECD Manufacturing Sectors

Sector	η_{KL}		η_{EL}		η_{ML}	
	VCM	**TL**	**VCM**	**TL**	**VCM**	**TL**
Chemical, Rubber, Plastics and Fuel Products	-0.75***	-0.54***	0.07	0.42***	0.42***	0.40***
	(0.14)	(0.10)	(0.12)	(0.09)	(0.04)	(0.03)
Electrical and Optical Equipment	-0.39***	-0.58***	0.29***	0.23***	0.40***	0.37***
	(0.12)	(0.10)	(0.05)	(0.05)	(0.03)	(0.02)
Food Products, Beverages, and Tobacco	0.36***	0.33***	0.54***	0.47***	0.08***	0.08***
	(0.07)	(0.06)	(0.12)	(0.12)	(0.01)	(0.01)
Basic Metals and Fabricated Metal Products	-0.75***	-0.56***	0.61***	0.48***	0.23***	0.25***
	(0.05)	(0.05)	(0.10)	(0.10)	(0.02)	(0.02)
Pulp, Paper, Paper Products, Printing and Publishing	-0.79***	-0.44**	0.65***	0.55***	0.42***	0.36***
	(0.16)	(0.15)	(0.19)	(0.15)	(0.05)	(0.05)

Note. VCM - Vintage Capital Model, TL - Translog Model. All Elasticities are Calculated at Sample Means.
Standard errors (in parentheses) are based on covariance calculations of elasticity formula (12) . *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 22: Estimated Cross-Price Elasticities of Capital Demand in OECD Manufacturing Sectors

Sector	η_{LK}		η_{EK}		η_{MK}	
	VCM	**TL**	**VCM**	**TL**	**VCM**	**TL**
Chemical, Rubber, Plastics and Fuel Products	0.09**	0.25***	0.46***	0.23***	0.09***	0.12***
	(0.03)	(0.03)	(0.07)	(0.06)	(0.02)	(0.02)
Electrical and Optical Equipment	0.10***	0.12***	-0.15***	-0.07	0.08***	0.12***
	(0.02)	(0.02)	(0.05)	(0.05)	(0.02)	(0.02)
Food Products, Beverages, and Tobacco	0.08***	0.02	0.28***	0.14**	0.17***	0.19***
	(0.01)	(0.02)	(0.06)	(0.06)	(0.01)	(0.01)
Basic Metals and Fabricated Metal Products	0.17***	0.23***	-0.02	0.05	0.08***	0.07***
	(0.02)	(0.03)	(0.04)	(0.06)	(0.01)	(0.01)
Pulp, Paper, Paper Products, Printing and Publishing	0.09***	0.47***	0.05	0.05	0.09***	0.04
	(0.02)	(0.02)	(0.11)	(0.08)	(0.03)	(0.02)

Note. VCM - Vintage Capital Model, TL - Translog Model. All Elasticities are Calculated at Sample Means.
Standard errors (in parentheses) are based on covariance calculations of elasticity formula (12) . *** p<0.01, ** p<0.05, * p<0.1

Table 23: Estimated Cross-Price Elasticities of Materials Demand in OECD Manufacturing Sectors

Sector	η_{LM}		η_{KM}		η_{EM}	
	VCM	**TL**	**VCM**	**TL**	**VCM**	**TL**
Chemical, Rubber, Plastics and Fuel Products	0.54***	0.55***	0.73***	0.50***	-0.68***	-0.73***
	(0.10)	(0.11)	(0.09)	(0.10)	(0.09)	(0.10)
Electrical and Optical Equipment	0.63***	0.54***	0.57***	0.97***	0.12	0.04
	(0.03)	(0.03)	(0.13)	(0.14)	(0.09)	(0.09)
Food Products, Beverages, and Tobacco	0.77***	0.78***	0.44***	0.38***	0.52***	0.44***
	(0.08)	(0.09)	(0.07)	(0.07)	(0.12)	(0.12)
Basic Metals and Fabricated Metal Products	0.49***	0.47***	0.71***	0.65***	0.60***	0.45***
	(0.08)	(0.11)	(0.06)	(0.06)	(0.12)	(0.10)
Pulp, Paper, Paper Products, Printing and Publishing	0.44***	0.47***	0.11	0.05	-0.08	0.04
	(0.04)	(0.02)	(0.14)	(0.15)	(0.19)	(0.19)

