Assessing Energy Price Induced Improvements in Efficiency of Capital in OECD Manufacturing Industries

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Abstract

To assess how capital stocks adapt to energy price changes, it is necessary to account for the impacts on different vintages of capital and to account separately for price-induced and autonomous improvements in the energy efficiency of capital stock. The results of econometric analysis for five manufacturing industries in 19 OECD countries between 1990 and 2005 indicate that higher energy prices resulted in smaller energy

use due to both improved energy efficiency of capital stock and reduced demand for the energy input. The investment response to energy prices varied considerably across manufacturing industries, being more significant in energy-intensive sectors. The results of policy simulations indicate that a carbon tax can deliver significant reductions in energy consumption in the medium run with modest declines in energy-using capital stock.

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1 Introduction

Empirical analysis of the effect of energy prices on manufacturing input use has been so far limited by the ability of econometric models to reflect the adaptation of the capital stock to energy price changes. Griffin and 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 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 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 (Pindyck and Rotemberg 1983). Second, these models can say very little about the *sources* of changes in energy demand and energy efficiency (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 and 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 important limitation. Drawing from earlier works by Fuss (1977), Berndt et al. (1981), Atkeson and Kehoe (1999), Popp (2001), Sue Wing (2008), and, especially, Pindyck and Rotemberg (1983), we set up a structural, dynamic, and intertemporally consistent econometric model, which explicitly incorporates the capital stock, and separately accounts for the transitional dynamics of capital due to changes in input prices and autonomous capital efficiency improvements. Specifically, we expand the traditional estimation of energy, materials, and labour responses to input price changes by including vintages for the capital stock.¹ Each vintage of the capital

¹The idea of using vintage capital in economic analysis dates back to Johansen (1959),

stock has its own energy efficiency, which is a function of input prices at the time of investment, and exogenous technological change. As with most new model developments, introducing capital vintages is costly; to make the model estimable we have to assume that the services of assets of different vintages are perfect substitutes, and these assets depreciate geometrically at a constant rate. Under those assumptions we can represent the efficiency of the capital stock with a single index, weighted by the relative efficiencies of the past vintages of capital.² Adding vintage structure captures the adaptation of capital stock to energy prices, while preserving the flexibility of substitution between input factors to production (labour, energy and materials).

Our paper is relevant to several recent studies aimed at understanding determinants of energy efficiency improvements. Perhaps the most closely related paper is Koopmans and te Velde (2001), who also develop a vintage capital model of energy demand, in which the efficiency of energy-using capital stocks responds endogenously to energy prices. Unlike our paper, Koopmans and te Velde (2001) do not structurally estimate the parameters of their model. Instead they calibrate their model based on a large bottom-up database for the economy of the Netherlands, and then solve it numerically. They find that the average pace at which new, energy-efficient technologies become available varies across time, thus elucidating the key weakness of the bottom-up modeling approach, which relies on extrapolation of historical trends of energy efficiency improvements. Metcalf (2008) adapts an index number based theoretical approach, and finds that roughly three-quarters of the improvements in the U.S. energy intensity since 1970 results from efficiency improvements due to rising energy prices and per-capita income. Sue Wing (2008) estimates a structural model, which 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

who introduced this concept in the context of deterministic growth model. Other notable contributions investigating different properties of vintage capital include Solow et al. (1966), Sheshinski (1967), Malcomson (1975), Fuss (1977), and, more recently, Chari and Hopenhayn (1991), Benhabib and Rusticini (1991), and Boucekkin et al. (1997). In the energy and environmental economics literature, vintage capital models have been intensively used mainly in the context of understanding the properties of embodied energy-saving technological progress. Recent contributions include Meijers (1994), Mulder et al. (2003), Hart (2004), Pérez-Barahona and Zou (2006), and Azomahou et al. (2012).

²In this regard our econometric approach is similar to Haas and Schipper (1998) and Koopmans and te Velde (2001), who advocate calculating an index of energy efficiency, and using it directly in econometric specification for energy demand. The index of Haas and Schipper (1998) though is obtained through factor decomposition, and is thus purely exogenous.

transitory energy savings, while innovation induced by energy prices had only a minor impact.” (Sue Wing 2008, p.21). However, neither of the studies investigated the significance of price-induced improvements in the energy efficiency of capital stock.

The distinction between energy price-induced and autonomous changes in efficiency of capital stock presented in this paper is important for both researchers and policy makers, especially in the context of climate change mitigation. The ease of adjusting the capital stock is a critical determinant of the short-run transition costs of a energy and climate policies. The choice of input efficiency made at the time of investment has long-term implications. An energy-inefficient and capital-intensive power plant or manufacturing belt typically stays in production for many years before it retires from the production process. Upgrades to achieve better energy efficiency are not always technologically feasible or might be too costly to implement. Jacoby and Sue Wing (1999, p. 73) argue that “each year of delay [to implementing climate policies] introduces more emission-producing activities that must be squeezed out of the system and shortens the time horizon for change, raising the carbon price required to produce the needed changes in capital structure.” 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 prices provides guidance for decarbonization trajectories.³ Market-based climate policies aimed at reduction in fossil fuel consumption will succeed if firms’ investment is responsive to energy prices.

Our model is estimated for five manufacturing industries in 19 OECD countries between 1990 and 2005 using a restricted variable 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

³Many 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.

of energy demand at the sector level. The assumption of constant efficiency of capital stock is rejected for all sectors.

The results for all industries indicate that energy prices result in smaller energy use due to both improved energy efficiency of capital stock and reduced demand for energy input. Estimated own-price elasticities of energy demand vary in the range of 0.21 and 0.86, and are in line with previous estimates. Estimated elasticities of energy input efficiency with respect to energy price vary between 0.015 (electrical and optical equipment industry) to 1.1 (for petrochemical industry). The investment response to energy prices thus varies considerably across manufacturing industries, being more significant in energy-intensive industries. We also find substantial autonomous improvements in the energy efficiency of capital stock over recent decades, ranging between 2 and 4 percent per annum. These results indicate 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 substantial reductions in energy use in energy intensive sectors. To illustrate this point we conduct a counterfactual analysis of an increase in energy prices due to a \$30 / ton greenhouse gas emissions tax for the U.K. petrochemical and electrical industries (i.e., the most and the least energy-intensive industries in the sample). The results of this analysis indicate that an increase in energy prices results in a considerable decline in energy use. The combined (i.e., operational and investment) own-price elasticity of energy demand is between 0.7 and 0.8. At the same time, the reductions in capital stock in the medium-run are negligible. In the petrochemical industry, the decline in capital stock resulting from short-run energy-capital complementarity is offset by increasing demand for more energy-efficient capital. In the electrical industry energy using capital stocks are little changed because of weak complementarity between energy and capital.

The rest of this paper is structured as follows. 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 Vintage Capital Model of Energy Demand

We introduce a dynamic partial equilibrium model that separately accounts for investment and operational (production) decisions in the 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 of 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 the 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 manufacturing assets based on a specific production technology. Following the economic literature of capital measurement (Diewert 1980, Jorgenson 1980, Jorgenson et al. 1987), we can refer to these manufacturing assets acquired at different points in time as different *vintages* of capital. For each capital vintage, firms choose the optimal level of input efficiency of production technology, given autonomous efficiency improvements (Webster et al. 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 and Huntington 2002, Adeyemi and 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 (Pindyck 1999, Alquist and Kilian 2010).⁴ Second, energy costs are a 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 (Howarth and Andersson 1993). Third, recent evidence

⁴Some energy price developments can be forecasted, e.g., due to pre-announced energy and climate policies. Our study refers to the historic responses to energy price developments, which were largely driven by resource discoveries, technological innovations, macroeconomic fluctuations, and geopolitical developments – all these factors are rather difficult to anticipate.

from rigorous econometric studies based on micro-level data suggest that average consumer beliefs are indistinguishable from a no-change forecast (Allcott et al. 2011, Anderson et al. 2013), and “researchers are likely to be justified in assuming that average consumers employ a no-change forecast in most circumstances” (Anderson et al. 2013, p.401). Finally, lagged energy prices could matter over the very long-term, as new technologies penetrate the market, which is not the focus of this study.

Once the investment is made, the new energy-using capital stock remains operational until it depreciates away or is replaced. The replacement of existing capital stock is, however, costly in the short-run. Our vintage capital model thus fits in the framework introduced by Fuss (1977), in which the substitution of factors of production is easier ex-ante than ex-post. An important characteristic of such a framework, as noted by Koopmans and te Velde (2001, p. 58), is that “following an unexpected energy price increase, the energy efficiency of new vintages will improve more than the energy efficiency of existing vintages. A price change achieves its full impact only after the capital stock has been completely renewed. Hence, price elasticities are larger in the long run than in the short run.” In the extreme case of infinitely large capital adjustment costs our model becomes similar to the Atkeson and Kehoe (1999) “putty-clay” model of energy use.

We then consider production decisions based on the dynamic factor demand model of Pindyck and Rotemberg (1983), where firms minimize expected input costs (including capital adjustment costs) to produce the optimal time path of labor, capital, energy, and materials consumption to achieve 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.

2.1 Investment in 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.⁵ We can therefore view each manufacturing sector as consisting of a

⁵This assumption follows the theoretical literature discussed above and is useful for simplifying the derivations. Of course both input and product markets of many industries, including those studied in this paper, are characterized by some degree of strategic behavior of their market participants. The strategic behaviour will have limited impact on both theoretical

single firm that has certain production technology, or, equivalently, as consisting of many firms whose aggregate technology is represented by our model (Pindyck and Rotemberg 1983). At any time t the firm i is fully flexible in its choice of labor ($x_{i,t}^l$), energy ($x_{i,t}^e$), and materials ($x_{i,t}^m$) inputs. The capital stock ($x_{i,t}^k$) is quasi-fixed (i.e., fixed in the short run, and flexible in the long run), and has vintage representation. Each vintage of capital stock has its own technological efficiency with respect other inputs to the production function. The investment in factor efficiency of a capital vintage is sunk, i.e., the production technology is inflexible in terms of the capital efficiency requirements. We assume that the services of assets of different vintages are perfect substitutes, and these assets depreciate geometrically at constant rate δ .⁶ Under those assumptions Jorgenson et al. (1987, pp. 40-49) have shown that the flow of capital services is a weighted sum of past investments, with the weights corresponding to the relative efficiencies of the different vintages of capital. Investment in a capital vintage in period q can then be inferred from the following equation:

$$I_{i,q} = x_{i,q}^k - (1 - \delta)x_{i,q-1}^k. \quad (1)$$

We assume that in any period q the efficiency of a vintage of capital stock, $x_{i,q}^k$, with respect to other inputs, labor, $x_{i,q}^l$, energy, ($x_{i,q}^e$), and materials, ($x_{i,q}^m$), is represented by an index $\gamma_{i,q}^j$, where $j = l, e, m$. The index $\gamma_{i,q}^j$ measures the amount of labor, energy and materials inputs required to produce the input service, i.e., output of useful work (however measured).⁷ While firms make

predictions and the quality of the econometric estimates to the extent that such behavior results in constant mark-ups charged by the market participants. More important concern for our econometric estimates is an unobserved change in market structure that results in anticipated changes to mark-ups and thus in investment choices that are not explained by current input prices. On the production side, strategic behavior can motivate producers to (i) underinvest in production capacity and (ii) reduce the production volume. Neither of these decisions should affect the cost minimizing strategy of the manufacturing firms, at least in the first order, and will therefore not have a significant impact on the elasticity estimates.

⁶An important characteristic of many vintage capital models is that the life time of vintages is endogenously determined, implying an endogenous depreciation rate. It is obviously attractive to allow for endogenous determination of capital replacement based on intertemporal costs of re-investment in both theoretical and numerical simulation models. Unfortunately, this feature is more difficult to implement in empirical assessments. Manufacturing plants do keep track records of maintenance and re-investments pursued since commissioning, however this is very difficult to approximate externally. In practice, new additions to capital stock, its replacement, and scraping depend on a number of factors, such as (i) outside investment opportunities (e.g., many of the OECD energy-intensive industries invested in growing Asian markets with higher expected returns on capital), (ii) global and country-wide macroeconomic fluctuations, (iii) regulatory policies (e.g., changes in regulations affecting labor markets, environmental compliance costs, or market conduct). Incorporating all those factors would go way beyond the scope of this paper.

⁷For example, if average internal temperature is taken as the appropriate measure of useful

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' 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 , $x_{i,q}^j$, and the index of input efficiency of capital vintage, $\gamma_{i,q-1}^j$, determine the input service to the production function, $\tilde{x}_{i,q}^j$:

$$\tilde{x}_{i,q}^j = \frac{x_{i,q}^j}{\gamma_{i,q-1}^j}, \quad \gamma_{i,q}^j > 0, \quad (2)$$

Similarly, the relationship between the price of the input in period q , $w_{i,q}^j$ and the price of service $\tilde{w}_{i,q}^j$ is given by

$$\tilde{w}_{i,q}^j = w_{i,q}^j \gamma_{i,q-1}^j. \quad (3)$$

Equations (2) and (3) imply that the lower is the value of the index of the input efficiency of capital vintage, $\gamma_{i,q-1}^j$, the more services capital vintage $x_{i,q}^k$ 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,

$$\gamma_{i,t}^k = 1. \quad (4)$$

The input efficiency of capital vintage q that firms choose to produce a flow of services from energy, labour, and materials is determined endogenously based on input prices and the exogenous technological change⁸

$$\gamma_{i,q}^j = (1 - \zeta)^q \left(\frac{w_{i,q}^j}{\bar{w}^j} \right)^{-\phi^j}, \quad j = l, e, m, \quad (5)$$

where $\bar{w}$ is the average price of input j across countries and all time periods,⁹

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.

