WPS7857

Policy Research Working Paper 7857

Capital Adjustment and the Optimal Fuel Choice

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October 2016

Abstract

This paper analyzes the important, yet often ignored, link between capital adjustment and the choice of fuels used by manufacturing firms. A novel econometric framework, which explicitly incorporates heterogeneous fuel-using capital stocks in the estimation of optimal fuel choice, is applied to a large panel of Irish manufacturing firms. The econometric estimates show a significant variation in the optimal response of capital to changing fuel prices across different fuel-using technologies. For all the technologies, significant costs to capital adjustment are found. The costs are much larger compared with earlier estimates of adjustment costs based on lagged values of output and fuel prices. The findings imply that the path to full adjustment of capital stocks in response to changing fuel prices may be much longer than was previously thought.

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Keywords: capital adjustment, fuel choice

JEL: D22, D24, Q41

*This work makes use of data from the Central Statistics Office (CSO). The possibility for controlled access to the confidential micro-dataset on the premises of the CSO is provided for in the Statistics Act 1993. The use of CSO data in this work does not imply the endorsement of the CSO in relation to the interpretation or analysis of the data. This work uses a research dataset which may not exactly reproduce statistical aggregates published by the CSO. We thank Gerard Doolan of the CSO for support with the data and clearance. A significant amount of data preparation work was previously carried out by Stefanie Haller and we are very grateful to have been able to use these previously prepared data. We also thank Nolan Ritter, Mike Toman, and the participants of EMEE 2016 workshop for helpful suggestions and comments. Hyland gratefully acknowledges financial support from the ESRI Energy Policy Research Centre. The views expressed in this paper are those of the authors and do not represent the views of the World Bank, its board of directors or the countries they represent.

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1 Introduction

This research aims to bring new insights into the issue of interfuel substitution by revisiting the important and largely overlooked relationship between the dynamics of capital stocks and the optimal fuel choice. The ability of firms to switch between fuel sources has important implications for economic growth, particularly in the context of economic adjustment to oil price shocks and climate policies (as highlighted by Hall (1986) Acemoglu et al. (2012), Stern (2012) and Papageorgiou et al. (2016), among others), and there is a large body of economic literature that looks at the issue of fuel substitution. However, few of these studies explicitly model the choice of fuels and corresponding fuel-using capital stocks. Earlier empirical studies of interfuel substitution, such as Fuss (1977) and Pindyck (1979), employed a two-stage approach that, in the first stage, estimates the degree of substitutability between different fuels and, in the second stage, estimates the relationship between the energy aggregate and other factors of production. More recent studies (for example, Jones (1995); Bjørner and Jensen (2002); Urga and Walters (2003); Serletis and Shahmoradi (2008); Serletis et al. (2010)) have followed the same approach and mainly focused on methodological innovations of the first stage, introducing dynamic functional forms for estimating demand for different fuels. The validity of such approaches hinges on the assumption that energy and other factors are weakly separable in the production process. This assumption rules out the possibility that firms determine jointly their fuel mix and capital stock, nor does it allow for the possibility that there may be capital adjustment costs associated with a change in the energy inputs used.[1]

A similar approach has been used to address inter-fuel substitution in large scale energy and environmental computational models, in particular, computable general equilibrium (CGE) models and integrated assessment models. For example, in the energy-environment extension of a well known GTAP CGE model, the GTAP-E model (Burniaux and Truong, 2002), the production function is modeled using a technology tree, based on a nested CES production function. This structure assumes that primary and intermediate factors of production are weakly separable. In the first nest of the production function, the energy aggregate is calculated based on substitution between different fuel types. In the second nest, this energy aggregate is combined with capital inputs to form a capital-energy composite. In the following nest, capital and energy are combined with labor and material inputs to produce output. This approach has been largely adopted in a variety of other climate-economy integrated assessment models (see, e.g., Paltsev et al., 2005; Burniaux and Château, 2008).

We argue that this approach, adopted in both econometric and economic modeling studies of energy and environment, has several important limitations. The first limitation relates to the choice of the nesting structure used by these models. The assumption that the choice of fuels used in the aggregate energy mix is separable from decisions related to the optimal choice

[1] A recent study by Papageorgiou et al. (2016) is the only known attempt to simultaneously model capital and energy choices, however their analysis is static and limited to choice between "clean" and "dirty" energy aggregates.

of capital ignores the short-run complementarity between energy and capital inputs for a given production technology. In reality, capital stocks tend to be highly idiosyncratic, and very few types of energy-using technologies can utilize multiple fuels (Steinbuks, 2012).[2] That is, the relationship between capital technologies and corresponding fuels is fixed, at least in the short term. This implies that firms do not pick a particular fuel, but rather a particular technology bundle that combines capital with a specific type of energy input.

The second potential limitation of the approach is that the capital adjustment process is not properly accounted for. The economic and econometric models of interfuel substitution are either static, where capital adjustment is ignored, or recursive dynamic, where capital adjustment costs are implicitly estimated using lagged values of output or prices as a proxy for capital. This implicit estimation largely ignores asymmetries in capital adjustment due to irreversibilities of capital, and is prone to measurement error as non-capital inputs to production tend to adjust faster. Failing to account for the capital adjustment process and its associated costs contradicts the economic literature that finds these costs non-trivial; see, for example, Caballero (1999), Caballero and Engel (1999), and Caballero and Engel (2003). Furthermore, the more specific role of adjustment costs in the transition to low-carbon and energy-efficient technologies has been highlighted by Jacoby and Wing (1999), Wing (2008), and Steinbuks and Neuhoff (2014).

Our paper proposes a novel approach to analyze interfuel substitution that explicitly incorporates heterogeneous energy-using capital stocks in the estimation of optimal fuel choice. We model the capital and energy use decisions jointly, implying that firms choose capital and energy inputs concurrently. The fundamental choice that firms make is among different competing fuel-using technologies; this contrasts with the two-step approach in which firms first choose which fuels to use and then choose the other factor inputs.

Our analysis draws on two previous studies; one that is concerned with energy and capital utilization (Atkeson and Kehoe, 1999), and another that deals with the adjustment dynamics of heterogeneous capital goods (Goolsbee and Gross, 2000). Following Atkeson and Kehoe (1999), we assume that energy inputs and capital stocks are complements in the short run as, for a given level of capital stocks, a fixed quantity of energy inputs is needed. In the long run capital and energy will be substitutable as firms can respond to rising energy prices by investing in new, presumably less energy-intensive, capital stocks. We incorporate this "putty-clay" structure of Atkeson and Kehoe (1999) in the modeling framework of Goolsbee and Gross (2000) to estimate the form of adjustment costs for heterogeneous capital stocks. Specifically, we develop a structural model of the demand for different types of fuel-using technologies, which we estimate in two stages. In our model, the "types" of energy-using capital refer to the specific fuels used to run the capital stocks. In the first stage, we estimate the frictionless stock of each type of capital for firms in our data. The frictionless stock of capital is the optimal amount of each type of capital that firms would employ in the absence of any adjustment costs. In the second stage we estimate non-parametrically the relationship between frictionless and actual capital stocks to

[2]One example of such technologies is a combined cycle turbine for electricity generation.

reveal information on the nature of the adjustment costs faced by firms.

