Capital Adjustment and the Optimal Fuel Choice

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This paper analyzes the important, yet often ignored, link between capital adjustment and the choice of fuels used by manufacturing firms. We propose a novel econometric framework, which explicitly incorporates heterogenous fuel-using capital stocks in the estimation of optimal fuel choice, and apply it to a large panel of Irish manufacturing firms. Our econometric estimates show a significant variation in optimal response of capital to changing fuel prices across different fuel-using technologies. For all these technologies, we find significant costs to capital adjustment. These costs are much larger compared to earlier estimates of adjustment costs based on lagged values of output and fuel prices. This implies that the path to full adjustment of capital stocks in response to changing fuel prices may be much longer than previously thought.

Keywords: capital adjustment, fuel choice
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1 Introduction

The ability of firms to substitute from dirty to cleaner fuels in the face of changing prices has important implications in terms of the effectiveness and costliness of climate policy (as has been discussed by, for example, Stern, 2012 and Acemoglu et al., 2012). 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.

There is a large body of economic literature that looks at the issue of fuel substitution. However, few, if any of these studies do 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, (Jones, 1995; Bjørner and Jensen, 2002; Urga and Walters, 2003; Serletis and Shahmoradi, 2008; Serletis et al., 2010), for example, 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 approach 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.

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 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).[1] That is the

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

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 heterogenous 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 studies that are concerned of energy and capital utilization (Atkeson and Kehoe, 1999), as well as adjustment dynamics of heterogenous 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 capital adjustment costs for heterogenous 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 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.

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, the demand for capital, 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 each period t a firm j maximizes its profit function, $\Pi_{j,t}$, given by

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

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

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

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 $V_{i,j,t} \cong \tilde{V}_{i,j,t} = \tilde{V}_{i,j} \cdot \tilde{V}_{j,t}$, so that $\ln(\widetilde{V}_{i,j,t}) = \ln(\widetilde{V}_{i,j}) + \ln(\widetilde{V}_{i,t})$, where $\widetilde{V}_{i,t}$, 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

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

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.

2.2 Empirical specification

2.2.1 Predicting the frictionless stock of capital

The econometric estimation of equation (4) includes a number of additional control variables to account for unobservable effects correlated with the choice of energy-using capital. These include firm capacity utilization, $U_{i,j,t}$, real sectoral growth rates, Y_t, and a time trend, T_t, that captures exogenous technological progress. With these additions, equation (4) becomes:

$$\ln(K^f_{i,j,t} \cdot U_{i,j,t}) = \widetilde{V}_{i,j} + \gamma \ln \widetilde{V}_{i,t} + \frac{1}{\alpha - 1} \ln \left[p^K_{i,t}(r_t + \delta) + \frac{p^E_{i,t}}{\widetilde{V}_{i,j,t}} \right] + \beta Y_t + \tau T_t + \epsilon_{i,j,t}, \tag{5}$$

Equation (5) can be estimated using either a fixed or random effects model. Hausman tests indicate the appropriateness of using fixed-effects estimation in the case of all four types of capital. Therefore, we estimate the frictionless stock of fuel-using capital for electricity, natural gas, oil and coal using equation-by-equation fixed-effects estimation. To account for the fact that the errors may be correlated across each of these four equations, as a robustness test we also estimate the frictionless stock of capital for each fuel within a seemingly-unrelated regression (SUR) model, wiping each equation of fixed effects by demeaning the data. As the majority of firms in our data utilize no coal-fired capital, we do not include coal-using capital in our systems estimation. The results of the SUR estimation are presented in the Appendix. While there are some differences in the estimated coefficients between the OLS and SUR estimates, the differences are generally small and do not affect the interpretation of the results.

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_i^f, 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:

$$\frac{K^f_{i,j,t}}{K_{i,j,t}} = \theta exp(-\epsilon_{i,j,t}) \tag{6}$$

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 (6) 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:

$$\frac{I_{i,j,t+1}}{K_{i,j,t}} = f\left(\frac{K^f_{i,j,t}}{K_{i,j,t}}\right) + \eta_{i,j,t} \tag{7}$$

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 (7) is estimated using the Nadarya-Watson estimator (which is based on a polynomial of degree zero) to allow for flexible estimation[2]; 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 are 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 (7) represents the magnitude of 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:

$$\delta K_t = \lambda(K_t^f - K_{t-1}) \tag{8}$$

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 are likely to differ for different levels of desired investment, Chow tests are conducted to test the continuity of the slope of the investment function.