⁸As we explained earlier our model focuses on medium-term investment decisions, where firms choose between different types of capital from an existing portfolio of available technologies. Exogenous technological change here captures the fact that available technologies improve gradually over time.

⁹We have chosen the OECD average input price across countries and all time periods to

ϕ^j is the elasticity of the efficiency of input j with respect to input price changes, and ζ is the rate of exogenous Hicks-neutral technological change.¹⁰ In the technical appendix (section A.1) we show that this equation is consistent with the profit maximization (cost minimization) 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 :

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

where $I_{i,q}$ is the vintage investment in period q , and δ is the rate of economic depreciation of capital stock.¹¹

Because we do not know the values of the index of input efficiency of capital stock for vintages outside the observed sample, we 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

$$\gamma_{i,t}^j = (1 - \delta)^t \frac{x_{i,0}^k}{x_{i,t}^k} \left(\frac{w_{i,0}^j}{\bar{w}^j} \right)^{-\phi^j} + \sum_{q=1}^t (1 - \zeta)^q \left(\frac{w_{i,q}^j}{\bar{w}^j} \right)^{-\phi^j} \frac{I_{i,q} (1 - \delta)^{t-q}}{x_{i,t}^k}, \quad j = l, e, m, \quad (7)$$

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 the observed sample.¹²

reflect the effects of globalization and industry migration. We also considered the input price based on the country average across time: $\bar{w}_i^j = \sum_{t=1}^T w_{i,t}^j / T$. Estimation results were not different.

¹⁰In the next section we also allow for non-neutral disembodied technological change in firms' operational choice problem.

¹¹Interpretation 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.

¹²We 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.

2.2 Production of Input Factors

Derivation of the operational choice of input factors is based on the dynamic factor demand model of Pindyck and Rotemberg (1983). We assume that the production technology is represented by a restricted variable cost function. Conditional on realization of capital stock, $x_{i,t}^k$, and output $Y_{i,t}$ at time t , the minimum real expenditure on labor, energy, and materials is given by a function $C(\tilde{w}_{i,t}^l, \tilde{w}_{i,t}^e, \tilde{w}_{i,t}^m, x_{i,t}^k, Y_{i,t}, t)$. The function C is assumed to be increasing and concave in input prices of labor, energy, and materials, and decreasing and convex in capital stock. The changes in capital stock are subject to adjustment costs, represented by a convex function, $c(I_t)$.

Factor demands are given by the solution to the following dynamic optimization problem:

$$\min_{\tilde{w}^l, \tilde{w}^e, \tilde{w}^m, x^k} \mathbb{E} \sum_{t=\tau}^T R_t [C(\tilde{w}_{i,t}^l, \tilde{w}_{i,t}^e, \tilde{w}_{i,t}^m, x_{i,t}^k, Y_{i,t}, t) + w_{i,t}^k x_{i,t}^k + c(I_t)], \quad (8)$$

subject to equation (1), where $\mathbb{E}$ denotes the expectational operator, and R_t is the discount rate for revenues accumulating at time t . The expectation operator in the objective function (8) applies to the future values of $\tilde{w}_{i,t}^l, \tilde{w}_{i,t}^e, \tilde{w}_{i,t}^m$ and $Y_{i,t}$, which are treated as random. Differentiating the objective function (8) with respect to choice variables $\tilde{w}^l, \tilde{w}^e, \tilde{w}^m$, and x^k yields the following equations:

$$\frac{\partial C_{i,t}}{\partial \tilde{w}_{i,t}^j} = \tilde{x}_{i,t}^j, \quad j = l, e, m, \quad (9)$$

$$\frac{\partial C_{i,t}}{\partial x_{i,t}^k} + w_{i,t}^k + \frac{\partial c(x_{i,t}^k - (1 - \delta)x_{i,t-1}^k)}{\partial x_{i,t}^k} + \mathbb{E} \left[R_t \frac{\partial c(x_{i,t+1}^k - (1 - \delta)x_{i,t}^k)}{\partial x_{i,t}^k} \right] = 0, \quad (10)$$

and

$$\lim_{t \rightarrow \infty} \mathbb{E} \left\{ R_t \left[\frac{\partial C_{i,t}}{\partial x_{i,t}^k} + w_{i,t}^k + \frac{\partial c(x_{i,t}^k - (1 - \delta)x_{i,t-1}^k)}{\partial x_{i,t}^k} \right] \right\} = 0. \quad (11)$$

Equation (9) is the standard result of Shephard's Lemma. Equation (10) is the Euler equation, which describes the (expected) evolution of the quasi-fixed capital stock. Equation (11) is the transversality condition, which ensures that the quantity capital that firms expect to hold is not very much different from

the quantities they would hold in the absence of adjustment costs.

2.3 Specification and Estimation of the Vintage Capital Model

Before estimating the vintage capital model we must specify the functional forms of the expenditure function, C , and the adjustment cost function, $c(I)$. Following Pindyck and Rotemberg (1983), we assume that the restricted variable cost function can be approximated by the translog model:

$$\begin{aligned} \log C_{i,t} = & \alpha_0 + \sum_j \alpha_{ij} \log \tilde{w}_{i,t}^j + \alpha_{iK} \log x_{i,t}^k + \alpha_{iY} \log Y_{i,t} + \alpha_{i\tau} t \quad (12) \\ & + \frac{1}{2} \sum_j \sum_p \beta_{jk} \log \tilde{w}_{i,t}^j \log \tilde{w}_{i,t}^p + \sum_p \beta_{jK} \log \tilde{w}_{i,t}^j \log x_{i,t}^k \\ & + \sum_j \beta_{jY} \log \tilde{w}_{i,t}^j \log Y_{i,t} + \sum_j \beta_{j\tau} \log \tilde{w}_{i,t}^j t \\ & + \beta_{KY} \log x_{i,t}^k \log Y_{i,t} + \beta_{K\tau} \log x_{i,t}^k t + \beta_{Y\tau} \log Y_{i,t} t \\ & + \frac{1}{2} \beta_{KK} (\log x_{i,t}^k)^2 + \frac{1}{2} \beta_{YY} (\log Y_{i,t})^2 + \frac{1}{2} \beta_{\tau\tau} t^2, \quad j, p = l, e, m. \end{aligned}$$

We add the time trend, t , in equation (12) to allow for factor-specific disembodied technological progress. The adjustment cost function for capital stock is assumed quadratic, that is

$$c(I_{i,t}) = \lambda I_{i,t}^2 / 2. \quad (13)$$

With this specification, equations (9) and (10) become

$$S_{i,t}^j = \alpha_{ij} + \beta_{jK} \log x_{i,t}^k + \beta_{jY} \log Y_{i,t} + \beta_{j\tau} t + \sum_j \beta_j \log \tilde{w}_{i,t}^j, \quad j = l, e, m, \quad (14)$$

and

$$\begin{aligned} C_{i,t} S_{i,t}^K / x_{i,t}^k + w_{i,t}^k + \lambda (x_{i,t}^k - (1 - \delta) x_{i,t-1}^k) \quad (15) \\ - \mathbb{E} \{ R_t (1 - \delta) \lambda [x_{i,t+1}^k - (1 - \delta) x_{i,t}^k] \} = 0, \end{aligned}$$

where

$$S_{i,t}^j = \frac{\partial \log C_{i,t}}{\partial \log \tilde{w}_{i,t}^j} = \frac{\tilde{w}_{i,t}^j \tilde{x}_{i,t}^j}{C} = \frac{w_{i,t}^j x_{i,t}^j}{C}, \quad j = l, e, m, \quad (16)$$

is the share of each input j in firms' total variable cost, and $S_{i,t}^K$ is defined as

$$S_{i,t}^K = \alpha_{iK} + \beta_{KK} \log x_{i,t}^k + \beta_{KY} \log Y_{i,t} + \beta_{K\tau} t + \sum_j \beta_{jK} \log \tilde{w}_{i,t}^j. \quad (17)$$

Combining equations (3), (7), (14), and (15) yields the system of equations to be estimated. Model estimation is confounded by several econometric issues, which require additional clarification. First, we assume that deviations of fitted cost share equations (14) and equation (15) from the logarithmic derivatives of the translog cost function (12) are the result of random errors in cost minimizing behavior. We append to equations (14) and (15) an additive disturbance term, ε_{ijt} , which is independently and identically normally distributed with mean vector zero and nonsingular covariance matrix Ω . This assumption implies that the supply of inputs is perfectly elastic, and therefore that input prices can be taken as exogenous (Berndt and Wood 1975, p. 261). However, input prices and quantities could be endogenous at the individual industry level, and render the estimated coefficients biased and inconsistent. To account for this endogeneity problem we use average estimates for input prices in the entire manufacturing sector.¹³ An alternative approach of instrumental variables estimation appears problematic primarily because of large measurement errors in energy prices at the individual industry level (see section below), and also because of the general difficulty of finding good instruments (Diewert and Fox 2008). As demonstrated by a number of studies (Griffin and Gregory 1976, Barnett et al. 1991, Burnside 1996), the small sample bias from a set of popular instrumental variables (lagged prices, population, taxes, government purchases) is not necessarily smaller than that obtained from actual prices.

Second, estimation of the Euler equation (15) would yield biased and inconsistent parameter estimates if there is a correlation between the actual variables at time t and the expected value of capital stock in period $t + 1$. To account for

¹³Endogeneity 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.

this problem we estimate the model in two stages. In the first stage we employ dynamic panel data estimation techniques (Arellano and Bover 1995, Blundell and Bond 1998) to instrument for the capital stock using lagged input prices and output as instruments. In the second stage we estimate the model using instrumented capital stock in lieu of actual capital stock.

Third, the system of equations to be estimated is a non-linear problem, where the parameters ϕ^j and ζ should be evaluated at each data point across the 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 as a *conditionally linear* problem. Conditional on realization of unknown parameters ϕ^j and ζ , the system of equations 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 a multidimensional stochastic grid search (Judd 1998, p. 296). To minimize the computational burden of a multidimensional grid search, based on earlier empirical findings (e.g., Jorgenson and Fraumeni 1981, Baltagi and Griffin 1988, Newell et al. 1999, Sue Wing 2008, Webster et al. 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 1.5.¹⁴ Because the cost share equations in the system of equations (14) add to one, only two share equations are estimated.

While the system of equations (3), (7), (14), and (15) 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 the dynamic factor demand model of Pindyck and Rotemberg (1983). We then use the likelihood-ratio test to evaluate the significance of the input efficiencies of capital stock in the models of energy demand.

To quantify the operational response to current price changes holding all previous prices constant, we compute own-price and cross-price elasticities of

¹⁴We have examined the model sensitivity to relaxing the range of estimation bounds, and the results turned out to be robust (no corner solutions).

substitution,¹⁵ as well as the elasticities of flexible input demand with respect to changes in output and capital stock.¹⁶ These elasticities are given by

$$\eta_{jj} = \frac{\partial \ln x_{i,t}^j}{\partial \ln w_{i,t}^j} = \frac{\beta_{jj} + \left(S_{i,t}^j\right)^2 - S_{i,t}^j}{S_{i,t}^j}, \quad j = l, e, m. \quad (18)$$

$$\eta_{pj} = \frac{\partial \ln x_{i,t}^j}{\partial \ln w_{i,t}^p} = \frac{\beta_{pj} + S_{i,t}^p S_{i,t}^j}{S_{i,t}^j}, \quad p, j = l, e, m, \quad p \neq j. \quad (19)$$

$$\eta_{jK} = \frac{\partial \ln x_{i,t}^j}{\partial \ln x_{i,t}^k} = \frac{\beta_{jK}}{S_{i,t}^j} + \alpha_{iK} + \beta_{KK} (\log x_{i,t}^k) + \sum_p \beta_{pK} \log \tilde{w}_{i,t}^j, \quad p, j = l, e, m. \quad (20)$$

and

$$\eta_{jY} = \frac{\partial \ln x_{i,t}^j}{\partial \ln Y_{i,t}} = \frac{\beta_{jY}}{S_{i,t}^j} + \alpha_{iY} + \beta_{YY} (\log Y_{i,t}) + \sum_p \beta_{pY} \log \tilde{w}_{i,t}^j, \quad p, j = l, e, m. \quad (21)$$

Estimated elasticities have a standard economic interpretation and capture several separate substitution effects, including within-firm input substitution and within-industry compositional changes.¹⁷ 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, the 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.

3 Data

The vintage capital model is estimated using panel data from 19 OECD countries between 1990 and 2005 separately for five manufacturing industries - food,

¹⁵We have also estimated Allen's and Morishima's partial elasticities of substitution. Because these elasticities have less straightforward interpretation (Fronzel 2004), and can be directly inferred from estimated cross-price elasticities, their estimates are not reported.

¹⁶To calculate these elasticities one needs the estimates of translog function (12), which is estimated separately.

¹⁷Sorting out between these effects is however beyond the scope of this paper.