Our results suggest that the costs of adjusting capital stocks in response to changing fuel prices are large for all types of capital. These costs are an order of magnitude higher than in studies where capital adjustment costs are implicitly estimated. Furthermore, we find that investment in fuel-using capital stocks may be irreversible; this is indicative of prohibitively large adjustment costs associated with divestment of assets. This implies that the path to full capital-stock adjustment in response to changing fuel prices may be much longer than previously thought.

These findings have important implications for both econometric and economic modeling studies of interfuel substitution. Failure to incorporate proper heterogeneous fuel-using capital adjustment dynamics in econometric studies will likely result in the downward biased long run elasticities of optimal fuel choice. Similarly, considering more appropriate nesting structure of capital energy interaction and revising the magnitude of fuel-using capital adjustment costs would yield an improvement in robustness of dynamic forward looking energy-environmental CGE models.

Our paper proceeds as follows: in section 2 we explain our theoretical model and outline our estimation strategy. In section 3 we present the data used in our analysis. Section 4 outlines the results of our model. Finally, in section 5 we briefly draw some concluding remarks.

2 Methods

2.1 Theoretical model

The conceptual framework for estimating fuel choice is based on the putty-clay model of energy use described by Atkeson and Kehoe (1999), extended to account for heterogeneous fuels. In our model there is a continuum of energy-using capital technologies (V_t) which are combined with energy fuels (E_t) in fixed proportions to yield a given amount of capital services (Z_t). Thus, in the short run, energy and capital are complements for a given technology choice. In the long run the technologies will be substitutable as firms can adjust their capital stocks by investing in machinery and equipment that utilizes other fuels.

Following Atkeson and Kehoe (1999) we assume that, in the short run, a unit of capital of fuel using technology V provides capital services in combination with a fixed quantity, $1/V$, of fuel E. Combining K units of capital of technology V with E units of fuel yields capital services (Z) as determined by:

$$Z = \min(K/V, E) f(V) \tag{1}$$

The intuition behind this is that if $E > K/V$ the fuel in excess of K/V is wasted, but if $E < K/V$ there is capital stock left idle. In our model, firms' final output would be produced by combining capital services (a function of capital stocks and fuel use) with labor and materials, which are assumed separable from the capital-energy composite: $Y = f(Z_t | L_t, M_t)$, and are therefore

ignored in this analysis.

Once we account for the putty-clay nature of fuel demand we can formulate firms' production, capital demand, and capital adjustment choices. These choices are based on the heterogeneous capital goods adjustment model of Goolsbee and Gross (2000), who estimate capital adjustment costs for the US airline industry using a two-step semi-structural approach. In the first step the authors derive the frictionless stock of capital, K_i^f, i.e., the stock of each type of capital, i, that a firm would have in the absence of adjustment costs. The difference between a firm's current capital stock and its frictionless capital stock (K_i^f/K_i) captures the firm's desired investment. In the second step Goolsbee and Gross (2000) estimate a firm's investment response as a function of its desired investment to reveal information about the form of adjustment costs facing the firm.

Following Goolsbee and Gross (2000), we assume that in period t a firm j maximizes its profit function, $\Pi_{j,t}$, given by:

$$\Pi_{j,t} = \max_{z_{i,j,t}} \Gamma\left(z_{1,j,t}, ..., z_{n,j,t}; G_{j,t}\right) - p_{i,t}^K (r_t + \delta) K_{i,j,t} - p_{i,t}^E E_{i,j,t}, \tag{2}$$

where $\Gamma(\cdot)$ is the firm's production function; $z_{i,j,t}$ are the services from the capital technology utilizing fuel i as defined by equation (1); $G_{j,t}$ is the composite of all unobservable fixed factors affecting the firm's profitability; $p_{i,t}^K$ is sales price of capital technology utilizing fuel i; r_t is the interest rate, δ is the capital depreciation rate, and $p_{i,t}^E$ is the input price of fuel i. We assume that the production function takes the form:

$$\Gamma\left(z_{1,j,t}, ..., z_{n,j,t}; G_{j,t}\right) = \sum_{i=1}^{n} \left(z_{i,j,t}^{\alpha}\right)^{\frac{\rho}{\alpha}} G_{j,t}^{\beta} \tag{3}$$

Applying the putty-clay model of Atkeson and Kehoe (1999), capital and energy are used in fixed proportions in the short run as determined by technological constraints, thus, $K_{i,j,t}/V_{i,j,t} = E_{i,j,t}$. We assume that the efficiency of capital stock varies by sector and over time. The efficiency of sector-level capital is calculated, for each type of capital, by dividing the total stock of capital-type i in each sector by aggregate sectoral output. We assume that the firm-year variation in the efficiency of capital stock is small enough to be ignored. This implies that $V_{i,j,t} \cong \tilde{V}_{i,j,t} = \tilde{V}_{i,j} \cdot \tilde{V}_{i,t}$, so that $\ln(\tilde{V}_{i,j,t}) = \ln(\tilde{V}_{i,j}) + \ln(\tilde{V}_{i,t})$, where $\tilde{V}_{i,t}$, is the time-varying sector-level efficiency of fuel-using technology i, and $\widetilde{V}_{i,j}$ are the firm-level technology fixed effects. Under these assumptions the first-order condition for optimal capital using fuel i (in log-linearized form) can be re-written as:

$$\ln(K_{i,j,t}^f) = \ln \widetilde{V}_{i,t} + \ln \widetilde{V}_{i,j} + \frac{1}{\alpha - 1} \ln \left[p_{i,t}^K (r_t + \delta) + \frac{p_{i,t}^E}{\widetilde{V}_{i,j,t}} \right]. \tag{4}$$

The frictionless stock of capital using fuel i is a function of the price of fuel i, the cost of capital, and the efficiency of capital stock. As noted by Goolsbee and Gross (2000), the estimated coefficient on the cost variable corresponds to $-\sigma = \frac{1}{\alpha - 1}$, i.e., the negative elasticity of substitution between fuel-using technologies.

2.2 Empirical specification

2.2.1 Predicting the frictionless stock of capital

For the econometric estimation of equation (4) we include a number of additional control variables to account for unobservable effects correlated with the choice of energy-using capital. These are real sectoral output growth rates, Y_t, which we include to control for the effect of demand on capital stocks. We also include a time trend, T_t, that captures exogenous technological progress. Additionally we wish to account for capacity utilization in our model; firms may not have the capital stocks running at full capacity at all times as there may be times at which it is not optimal for them to do so. Thus, firms do not maximize profit only with respect to capital stocks, but rather with respect to capital stocks adjusted for capacity utilization ($U_{i,j,t}$). Therefore, the profit function becomes:

$$\Pi_{j,t} = \max_{z_{i,j,t}} \Gamma\left(z_{1,j,t}, ..., z_{n,j,t}; G_{j,t}\right) - p^K_{i,t}(r_t + \delta)K_{i,j,t} - p^E_{i,t}E_{i,j,t} * U_{i,j,t}, \tag{5}$$

And, including the additional control variables, the empirical specification we estimate becomes:

$$\ln(K^f_{i,j,t} \cdot U_{i,j,t}) = \widetilde{V}_{i,j} + \gamma \ln \widetilde{V}_{i,t} + \frac{1}{\alpha - 1} \ln \left[p^K_{i,t}(r_t + \delta) + \frac{p^E_{i,t} * U_{i,j,t}}{\widetilde{V}_{i,j,t}} \right] + \beta Y_t + \tau T_t + \epsilon_{i,j,t}, \tag{6}$$

Equation 6 is estimated for each type of capital, i. However, it is likely that firms make decisions regarding capital stocks and utilization for each technology while simultaneously taking account of the other types of capital that they use. Thus, we estimate the frictionless stock of capital for each fuel-using technology within a seemingly-unrelated regression (SUR) model. This accounts for the fact that the errors may be correlated across the optimization of each technology. As the majority of firms in our data utilize no coal-fired capital, including coal-using capital in the system leads to a much smaller sample size, thus we estimate two separate systems of equations; one including coal and one without. The firms utilizing coal are found only in a small number of energy-intensive sectors.

