The Economic and Social Review, Vol. 47, No. 2, Summer, 2016, pp. 185-211

Analysing Residential Energy Demand: An Error Correction Demand System Approach for Ireland

JOHN CURTIS*
Economic and Social Research Institute, Dublin

BRIAN STANLEY
Economic and Social Research Institute, Dublin

Abstract: This paper analyses the Irish residential energy demand system by using variants of Deaton and Muellbauer's Almost Ideal Demand System model. Annual data from 1970 to 2013 are employed to estimate a demand system for solid fuels, oil, gas and electricity with the models incorporating quadratic and demographic terms to estimate long-run price and expenditure elasticities. This is the first attempt in an Irish context to estimate an energy demand system for the residential sector. Error correction models were also estimated to recover short-run elasticities. Against the backdrop of onerous climate and energy efficiency policy targets, and given the residential sector's substantial energy use, it is important to update energy demand elasticity estimates to better inform policy instrument design.

I INTRODUCTION

The curtailment and more efficient use of energy is an objective of several environmental policies driven by the fact that fossil fuel combustion is one of the main sources of the growth in global greenhouse gas emissions since 1970 (IPCC, 2014). For example, in January 2014 the EU Commission published a 2030 Climate and Energy Policy Framework that included a target reduction in greenhouse gas emissions of 40 per cent below the 1990 level, an EU-wide

Acknowledgements: Funding from the ESRI's Energy Policy Research Centre is gratefully acknowledged. We are appreciative of Valeria di Cosmo, Seán Lyons, Niall McInerney, Edgar Morgenroth and an anonymous referee's helpful comments and suggestions. All remaining errors or omissions are our own.

* Corresponding author: John Curtis, Economic and Social Research Institute, Whitaker Square, Sir John Rogerson's Quay, Dublin 2, Ireland. john.curtis@esri.ie

binding target for renewable energy of at least 27 per cent, and renewed ambitions for energy efficiency policies (European Commission, 2014). This framework was subsequently endorsed by the European Council in October 2014 (European Council, 2014). In recent years carbon taxes have been advocated as a mechanism to control emissions associated with fossil fuel combustion, whereas historically energy taxes were an important source of government revenues or earmarked for specific purposes like road infrastructure (OECD, 2013). There is an ongoing policy need for information on the price elasticity of energy demand to improve the efficacy of energy taxes.

There is a wide-ranging debate in the literature on energy elasticities. Energy price elasticities vary across countries due to cultural or climatic differences though there was some consensus in the 1970s and early 1980s that own-price elasticity of energy varied in the range of –0.03 to –0.5 (Kouris, 1983; Taylor, 1977). But since then price elasticities for energy have been gradually decreasing over time and there is also evidence that energy demand is more price responsive in poorer countries (Seale Jr and Solano, 2012). Price elasticities are fuel- and sector-specific (Smyth, 1996; Di Cosmo and Hyland, 2013) and differ in the short and long run (Blázquez *et al.*, 2013; IMF Staff, 2011). In addition estimated elasticity values can vary depending on estimation methods (Davis and Kilian, 2011; Menegaki, 2014). Therefore, to inform policy decisions, there is an ongoing need to update estimates of energy elasticities by country, sector and fuel. This is particularly relevant in the residential sector given its high energy demand. Within residential energy demand analysis, households are often considered a homogenous group. This decision is often due to insufficient data to assume otherwise because the data are often sector-level time-series data, which is the case in the analysis undertaken here. However, the residential sector possibly merits further disaggregation. For instance, path dependence, where households are confined to use specific fuels based on their heating systems means that switching between fuels is impossible without further investment.

The residential sector represents a large share of final energy consumption, in Ireland it is approximately 25 per cent (Howley and Holland, 2013). Nearly 40 per cent of European final energy consumption occurs in buildings, and two-thirds of energy use in residential buildings is for space heating (European Commission, 2011). Against the backdrop of onerous climate and energy efficiency policy targets, and given the residential sector's substantial energy use it is important to gauge the sector's response to policy instruments to better inform policy decisions. This paper seeks to update and further disaggregate energy elasticity estimates for the Irish residential sector. It builds on an extensive literature estimating energy elasticities for the Irish residential sector (Leser, 1962, 1964; Pratschke, 1969; O'Riordan, 1975; Murphy, 1976; McCarthy, 1977; Reilly, 1986; Conniffe and Scott, 1990; Conniffe, 2000; Scott *et al*., 2008; Hennessy and FitzGerald, 2011; Di Cosmo and Hyland, 2013). This paper also complements an international literature that shows wide variability in elasticity estimates across countries (Asche *et al*., 2008; Alberini *et al*., 2011).