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).¹⁸ 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.¹⁹ Due to data limitations on capital stocks the analysis was not possible for other sectors as well as 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 Jorgenson et al. (1987) and Jorgenson et al. (2005).²⁰ The EU KLEMS database comprises data on production inputs, labor and capital input prices²¹, and output at the industry level for the European Union, the United States, the Republic of 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 restrictive, this is a standard assumption made in inter-country studies of energy demand. To the best of our knowledge there is no study addressing this issue, and doing so is beyond the scope of this paper. However, we 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.²² A full list of variables, countries and the descriptive statistics for the final dataset are shown in Tables A.1-A.7 (technical appendix, section A.2).

Based on the estimates from Timmer et al. (2007, Appendix 1) we set economic depreciation rates at 11 percent in the food processing industry, and 10 percent in all other industries. Because we do not have estimates for the rate for

¹⁸To preserve space in the text these industries are further referred to as food processing, pulp and paper products, petrochemical, metals, and electrical industries.

¹⁹For 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.

²⁰For more details, see Timmer et al. (2007) and O’Mahony and Timmer (2009).

²¹Data on the price of capital services were not available for some countries. For these countries following Andrikopoulos et al. (1989) and Cho et al. (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.

²²This 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.

revenues accumulating at time t , R_t , we set it to 0.95. We performed sensitivity analysis assuming different values of R_t , and the results were not significantly different.

The EU KLEMS dataset does not include information on input prices for energy and materials. We use the International Energy Agency (IEA) *Energy Prices and Taxes* database to extract the data on end-use prices for key fuels used in the OECD manufacturing industries.²³ We also use the IEA *World Energy Statistics and Balances* database to obtain industrial fuel consumption data. We then 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. To examine the robustness of our energy price calculations we calculate industrial fuel expenditure using data from the IEA databases and compare it with industrial energy expenditure reported in the EU KLEMS database. Correlation between the two series was close to 0.99 for the manufacturing sector aggregate. Unfortunately, these correlations were considerably lower for individual industrial sectors, which indicates poorer correspondence between IEA and EU KLEMS at less aggregate levels. We therefore employ energy price data for the manufacturing sector aggregate.

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 the 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 the base year, and converted into U.S. dollars at nominal exchange rates.²⁴

Figure 1 shows the average energy prices in the manufacturing sector across OECD countries in 2005. The highest energy prices are in Italy, Ireland, Japan and Sweden, and the lowest are in Australia, the 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 (International Energy Agency

²³Specifically, we consider the following energy products - oil and petroleum 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).

²⁴We 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.

2008). This may reflect constraints on national energy tax policies, which are major drivers of international energy price differences,²⁵ posed by countries' concerns to maintain their international competitiveness in the manufacturing sector (Brack et al. 2000).

4 Results of Estimation of the Vintage Capital Model

The empirical estimates of stochastic specification (3), (7), (14), and (15) applied separately to each of the five industries over the period 1990 - 2005 across 19 OECD countries are presented in Tables A.8-A.12 (technical appendix, section A.2). We present the results for both the vintage capital model, and the dynamic factor model of energy demand of Pindyck and Rotemberg (1983), in which the indices of the 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 the input efficiency

²⁵For 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).

of capital stock from the vintage capital model. Tables A.13-A.17 (technical appendix, section A.2), demonstrate the variation of estimated elasticities across countries. Estimated cross-price elasticities of other input demands are presented in Tables A.18 and A.19, (technical appendix, section A.2). Figures A.1-A.5 (technical appendix, section A.3) show the values of the calculated indices of input efficiency of capital stock.

The regression results show that the vintage capital model generally provides a better explanation of energy demand. The R-squared values are higher for the vintage capital model (Tables A.8-A.12, technical appendix, section A.2). The likelihood ratio test indicates that the dynamic factor demand model restriction of input efficiencies of capital stock being equal to 1 is rejected at the 1 percent level of significance for all five industry estimates.

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

Sector	η_l		η_{ee}		η_{mm}	
	VCM	P-R	VCM	P-R	VCM	P-R
Chemical, Rubber, Plastics and Fuel Products	-0.91*** (0.10)	-0.90*** (0.09)	-0.21 (0.57)	-0.48* (0.25)	-0.43*** (0.09)	-0.45*** (0.09)
Electrical and Optical Equipment	-0.88*** (0.16)	-0.87*** (0.15)	-0.66*** (0.17)	-0.38 (0.32)	-0.36*** (0.09)	-0.34*** (0.09)
Food Products, Beverages, and Tobacco	-1.16*** (0.14)	-1.00*** (0.10)	-0.34** (0.17)	-0.41*** (0.15)	-0.22*** (0.05)	-0.22*** (0.05)
Basic Metals and Fabricated Metal Products	-1.17*** (0.21)	-1.10*** (0.19)	-0.86*** (0.01)	-1.05*** (0.05)	-0.43*** (0.07)	-0.44*** (0.07)
Pulp, Paper, Paper Products, Printing and Publishing	-0.83*** (0.11)	-0.79*** (0.10)	-0.55*** (0.18)	-0.54*** (0.19)	-0.46*** (0.07)	-0.45*** (0.07)

Notes. η_l , η_{ee} , and η_{mm} denote respectively own price elasticities of labor, energy, and materials demand.

VCM: Vintage Capital Model, P-R: Pindyck and Rotemberg (1983) Model. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

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 countries and sectors have the expected signs and reasonable magnitudes. The estimated elasticities did not have the expected sign in some countries, where input cost shares were close to zero (see Tables A.13-A.17, technical appendix, section A.2). This is a well-known problem documented in previous studies using a translog model (Urga and Walters 2003). However, in almost all cases, the elasticities were not statistically different from zero. Based on the vintage capital model estimates, own-price elasticity of labor demand varies between -0.83 and -1.17, own-price elasticity of energy demand varies between -0.21 and

-0.86, and own-price elasticity of materials demand varies between -0.22 and -0.46. These results fall within the range of magnitudes of elasticities surveyed in Barker et al. (1995) and the estimates from several recent studies on energy demand in the OECD manufacturing sector.²⁶ The vintage capital model and the dynamic factor demand model yield comparable estimates for labor and materials demand, and different estimates for energy demand. The estimated elasticities of energy demand based on the vintage capital model are higher for the electrical industry, and smaller for the petrochemical, metals, and food processing industries. The estimated elasticities of energy demand for the pulp and paper industry are of comparable magnitudes across the two models.

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

Sector	η_{el}		η_{em}		η_{eK}		η_{eY}	
	VCM	P-R	VCM	P-R	VCM	P-R	VCM	P-R
Chemical, Rubber, Plastics and Fuel Products	0.08 (0.18)	0.26*** (0.08)	-0.31 (0.93)	-0.20 (0.79)	0.14 (0.28)	0.12 (0.43)	1.03*** (0.27)	1.21*** (0.24)
Electrical and Optical Equipment	0.15 (0.15)	0.21* (0.12)	1.43*** (0.46)	0.48*** (0.10)	0.53 (0.39)	0.17 (0.29)	0.55** (0.27)	0.81*** (0.21)
Food Products, Beverages, and Tobacco	0.43*** (0.06)	0.31*** (0.05)	0.56*** (0.06)	0.56*** (0.06)	-0.27 (0.31)	-0.29 (0.31)	0.42 (0.30)	0.65*** (0.22)
Basic Metals and Fabricated Metal Products	0.44*** (0.09)	0.61*** (0.13)	0.50*** (0.08)	0.39*** (0.11)	-0.20 (0.38)	0.09 (0.38)	1.00*** (0.23)	1.06*** (0.23)
Pulp, Paper, Paper Products, Printing and Publishing	0.82*** (0.26)	0.58*** (0.14)	0.29* (0.17)	0.44*** (0.10)	0.21 (0.42)	0.13 (0.38)	1.10** (0.43)	1.19*** (0.25)

Notes. η_{el} , η_{em} , η_{eK} , and η_{eY} denote elasticities of energy demand with respect to respectively wages, materials' prices, capital and output. VCM: Vintage Capital Model, P-R: Pindyck and Rotemberg (1983) Model. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 2 shows the estimated elasticities of energy demand with respect to real wages and materials prices, capital stock, and output. As expected, labor is a substitute for energy across all industries. Materials and energy inputs are substitutes across all industries, except for the petrochemical industry. The estimated cross-price elasticity of energy demand with respect to materials prices is negative for the petrochemical industry, implying complementarity between energy and materials, however it is not statistically significant. The estimated elasticities of energy demand with respect to change in capital stock indicate that, in the short-run, energy and capital are complements in the petrochemical, pulp and paper, and electrical industries, and are substitutes in the food

²⁶Enevoldsen et al. (2007) energy demand elasticity estimates range between -0.44 and -0.38 for 15 industrial sectors in Norway, Denmark, and Sweden. Agnolucci (2009) estimates a price elasticity of -0.64 for the German and British industrial sectors over the period 1978-2004. Adeyemi and Hunt (2007) model asymmetric energy demand response for 15 OECD countries over the period 1962-2003, and find elasticities between -0.68 (price recoveries) and -0.30 (price cuts).

processing and metals industries. However, these elasticities are not statistically significant from zero. These results indicate that estimated differences in cross-price elasticities of input demand from previous empirical studies (Thompson and Taylor 1995) can be, in part, attributed to aggregation across different industry samples. The estimated elasticities of energy demand with respect to changes in output are close to one in the energy-intensive petrochemical, metals, and pulp and paper industries. This result suggests that, in the short-run, increases in output result in proportional increases in energy consumption. The estimated elasticities of energy demand with respect to changes in output are less than one in the food processing and electrical industries. This result indicates that in these industries there will be substitution away from energy as output increases.

Tables A.18 and A.19 (technical appendix, section A.2) show the estimated elasticities of labor and materials demand with respect to real wages, energy, and materials prices, capital stock, and output. The demand for labor input declines with growth in capital stock and energy prices, and increases with growth in materials prices. It also increases in a greater proportion than other inputs to production as output grows. The demand for materials input declines as capital stock grows, and increases with growth in real wages and energy prices.

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. The estimated elasticities are (with few exceptions) statistically significant, and vary significantly across sectors. The estimated elasticity of labor input efficiency with respect to wages varies from 0.16 to 1.24 with the highest investment response in the food processing industries. The estimated elasticity of energy input efficiency with respect to energy prices ranges between 0.015 and 1.1. 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.).²⁷

The investment response to energy prices is strong in the petrochemical and metals industries, and is close to zero in the pulp and paper products and electrical industries. A possible explanation for the observed differences in estimated elasticities of energy input efficiency across sectors is the higher

²⁷More detailed comparison of estimated elasticities to quoted studies is difficult, because all those studies use different econometric methodologies and datasets.

energy intensity of the petrochemical and metals industries. The pulp and paper products industry is also energy intensive, but investment volumes have been small (therefore also investment response to energy prices) in the observation period. The pulp and paper products industry also has the highest standard error of estimated elasticities, making further comparisons difficult.

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

Sector	ϕ^l	ϕ^e	ϕ^m	ζ
Chemical, Rubber, Plastics and Fuel Products	0.68*** (0.05)	1.10*** (0.13)	0.03 (0.10)	0.03** (0.01)
Electrical and Optical Equipment	0.16*** (0.04)	0.02 (0.08)	1.19*** (0.18)	0.019 (0.01)
Food Products, Beverages, and Tobacco	1.24*** (0.05)	0.50*** (0.12)	0.02 (0.24)	0.023* (0.01)
Basic Metals and Fabricated Metal Products	0.90*** (0.05)	1.08*** (0.12)	0.57** (0.24)	0.024* (0.01)
Pulp, Paper, Paper Products, Printing and Publishing	0.62*** (0.03)	0.02 (0.27)	0.85** (0.33)	0.038*** (0.01)
Change in Input Prices in OECD Manufacturing, 1990-2005	22.33	16.4	-6.29	

Notes. ϕ^l , ϕ^e , and ϕ^m denote elasticities of input efficiency with respect to wages, energy and materials' prices. ζ denotes the rate of exogenous technological change.

Standard errors (in parentheses) are based on bootstrap simulations. *** p<0.01, ** p<0.05, * p<0.1.

The estimated elasticity of materials efficiency with respect to materials prices varies from 0.57 to 1.19 in the electrical, pulp and paper products and metals industries, and is close to zero in the petrochemical 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 the petrochemical and food processing industries would support the hypothesis of asymmetric investment demand response to input prices (see e.g., Borenstein et al. 1997, Peltzman 2000, Gately and Huntington 2002). The parameter ζ is positive in all industries, with further inter-industry comparisons difficult to make due to the high standard error of the estimates. The average growth varies between 0.019 and 0.038 across industries, indicating that autonomous technological change increases the input efficiency of capital stock.²⁸ These results are comparable

²⁸Estimate of annual exogenous technological change in the pulp and paper products industries is 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 econometric analysis using a detailed engineering description of production activities and of the innovations to them (Kopp and Smith 1985), and are beyond the scope of this paper.

to Sue Wing's (2008) estimates of energy efficiency elasticities with respect to autonomous technology improvements in the range of -0.03 to 0.08.²⁹

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

Figure 2 shows the estimated effect of energy prices and the exogenous technological change on the efficiency of energy input based on the example of the U.S. manufacturing industries. Between 1990 and 2005 the energy efficiency of capital stock increased in all sectors, ranging from 17% in the electrical industry to 32% in the pulp and paper industry. In less energy-intensive sectors (see Tables A.3 - A.7, technical appendix, section A.2.), such as the pulp and paper, and electrical industries, more than 90 percent of energy efficiency improvements are attributable to exogenous technological change. In more energy-intensive industries the contribution of energy prices is larger. In the petrochemical and metals industries, energy prices respectively account for 17 and 26 percent of total improvements in energy efficiency. However, even in these industries the relative effect of exogenous technological change is more significant. These results are consistent with Greenwood et al. (1997), who find that investment-specific technological change accounts for the major part of efficiency growth.