In the estimation of equation 6 we account for the presence of fixed effects. These fixed effects are removed by demeaning the data prior to estimation. Finally, following Goolsbee and Gross (2000), we constrain the coefficients on the cost term to be the same across all fuel-using technologies, this allows us to present a single estimate for the price elasticity of energy-using capital.

2.2.2 Estimating the form of adjustment costs

The predicted values from equation (5) give us the frictionless stock of each type of capital K^f_i, i.e., the stock of capital that a firm would hold in the absence of adjustment costs. As outlined

by Goolsbee and Gross (2000), the difference between the predicted and observed capital stock represents a firm's desired investment. Thus, desired investment can be calculated as:

$$\frac{K^f_{i,j,t}}{K_{i,j,t}} = \theta exp(-\epsilon_{i,j,t}) \tag{7}$$

Where, $K^f_{i,j,t}$ and $K_{i,j,t}$ denote the frictionless and actual stocks of capital i, held by firm j in time t, and $\epsilon_{i,j,t}$ is the error term from equation (5). If the ratio of K^f to K is greater than one, a firm would, in the absence of any costs of adjustment, invest in additional capital stocks. Conversely, for values less than one firms wish to divest some of their assets. The θ term in equation 7 is what Goolsbee and Gross (2000) refer to as the "scale factor". This term captures the fact that frictionless and desired investment may not be identical. For example, in periods of significant sectoral growth, desired investment may exceed actual investment by a factor greater that what can be represented by adjustment costs. We follow Goolsbee and Gross (2000) and do not make any assumptions regarding the size of this parameter, instead we set the scale factor to be equal to one. This will not affect the form of the adjustment costs we estimate, but in level terms they may be off by a constant factor.

We use kernel regressions to estimate the relationship between the firms' desired investment and actual investment levels. This approach provides greater flexibility as it allows the relationship between these values, and thus the adjustment costs, to vary by investment level. The estimation takes the form:

$$\frac{I_{i,j,t+1}}{K_{i,j,t}} = f\left(\frac{K^f_{i,j,t}}{K_{i,j,t}}\right) + \eta_{i,j,t} \tag{8}$$

Plots of the kernel regression functions will tell us about the form of adjustment costs facing firms. Furthermore, the estimated slopes of these functions provide a measure of the size of the adjustment costs that firms face.

Equation (8) is estimated using the Nadarya-Watson estimator (which is based on a polynomial of degree zero) to allow for flexible estimation[3]; Goolsbee and Gross (2000) note that this estimator places almost no restrictions on the shape of the adjustment cost function. The bandwidth (b) for the kernel estimates is determined using the same formula as Goolsbee and Gross (2000); $b = 2.347 * \sigma * n^{-1/5}$, where σ is the standard deviation of the X variable, and n refers to the number of observations.

The slope of the function in equation (8) represents the magnitude of the adjustment costs. Caballero and Engel (2003) note that, under the quadratic adjustment cost model, the speed of adjustment, as indicated by the slope of the investment function, conveys information about the adjustment costs:

[3]We also tried estimating the kernel regressions using a polynomial of degree one, but found that this resulted in over-smoothing of the investment function.

$$\delta K_t = \lambda(K_t^f - K_{t-1}) \tag{9}$$

Here K_t and K_t^f represent the actual and optimal levels of capital at time t, while the λ parameter represents how much of the gap between these values is bridged in each time period. Lower values of λ imply slower rates of adjustment and, thus, higher adjustment costs. As adjustment costs may differ for different levels of desired investment, Chow tests are conducted at different points along the investment function to test the continuity of its slope for each type of capital.

3 Data

3.1 Overview

We use a panel of firm-level data for manufacturing firms in the Republic of Ireland. These data are collected by the Irish Central Statistics Office (CSO) via the annual Census of Industrial Production (CIP). Response to the CIP is compulsory for firms operating in the Irish manufacturing sector with three or more persons engaged. The census collects data on various accounting measures such as sector of operation (at the NACE 4 digit level), location, sales, employment, intermediate inputs, capital acquisitions and trade. While all firms of three or more employees are surveyed, larger firms are asked to complete a more detailed questionnaire which includes, among other additional information, information on energy expenditure disaggregated by fuel type (smaller firms are asked only for aggregate energy expenditure). As we are interested in adjustment costs of fuel-using capital by type of fuel, we concentrate our analysis on these larger firms and for the period from 2004 to 2009, when these more detailed data were collected on an annual basis. Our final dataset contains approximately 8,600 firm-year observations.

The census does not ask firms to report a price for capital, therefore, the price of capital we use in our model is the market cost of capital as estimated for Irish manufacturing firms by Žnuderl and Kearney (2013). This cost is a function of the investment price and the nominal interest and depreciation rates. Additionally, fuel prices are not recorded in the census and, as such, a number of external sources are used. The prices of oil and coal are from the ESRI Databank (ESRI, 2012), while the prices of electricity and natural gas come from Eurostat's price series for industrial users.[4] The Eurostat price data vary according to the quantity of fuel used. In Ireland firms face decreasing block pricing for electricity and gas, whereby prices are lower at higher consumption levels. However, as we do not observe the quantity used, firms are assigned to consumption-based price bands as follows: for each two-digit NACE sector we calculate the energy intensity of output in that sector by dividing total sectoral electricity and gas usage (based on aggregate data) by total sectoral output. This gives us an average, sector-level measure of energy-intensity of output separately for electricity and natural gas. Then, for

[4] http://ec.europa.eu/eurostat/web/energy/data/main-tables

each firm we impute the volume of electricity and natural gas that it consumes by multiplying its output, as recorded in our data, by the average level of energy-intensity of the sector in which the firm operates. Based on this inferred consumption, we assign firms to Eurostat end-user price bands for electricity and natural gas. For model estimation, all prices are represented as indices, based on real 2007 values.

Using information in our data set we can account for the level of utilization of fuel-using capital stocks ($U_{i,j,t}$). For each firm in the data we observe its fuel inventories at the beginning and at the end of each year.[5] Based on these data we calculate an average annual fuel utilization rate. This is given by taking the total fuel consumption in that period - which is the sum of the value of opening stocks plus fuel purchases minus closing stocks, and dividing this by the total value of fuel available for consumption - the sum of opening stocks plus purchases.

3.2 Calculation and disaggregation of fuel-using capital stocks

The census asks firms for information on capital acquisitions by type of capital. Capital acquisitions data are disaggregated as follows: acquisitions of computer equipment; computer software; plant machinery and equipment; motor vehicles; building and construction work; buildings purchased; land purchased; capitalized R&D, and "other". In our analysis we focus on the plant machinery and equipment component of capital, where substitution between different types of fuel-using stocks is technologically feasible. Capital stocks are calculated using the perpetual inventory method and based on capital acquisitions and disposals, as recorded in the data. The starting stocks are calculated based on the CSO's industry-level breakdown for the previous year and then subsequently disaggregated to the firm level using each firm's share of fuel use in total industry-level fuel use. A detailed description of how this variable is created, including information on depreciation rates and assumed assets lives, is provided by Haller (2014) and Haller and Hyland (2014).