3 Data

Our data set is the Census of Industrial Production (CIP) for the Republic of Ireland. The CIP is conducted annually by the Central Statistics Office (CSO), and response to the survey is compulsory. The purpose of the census is to produce structural information on various accounting measures such as industry classification, location, sales, employment, intermediate inputs, capital acquisitions and trade. Larger firms are asked to complete a more detailed questionnaire which includes information on energy expenditure by fuel. We concentrate our analysis on these firms and for the period from 2004 to 2009, when data on fuel expenditure were collected on an annual basis. We exclude from our analysis firms directly engaged in the energy sector, i.e. those involved in mining and extraction, and utilities. This leaves us with approximately 8,600 firm-year observations.

The census also asks firms for information on capital acquisitions by type of capital. Capital acquisitions data is 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

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[2] 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.

fuel-using stocks is technologically feasible. Firms report acquisitions and disposal of capital, but not stocks. Stocks are calculated using the perpetual inventory method; for more details please refer to Haller and Hyland (2014).

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.

Fuel prices are not recorded in our data and, as such, a number of external sources are used. The prices of oil and coal are from the ESRI Databank (ESRI, 2012). The price of electricity and natural gas come from Eurostat's price series for industrial users.[3] 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 electricity and gas used in that sectoral (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 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 price bands for electricity and natural gas, based on end-user prices.

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. For each firm in the data we observe its fuel inventories at the beginning and at the end of each year.[4] Based on these data we calculate an average annual utilization rate for natural-gas, oil and coal-fired capital. 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, purchases and closing stocks. We assume that it is not possible to store electricity and, therefore, utilization of electricity-using capital stocks will always be 100%.

3.1 Descriptive statistics

Table 1 below presents some basic descriptive statistics for firms in our data. The average firm employees approximately 120 people, and has an annual turnover of €74 million. Firms are highly heterogeneous in terms of levels of output and their fuel expenditures, as illustrated by the large standard deviations on these variables.

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

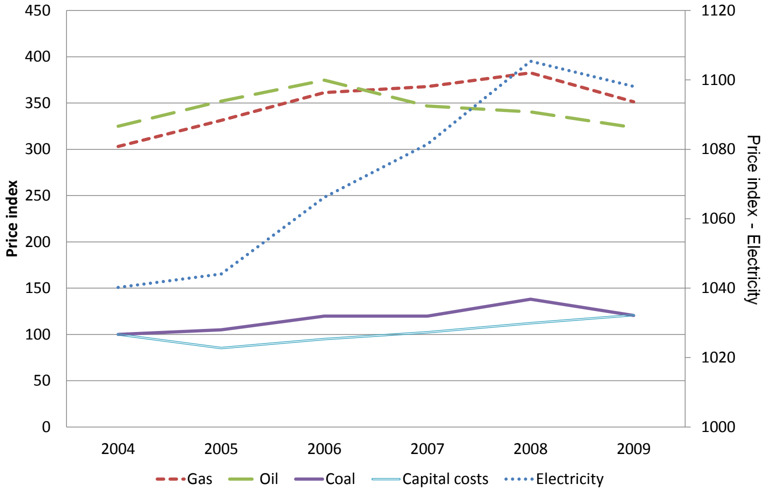
[4] This information is available for the sum of all fuels, but not disaggregated by fuel type.

Table 1: Descriptive statistics

	Mean	Std dev	Median
Employees (#)	121	251	49
Output (€1000)	74,423	492,579	7,848
Expenditure - electr. (€1000)	384	1,593	73
Expenditure - natural gas (€1000)	162	2,145	0
Expenditure - oil (€1000)	100	1,644	1
Price - electricity (€/TOE)	1,506	285	1,522
Price - natural gas (€/TOE)	459	128	427
Price - oil (€/TOE)	494	108	509

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 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. 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. Therefore, the price index for electricity is represented on a separate axis.