²⁹The opposite sign is used here as Sue Wing (2008) reports the estimates of energy *intensity* elasticities with respect to autonomous technology improvements.

As we pointed out in previous sections of this study, the important assumption necessary to estimate our model is that assets depreciate geometrically at a constant rate. To understand the implications of this assumption for our empirical results, we also conducted sensitivity analysis, imposing 5% and 15% rates of depreciation in addition to the initial value of 10%. The results of the sensitivity analysis are summarized in the technical appendix, Tables A.20-A.22. The estimated elasticities are robust to these perturbations. The estimates of own-price elasticities of input demand and cross-price elasticities of energy demand are insensitive to changes in the assumed rate of asset depreciation. The estimates of elasticities of input efficiency with respect to input prices, and the estimated rate of exogenous technological change are little changed for the electrical and pulp and paper industries. For the other three industries we see that the elasticities of input efficiency with respect to input prices increase as the depreciation rate declines. This result is consistent with our theoretical framework - longer life of capital stocks raises their ex-post replacement costs and induces stronger ex-ante investment in more efficient capital. The estimated rate of exogenous technological change also changes, declining for the petrochemical and metals industries, and increasing for the food processing industry. However, given the large standard errors of these estimates, we cannot conclude that these differences are significant in the statistical sense.

Another important assumption affecting the robustness of our estimates is that expectations of input prices are based on their current prices (and that future price developments are random). In the earlier section we presented a number of arguments in support of this assumption. If instead the market participants' expectations of input prices were determined by the long-term equilibrium path, current prices should not affect their investment choices. Correspondingly, the respective elasticity estimates should be close to zero. However, we do obtain significant estimates for the response of investment to energy prices, at least for three industries. Therefore, energy price expectations seem to vary with current energy prices. These expectations might only vary over the short term with subsequent reversion to a long term trend. In this case our investment elasticity estimates should be interpreted as the lower bounds to their actual absolute values.

5 Simulated Effects of a Carbon Tax

The results of the vintage capital model indicate that energy-price induced improvements in capital stock can be significant in determining the future energy efficiency of production. Thus 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 an unanticipated greenhouse gas emissions tax on energy consumption. Specifically, we utilize the model of equations (3), (7), (12), (14), and (15) to simulate the effect of a hypothetical carbon dioxide emissions tax implemented in 2006 (the first year after sample period) for two cases of the petrochemical and the electrical industries. Table 1 shows that both industries do respond to energy price increases in the short run. However, the longer term price-induced investment response is non-trivial in the former industry (as shown in Table 3, and Figure 2 above), while it is close to zero in the latter. To minimize the impact of cross-country differences for the purposes of illustration we are focus on a particular country - the United Kingdom.

We assume that all input prices, except for the energy price, and output remain at their 2005 levels (e.g. $\Delta Y_{i,t} = \Delta w_{i,t}^{j=k,l,m} = 0, t > 2005$). In the counterfactual scenario, we assume there is a \$30 tax per ton of emitted greenhouse gas. Using the data for the sector fuel consumption in the UK petrochemical and electrical industries, which we obtain from the UK Department of Energy and Climate Change publication *Energy Consumption in the United Kingdom*, we find that one ton of the fuel mix emits, respectively, 2.44 and 2.2 tons of the CO₂ in the petrochemical and electrical industries (computation details are available in Tables A.23 and A.24, technical appendix, section A.2).³⁰ We assume that energy-using capital stock in both manufacturing sectors is idiosyncratic in fuel mix, so no interfuel substitution is possible.³¹ Then, a \$30 tax per ton of greenhouse gas for these industries corresponds to an additional mark-up of \$73 and \$66 per *toe*, or a 17 and 11 percent increase in energy input prices.

³⁰The 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* $\approx 40 \times 10^6$ BTU).

³¹Steinbuks (2012) estimated econometric model of interfuel substitution for 15 energy-intensive UK manufacturing sectors between 1990 and 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 (Woodland 1993, Bjorner and Jensen 2002).

Carrying out the simulations involves the recursive solution to the system of non-linear equations (3), (7), (12), (14), and (15) with seven endogenous variables ($x_t^l, x_t^k, x_t^e, x_t^m, \gamma^l, \gamma^e$, and γ^m). Simulations are run in the General Algebraic Modeling System (GAMS), a high-level modeling system for mathematical programming problems, employing the non-linear equation solver CONOPT (Drud 1996).

5.1 Petrochemical Industry

Figures 3 and 4 illustrate simulation results for the U.K. petrochemical industry. Both figures show percentage changes in capital, labor, energy, and materials inputs over time.³² These percentage changes are relative to the base year 2005, at which time we assume that all factor inputs are in steady-state equilibrium.

Figure 3: Effect of \$30 Carbon Tax on Energy Consumption in the U.K. Petrochemical Industry (Assuming no Price Induced Investment Response)

Figure 3 shows the effect of an unanticipated 17 percent increase in the energy input price, assuming no investment response to energy prices (e.g., $\phi^e = 0$). Under this assumption changes in energy efficiency in capital stock

³²Figures 3 and 4 show somewhat erratic fluctuations along the optimal time paths for capital, labor, energy, and materials inputs. These small fluctuations reflect optimization errors of a non-linear solver and should be ignored.

are purely exogenous (at the estimated rate $\zeta = 0.026$), and the model dynamics become similar to those in the dynamic factor demand model of Pindyck and Rotemberg (1983). The major impact is a significant drop in the use of both capital and energy (which are complements in the petrochemical industry). Energy, a flexible factor, falls by 10.3 percent in the first period. Energy consumption then increases, reflecting the rebound effect from exogenous energy efficiency improvements (Khazzoom 1980), but decreases in subsequent periods in conjunction with the drop in the use of capital. By 2020 energy consumption falls by 8.1 percent. Because of adjustment costs, capital falls gradually. Similar to the model of Pindyck and Rotemberg (1983), the adjustment of capital stock is fairly rapid; three-fourths of the total drop in capital occurs in seven years, so that substantial net disinvestment occurs during the first two or three years. In the absence of a price-induced investment response, the increase in the energy input price results in a substitution of energy and capital for labor and materials. The consumption of labor and materials inputs increases by 2.2 and 5.5 percent, respectively, by 2020.

Figure 4: Effect of \$30 Carbon Tax on Energy Consumption in the U.K. Petrochemical Industry (Assuming Price Induced Investment Response)

Figure 4 shows the effect of the same increase in the energy input price, now allowing for both exogenous and endogenous investment response to en-

ergy prices (e.g., $\phi^e = 1.1$ and $\zeta = 0.026$). Similar to the model without the investment response to energy prices, there is a significant drop in the use of energy, which falls by 10.3 percent in the first period. However, the decline in capital stock is much less pronounced. The capital stock declines by 2.6 percent in 2006, and falls to its minimum of 4.8 percent in 2009. In the medium run, the capital stock increases with rising demand for energy-efficient capital. By 2020 the capital stock returns to its level preceding the increase in energy prices. On the contrary, energy consumption continues to decline in the medium run as capital stock becomes more energy efficient. Overall, our simulations show that a 17 percent increase in the energy input price due to the greenhouse gas tax lowers energy consumption by 13.1 percent by 2020. This implies a composite (operational and investment) elasticity of energy demand of about -0.8. These results indicate that energy and climate policies that increase energy costs may result in significant reductions in energy use without compromising sector-level investment in the industries with large price-induced investment response.

5.2 Electrical Industry

As our estimated elasticity of energy efficiency with respect to energy prices is close to zero for the electrical industry, simulation results with and without energy price induced investment responses do not differ much. Figure 5 shows the simulation results for both scenarios assuming an unanticipated 11 percent increase in energy input prices (induced by the GHG emissions tax). The major impact of the energy price increase is a significant drop in the use of energy and materials (which are complements according to our estimates for the electrical industry). Energy consumption falls by 9.2 percent whereas materials consumption declines by 3.2 percent in the first period. The consumption of both inputs subsequently increases, reflecting exogenous improvements in energy- and materials-using technologies. By 2020 the consumption of energy falls by 7.9 percent (implying a medium-term energy demand elasticity of about -0.7), and the consumption of materials declines by 0.8 percent compared to their 2005 levels. The capital stocks are little changed, reflecting a small degree of substitution between energy and capital in the electrical industry. The increase in the energy input price results in a substitution of labor for energy. By 2020 the consumption of labor increases by 2.7 percent compared to its 2005 levels.

Similar to the petrochemical industry, our results indicate that an increase in energy prices may result in significant reductions in energy use without com-

promising sector-level investment. In the case of the electrical industry, this finding is driven by an entirely different channel - weak complementarity between energy and capital.

Figure 5: Effect of \$30 Carbon Tax on Energy Consumption in the U.K. Electrical Industry

6 Concluding Remarks

We have expanded the traditional estimation of energy, materials, and labour responses to input price changes by including vintages of the capital stock. The model accounts for transitional dynamics of capital in response to energy prices, and allows for more efficient use of inputs to production 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 five 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 dynamic factor demand model of energy demand is rejected for all industries in the sample. The estimated elasticities of energy input efficiency with respect to energy prices vary between 0.015 and 1.1. The investment response to energy prices thus varies significantly across manu-

facturing industries, being significant in some (typically more energy-intensive) industries and negligible in others. We also find substantial autonomous improvements in the energy efficiency of capital stock over recent decades, ranging between 2 and 4 percent per annum. 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 substantial reductions in energy use in energy intensive sectors. The results of our counterfactual simulations indicate that an increase in energy prices results in a considerable decline in energy use. The combined operational and investment own-price elasticity of energy demand based on these simulations is between 0.7 and 0.8. At the same time, the reductions in capital stock in the medium-run are negligible. In the petrochemical industry, the decline in capital stock resulting from short-run energy-capital complementarity is offset by increasing demand for more energy-efficient capital. In the electrical industry, energy-using capital stocks are little changed because of weak complementarity between energy and capital.

In further work it will be interesting to address the 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 a larger number of industries; and (3) including non-OECD countries in the data set.

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Technical Appendix

A.1 Derivation of Equation (5)

This section demonstrates that equation (5) is consistent with the profit maximization (cost minimization) choice of a firm that faces a technology cost function. The firm's choice of production technology depends on the input cost savings from a new technology and the costs of setting up the new technology. Let us assume that the index of input efficiency of a capital vintage in period $q - 1$ equals to $\frac{1}{(1-\zeta)^{q-1}}$, where the parameter ζ captures the exogenous rate of technological change. If in period q the firm installs the same technology, based on equation (2) the cost of input services to the production function in period $q + 1$, $F_{i,q+1}^j$, will be given by

$$F_{i,q+1}^j = E \left(w_{i,q+1}^j \tilde{x}_{i,q+1}^j \right) = (1 - \zeta)^q E \left(w_{i,q+1}^j x_{i,q+1}^j \right), \quad (22)$$

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 $\gamma_{i,q}^j$, based on equation (2) the cost of input services to the production function in period $q + 1$, $F_{i,q+1}^{'j}$, will be given by:

$$F_{i,q+1}^{'j} = E \left(w_{i,q+1}^j \tilde{x}_{i,q+1}^j \right) = \frac{(1 - \zeta)^q}{\gamma_{i,q}^j} E \left(w_{i,q+1}^j x_{i,q+1}^j \right) < F_{i,q+1}^j. \quad (23)$$

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 $\gamma_{i,q}^j$ can be represented by a continuous, twice-differentiable, and convex cost function $g \left(\gamma_{i,q}^j \right)$.

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

$$\pi_{i,t}^j = \left(1 - \frac{1}{\gamma_{i,q}^j} \right) (1 - \zeta)^q E \left(w_{i,q+1}^j x_{i,q+1}^j \right) - g \left(\gamma_{i,q}^j \right) E \left(x_{i,q+1}^j \right). \quad (24)$$

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

$$E\left(x_{i,q}^j\right) = \xi\left(w_{i,q}^j\right), \quad (25)$$

and that the input prices exhibit a random walk³³, so that current input prices are the best predictors of future input costs:

$$E\left(w_{i,q+1}^j\right) = w_{i,q}^j, \quad (26)$$

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

$$g\left(\gamma_{i,q}^j\right) = \frac{h}{\varphi}\left(\gamma_{i,q}^j\right)^\varphi, \quad (27)$$

where h and φ are positive constants determining the curvature of the cost function. Using equations (25), (26), and (27) in equation (24), and maximizing the resulting expression with respect to $\gamma_{i,q}^j$ yields the closed form solution for the firm's optimal index of input efficiency of capital vintage q :

$$\gamma_{i,q}^{*j} = (1 - \zeta)^q \left(\frac{w_{i,q}^j}{h}\right)^{\frac{1}{\varphi+1}}. \quad (28)$$

Let $h = \bar{w}^j$, where $\bar{w}^j = \frac{\sum_{i=1}^n \sum_{t=1}^T w_{i,t}^j}{nT}$ is the average price of input j across countries and all time periods.³⁴

Then equation (28) becomes:

$$\gamma_{i,q}^{*j} = (1 - \zeta)^q \left(\frac{w_{i,q}^j}{\bar{w}^j}\right)^{-\phi^j}, \quad (29)$$

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 (29) 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 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

³³This assumption is consistent with evidence found in empirical studies (see e.g., Ashenfelter and Card 1982, Pindyck 1999).