For our analysis, we are interested in the machinery and equipment component of capital stocks, disaggregated by type of capital - where type refers to the fuel used. To break down the machinery and equipment component by fuel used we follow Steinbuks (2012) and use data from the TIMES model for Ireland (Gallachóir et al., 2012). We calculate five components of equipment based on the TIMES data, they are: those that can only run on electricity (for example, electrical motors and refrigeration units); those that run on electricity, but where other fuels can be used (for example high- and low-temperature heating processes)[6]; those that run on natural gas; those that run on oil; and those that run on coal.[7] Average sectoral-level capital stocks in 2004 (the first year of our data) for each of the five subcomponents are given in Table 1.

[5]This information is available for the sum of all fuels, but not disaggregated by fuel type.

[6]These are referred to as "Electricity (no substitution possible)" and "Electricity (substitution possible)" respectively in Table 2.

[7]For machinery that runs on natural gas, oil or coal, we assume other fuel options are always available for these processes.

Table 1: Average breakdown of machinery by sector and type in 2004 (000s of €2007)

	Electricity (no sub)	Electricity (sub possible)	Natural gas	Oil	Coal
Sector manufacturing:					
Food & beverages	1,735	2,041	2,019	3,018	821
Textiles & textile products	445	1,694	212	572	-
Wood & wood products	868	-	51	63	2,568
Pulp, paper & publishing	829	2,271	481	547	-
Chemicals & man-made fiber	11,979	5,946	6,985	3,585	-
Rubber & plastic products	1,569	847	282	681	-
Other non-metallic minerals	438	596	304	3,566	1,726
Metal products	154	172	1,631	488	-
Machinery & equip. n.e.c.	1,256	5,723	1,745	2,094	-
Electrical & optical equip.	6,171	4,585	11,626	4,444	-
Transport equipment	953	5,049	706	1,412	-

Table 1 shows the relative importance of machinery and equipment driven by electricity. With only a few exceptions, capital stocks in all sectors are dominated by electricity-using capital. Not only is the component of capital where only electricity can be used (e.g., for motors and lighting) large, but processes where it is possible to use other fuels (e.g., drying and separation process) are frequently dominated by electricity also. After electricity, capital stocks are mostly based on natural gas or oil, which of these two fuels is the more prominent varies notably from sector to sector. For example, for the sector producing electrical and optical equipment, natural-gas-fired capital stocks are significantly more important whereas for the sector producing non-metallic minerals (generally a much more energy-intensive sector), the majority of the machinery and equipment used runs on oil.

Another important feature of the capital stocks held by firms in our data, illustrated in Table 1, is the fact that very few sectors hold any coal-fired machinery and equipment. The sectors in which there is coal-fired equipment in place are those that are generally characterized by higher levels of energy intensity.

3.3 Descriptive statistics

Table 2 below presents some basic descriptive statistics for firms in our data. Over the period from 2004 to 2009, the average firm employed 120 people, and had an annual turnover of €74 million. Firms are highly heterogeneous in terms of levels of output and size, as illustrated by the large standard deviations on these variables. Approximately six percent of the firms in our data are multi-unit firms and approximately 26 percent are foreign-owned. At an average rate of 98 percent, the utilization rate of fuel-using capital is very high; this suggests that capital costs are a much more important component of total operating costs than fuel costs.

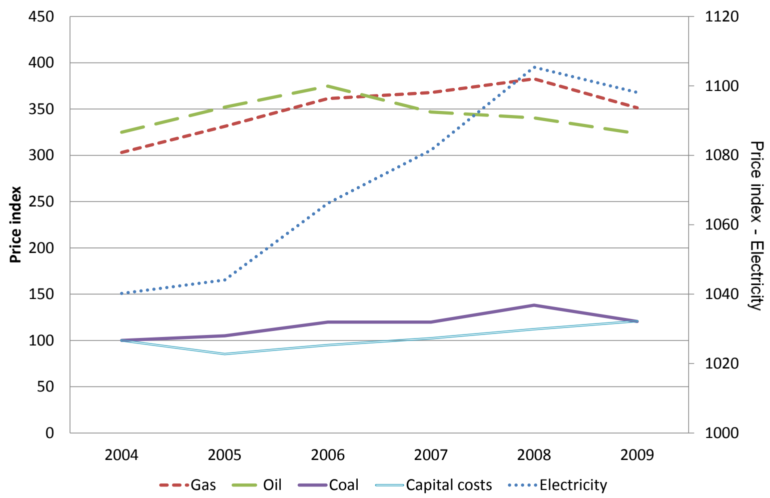
As there is a large divergence in the energy prices in terms of their absolute values, all fuel price indices are normalized by the price of coal in the base year (i.e., 2004). The evolution of

Table 2: Descriptive statistics

	Mean	Std dev	Median	Mean value in:		
				2004	2007	2009
Output (000's real 2007€)	74,422.96	492,579.00	7,847.76	68,301.32	81,417.79	74,830.32
Number of employees	120.95	250.52	49.00	119.55	125.68	112.14
Multi-unit dummy	0.06	0.25	0	0.06	0.07	0.06
Foreign-owned dummy	0.28	0.45	0	0.28	0.27	0.28
Fuel utilization	0.98	0.10	1.00	0.97	0.98	0.98
Sectoral output index (2004 = 100)	1.01	20.21	100.00	100.00	113.58	80.02
Capital expenditure - by type (000's real 2007€):						
Electricity (substitution possible)	2,811.25	17,476.73	421.13	2,512.86	2,823.94	3,067.49
Electricity (no subs. possible)	2,913.82	22,198.33	296.46	2,489.22	2,940.55	3,254.56
Gas	3,291.14	38,223.11	329.13	2,733.12	3,347.32	3,647.28
Oil	2,355.98	15,519.58	353.48	2,000.17	2,375.36	2,625.97
Coal	430.99	2,245.60	0.00	375.51	426.95	478.40
Price indices:						
(Fuel prices indices are relative to the price of coal)						
Capital (2004 = 100)	101.96	11.27	100.00	100.00	102.34	120.90
Electricity	1,071.13	24.77	1,066.18	1,040.19	1,081.49	1,098.12
Gas	348.61	26.34	351.33	303.13	337.79	351.33
Oil	344.15	17.43	346.84	324.95	346.48	323.51
Coal (2004 = 100)	116.63	12.27	119.83	100.00	119.83	120.55

these prices is illustrated in Figure 1. On average over the period studied, the price of electricity is very high relative to that of the other fuels (and is thus represented on a separate axis). In 2004 the price of electricity per TOE is approximately ten times higher than coal, and three times greater than natural gas and oil. In general electricity prices in Ireland are expensive relative to other European countries. This is largely due to high dependency on imported fossil fuels. Ireland also has high transmission and distribution costs due to the dispersed nature of the population.

Figure 1: Price indices



For the majority of fuels, prices are trending upwards until 2008, at which point there is a relative decline. For firms in our data, the average oil price declines after 2006 - this is driven by decreases in the price of the heavy fuel oil component of the oil price (the price of the light fuel oil component continued to trend upwards until 2008). The price of electricity increases significantly from 2005 to 2008 - this is driven largely by increasing natural gas prices, as the vast majority of electricity generated in Ireland comes from natural-gas-fired power plants. In recent years, the need to invest in the network to bring renewable generation sources (generally located far from load centers) on stream has further added to electricity costs.