The current paper is the first in an Irish energy context to estimate a sector-specific multi-fuel demand system based on the almost ideal demand system (AIDS) of Deaton and Muellbauer (1980). The analysis focuses on the residential sector and estimates a series of AIDS models incorporating both quadratic expenditure and demographics terms. We also estimate error-correction models to recover short-run as well as long-run equilibrium elasticity estimates. The estimated results complement and extend elasticity estimates for the residential sector, in particular for oil and solid fuels.

The remainder of the paper is organised as follows. Section II reviews energy demand estimation literature. Section III describes the equilibrium and error corrected AIDS models we estimate, as well as quadratic almost ideal demand system (QUAIDS) variants. Section IV reports the empirical results, the policy implications of which are discussed in Section V. Section VI concludes.

II LITERATURE

The energy demand literature is quite heterogeneous in methodological approach. For instance, in a review of methods used for modelling energy use in the residential sector, Swan and Ugursal (2009) reference a range of engineering and statistical/econometric techniques applied to top-down and bottom-up approaches. Econometric models include single demand equations, e.g. Haas and Schipper (1998); vector autoregressive (VAR) models, e.g. Azgun (2011); and autoregressive distributed lag (ARDL) models, e.g. Dergiades and Tsoulfidis (2008). In this paper we estimate an energy demand system with individual fuels for one sector of the economy, of which there are few examples in the literature. Labandeira *et al*. (2006) is a notable application, where they estimate a demand system for residential energy demand in Spain. An advantage of the demand system approach is that it can more easily estimate cross-price effects between different energy products. Labandeira *et al*. utilise the AIDS/QUAIDS demand models, similar to the approach here, but their data are from household panel surveys across three years compared to aggregate household time series data used in this application, meaning that the results will not be precisely comparable. While data and research questions influence methodological approach, which in turn can affect estimated elasticity values (Menegaki, 2014), all the approaches provide insight into energy demand preferences.

Residential energy demand studies are more numerous than for other sectors. This may be due to the sector's large share of final energy demand but may also reflect the complexity of residential energy demand or the greater attention of policy makers for the sector. Some studies focus on aggregate energy demand (Haas and Schipper, 1998; Agostini *et al*., 1992) finding that residential energy demand across OECD countries is price inelastic, at less than –0.33. These estimates echo results for the United Kingdom, Scotland and Northern Ireland (Smyth, 1996) and the Republic of Ireland (Conniffe and Scott, 1990), though Lyons *et al*. (2009) more recently estimate a slightly higher elasticity at –0.53.

Empirical evidence suggests that elasticity values are fuel-specific (Di Cosmo and Hyland, 2013) and accordingly many analyses of residential energy demand focus on individual fuels. Jamil and Ahmad (2011) review over 12 studies of electricity demand, roughly half of which relate to the residential sector. The empirical consensus is that electricity demand is inelastic, for the most part less than –0.5 but with estimates as low as –0.04. Asche *et al*. (2008) also find electricity to be highly inelastic across many European countries. However, Alberini *et al*. (2011) for the United States and Krishnamurthy and Kriström (2015) for 11 other OECD countries, estimate substantially higher electricity price elasticities ranging between –0.67 and –1.5. But these latter studies use survey data, whereas the lower value elasticity estimates are generally from time series analyses. In the case of gas, Asche *et al*. also estimate price elasticities that vary considerably across countries. Regardless of whether the elasticity estimates are economy-wide or sector-specific, the estimates vary substantially by country, which highlights the need for sector, country, as well as fuel-specific elasticity estimates.