³⁴Note that because $\bar{w}^j$ is a constant, the cost of installing new technology given by equation (27) does not really depend on input prices. It is just a (somewhat arbitrary chosen) scaling factor.

choosing more efficient technologies for the production process (see e.g., Khaz-zoom 1980, Train 1986).

A.2 Tables

Table A.1: List of Variables

Variable	Description	Units
s_l	Share of Labor in Total Variable Cost	
s_e	Share of Energy in Total Variable Cost	
s_m	Share of Materials in Total Variable Cost	
x^k	Sector Capital Stock	\$ million
Y	Sector Output	\$ million
w_l	Average Wage	\$ / hour
w_k	Average Rental Price of Capital	percent
w_e	Average Price of Energy	\$ / toe
w_m	Average Price of Materials	\$ / metric ton
INT	Sector Energy Intensity	toe / \$1000

Note. All currency values are in real terms deflated to 1995 base year.

Table A.2: 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 A.3: Descriptive Statistics (1995): Chemical, Rubber, Plastics and Fuel Products

Country	s_l	s_e	s_m	x^k	Y	w_l	w_k	w_e	w_m	INT
Australia	0.21	0.26	0.53	17620	22689	15.0	0.13	332.7	842.1	0.59
Austria	0.30	0.12	0.58	17459	14163	23.7	0.11	406.7	1153.1	0.22
Belgium	0.24	0.18	0.58	47484	42620	32.7	0.11	327.5	1221.2	0.39
Denmark	0.35	0.19	0.47	236165	10480	26.4	0.12	354.5	1048.7	0.42
Finland	0.22	0.22	0.56	141839	10145	25.2	0.13	411.4	1064.0	0.52
France	0.30	0.20	0.50	12565	143280	26.5	0.12	314.2	1219.7	0.50
Germany	0.21	0.30	0.49	12069	238281	32.1	0.10	432.9	1394.4	0.30
Greece	0.21	0.43	0.36	3384	7076	7.6	0.21	354.2	1182.9	0.95
Ireland	0.18	0.23	0.58	93105	12382	14.8	0.12	372.6	1709.9	0.08
Italy	0.21	0.07	0.71	34752	118146	17.4	0.18	405.4	1296.2	0.44
Japan	0.24	0.10	0.67	1840447	527805	26.2	0.07	729.3	1162.5	0.08
Korea	0.18	0.34	0.48	74236	89309	6.4	0.16	277.5	1077.9	0.92
Luxembourg	0.26	0.03	0.71	2523	1482	29.3	0.11	360.6	1709.5	0.06
Netherlands	0.17	0.26	0.57	77229	52757	26.1	0.11	333.8	1281.0	0.57
Portugal	0.16	0.32	0.52	5666	8168	6.0	0.16	308.8	1134.9	0.81
Spain	0.26	0.26	0.48	26172	59174	16.3	0.13	318.6	1226.9	0.63
Sweden	0.23	0.29	0.47	59809	17789	22.1	0.15	327.7	947.8	0.48
United Kingdom	0.28	0.19	0.52	116519	110267	18.3	0.13	296.8	1036.1	0.48
United States	0.29	0.29	0.42	1016017	650382	24.3	0.11	262.8	1313.4	0.72
OECD-19	0.24	0.23	0.54	201845	112442	20.9	0.13	364.6	1211.7	0.48

Table A.4: Descriptive Statistics (1995): Electrical and Optical Equipment

Country	s_l	s_e	s_m	x^k	Y	w_l	w_k	w_e	w_m	INT
Australia	0.35	0.03	0.62	4852	7667	15.0	0.13	332.7	842.1	0.06
Austria	0.43	0.01	0.56	11084	12074	23.7	0.11	406.7	1153.1	0.03
Belgium	0.38	0.01	0.61	9911	10979	32.7	0.11	327.5	1221.2	0.02
Denmark	0.46	0.02	0.53	65033	6490	26.4	0.12	354.5	1048.7	0.02
Finland	0.32	0.02	0.67	64000	11699	25.2	0.13	411.4	1064.0	0.01
France	0.36	0.01	0.63	6069	83511	26.5	0.12	314.2	1219.7	0.04
Germany	0.24	0.01	0.75	12213	171027	32.1	0.10	432.9	1394.4	0.03
Greece	0.26	0.03	0.71	718	1276	7.6	0.21	354.2	1182.9	0.07
Ireland	0.32	0.02	0.66	28423	12896	14.8	0.12	372.6	1709.9	0.01
Italy	0.16	0.01	0.84	17659	61458	17.4	0.18	405.4	1296.2	0.05
Japan	0.33	0.02	0.65	1175540	559964	26.2	0.07	729.3	1162.5	0.02
Korea	0.22	0.02	0.75	61076	85829	6.4	0.16	277.5	1077.9	0.06
Luxembourg	0.41	0.01	0.58	195	200	29.3	0.11	360.6	1709.5	0.03
Netherlands	0.36	0.01	0.63	8984	20742	26.1	0.11	333.8	1281.0	0.02
Portugal	0.19	0.01	0.80	2776	4934	6.0	0.16	308.8	1134.9	0.02
Spain	0.31	0.01	0.68	11794	23726	16.3	0.13	318.6	1226.9	0.05
Sweden	0.32	0.02	0.65	21009	18037	22.1	0.15	327.7	947.8	0.01
United Kingdom	0.31	0.01	0.67	69535	74476	18.3	0.13	296.8	1036.1	0.04
United States	0.43	0.01	0.55	749067	542450	24.3	0.11	262.8	1313.4	0.04
OECD-19	0.32	0.02	0.66	122102	89970	20.9	0.13	364.6	1211.7	0.03

Table A.5: Descriptive Statistics (1995): Food Products, Beverages, and Tobacco

Country	s_l	s_e	s_m	x^k	Y	w_l	w_k	w_e	w_m	INT
Australia	0.21	0.03	0.76	30392	34496	15.0	0.13	332.7	842.1	0.06
Austria	0.27	0.03	0.70	16733	16313	23.7	0.11	406.7	1153.1	0.05
Belgium	0.19	0.03	0.79	21560	31772	32.7	0.11	327.5	1221.2	0.06
Denmark	0.26	0.04	0.70	145553	20852	26.4	0.12	354.5	1048.7	0.05
Finland	0.19	0.03	0.78	92348	11059	25.2	0.13	411.4	1064.0	0.04
France	0.19	0.02	0.79	12842	137949	26.5	0.12	314.2	1219.7	0.07
Germany	0.21	0.02	0.77	9019	170822	32.1	0.10	432.9	1394.4	0.07
Greece	0.18	0.02	0.80	5014	13943	7.6	0.21	354.2	1182.9	0.05
Ireland	0.20	0.03	0.77	30041	15120	14.8	0.12	372.6	1709.9	0.04
Italy	0.17	0.02	0.81	16162	96923	17.4	0.18	405.4	1296.2	0.05
Japan	0.29	0.02	0.69	1143357	376455	26.2	0.07	729.3	1162.5	0.02
Korea	0.15	0.02	0.83	20561	49716	6.4	0.16	277.5	1077.9	0.06
Luxembourg	0.28	0.02	0.69	799	639	29.3	0.11	360.6	1709.5	0.05
Netherlands	0.15	0.02	0.83	53015	55076	26.1	0.11	333.8	1281.0	0.04
Portugal	0.12	0.01	0.86	6336	13024	6.0	0.16	308.8	1134.9	0.04
Spain	0.20	0.02	0.78	10661	76792	16.3	0.13	318.6	1226.9	0.04
Sweden	0.18	0.02	0.81	52200	16001	22.1	0.15	327.7	947.8	0.04
United Kingdom	0.24	0.03	0.74	78211	96897	18.3	0.13	296.8	1036.1	0.07
United States	0.23	0.02	0.75	654066	457682	24.3	0.11	262.8	1313.4	0.05
OECD-19	0.21	0.02	0.77	126256	89028	20.9	0.13	364.6	1211.7	0.05

Table A.6: Descriptive Statistics (1995): Basic Metals and Fabricated Metal Products

Country	s_l	s_e	s_m	x^k	Y	w_l	w_k	w_e	w_m	INT
Australia	0.23	0.06	0.70	33712	30715	15.0	0.13	332.7	842.1	0.15
Austria	0.35	0.06	0.59	17226	16236	23.7	0.11	406.7	1153.1	0.11
Belgium	0.27	0.07	0.66	19123	26954	32.7	0.11	327.5	1221.2	0.17
Denmark	0.40	0.06	0.54	76145	6980	26.4	0.12	354.5	1048.7	0.06
Finland	0.34	0.04	0.61	82963	11477	25.2	0.13	411.4	1064.0	0.10
France	0.39	0.03	0.58	5429	95603	26.5	0.12	314.2	1219.7	0.11
Germany	0.21	0.05	0.74	11240	181713	32.1	0.10	432.9	1394.4	0.11
Greece	0.26	0.12	0.62	1161	4340	7.6	0.21	354.2	1182.9	0.28
Ireland	0.27	0.05	0.68	67848	1576	14.8	0.12	372.6	1709.9	0.11
Italy	0.38	0.05	0.57	1471	108906	17.4	0.18	405.4	1296.2	0.10
Japan	0.28	0.05	0.68	891065	466726	26.2	0.07	729.3	1162.5	0.05
Korea	0.16	0.07	0.77	49579	77413	6.4	0.16	277.5	1077.9	0.20
Luxembourg	0.24	0.09	0.68	617	3088	29.3	0.11	360.6	1709.5	0.21
Netherlands	0.35	0.03	0.61	23712	21877	26.1	0.11	333.8	1281.0	0.07
Portugal	0.30	0.05	0.65	2601	5336	6.0	0.16	308.8	1134.9	0.13
Spain	0.27	0.05	0.68	22907	45777	16.3	0.13	318.6	1226.9	0.12
Sweden	0.32	0.06	0.63	50987	20544	22.1	0.15	327.7	947.8	0.10
United Kingdom	0.35	0.05	0.60	41290	67240	18.3	0.13	296.8	1036.1	0.14
United States	0.35	0.04	0.60	389500	366766	24.3	0.11	262.8	1313.4	0.12
OECD-19	0.30	0.06	0.64	94136	82067	20.9	0.13	364.6	1211.7	0.13

Table A.7: Descriptive Statistics (1995): Pulp, Paper, Paper Products, Printing and Publishing

Country	s_l	s_e	s_m	x^k	Y	w_l	w_k	w_e	w_m	INT
Australia	0.42	0.03	0.55	15391	15502	15.0	0.13	332.7	842.1	0.06
Austria	0.33	0.04	0.63	12284	10422	23.7	0.11	406.7	1153.1	0.07
Belgium	0.31	0.03	0.65	12272	11929	32.7	0.11	327.5	1221.2	0.08
Denmark	0.43	0.05	0.52	89714	6767	26.4	0.12	354.5	1048.7	0.03
Finland	0.34	0.03	0.63	43679	22378	25.2	0.13	411.4	1064.0	0.17
France	0.43	0.02	0.55	5308	60939	26.5	0.12	314.2	1219.7	0.07
Germany	0.23	0.10	0.67	33623	97837	32.1	0.10	432.9	1394.4	0.08
Greece	0.37	0.07	0.55	574	2511	7.6	0.21	354.2	1182.9	0.17
Ireland	0.32	0.04	0.64	23331	5482	14.8	0.12	372.6	1709.9	0.03
Italy	0.26	0.02	0.73	8475	42764	17.4	0.18	405.4	1296.2	0.07
Japan	0.40	0.03	0.56	462094	231808	26.2	0.07	729.3	1162.5	0.03
Korea	0.31	0.04	0.64	11917	22281	6.4	0.16	277.5	1077.9	0.12
Luxembourg	0.38	0.02	0.61	451	371	29.3	0.11	360.6	1709.5	0.03
Netherlands	0.39	0.02	0.58	24013	20733	26.1	0.11	333.8	1281.0	0.05
Portugal	0.25	0.07	0.68	6553	5241	6.0	0.16	308.8	1134.9	0.15
Spain	0.31	0.06	0.63	30609	26319	16.3	0.13	318.6	1226.9	0.08
Sweden	0.31	0.04	0.66	25052	22928	22.1	0.15	327.7	947.8	0.11
United Kingdom	0.42	0.02	0.57	58868	62542	18.3	0.13	296.8	1036.1	0.04
United States	0.46	0.03	0.51	438682	359368	24.3	0.11	262.8	1313.4	0.08
OECD-19	0.35	0.04	0.61	68573	54112	20.9	0.13	364.6	1211.7	0.08