From 2004 to 2005 there was a small decline in the cost of capital for Irish manufacturing firms, which was largely reversed by 2006. This variable then followed a modest upward trend to 2009 driven by changes in the interest rate and a modest increase in the depreciation rate for the machinery-and-equipment component of capital.

4 Results

4.1 System estimation results

As noted in Section 2, the first step of the analysis involves estimating the frictionless stock of capital for each fuel type. The results of the system estimations are presented in Table 3 below. Our main estimates are based on a system that does not include coal-using capital stocks; as only a small proportion of firms in our data utilize coal-fired capital (approximately one-quarter), the inclusion of coal in the system leads to a much reduced sample size and inference based on a small number of unrepresentative firms.[8] However, as a robustness check we also estimate the system including coal; the results are presented in Table 4 below.

Table 3: Equation (5) - System estimation results

	Electricity	Natural gas	Oil
Cost ($\frac{1}{1-\alpha}$)	-0.2359	-0.2359	-0.2359
	(0.0166)***	(0.0166)***	(0.0166)***
Efficiency(γ)	0.1337	0.0689	0.0075
	(0.0079)***	(0.0043)***	(0.0025)***
Sectoral growth (β)	0.0011	0.0005	0.0006
	(0.0002)***	(0.0002)***	(0.0001)***
Time trend (τ)	0.0031	0.0238	0.0259
	(0.0018)*	(0.0017)***	(0.0016)***

_N = 8,084. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The results show that there is a negative relationship between the stock and cost of capital, as would be expected. As noted previously, the estimated coefficient on the cost term corresponds to the elasticity of substitution across fuel-using capital stocks with respect to their capital costs. With a estimated coefficient of -0.24, Table 3 illustrates that the demand for fuel-using capital is highly inelastic with respect to changes in its running costs.

Turning to the other parameters included in the estimation, there are some notable differences across fuels in terms of the magnitude of the coefficients, but in all cases, the signs on the coefficients are the same across fuels and in line with our priors. For all capital types, the efficiency variable, calculated at the sector level, is positive and significant. It is to be expected that capital is more highly valued if it is more efficient. Increases in efficiency have the largest effect on the demand for electricity-driven capital. The sectoral growth term is also positive and significant for all types of capital - indicating higher demand for capital as output increases. This variable will also reflect firm entry and exit, and thus captures sector composition effects.[9] Finally, we note that the time trend variable is always positive and significant indicating that the demand for each type of capital is growing over time.

[8] As noted previously, firms utilizing coal are found only in a small number of energy-intensive sectors.

[9] For discussions of the relationship between sectoral activity level, sectoral composition and energy use refer to, for example, Ang et al. (2015); Su and Ang (2012); Ang and Choi (1997).

It should be noted that our both the dependent variable and the independent capital costs variable in our data may be subject to measurement error.[10] Measurement error in the dependent variable may result in inefficient estimates. However, we are not overly concerned about this as, even with the possibility of measurement error in the capital stocks, the coefficients on the explanatory variables remain statistically significant. Measurement error in the cost variable may be a greater cause for concern as measurement error in an independent variable can give rise to attenuation bias.[11] Specifically, measurement error may bias the estimated coefficients towards zero; thus the price elasticity estimates of the demand for capital presented in Table 3 may present lower-bound estimates of the true value.

The SUR estimation results for those firms that, in addition to using electricity, natural gas and oil, also utilize coal-fired capital equipment are presented in Table 4. The sample size is much reduced in this system estimation, and only three NACE 2-digit sectors (notably, the three most energy-intensive of Irish manufacturing) are represented. The results confirm our priors that these firms are notably different from the full sample. What is particularly striking from the results is that these firms show a much lower elasticity of demand for capital stocks in response to changing running costs. Also notable is that, for these firms, increased efficiency of natural gas, oil and coal-fired capital leads to a decrease in the demand for these stocks; possibly indicating that as the stocks become more efficient firms demand less of them as the same levels of output can be produced with lower stock levels. For all types of capital however there is a positive relationship between stocks and the sectoral growth and time trend variables, the coefficients on these variables are also very similar across the four types of capital.

Table 4: Equation (5) - System estimation results including coal

	Electricity	Natural gas	Oil	Coal
Cost ($\frac{1}{1-\alpha}$)	-0.0126	-0.0126	-0.0126	-0.0126
	(0.0050)**	(0.0050)**	(0.0050)**	(0.0050)**
Efficiency(γ)	0.0234	-0.0057	-0.0060	-0.0019
	(0.0031)***	(0.0018)***	(0.0027)**	(0.0006)***
Sectoral growth (β)	0.0012	0.0012	0.0011	0.0012
	(0.0004)***	(0.0004)***	(0.0004)***	(0.0004)***
Time trend (τ)	0.0206	0.0259	0.0237	0.0254
	(0.0031)***	(0.0030)***	(0.0030)***	(0.0029)***

_N = 2,210. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

An indication of the magnitude of the adjustment costs for firms in our data is given by looking at the differences between firms' actual stock of capital and the stock predicted by our model (which represents each firm's frictionless stock of capital). Useful metrics for comparing actual values with model estimates are the symmetric mean and median absolute percentage error (sMAPE and sMdAPE), which we calculate based on the results presented in Table 3. The

[10]A discussion of measurement error in panel data models is provided by Griliches and Hausman (1986).
[11]Research discussing measurement error and its effects include Griliches (1974) and Griliches (1986).

sMAPE is a commonly-used measure of forecast accuracy, and is based on percentage difference between the predicted and actual values, taken on average across values of i. The formula for calculating the sMAPE is:

$$sMAPE = \frac{1}{n}\sum \frac{|F_i - A_i|}{|A_i| + |F_i|} \tag{10}$$

While sMAPE takes the mean across i, sMdAPE uses the median value.

Table 5: Magnitude of adjustment costs

	Electricity	Natural gas	Oil
sMAPE	23%	23%	22%
sMdAPE	19%	19%	19%

Table 5 shows that the average difference between actual and frictionless stocks of capital for firms in our data ranges from 22 percent for coal-fired capital to 23 percent for capital that runs on electricity and natural gas. The range of median values is approximately 19 percent for all types of capital. These preliminary comparisons of the actual versus predicted capital stocks are indicative that, for many firms in the data, their current stocks of capital are significantly different from their frictionless levels, which suggests that capital adjustment costs may be substantial.