Note. VCM - Vintage Capital Model, TL - Translog Model. All Elasticities are Calculated at Sample Means.
Standard errors (in parentheses) are based on covariance calculations of elasticity formula (12) . *** p<0.01, ** p<0.05, * p<0.1

Table 24: Greenhouse Gas Emissions in UK Petrochemical Sector in 2005

Fuel Type	**Fuel Consumption (ktoe)****	**Fuel Share (%)**	**CO2 Emission per toe**	**CO2 emission per Share**
Gasoil / Diesel	1078	0.10	2.90	0.28
Residual Fuel Oil	1970	0.18	3.13	0.56
Liquefied Petroleum Gases	45	0.00	2.50	0.01
Coal	207	0.02	3.70	0.07
Natural gas	4583	0.41	2.17	0.90
Electricity	3188	0.29	2.17*	0.63
Total	11071	1.00		2.44

* Assuming Natural Gas as a Base Load Factor in Electricity Generation
** Excluding SIC 2310 (Manufacture of Coke Oven Products)

C Figures

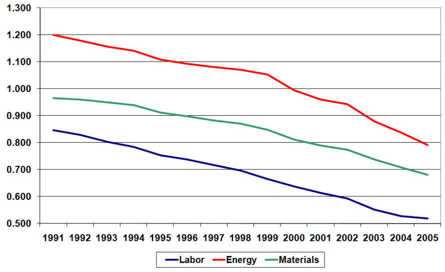

Figure 5: Capital Stock Efficiency Indexes, Chemical, Rubber, Plastics and Fuel Products, United States, 1991-2005

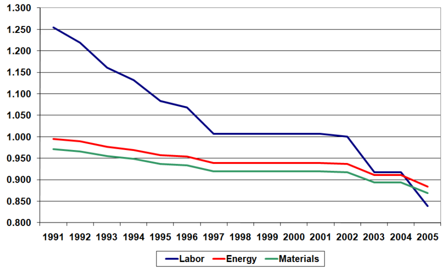

Figure 6: Capital Stock Efficiency Indexes, Electrical and Optical Equipment, United States, 1991-2005

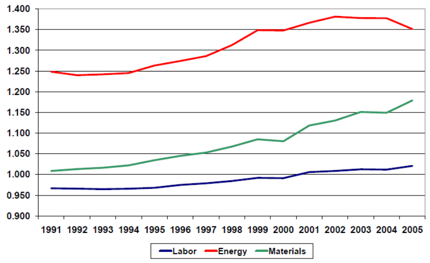

Figure 7: Capital Stock Efficiency Indexes, Food Products, Beverages, and Tobacco, United States, 1991-2005

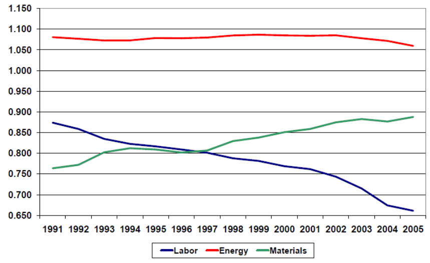

Figure 8: Capital Stock Efficiency Indexes, Basic Metals and Fabricated Metal Products, United States, 1991-2005

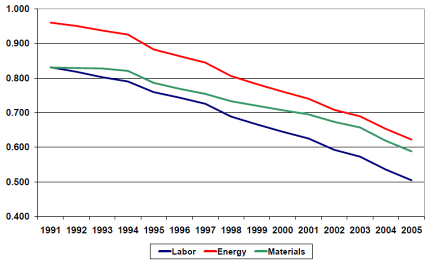

Figure 9: Capital Stock Efficiency Indexes, Pulp, Paper, Paper Products, Printing and Publishing, United States, 1991-2005