Table A.8: Parameter Estimates: Chemical, Rubber, Plastics and Fuel Products

	VCM		P-R	
	coef.	s.e.	coef.	s.e.
Labor Share Equation: Wage	0.05***	(0.01)	0.02**	(0.01)
Labor Share Equation: Capital	0.08***	(0.02)	0.07***	(0.02)
Labor Share Equation: Energy Price	0.003	(0.01)	0.02**	(0.01)
Labor Share Equation: Materials Price	0.03***	(0.01)	0.02	(0.01)
Labor Share Equation: Output	-0.07***	(0.01)	-0.06***	(0.01)
Labor Share Equation: Time Trend	-0.003***	(0.0005)	-0.004***	(0.0005)
Labor Share Equation: Constant	0.3***	(0.005)	0.3***	(0.005)
Energy Share Equation: Wage	-0.02	(0.03)	0.005	(0.02)
Energy Share Equation: Capital	0.04	(0.03)	0.06*	(0.03)
Energy Share Equation: Energy Price	0.08***	(0.02)	0.04*	(0.02)
Energy Share Equation: Materials Price	-0.1***	(0.02)	-0.1***	(0.03)
Energy Share Equation: Output	0.03	(0.03)	0.01	(0.03)
Energy Share Equation: Time Trend	-0.001	(0.001)	0.00007	(0.001)
Energy Share Equation: Constant	0.3***	(0.01)	0.3***	(0.01)
Euler Equation for Capital: Adjustment Term	0.8***	(0.1)	0.9***	(0.1)
Euler Equation for Capital: Wage	1.5***	(0.2)	1.2***	(0.2)
Euler Equation for Capital: Capital	0.2	(0.3)	0.2	(0.3)
Euler Equation for Capital: Energy Price	0.8***	(0.2)	0.6***	(0.2)
Euler Equation for Capital: Materials Price	0.1	(0.2)	0.2	(0.2)
Euler Equation for Capital: Output	-2.6***	(0.2)	-2.6***	(0.2)
Euler Equation for Capital: Time Trend	0.05***	(0.009)	0.02***	(0.008)
Euler Equation for Capital: Constant	-2.2***	(0.09)	-2.2***	(0.08)
Number of observations	263		263	
Labor Share Equation: R^2	0.91		0.91	
Energy Share Equation: R^2	0.89		0.88	
Euler Equation for Capital Stock: R^2	0.95		0.94	
LR Test: $\phi_l = \phi_e = \phi_m = \zeta = 0$, χ_2 (pval)			36.73 (0.00)	

Notes. VCM: Vintage Capital Model. P-R: Pindyck and Rotemberg (1983) Model.
coef.: estimated coefficient. s.e.: standard error. *** p<0.01, ** p<0.05, * p<0.1

Table A.9: Parameter Estimates: Electrical and Optical Equipment

	VCM		P-R	
	coef.	s.e.	coef.	s.e.
Labor Share Equation: Wage	0.07***	(0.009)	0.06***	(0.009)
Labor Share Equation: Capital	0.05***	(0.01)	0.05***	(0.01)
Labor Share Equation: Energy Price	0.06***	(0.01)	0.06***	(0.01)
Labor Share Equation: Materials Price	-0.01	(0.02)	0.002	(0.01)
Labor Share Equation: Output	-0.09***	(0.009)	-0.09***	(0.009)
Labor Share Equation: Time Trend	-0.004***	(0.0007)	-0.006***	(0.0007)
Labor Share Equation: Constant	0.5***	(0.009)	0.5***	(0.007)
Energy Share Equation: Wage	-0.002*	(0.001)	-0.002	(0.001)
Energy Share Equation: Capital	0.009***	(0.002)	0.006***	(0.002)
Energy Share Equation: Energy Price	0.004**	(0.002)	0.008***	(0.002)
Energy Share Equation: Materials Price	0.010***	(0.003)	-0.002	(0.002)
Energy Share Equation: Output	-0.006***	(0.001)	-0.004***	(0.001)
Energy Share Equation: Time Trend	-0.0001	(0.0001)	-0.0001	(0.0001)
Energy Share Equation: Constant	0.02***	(0.001)	0.02***	(0.001)
Euler Equation for Capital: Adjustment Term	0.4**	(0.2)	0.3*	(0.2)
Euler Equation for Capital: Wage	0.4***	(0.1)	0.4***	(0.09)
Euler Equation for Capital: Capital	0.1	(0.1)	0.2	(0.1)
Euler Equation for Capital: Energy Price	0.03	(0.1)	-0.08	(0.1)
Euler Equation for Capital: Materials Price	-0.3*	(0.2)	0.04	(0.1)
Euler Equation for Capital: Output	-0.6***	(0.09)	-0.7***	(0.09)
Euler Equation for Capital: Time Trend	0.008	(0.007)	0.004	(0.008)
Euler Equation for Capital: Constant	-2.1***	(0.09)	-2.0***	(0.07)
Number of observations	263		263	
Labor Share Equation: R^2	0.93		0.93	
Energy Share Equation: R^2	0.79		0.77	
Euler Equation for Capital Stock: R^2	0.87		0.86	
LR Test: $\phi_l = \phi_e = \phi_m = \zeta = 0$, χ_2 (pval)		18.54 (0.00)		

Notes. VCM: Vintage Capital Model. P-R: Pindyck and Rotemberg (1983) Model.
coef.: estimated coefficient. s.e.: standard error. *** p<0.01, ** p<0.05, * p<0.1

Table A.10: Parameter Estimates: Food Products, Beverages, and Tobacco

	VCM		P-R	
	coef.	s.e.	coef.	s.e.
Labor Share Equation: Wage	0.07***	(0.01)	0.04***	(0.008)
Labor Share Equation: Capital	-0.004	(0.009)	0.008	(0.01)
Labor Share Equation: Energy Price	0.0009	(0.007)	0.007	(0.006)
Labor Share Equation: Materials Price	0.01	(0.007)	0.01*	(0.008)
Labor Share Equation: Output	-0.06***	(0.009)	-0.05***	(0.009)
Labor Share Equation: Time Trend	0.002***	(0.0003)	0.001***	(0.0003)
Labor Share Equation: Constant	0.2***	(0.004)	0.2***	(0.004)
Energy Share Equation: Wage	0.005	(0.004)	0.002	(0.003)
Energy Share Equation: Capital	-0.010***	(0.004)	-0.009**	(0.004)
Energy Share Equation: Energy Price	0.01***	(0.003)	0.01***	(0.002)
Energy Share Equation: Materials Price	-0.005*	(0.003)	-0.005	(0.003)
Energy Share Equation: Output	-0.01***	(0.004)	-0.01***	(0.003)
Energy Share Equation: Time Trend	0.0005***	(0.0001)	0.0003***	(0.0001)
Energy Share Equation: Constant	0.02***	(0.001)	0.02***	(0.001)
Euler Equation for Capital: Adjustment Term	0.9***	(0.2)	0.9***	(0.2)
Euler Equation for Capital: Wage	0.4***	(0.1)	-0.1	(0.08)
Euler Equation for Capital: Capital	0.01	(0.1)	-0.07	(0.1)
Euler Equation for Capital: Energy Price	-0.02	(0.07)	0.04	(0.06)
Euler Equation for Capital: Materials Price	0.06	(0.08)	0.2**	(0.08)
Euler Equation for Capital: Output	-0.4***	(0.1)	-0.2	(0.1)
Euler Equation for Capital: Time Trend	-0.009***	(0.003)	-0.008**	(0.003)
Euler Equation for Capital: Constant	-1.5***	(0.04)	-1.5***	(0.04)
Number of observations	263		263	
Labor Share Equation: R^2	0.96		0.96	
Energy Share Equation: R^2	0.72		0.71	
Euler Equation for Capital Stock: R^2	0.97		0.96	
LR Test: $\phi_l = \phi_e = \phi_m = \zeta = 0$, χ_2 (pval)	28.5 (0.00)			
Notes. VCM: Vintage Capital Model. P-R: Pindyck and Rotemberg (1983) Model.				
coef.: estimated coefficient. s.e.: standard error. *** p<0.01, ** p<0.05, * p<0.1				

Table A.11: Parameter Estimates: Basic Metals and Fabricated Metal Products

	VCM		P-R	
	coef.	s.e.	coef.	s.e.
Labor Share Equation: Wage	0.1***	(0.01)	0.1***	(0.01)
Labor Share Equation: Capital	0.06***	(0.01)	0.07***	(0.01)
Labor Share Equation: Energy Price	0.01	(0.01)	0.003	(0.010)
Labor Share Equation: Materials Price	-0.04***	(0.01)	-0.05***	(0.01)
Labor Share Equation: Output	-0.1***	(0.01)	-0.1***	(0.01)
Labor Share Equation: Time Trend	-0.002***	(0.0004)	-0.005***	(0.0004)
Labor Share Equation: Constant	0.4***	(0.006)	0.4***	(0.005)
Energy Share Equation: Wage	0.006	(0.007)	0.02**	(0.006)
Energy Share Equation: Capital	0.01*	(0.008)	0.02**	(0.008)
Energy Share Equation: Energy Price	0.004	(0.006)	-0.005	(0.005)
Energy Share Equation: Materials Price	-0.007	(0.008)	-0.01*	(0.007)
Energy Share Equation: Output	-0.004	(0.007)	-0.002	(0.006)
Energy Share Equation: Time Trend	-0.0003	(0.0003)	-0.0006***	(0.0002)
Energy Share Equation: Constant	0.04***	(0.004)	0.04***	(0.003)
Euler Equation for Capital: Adjustment Term	0.8***	(0.2)	0.8***	(0.2)
Euler Equation for Capital: Wage	0.9***	(0.1)	0.6***	(0.1)
Euler Equation for Capital: Capital	0.5***	(0.1)	0.6***	(0.1)
Euler Equation for Capital: Energy Price	0.04	(0.10)	0.08	(0.09)
Euler Equation for Capital: Materials Price	0.10	(0.1)	0.03	(0.1)
Euler Equation for Capital: Output	-0.9***	(0.10)	-0.8***	(0.10)
Euler Equation for Capital: Time Trend	0.007*	(0.004)	-0.01***	(0.004)
Euler Equation for Capital: Constant	-1.5***	(0.06)	-1.4***	(0.04)
Number of observations	263		263	
Labor Share Equation: R^2	0.95		0.95	
Energy Share Equation: R^2	0.72		0.73	
Euler Equation for Capital Stock: R^2	0.90		0.89	
LR Test: $\phi_l = \phi_e = \phi_m = \zeta = 0$, χ_2 (pval)		40.7 (0.00)		

Notes. VCM: Vintage Capital Model. P-R: Pindyck and Rotemberg (1983) Model.
coef.: estimated coefficient. s.e.: standard error. *** p<0.01, ** p<0.05, * p<0.1

Table A.12: Parameter Estimates: Pulp, Paper, Paper Products, Printing and Publishing

	VCM		P-R	
	coef.	s.e.	coef.	s.e.
Labor Share Equation: Wage	0.06**	(0.02)	0.05***	(0.02)
Labor Share Equation: Capital	0.02	(0.02)	0.01	(0.02)
Labor Share Equation: Energy Price	0.02	(0.02)	0.02	(0.01)
Labor Share Equation: Materials Price	-0.03	(0.02)	-0.03	(0.02)
Labor Share Equation: Output	-0.03*	(0.02)	-0.03*	(0.01)
Labor Share Equation: Time Trend	-0.0001	(0.0007)	-0.001	(0.0008)
Labor Share Equation: Constant	0.5***	(0.01)	0.5***	(0.008)
Energy Share Equation: Wage	0.02*	(0.008)	0.007	(0.006)
Energy Share Equation: Capital	0.02***	(0.007)	0.01**	(0.007)
Energy Share Equation: Energy Price	0.01**	(0.006)	0.01***	(0.005)
Energy Share Equation: Materials Price	-0.01	(0.008)	-0.005	(0.006)
Energy Share Equation: Output	-0.02***	(0.005)	-0.01***	(0.005)
Energy Share Equation: Time Trend	-0.00003	(0.0003)	-0.0003	(0.0003)
Energy Share Equation: Constant	0.03***	(0.004)	0.03***	(0.003)
Euler Equation for Capital: Adjustment Term	1.5***	(0.1)	1.6***	(0.1)
Euler Equation for Capital: Wage	0.9***	(0.3)	0.6***	(0.2)
Euler Equation for Capital: Capital	0.4*	(0.2)	0.3	(0.2)
Euler Equation for Capital: Energy Price	0.2	(0.2)	0.3*	(0.2)
Euler Equation for Capital: Materials Price	-0.02	(0.3)	-0.05	(0.2)
Euler Equation for Capital: Output	-1.2***	(0.2)	-1.0***	(0.2)
Euler Equation for Capital: Time Trend	-0.02*	(0.009)	-0.04***	(0.01)
Euler Equation for Capital: Constant	-1.3***	(0.1)	-1.2***	(0.1)
Number of observations		263		263
Labor Share Equation: R^2		0.88		0.88
Energy Share Equation: R^2		0.85		0.84
Euler Equation for Capital: R^2		0.87		0.87
LR Test: $\phi_l = \phi_e = \phi_m = \zeta = 0$, χ_2 (pval)		16.58 (0.00)		

Notes. VCM: Vintage Capital Model. P-R: Pindyck and Rotemberg (1983) Model.
coef.: estimated coefficient. s.e.: standard error. *** p<0.01, ** p<0.05, * p<0.1

Table A.13: Estimated Input Demand Own-Price Elasticities by Country: Chemical, Rubber, Plastics and Fuel Products