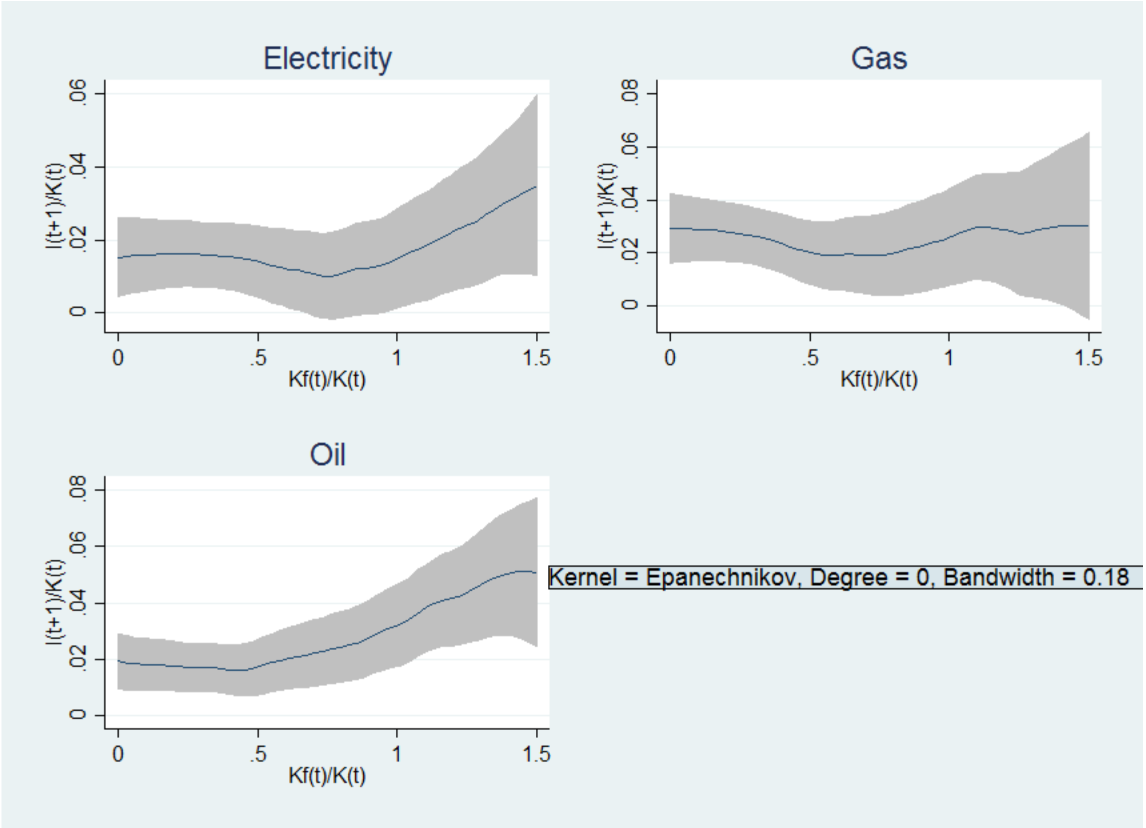
4.2 Kernel estimation results

We next turn to the results from our non-parametric, kernel estimation. As outlined in Section 2, for each type of capital, i, we generate a variable $\frac{K^*_{it}}{K_{it}}$ that represents the gap between frictionless and current capital stocks at time t, based on the estimates presented in Table 3. Using non-parametric regression we estimate the function presented in equation (8); the results are displayed in Figure 2 for electricity, natural gas and oil-fired capital.

Before proceeding to the estimated investment functions, it is important to note the four possible shapes of the desired investment function outlined by Goolsbee and Gross (2000).[12] In the absence of any adjustment costs, the investment function will cross the X axis when the ratio of the frictionless to the actual capital stock is exactly equal to one, and the slope of this function will be equal to one. This implies that any gap between actual and desired investment will be closed immediately. If the adjustment costs are quadratic, the relationship between actual and desired investment will be linear, but the slope will be less than one, implying that a constant part of the gap between actual and desired investment will be closed in each period. If there are large adjustment costs associated with disinvestment, or if investment is irreversible, this will be indicated by a flat region in the investment function when actual capital stock exceeds the frictionless level. Finally, Goolsbee and Gross (2000) note that non-convexities in adjustment costs will manifest themselves as convexities in the investment response function

[12] For further details refer to Andrew B. Abel (1994); Dixit and Pindyck (1994).

Figure 2: Investment in fuel-using capital



when desired capital is greater than actual capital, indicating that large deviations in the levels of desired investment lead to proportionately larger changes in actual investment, relative to small deviations in investment levels.

Figure 2 shows the investment response of fuel-using capital stocks when the current stocks of capital (K_t) are not equal to their frictionless levels (K_t^f). Looking first at electricity-using capital stocks, the adjustment path of electricity-using capital appears to be divided into two components. In the region of the graph where the frictionless stock of capital is less than the actual capital, i.e., $\frac{K_t^f}{K_t} < 1$, firms would like to divest their capital assets. However, this region of the investment response function is relatively flat. This suggests irreversibility of investment, meaning that for increasing costs of electricity-using capital stock firms will not be able to divest their assets or that to do so would be prohibitively costly.

For values of K_t^f/K_t greater than one, the slope of the investment response function is positive, although clearly less than one - indicating that firms will invest when their capital stocks are below the desired level, but investment will have associated adjustment costs and thus the frictionless level of capital stocks will not be reached within a single time period. A Chow test was carried out to test the equality of the slope of the investment response function before and

after the point of inflection (0.75), and the null hypothesis of equal slopes was strongly rejected (Prob>F = 0.000). The average slope of the investment function to the right of the inflection point is 0.034. According to the partial adjustment model, this parameter indicates how much of the gap between frictionless and actual stocks is reduced within each period, where a value of one would imply instantaneous adjustment. A value of 0.034 implies a slow adjustment process, and shows that capital adjustment costs are large.

The estimated kernel function for natural-gas-using capital stocks is somewhat less smooth than was the case for electricity, but the graph does illustrate a similar path of adjustment. Once again the investment response function is relatively flat for values of $\frac{K_t^f}{K_t}$ less than one, this region of inaction again indicating irreversibility of investment. When the frictionless level of capital is greater than the current level, the investment response is positive but slow, as suggested by the extremely flat slope of this portion of the response function. In this region of the estimated polynomial, the slope of the investment response function is only 0.014, indicating a very long path to full adjustment. Again a Chow test for equality of slopes on either side of the point of inflection strongly rejects the hypothesis that the slopes are equal: Prob>F = 0.000.

Turning next to the path of adjustment for oil-using capital stocks, once again the investment response function is characterized by a region of inaction where a firm cannot divest its stocks despite the fact that it holds more oil-using capital than it desires. Beyond the point of inflection firms do adjust stocks, but the slope of less than one indicates the presence of adjustment costs. The slope of the function beyond the inflection point is 0.037, again indicating a slow path to full adjustment.

4.3 Investment response to changing energy prices

We illustrate the effect of the adjustment costs on the investment response for the different types of capital by simulating a 10 percent change (increase or decrease) in the price of each of the fuel types. Due to the irreversibility of capital investments - as illustrated by the regions of inaction in Figures 2 above, firms will not be able to reduce their stock of capital in response to increasing fuel prices (or rather it would be excessively costly for them to do so). Thus price increases of 10 percent have no effect on capital divestment; firms must wait for the capital in excess of the desired amount to depreciate away.

On the other hand, when the price of a particular fuel falls, firms will respond in order to bring their current level of capital closer to the new frictionless level. However, due to the presence of adjustment costs, full adjustment of stocks to the new frictionless level will take a significant amount of time - this is illustrated in Table 6 below.

Table 6: Investment response to a 10% fuel price decrease

	K_1	K_2^*	Years to adjust
Electricity	€618,441	€622.1,76	28
Natural gas	€393,910	€393,927	72
Oil	€393,206	€393,406	26

In period one, the average firms holds €618,441 worth of electricity-using capital stock. A 10 percent decrease in the price of electricity will mean that a firm will want to hold approximately €622,000 worth. Full adjustment to this new level of capital stock will, according to the results of equation (9), take 28 years. The path to full adjustment is similar for oil-fired capital equipment while, for natural-gas-using capital the full adjustment process is notably longer. In all cases the speed of adjustment is slow, indicating significant adjustment costs.