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.

3.2 Disaggregating machinery and equipment by fuel type

As mentioned in Section 3.1, we are interested in the machinery and equipment component of capital stocks, disaggregated by type of capital - where type refers to the fuel used. As these details are not available in the CIP, following Steinbuks (2012), we use data from the TIMES model for Ireland (Gallachóir et al., 2012), and apply it to the first year of our data (2004) to disaggregate machinery and equipment into five subcomponents based on the breakdown in the TIMES data. The subcomponents of machinery and equipment 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); those that run on natural gas; on oil; and on coal.[5] Average sectoral capital stocks in 2004 for each of the five subcomponents are given in Table 2 below.

Table 2: Average breakdown of machinery by sector and type in 2004 (000s of €2007)

Sector manufacturing:	Electr. only	Electricity	Natural gas	Oil	Coal
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	-

Some interesting patterns can be seen in Table 2 above. Firstly, Table 2 shows the relative importance of machinery and equipment driven by electricity in almost all sectors. With only a

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

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 run on oil.

Another important feature of the capital stocks held by firms in our data, illustrated in Table 2, is the fact that very few sectors hold any coal-fired machinery and equipment. The sectors in which there are some coal-fired equipment in place are those that are generally characterized by higher levels of energy intensity.

4 Results

4.1 Fixed-effects 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 fixed-effects estimations are presented in Table 3 below.

Table 3: Equation (5) - fixed-effects estimation results

	Elec	Natural gas	Oil	Coal
Cost ($\frac{1}{1-\alpha}$)	-0.632	-0.015	-0.176	-0.065
	(0.034)***	(0.037)	(0.031)***	(0.066)
Efficiency (γ)	0.178	0.165	0.040	-0.015
	(0.013)***	(0.011)***	(0.008)***	(0.010)
Time (τ)	0.000	0.011	0.024	0.032
	(0.002)	(0.002)***	(0.002)***	(0.006)***
Growth (β)	0.001	0.001	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.001)**
_cons	5.493	-16.807	-41.892	-58.519
	(4.330)	(4.984)***	(4.197)***	(11.648)***
N	8,061	8,461	8,461	2,382

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The results show that, for all types of capital, there is a negative relationship between the stock and cost of capital, as would be expected. Of the four types of capital, demand for electricity-using capital is most responsive to changes in running costs, a combination of the costs of capital and the fuel price. The demand for oil-using capital is much less responsive to changing costs. In the case of coal and natural-gas-using capital stocks, the cost term is also negative, but not statistically significant. It is not unexpected that the demand for coal-fired capital is unresponsive to changing costs as coal is an idiosyncratic fuel. Indeed, for a significant numbers of firms in our data, no coal-fired capital is employed. Those firms that do use coal are operating in the most energy-intensive sectors and, therefore, may differ from other firms in many respects. Furthermore, the price of coal is low relative to other fuels and, thus, modest changes in coal prices are unlikely to have a large effect on operating costs. For natural gas, it is possible that a significant proportion of natural-gas-using capital stocks are utilized for space heating, which may not be amenable to adjustment when prices change.

For all capital types, with the exception of coal-using capital, 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. The sectoral growth term is 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 capture sector composition effects.[6] Finally, we note that the time trend variable is (with the exception of electricity) positive and significant indicating that the demand for capital is growing over time.

We can get an idea of the magnitude of the adjustment costs for firms in our data 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). The 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. It is calculated as follows:

$$sMAPE = \frac{1}{n} \sum \frac{|F_i - A_i|}{|A_i| + |F_i|} \tag{9}$$

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

Table 4: Magnitude of adjustment costs

	Electricity	Natural gas	Oil	Coal
sMAPE	22%	25%	25%	22%
sMdAPE	17%	19%	20%	17%

Table 4 shows that the average difference between actual and frictionless stocks of capital for firms in our data range from 22% for electricity and coal using capital, to 25% for natural gas, while the median values range from 17% to 19%. 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, indicating that capital adjustment costs may be significant.