Country	Model I (Vintage Capital)						Model II (Pindyck-Rotemberg)					
	η_{ll}		η_{ee}		η_{mm}		η_{ll}		η_{ee}		η_{mm}	
Austria	-0.82	(0.04)	-0.05	(0.25)	-0.35	(0.07)	-0.82	(0.04)	-0.47	(0.10)	-0.37	(0.07)
Belgium	-0.92	(0.07)	-0.39	(0.02)	-0.42	(0.04)	-0.92	(0.06)	-0.57	(0.04)	-0.44	(0.05)
Denmark	-0.81	(0.03)	-0.40	(0.02)	-0.47	(0.02)	-0.80	(0.03)	-0.58	(0.01)	-0.49	(0.02)
Finland	-0.95	(0.04)	-0.40	(0.02)	-0.50	(0.02)	-0.94	(0.04)	-0.51	(0.03)	-0.53	(0.02)
France	-0.95	(0.04)	-0.41	(0.01)	-0.41	(0.01)	-0.94	(0.04)	-0.57	(0.01)	-0.43	(0.01)
Germany	-0.76	(0.05)	-0.38	(0.03)	-0.49	(0.02)	-0.75	(0.05)	-0.58	(0.01)	-0.51	(0.02)
Greece	-0.94	(0.02)	-0.34	(0.02)	-0.58	(0.02)	-0.93	(0.02)	-0.43	(0.03)	-0.62	(0.02)
Ireland	-0.88	(0.04)	0.61	(0.55)	-0.26	(0.03)	-0.87	(0.04)	-0.18	(0.26)	-0.28	(0.03)
Italy	-0.96	(0.04)	-0.41	(0.01)	-0.39	(0.02)	-0.95	(0.04)	-0.58	(0.01)	-0.41	(0.03)
Japan	-0.93	(0.04)	-0.13	(0.06)	-0.28	(0.01)	-0.92	(0.03)	-0.51	(0.03)	-0.30	(0.01)
Korea	-1.04	(0.06)	-0.39	(0.02)	-0.46	(0.04)	-1.03	(0.06)	-0.51	(0.04)	-0.49	(0.04)
Luxembourg	-0.84	(0.05)	2.22	(0.41)	-0.25	(0.03)	-0.83	(0.05)	0.60	(0.20)	-0.27	(0.03)
Netherlands	-1.04	(0.06)	-0.41	(0.01)	-0.40	(0.02)	-1.03	(0.06)	-0.56	(0.02)	-0.42	(0.02)
Portugal	-1.06	(0.05)	-0.39	(0.02)	-0.47	(0.03)	-1.05	(0.04)	-0.50	(0.03)	-0.50	(0.03)
Spain	-0.91	(0.04)	-0.41	(0.02)	-0.49	(0.03)	-0.91	(0.04)	-0.54	(0.04)	-0.52	(0.04)
Sweden	-0.86	(0.03)	-0.40	(0.01)	-0.51	(0.03)	-0.85	(0.03)	-0.54	(0.04)	-0.54	(0.04)
United Kingdom	-0.80	(0.02)	-0.39	(0.03)	-0.46	(0.03)	-0.80	(0.02)	-0.58	(0.01)	-0.48	(0.03)
United States	-0.81	(0.03)	-0.41	(0.01)	-0.53	(0.02)	-0.80	(0.03)	-0.55	(0.02)	-0.56	(0.02)

Note: Standard errors in parentheses.

Table A.14: Estimated Input Demand Own-Price Elasticities by Country: Electrical and Optical Equipment

Country	Model I (Vintage Capital)						Model II (Pindyck-Rotemberg)					
	η_{ll}		η_{ee}		η_{mm}		η_{ll}		η_{ee}		η_{mm}	
Australia	-0.80	(0.05)	-0.77	(0.02)	-0.41	(0.04)	-0.79	(0.05)	-0.59	(0.04)	-0.39	(0.04)
Austria	-0.78	(0.07)	-0.66	(0.03)	-0.42	(0.05)	-0.77	(0.07)	-0.38	(0.06)	-0.40	(0.05)
Belgium	-0.79	(0.04)	-0.64	(0.09)	-0.41	(0.03)	-0.78	(0.04)	-0.35	(0.17)	-0.39	(0.03)
Denmark	-0.83	(0.07)	-0.62	(0.05)	-0.39	(0.05)	-0.81	(0.07)	-0.31	(0.09)	-0.37	(0.05)
Finland	-0.96	(0.11)	-0.36	(0.23)	-0.30	(0.06)	-0.95	(0.10)	0.16	(0.43)	-0.28	(0.06)
France	-0.89	(0.04)	-0.73	(0.03)	-0.35	(0.03)	-0.88	(0.04)	-0.51	(0.06)	-0.33	(0.02)
Germany	-0.72	(0.03)	-0.73	(0.03)	-0.47	(0.03)	-0.71	(0.03)	-0.51	(0.06)	-0.45	(0.03)
Greece	-0.93	(0.03)	-0.83	(0.00)	-0.34	(0.02)	-0.91	(0.03)	-0.71	(0.01)	-0.32	(0.02)
Ireland	-1.24	(0.17)	-0.34	(0.21)	-0.19	(0.06)	-1.21	(0.16)	0.22	(0.38)	-0.18	(0.06)
Italy	-0.85	(0.05)	-0.79	(0.05)	-0.38	(0.03)	-0.84	(0.05)	-0.64	(0.10)	-0.36	(0.03)
Japan	-0.87	(0.02)	-0.78	(0.02)	-0.37	(0.01)	-0.86	(0.02)	-0.60	(0.03)	-0.35	(0.01)
Korea	-1.15	(0.05)	-0.80	(0.06)	-0.23	(0.02)	-1.12	(0.05)	-0.65	(0.11)	-0.22	(0.02)
Luxembourg	-0.73	(0.03)	-0.69	(0.02)	-0.45	(0.03)	-0.72	(0.03)	-0.44	(0.05)	-0.43	(0.03)
Netherlands	-0.79	(0.02)	-0.65	(0.05)	-0.41	(0.02)	-0.78	(0.02)	-0.36	(0.09)	-0.39	(0.02)
Portugal	-1.09	(0.04)	-0.61	(0.13)	-0.24	(0.02)	-1.07	(0.04)	-0.29	(0.25)	-0.22	(0.02)
Spain	-0.92	(0.06)	-0.79	(0.02)	-0.34	(0.03)	-0.91	(0.06)	-0.62	(0.04)	-0.32	(0.03)
Sweden	-0.89	(0.06)	-0.34	(0.11)	-0.34	(0.04)	-0.87	(0.05)	0.20	(0.20)	-0.32	(0.03)
United Kingdom	-0.85	(0.05)	-0.70	(0.04)	-0.37	(0.04)	-0.84	(0.05)	-0.45	(0.07)	-0.35	(0.03)
United States	-0.67	(0.04)	-0.72	(0.02)	-0.51	(0.03)	-0.66	(0.04)	-0.50	(0.04)	-0.48	(0.03)

Note: Standard errors in parentheses.

Table A.15: Estimated Input Demand Own-Price Elasticities by Country: Food Products, Beverages, and Tobacco

Country	Model I (Vintage Capital)						Model II (Pindyck-Rotemberg)					
	η_{ll}		η_{ee}		η_{mm}		η_{ll}		η_{ee}		η_{mm}	
Australia	-1.14	(0.02)	-0.41	(0.08)	-0.22	(0.01)	-0.99	(0.02)	-0.47	(0.07)	-0.22	(0.01)
Austria	-1.00	(0.05)	-0.47	(0.10)	-0.28	(0.03)	-0.89	(0.04)	-0.53	(0.09)	-0.28	(0.03)
Belgium	-1.18	(0.02)	-0.41	(0.07)	-0.20	(0.01)	-1.02	(0.02)	-0.47	(0.06)	-0.20	(0.01)
Denmark	-1.16	(0.04)	-0.33	(0.06)	-0.21	(0.01)	-1.01	(0.03)	-0.40	(0.06)	-0.21	(0.01)
Finland	-1.15	(0.04)	-0.31	(0.14)	-0.21	(0.02)	-1.00	(0.03)	-0.39	(0.12)	-0.21	(0.02)
France	-1.17	(0.04)	-0.47	(0.04)	-0.21	(0.01)	-1.01	(0.03)	-0.53	(0.03)	-0.21	(0.01)
Germany	-1.02	(0.04)	-0.59	(0.05)	-0.28	(0.02)	-0.90	(0.03)	-0.63	(0.04)	-0.28	(0.02)
Greece	-1.21	(0.03)	-0.36	(0.05)	-0.20	(0.01)	-1.04	(0.02)	-0.43	(0.04)	-0.19	(0.01)
Ireland	-1.28	(0.04)	-0.32	(0.11)	-0.17	(0.01)	-1.09	(0.03)	-0.39	(0.10)	-0.17	(0.01)
Italy	-1.14	(0.03)	-0.47	(0.13)	-0.22	(0.01)	-0.99	(0.02)	-0.52	(0.11)	-0.22	(0.01)
Japan	-0.97	(0.02)	-0.18	(0.06)	-0.28	(0.01)	-0.86	(0.02)	-0.27	(0.05)	-0.28	(0.01)
Korea	-1.42	(0.07)	-0.33	(0.09)	-0.14	(0.01)	-1.18	(0.04)	-0.40	(0.08)	-0.14	(0.01)
Luxembourg	-0.97	(0.02)	-0.51	(0.06)	-0.30	(0.01)	-0.86	(0.01)	-0.56	(0.06)	-0.30	(0.01)
Netherlands	-1.32	(0.03)	-0.16	(0.12)	-0.16	(0.01)	-1.11	(0.02)	-0.25	(0.11)	-0.16	(0.01)
Portugal	-1.42	(0.11)	-0.20	(0.29)	-0.14	(0.02)	-1.18	(0.07)	-0.28	(0.25)	-0.14	(0.02)
Spain	-1.25	(0.04)	-0.07	(0.12)	-0.18	(0.01)	-1.06	(0.03)	-0.17	(0.10)	-0.17	(0.01)
Sweden	-1.10	(0.05)	-0.24	(0.08)	-0.23	(0.02)	-0.96	(0.04)	-0.33	(0.07)	-0.23	(0.02)
United Kingdom	-0.99	(0.05)	-0.41	(0.08)	-0.29	(0.02)	-0.87	(0.04)	-0.47	(0.07)	-0.29	(0.02)
United States	-1.05	(0.03)	-0.24	(0.04)	-0.25	(0.01)	-0.92	(0.02)	-0.33	(0.04)	-0.25	(0.01)

Note: Standard errors in parentheses.

Table A.16: Estimated Input Demand Own-Price Elasticities by Country: Basic Metals and Fabricated Metal Products

Country	Model I (Vintage Capital)						Model II (Pindyck-Rotemberg)					
	η_{ll}		η_{ee}		η_{mm}		η_{ll}		η_{ee}		η_{mm}	
Australia	-1.35	(0.06)	-0.87	(0.001)	-0.36	(0.02)	-1.27	(0.05)	-1.01	(0.01)	-0.37	(0.02)
Austria	-1.07	(0.08)	-0.87	(0.001)	-0.47	(0.04)	-1.02	(0.08)	-1.03	(0.01)	-0.48	(0.04)
Belgium	-1.26	(0.04)	-0.87	(0.003)	-0.39	(0.02)	-1.20	(0.04)	-1.00	(0.02)	-0.40	(0.02)
Denmark	-0.95	(0.03)	-0.83	(0.011)	-0.50	(0.02)	-0.91	(0.02)	-1.15	(0.02)	-0.51	(0.02)
Finland	-1.34	(0.09)	-0.87	(0.003)	-0.36	(0.03)	-1.26	(0.08)	-1.03	(0.02)	-0.37	(0.03)
France	-1.07	(0.04)	-0.86	(0.007)	-0.45	(0.03)	-1.01	(0.04)	-1.08	(0.02)	-0.46	(0.03)
Germany	-0.97	(0.06)	-0.87	(0.001)	-0.53	(0.03)	-0.92	(0.06)	-1.02	(0.02)	-0.54	(0.03)
Greece	-1.19	(0.05)	-0.85	(0.005)	-0.46	(0.01)	-1.13	(0.04)	-0.94	(0.01)	-0.47	(0.01)
Ireland	-0.98	(0.05)	-0.87	(0.005)	-0.53	(0.04)	-0.93	(0.05)	-1.02	(0.04)	-0.54	(0.04)
Italy	-1.14	(0.06)	-0.87	(0.003)	-0.42	(0.03)	-1.08	(0.06)	-1.05	(0.01)	-0.43	(0.03)
Japan	-1.26	(0.07)	-0.87	(0.002)	-0.38	(0.03)	-1.19	(0.07)	-1.05	(0.01)	-0.38	(0.03)
Korea	-1.78	(0.09)	-0.87	(0.004)	-0.28	(0.02)	-1.66	(0.08)	-1.00	(0.04)	-0.28	(0.02)
Luxembourg	-1.38	(0.07)	-0.87	(0.003)	-0.35	(0.03)	-1.30	(0.06)	-1.02	(0.03)	-0.36	(0.03)
Netherlands	-1.06	(0.04)	-0.85	(0.007)	-0.45	(0.02)	-1.01	(0.04)	-1.11	(0.01)	-0.45	(0.02)
Portugal	-1.16	(0.09)	-0.86	(0.018)	-0.41	(0.05)	-1.10	(0.08)	-1.08	(0.05)	-0.42	(0.05)
Spain	-1.16	(0.08)	-0.87	(0.003)	-0.42	(0.03)	-1.10	(0.07)	-1.05	(0.02)	-0.43	(0.03)
Sweden	-1.16	(0.05)	-0.87	(0.003)	-0.41	(0.02)	-1.10	(0.05)	-1.05	(0.02)	-0.42	(0.02)
United Kingdom	-0.97	(0.05)	-0.87	(0.002)	-0.51	(0.03)	-0.93	(0.04)	-1.04	(0.02)	-0.52	(0.03)
United States	-1.00	(0.05)	-0.86	(0.004)	-0.49	(0.03)	-0.95	(0.05)	-1.07	(0.01)	-0.50	(0.03)

Note: Standard errors in parentheses.