Our estimated adjustment costs are an order of magnitude higher than those estimated by other papers in the literature. For example, Jones (1995), based on results from a dynamic linear logit model, estimates an adjustment costs parameter of 0.72 - implying that almost 30% of the adjustment takes place within a single year. This is a much shorter adjustment path than our estimates suggest, and is similar to other studies that follow a similar approach to estimating adjustment. For example, Urga and Walters (2003) estimate a partial adjustment parameter of 0.73, implying that 27% of adjustment to a price change takes place within one year of that change occurring. A similar annual adjustment parameter is estimated by Cho et al. (2004); their estimates ($\lambda = 0.79$) implies that 21% of adjustment takes place within one year of a price change. Looking at adjustment separately according to firm size, Brännlund and Lundgren (2004) find that for the smallest firms (firms in the lowest quartile of the fuel-use distribution) 90% of the long run response to a price change occurs within one year; for larger firms the figure is 63%. More recently, Steinbuks (2012) finds that the adjustment rate differs depending on the purpose for which the fuels are used; for aggregate energy consumption 74% of the response occurs within the first year, while for thermal heating process adjustment is somewhat slower with 53% of adjustment occurring within one year.

All these estimates are based on implicit estimation of adjustment costs. They show that the most common method used in the literature to date, i.e., the inclusion of lagged values of output or prices, is understating the true costs of full adjustment of capital stocks. These results suggest that using observed values of capital, as we do in our model, can more accurately capture the path to the full adjustment, and thus the associated adjustment costs. To illustrate this point we re-estimate the adjustment costs for aggregate capital stocks by including lagged values of the dependent variables (i.e., using the standard approach in the literature). This results in an estimated lambda parameter of 0.877 which implies that approximately 12% of the adjustment process takes place within the first year, compared to an average of 3% based on our results using observed capital stocks.

5 Conclusions

This paper analyzes the important, yet often ignored, link between capital adjustment costs and the choice of fuels used by manufacturing firms. We formulate a structural model that accounts for the short run complementarity between fuel inputs and corresponding fuel-using capital stocks. Based on this model, we estimate, for each type of fuel-using capital, its frictionless stock that would be observed in a steady state. The observed deviations between actual and frictionless capital stocks reveal the level of adjustment costs faced by firms in our data.

Our econometric estimates show a significant variation in the optimal response of capital to changing fuel prices across different fuel-using technologies. For all these technologies, we find a significant gap between the frictionless and observed capital stocks, which indicates significant costs to capital adjustment. Furthermore, the shape of the investment response function shows a region of inaction when capital is above its frictionless level; this suggests there are prohibitively large costs to capital divestment. Our estimates of capital adjustment costs are an order of magnitude larger compared to earlier studies that rely on implicit estimation based on lagged values of output and fuel prices. Based on these findings we conclude that our approach may capture more realistic dynamics of fuel substitution which are currently missing from both econometric analysis of fuel substitution and from the energy-environment component of CGE models.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012) 'The Environment and Directed Technical Change.' *American Economic Review* 102(1), 131–66

Andrew B. Abel, Janice C. Eberly (1994) 'A Unified Model of Investment Under Uncertainty.' *The American Economic Review* 84(5), 1369–1384

Ang, BW, and Ki-Hong Choi (1997) 'Decomposition of Aggregate Energy and Gas Emission Intensities for Industry: A Refined Divisia Index Method.' *The Energy Journal* pp. 59–73

Ang, BW, XY Xu, and Bin Su (2015) 'Multi-country Comparisons of Energy Performance: The Index Decomposition Analysis Approach.' *Energy Economics* 47, 68–76

Atkeson, Andrew, and Patrick J. Kehoe (1999) 'Models of Energy Use: Putty-Putty versus Putty-Clay.' *American Economic Review* 89(4), 1028–1043

Bjørner, Thomas Bue, and Henrik Holm Jensen (2002) 'Interfuel Substitution within Industrial Companies: An Analysis Based on Panel Data at Company Level.' *The Energy Journal* 23(2), 27–50

Brännlund, Runar, and Tommy Lundgren (2004) 'A Dynamic Analysis of Interfuel Substitution for Swedish Heating Plants.' *Energy Economics* 26(6), 961–976

Burniaux, Jean-Marc, and Jean Château (2008) 'An Overview of the OECD Env-linkages Model'

Burniaux, Jean-Marc, and Truong P Truong (2002) 'GTAP-E: an Energy-Environmental Version of the GTAP Model.' *GTAP Technical Papers* p. 18

Caballero, Ricardo J (1999) 'Aggregate Investment.' *Handbook of Macroeconomics* 1, 813–862

Caballero, Ricardo J, and Eduardo Engel (2003) 'Adjustment Is Much Slower than You Think.' Technical Report, National Bureau of Economic Research

Caballero, Ricardo J, and Eduardo MRA Engel (1999) 'Explaining Investment Dynamics in US Manufacturing: A Generalized (S, s) Approach.' *Econometrica* 67(4), 783–826

Cho, Won G, Kiseok Nam, and Jose A Pagan (2004) 'Economic Growth and Interfactor/Interfuel Substitution in Korea.' *Energy Economics* 26(1), 31–50

Dixit, Avinash K, and Robert S Pindyck (1994) *Investment Under Uncertainty* (Princeton University Press)

ESRI (2012) www.esri.ie/irish_economy/databank, accessed on 16.01.2013

Fuss, Melvyn A. (1977) 'The Demand for Energy in Canadian Manufacturing: An Example of the Estimation of Production Structures with Many Inputs.' *Journal of Econometrics* 5(1), 89–116

Gallachóir, Brian P Ó, Alessandro Chiodi, Maurizio Gargiulo, Paul Deane, Denis Lavigne, and Ullash Kumar Rout (2012) 'Irish TIMES Energy Systems Model'

Goolsbee, Austan, and David B Gross (2000) 'Estimating the Form of Adjustment Costs with Data on Heterogeneous Capital Goods.' *Mimeograph, University of Chicago*

Griliches, Zvi (1974) 'Errors in Variables and Other Unobservables.' *Econometrica* 42(6), 971–998

_ (1986) 'Economic Data Issues.' *Handbook of Econometrics* 3, 1465–1514

Griliches, Zvi, and Jerry A Hausman (1986) 'Errors in Variables in Panel Data.' *Journal of Econometrics* 31(1), 93–118

Hall, Vivian Bruce (1986) 'Industrial Sector Fuel Price Elasticities Following the First and Second Major Oil Price Shocks.' *Economics Letters* 20(1), 79–82

Haller, Stefanie A (2014) 'Do Domestic Firms Benefit from Foreign Presence and Import Competition in Irish Services Sectors?' *The World Economy* 37(2), 219–243

Haller, Stefanie A., and Marie Hyland (2014) 'Capital-Energy Substitution: Evidence from a Panel of Irish Manufacturing Firms.' *Energy Economics* 45, 501–510

Jacoby, Henry D, and Ian Sue Wing (1999) 'Adjustment Time, Capital Malleability and Policy Cost.' *The Energy Journal* pp. 73–92

Jones, Clifton T. (1995) 'A Dynamic Analysis of Interfuel Substitution in U.S. Industrial Energy Demand.' *Journal of Business & Economic Statistics* 13(4), 459–465

Paltsev, Sergey, John M Reilly, Henry D Jacoby, Richard S Eckaus, James R McFarland, Marcus C Sarofim, Malcolm O Asadoorian, and Mustafa HM Babiker (2005) 'The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4.' Technical Report, MIT Joint Program on the Science and Policy of Global Change