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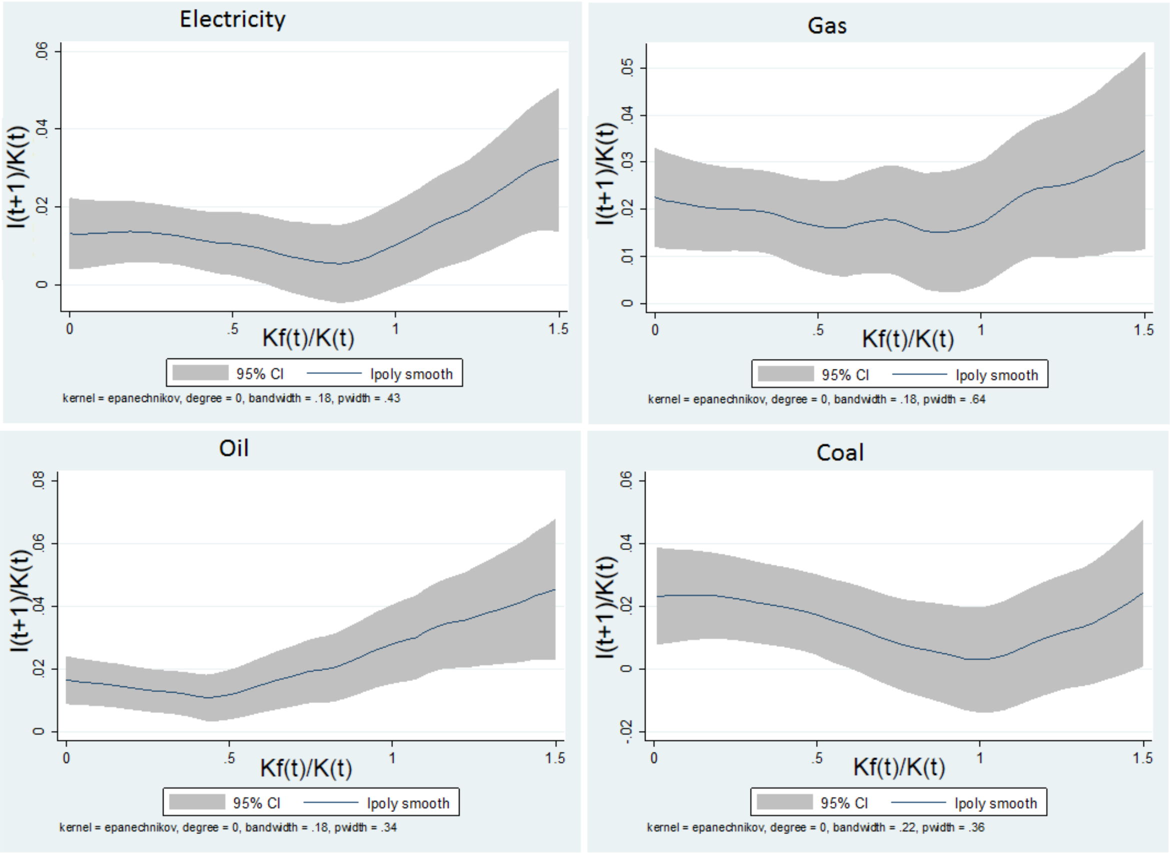
[6] For discussions of the relationship between sectoral activity level, sectoral composition and energy use refer to, for example, Ang et al. (2015); Su and Ang (2012); Ang and Choi (1997)

4.2 Kernel estimation results

We next turn to the results from our kernel estimates. 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. Using non-parametric regression we estimate the function presented in equation (7); the results are displayed in Figure 2 below for the four types of capital.

Figure 2: Investment in fuel-using capital stocks



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)[7]. In the absence of any adjustment costs, the investment function will cross the X axis when the ratio of frictionless to actual capital stock is exactly equal to one, and that 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

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

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 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 electricity-using capital stocks when the current stock of electricity-using capital (K_t) is not equal to the frictionless stock (K_t^f). 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., $\frac{K_t^f}{K_t} < 1$, a firm would like to divest its capital assets. However, this region of the investment response function is relatively flat. This suggest irreversibility of investment, meaning that for increasing costs of electricity-using capital stock a firm will not be able to divest its assets, or rather 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 a firm will invest when its 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 (0.8), and the null hypothesis of equal slopes was strongly rejected (F = 490.12, Prob>F = 0.00). The average slope of the investment function to the right of the inflection point is 0.04. 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 0.04 implies a slow adjustment process, and shows that capital adjustment costs are significant.