Table A.17: Estimated Input Demand Own-Price Elasticities by Country: Pulp, Paper, Paper Products, Printing and Publishing

Country	Model I (Vintage Capital)						Model II (Pindyck-Rotemberg)					
	η_U		η_{ee}		η_{mm}		η_U		η_{ee}		η_{mm}	
Australia	-0.75	(0.03)	-0.55	(0.03)	-0.51	(0.02)	-0.71	(0.03)	-0.55	(0.03)	-0.50	(0.02)
Austria	-0.90	(0.04)	-0.64	(0.03)	-0.41	(0.03)	-0.85	(0.04)	-0.64	(0.04)	-0.41	(0.02)
Belgium	-0.88	(0.03)	-0.61	(0.04)	-0.42	(0.03)	-0.83	(0.03)	-0.60	(0.04)	-0.42	(0.03)
Denmark	-0.72	(0.02)	-0.32	(0.13)	-0.52	(0.01)	-0.69	(0.02)	-0.31	(0.13)	-0.51	(0.01)
Finland	-1.01	(0.05)	-0.76	(0.01)	-0.41	(0.02)	-0.95	(0.04)	-0.76	(0.01)	-0.41	(0.02)
France	-0.83	(0.02)	-0.52	(0.03)	-0.44	(0.01)	-0.79	(0.02)	-0.52	(0.03)	-0.44	(0.01)
Germany	-0.77	(0.04)	-0.70	(0.03)	-0.52	(0.03)	-0.73	(0.04)	-0.70	(0.03)	-0.52	(0.03)
Greece	-0.76	(0.04)	-0.73	(0.02)	-0.54	(0.02)	-0.72	(0.04)	-0.72	(0.02)	-0.53	(0.02)
Ireland	-0.92	(0.15)	-0.17	(0.24)	-0.39	(0.09)	-0.87	(0.14)	-0.15	(0.25)	-0.38	(0.09)
Italy	-0.87	(0.05)	-0.64	(0.06)	-0.44	(0.02)	-0.82	(0.04)	-0.63	(0.06)	-0.43	(0.02)
Japan	-0.78	(0.02)	-0.60	(0.04)	-0.49	(0.02)	-0.74	(0.02)	-0.60	(0.05)	-0.49	(0.02)
Korea	-0.96	(0.05)	-0.68	(0.04)	-0.39	(0.02)	-0.91	(0.04)	-0.68	(0.05)	-0.38	(0.02)
Luxembourg	-0.83	(0.04)	-0.44	(0.11)	-0.44	(0.03)	-0.79	(0.04)	-0.43	(0.11)	-0.43	(0.03)
Netherlands	-0.77	(0.02)	-0.41	(0.07)	-0.48	(0.01)	-0.74	(0.02)	-0.40	(0.07)	-0.47	(0.01)
Portugal	-0.98	(0.05)	-0.66	(0.12)	-0.39	(0.03)	-0.92	(0.04)	-0.66	(0.12)	-0.38	(0.03)
Spain	-0.87	(0.03)	-0.60	(0.03)	-0.43	(0.02)	-0.82	(0.03)	-0.60	(0.03)	-0.42	(0.02)
Sweden	-0.88	(0.02)	-0.73	(0.01)	-0.45	(0.01)	-0.84	(0.02)	-0.73	(0.01)	-0.44	(0.01)
United Kingdom	-0.71	(0.03)	-0.26	(0.09)	-0.529	(0.03)	-0.67	(0.03)	-0.25	(0.09)	-0.52	(0.03)
United States	-0.62	(0.05)	-0.54	(0.03)	-0.62	(0.04)	-0.59	(0.05)	-0.53	(0.03)	-0.61	(0.04)

Note: Standard errors in parentheses.

Table A.18: Estimated Cross-Price Elasticities of Labor Demand in OECD Manufacturing Sectors

Sector	η_{le}		η_{lm}		η_{lK}		η_{lY}	
	VCM	P-R	VCM	P-R	VCM	P-R	VCM	P-R
Chemical, Rubber, Plastics and Fuel Products	-0.15 (0.11)	-0.04 (0.10)	0.98*** (0.16)	0.95*** (0.16)	-0.66** (0.26)	-0.86** (0.33)	1.09*** (0.21)	1.35*** (0.23)
Electrical and Optical Equipment	-0.21** (0.08)	-0.20** (0.08)	0.66*** (0.09)	0.65*** (0.09)	-0.37*** (0.07)	-0.46*** (0.11)	1.36*** (0.14)	1.42*** (0.18)
Food Products, Beverages, and Tobacco	-0.05** (0.02)	-0.07** (0.03)	0.73*** (0.04)	0.72*** (0.04)	0.23 (0.32)	0.09 (0.32)	1.32*** (0.23)	1.42*** (0.15)
Basic Metals and Fabricated Metal Products	0.002 (0.02)	0.06*** (0.02)	0.80*** (0.11)	0.83*** (0.12)	-0.74** (0.37)	-0.55 (0.37)	1.52*** (0.29)	1.46*** (0.28)
Pulp, Paper, Paper Products, Printing and Publishing	-0.04** (0.02)	-0.04** (0.02)	0.71*** (0.09)	0.68*** (0.08)	-0.46 (0.42)	-0.40 (0.30)	1.71*** (0.29)	1.71*** (0.09)

Note. VCM: Vintage Capital Model, P-R: Pindyck and Rotemberg (1983) Model. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A.19: Estimated Cross-Price Elasticities of Materials Demand in OECD Manufacturing Sectors

Sector	η_{ml}		η_{me}		η_{mK}		η_{mY}	
	VCM	P-R	VCM	P-R	VCM	P-R	VCM	P-R
Chemical, Rubber, Plastics and Fuel Products	0.33*** (0.06)	0.27*** (0.06)	0.27** (0.12)	0.30** (0.12)	0.06 (0.24)	-0.13 (0.29)	0.72*** (0.19)	1.00*** (0.21)
Electrical and Optical Equipment	0.43*** (0.10)	0.43*** (0.10)	0.11*** (0.01)	0.10*** (0.01)	-0.08 (0.05)	-0.20* (0.11)	0.89*** (0.08)	0.95*** (0.14)
Food Products, Beverages, and Tobacco	0.30*** (0.06)	0.26*** (0.05)	0.03*** (0.01)	0.03*** (0.01)	0.16 (0.31)	0.10 (0.32)	0.85*** (0.23)	1.03*** (0.15)
Basic Metals and Fabricated Metal Products	0.52*** (0.09)	0.48*** (0.09)	0.07*** (0.02)	0.06*** (0.02)	-0.41 (0.36)	-0.16 (0.36)	0.88*** (0.23)	0.93*** (0.24)
Pulp, Paper, Paper Products, Printing and Publishing	0.46*** (0.08)	0.45*** (0.08)	0.07*** (0.02)	0.07*** (0.02)	-0.32 (0.42)	-0.29 (0.30)	1.53*** (0.28)	1.54*** (0.09)

Note. VCM: Vintage Capital Model, P-R: Pindyck and Rotemberg (1983) Model. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A.20: Sensitivity Analysis: Own-Price Elasticities of Input Demand

Sector	η_{ll}		η_{ee}		η_{mm}	
	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$
Chemical, Rubber, Plastics and Fuel Products	-0.90*** (0.10)	-0.89*** (0.09)	-0.27 (0.50)	-0.29 (0.46)	-0.43*** (0.09)	-0.43*** (0.09)
Electrical and Optical Equipment	-0.88*** (0.16)	-0.88*** (0.16)	-0.66*** (0.17)	-0.67*** (0.16)	-0.35*** (0.09)	-0.37*** (0.09)
Food Products, Beverages, and Tobacco	-1.14*** (0.14)	-1.17*** (0.21)	-0.38** (0.16)	-0.28 (0.19)	-0.22*** (0.05)	-0.22*** (0.05)
Basic Metals and Fabricated Metal Products	-1.11*** (0.19)	-1.10*** (0.19)	-0.85*** (0.02)	-0.87*** (0.01)	-0.45*** (0.07)	-0.45*** (0.07)
Pulp, Paper, Paper Products, Printing and Publishing	-0.84*** (0.11)	-0.83*** (0.11)	-0.53** (0.19)	-0.53** (0.19)	-0.46*** (0.07)	-0.47*** (0.07)

Note. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.21: Sensitivity Analysis: Cross-Price Elasticities of Energy Demand

Sector	η_{el}		η_{em}		η_{eK}		η_{eY}	
	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$
Chemical, Rubber, Plastics and Fuel Products	0.12 (0.13)	0.03 (0.23)	-0.30 (0.92)	-0.34 (0.97)	0.08 (0.28)	0.19 (0.26)	1.05*** (0.26)	1.14*** (0.36)
Electrical and Optical Equipment	0.15 (0.15)	0.20 (0.13)	1.32*** (0.40)	1.49*** (0.49)	0.50 (0.39)	0.56 (0.39)	0.59** (0.27)	0.52* (0.27)
Food Products, Beverages, and Tobacco	0.46*** (0.07)	0.40*** (0.06)	0.56*** (0.06)	0.57*** (0.06)	-0.23 (0.29)	-0.28 (0.38)	0.34 (0.28)	0.56* (0.33)
Basic Metals and Fabricated Metal Products	0.30*** (0.07)	0.39*** (0.08)	0.82*** (0.08)	0.73*** (0.07)	-0.13 (0.28)	-0.25 (0.32)	0.90*** (0.31)	0.88*** (0.24)
Pulp, Paper, Paper Products, Printing and Publishing	0.84*** (0.27)	0.83*** (0.26)	0.20 (0.21)	0.22 (0.20)	0.35 (0.47)	0.69 (0.43)	0.95** (0.46)	0.60 (0.51)

Note. All Elasticities are Calculated at Sample Means. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.22: Sensitivity Analysis: Elasticities of Input Efficiency with Respect to Input Prices, and the Rate of Exogenous Technological Change

Sector	ϕ^l		ϕ^e		ϕ^m		ζ	
	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$	$\delta = 0.05$	$\delta = 0.15$
Chemical, Rubber, Plastics and Fuel Products	0.84*** (0.06)	0.66*** (0.05)	1.14*** (0.14)	0.74*** (0.09)	0.02 (0.06)	0.01 (0.04)	0.026** (0.01)	0.039** (0.02)
Electrical and Optical Equipment	0.12*** (0.03)	0.05*** (0.01)	0.01 (0.05)	0.07 (0.38)	1.19*** (0.18)	1.19*** (0.18)	0.012 (0.01)	0.013 (0.01)
Food Products, Beverages, and Tobacco	1.93*** (0.07)	0.72*** (0.03)	0.55*** (0.13)	0.58*** (0.14)	0.03 (0.36)	0.002 (0.03)	0.033* (0.02)	0.022* (0.01)
Basic Metals and Fabricated Metal Products	1.13*** (0.06)	0.72*** (0.04)	1.98*** (0.22)	1.10*** (0.12)	1.89** (0.80)	1.18** (0.50)	0.008* (0.004)	0.028* (0.01)
Pulp, Paper, Paper Products, Printing and Publishing	0.88*** (0.05)	0.55*** (0.03)	0.04 (0.50)	0.02 (0.33)	1.27** (0.49)	1.05** (0.41)	0.038*** (0.01)	0.039*** (0.01)

Note. Standard errors (in parentheses) are based on bootstrap simulations. *** p<0.01, ** p<0.05, * p<0.1

Table A.23: Greenhouse Gas Emissions in UK Petrochemical Industry in 2005

Fuel Type	Fuel Consumption (ktoe)**	Fuel Share, %	CO ₂ Emissions CO ₂ per toe	CO ₂ emission per share
Gasoil / Diesel	1078	0.10	2.9	0.28
Residual Fuel Oil	1970	0.18	3.13	0.56
Liquefied Petroleum Gases	45	0.004	2.5	0.01
Coal	207	0.02	3.7	0.07
Natural Gas	4583	0.41	2.17	0.9
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)

Table A.24: Greenhouse Gas Emissions in UK Electrical Industry in 2005

Fuel Type	Fuel Consumption (ktoe)	Fuel Share, %	CO ₂ Emissions CO ₂ per toe	CO ₂ emission per share
Gasoil / Diesel	29	0.03	2.9	0.08
Residual Fuel Oil	7	0.01	3.13	0.02
Liquefied Petroleum Gases	0	0.00	2.5	0.00
Coal	3	0.003	3.7	0.01
Natural Gas	380	0.36	2.17	0.78
Electricity	638	0.60	2.17*	1.31
Total	1056	1.00		2.20

* Assuming Natural Gas as a Base Load Factor in Electricity Generation

A.3 Figures

Figure A.1: Capital Stock Efficiency Indexes, Chemical, Rubber, Plastics and Fuel Products, United States, 1991-2005

Figure A.2: Capital Stock Efficiency Indexes, Electrical and Optical Equipment, United States, 1991-2005

Figure A.3: Capital Stock Efficiency Indexes, Food Products, Beverages, and Tobacco, United States, 1991-2005

Figure A.4: Capital Stock Efficiency Indexes, Basic Metals and Fabricated Metal Products, United States, 1991-2005

Figure A.5: Capital Stock Efficiency Indexes, Pulp, Paper, Paper Products, Printing and Publishing, United States, 1991-2005