Papageorgiou, Chris, Marianne Saam, and Patrick Schulte (2016) 'Substitution Between Clean and Dirty Energy Inputs-A Macroeconomic Perspective.' *Review of Economics and Statistics*

Pindyck, Robert S. (1979) 'Interfuel Substitution and the Industrial Demand for Energy: An International Comparison.' *The Review of Economics and Statistics* 61(2), 169–79

Serletis, Apostolos, and Asghar Shahmoradi (2008) 'Semi-Nonparametric Estimates of Interfuel Substitution in US energy demand.' *Energy Economics* 30(5), 2123–2133

Serletis, Apostolos, Govinda R Timilsina, and Olexandr Vasetsky (2010) 'Interfuel Substitution in the United States.' *Energy Economics* 32(3), 737–745

Steinbuks, Jevgenijs (2012) 'Interfuel Substitution and Energy Use in the UK Manufacturing Sector.' *The Energy Journal* 33(1), 1–29

Steinbuks, Jevgenijs, and Karsten Neuhoff (2014) 'Assessing Energy Price Induced Improvements in Efficiency of Capital in OECD Manufacturing Industries.' *Journal of Environmental Economics and Management* 68(2), 340–356

Stern, David I (2012) 'Interfuel Substitution: A Meta-Analysis.' *Journal of Economic Surveys* 26(2), 307–331

Su, Bin, and BW Ang (2012) 'Structural Decomposition Analysis Applied to Energy and Emissions: Some Methodological Developments.' *Energy Economics* 34(1), 177–188

Urga, Giovanni, and Chris Walters (2003) 'Dynamic Translog and Linear Logit Models: A Factor Demand Analysis of Interfuel Substitution in US Industrial Energy Demand.' *Energy Economics* 25(1), 1–21

Wing, Ian Sue (2008) 'Explaining the Declining Energy Intensity of the US Economy.' *Resource and Energy Economics* 30(1), 21–49

Žnuderl, Nuša, and Ide Kearney (2013) 'User Cost of Debt-Financed Capital in Irish Manufacturing Industry: 1985 - 2011.' *ESRI Working Paper No. 448*

Appendix

Results using lagged values

To test the robustness of our estimation results and to check for any potential simultaneity problems in our estimates, we re-run the systems model using lagged value of prices and efficiency. The results are presented in Table 7 below. While the coefficients on some of the variables (most notably the cost term) differ in terms of their order of magnitude from the main results presented in Table 3 above, the sign and the significance of the results do not change.

Table 7: System estimation using lagged exogenous variables

	Electricity	Natural gas	Oil
Cost ($\frac{1}{1-\alpha}$)	-0.1316	-0.1316	-0.1316
	(0.0160)***	(0.0160)***	(0.0160)***
Efficiency(γ)	0.0594	0.0341	0.0011
	(0.0081)***	(0.0045)***	(0.0027)
Sectoral growth (β)	0.0007	0.0006	0.0006
	(0.0002)***	(0.0002)***	(0.0002)***
Time trend (τ)	0.0007	0.0118	0.0114
	(0.0020)	(0.0019)***	(0.0017)***

_N = 6,383. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

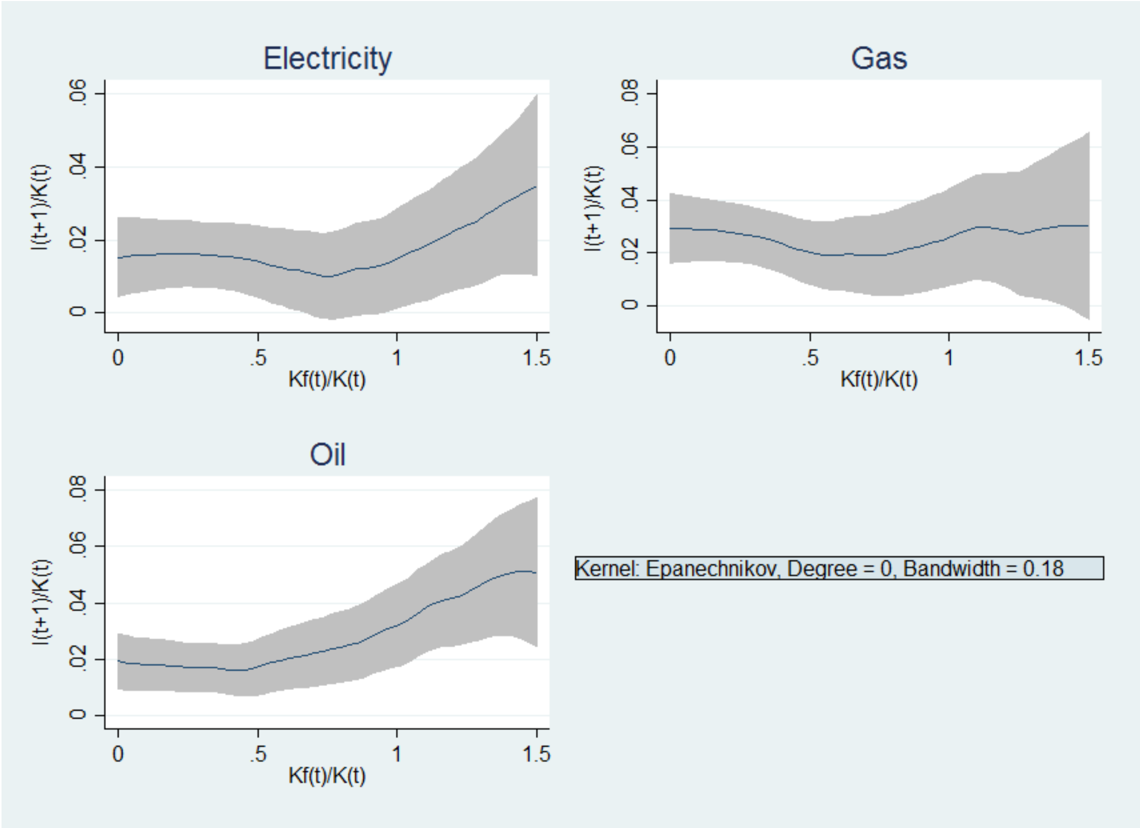
More importantly however, Table 8 shows that recalculating the SMAPE and SMdAPE based on these estimates results in almost identical values to those presented in Table 5. Furthermore, re-estimating the kernel regressions does not alter our conclusions regarding the importance of capital adjustment costs.

Table 8: Magnitude of adjustment costs - results based on lagged exogenous variables

	Electricity	Natural gas	Oil
sMAPE	23%	23%	22%
sMdAPE	18%	19%	19%

The kernel functions based on estimates using lags as instruments are displayed in Figure 3.

Figure 3: Investment in fuel-using capital - using lags as instruments



System including coal - estimated polynomials

The kernel regression functions for those firms that utilize coal in addition to electricity, gas and oil are displayed below. Figure 4 shows a similar adjustment path for capital as the polynomials displayed previously for the larger sample of firms using only three fuels. Again we find that there are significant costs to divesting assets - illustrated by the flat "region of inaction". Furthermore, the slope, much smaller than one, indicates the presence of significant adjustment costs to capital investment. In this case the confidence bands for larger values of K^f/K are much wider, due to the greatly reduced sample size.

Figure 4: Investment in fuel-using capital, firms that utilise coal