The estimated kernel function for natural-gas-using capital stocks is 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 indicating irreversibility of investment. When the frictionless level of capital is greater than the current level, the investment response is positive but slow. In this region of the estimated polynomial, the slope of the investment response function is 0.03, indicating a long path to full adjustment. Again a Chow test for equality of slopes on either side of the point of inflection rejects the hypothesis that the slopes are equal: F = 458.17, Prob>F = 0.00.

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 the it holds more oil-using capital than it desires. Beyond the point of inflection firms do adjust stocks, but the response is slow indicating the presence of significant adjustment costs - the slope of the function in the area where it is upward sloping is 0.03, again indicating a slow path to full adjustment.

Finally, Figure 2 also illustrates the investment response of coal-using capital stocks. A Chow test for a structural break in the investment response function at $\frac{K_t^f}{K_t} = 1$ rejects the null hypothesis of no structural break (F = 76.55, Prob>F = 0.00). The slope of the investment response functions when the frictionless stock of capital exceeds the current stock is 0.06, again indicating a slow adjustment process (albeit faster than for the other types of capital) due to the presence of adjustment costs.

4.3 Investment response to changing energy prices

We illustrate the effect of the adjustment costs on the investment response for the four different types of capital by simulating a ten 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 to 5 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 the table below.

Table 5: Investment response to a 10% fuel price decrease

	K_1	K_2^*	Years to adjust
Electricity	618.441	622.176	25
Natural gas	393.910	393.927	37
Oil	393.206	393.406	32
Coal	390.308	390.331	18

In period one, the average firms holds €618,441 worth of electricity-using capital stock. A ten percent decrease in the price of electricity will mean that a firm will want to hold €622,176 worth. Full adjustment to this new level of capital stock will, according to the results of equation (8) take 25 years. For natural gas and oil-using capital, the full adjustment process will take even longer, while for coal full adjustment to the new desired stock will take 18 years. 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 would suggested, 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, are 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.

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 complementarities 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 is currently missing in both econometric analysis of fuel substitution and in the energy-environment component of CGE models.

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Appendix

As noted in Section 2.2, our main model estimates are based on equation-by-equation fixed-effects regression. However, as decisions regarding the optimal level of fuel-using capital may be correlated across fuels, we re-estimate equation (5) using seemingly unrelated regression (SUR) techniques. In these estimates we omit coal-using capital stock as, for the majority of firms in the data, no coal-using stocks exist, thus including coal in this model would lead to a large decrease in the number of observations.

Table 6: Seemingly unrelated regression estimates of capital stock

	Electricity		Natural gas		Oil	
Price	-0.519	(0.023)***	0.046	(0.026)	-0.107	(0.024)***
Efficiency	0.114	(0.009)***	0.110	(0.005)***	0.016	(0.003)***
Time	0.006	(0.002)	0.010	(0.002)***	0.020	(0.002)***
Growth	0.001	(0.000)***	0.001	(0.000)***	0.001	(0.000)***
N	8,061		8,061		8,061	

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6 above confirms that for electricity- and oil-using capital, the relationship between capital costs and stock are negatively related. Furthermore, the size of the coefficients on the cost terms for these fuels are comparable to the fixed-effects estimates. For natural-gas-using capital the coefficient on price is, unexpectedly, positive; however, it is not statistically significant. The sectoral efficiency term is positive and significant for all types of capital and, as with the fixed-effects estimates, the time trend is positive and significant for capital stocks with the exception of electricity-using capital. All types of capital display a positive relationship between sectoral growth rate and capital stocks. For this variable, and for the time variable also, the coefficients estimated by the SUR model are very close in value to those estimated by the equation-by-equation fixed-effects model.

As the results from the SUR and fixed-effects models are highly similar, we do not believe that our results are being significantly impacted by any cross-equation correlations. Based on this we choose to use the fixed-effects model for our main estimates as it allows us to include estimates of the coal-using capital stocks without loosing a very large number of observations.