Asche *et al*. (2008) also highlight an important 'non-result' in their analysis. Similar to Maddala *et al*. (1997) they find that some of their elasticity estimates have implausible signs and values in the context of standard neoclassical economic theory. For example, finding a gas price elasticity of +0.765 for Spain and an electricity price elasticity of +0.106 for the Netherlands. These types of implausible results are less likely to be reported in the published literature but they are a feature of demand model estimation, one which we encounter in our estimates. Asche *et al*. partly attribute the implausible estimates to model estimators but are unable to explain why such estimates persist in their preferred models.[1]

Several of the previous studies on Irish energy demand are based on data from cross-section household expenditure surveys and from an elasticity

[1] Sen (1987), among others, have suggested that neoclassical economic theory is an inadequate framework to explain human behaviour and argue that a broader theoretical base is required in which ethical considerations are explicitly modelled as a motivating factor.

estimation perspective are restricted to income (or expenditure) elasticities of fuel demand (Leser, 1962, 1964; Pratschke, 1969; Murphy, 1976; Conniffe, 2000; Scott *et al*., 2008). The studies that estimate price elasticities follow a variety of methodological approaches. Some estimate residential sector demand systems covering all consumer expenditure and in those instances energy is treated as an aggregate fuel product (O'Riordan, 1975; McCarthy, 1977). Given that elasticity estimates vary by fuel type, this approach is less useful for policy purposes. Where demand systems have been estimated by fuel type (e.g. coal, gas, etc.) the demand system was for the entire economy rather than by economic sector (Reilly, 1986; Conniffe and Scott, 1990; Lyons *et al*., 2009). The associated elasticity estimates provide useful information for policy makers or energy companies though obviously the analysis is unable to reveal sector-specific behaviours. The papers by Hennessy and FitzGerald (2011) and Di Cosmo and Hyland (2013) take a different approach, modelling the entire energy system by sector and fuel, estimating demand equations for electricity and non-electricity fuels. Their estimates do not allow for cross price effects but are the only papers to date, along with Lyons *et al*. (2009), that have estimated both long-and short-run energy price elasticities for Ireland.

AIDS models are probably the most popular demand system specifications estimated, reflecting the benefit of flexible functional forms and also ease of estimation. To simplify estimation Deaton and Muellbauer (1980) suggested using a linear approximation with the Stone Price Index, commonly referred to as the linear approximate almost ideal demand system (LA/AIDS). A consequence of this approximation was that several approaches to computing elasticities were proposed, some of which lead to significant errors (Green and Alston, 1990). The most common method in the literature for calculating elasticities in LA/AIDS models is the special case where expenditure shares are assumed constant.[2] Alston *et al*. (1994) using Monte Carlo methods show that this approach provides quite accurate estimates compared to the correct formula for elasticities in LA/AIDS models. We continue the approach in the literature assuming constant expenditure shares when calculating elasticities LA/AIDS models.

III METHODS

3.1. *AIDS Models*

The AIDS model developed by Deaton and Muellbauer (1980) is a commonly used demand system specification. The popularity of the AIDS model is due in

[2] This approach has been attributed, among others, to Chalfant (1987).

part to its flexible functional form, as it does not impose *a priori* restrictions, and theoretical restrictions can be easily imposed or tested. The model is also easy to estimate. To simplify estimation Deaton and Muellbauer (1980, p.316) initially suggested approximating the specified transcendental logarithm price index function with the linear Stone Geometric Price Index. Since then advances in computing and software mean that fitting non-linear compared to linear systems is not much more difficult and a number of extensions of the model have been developed. Banks *et al*. (1997) developed a generalisation that includes a quadratic expenditure term, calling their model QUAIDS. The QUAIDS model itself has also been extended to incorporate demographic variables (Ray, 1983; Blacklow *et al*., 2010). The AIDS model is nested within these more general models.

The AIDS model is derived from an expenditure function that belongs to the price independent generalised logarithmic (PIGLOG) class of preferences and satisfies the necessary conditions for consistent aggregation across consumers. With appropriate choice for functional forms the associated market demand equations are consistent with the behaviour of a rational representative economic agent (Deaton and Muellbauer, 1980). For utility maximising consumers the demand functions in budget share form for the AIDS model can be written as follows

$$S_{it} = \alpha_i + \sum_{j=1}^{k} \gamma_{ij} \log p_{jt} + \beta_i \log \left\{ \frac{m_t}{a(p)} \right\} \tag{1}$$

where S_{it} is the i^{th} budget share in year t, p_{jt} is the price of j^{th} product and m_t represents total expenditure. The function $a(p)$ is the price index function which we define later. Lower-case Greek letters represent parameters to be estimated. The AIDS budget share equation incorporating demographics is given by equation (2)

$$S_{it} = \alpha_i + \sum_{j=1}^{k} \gamma_{ij} \log p_{jt} + (\beta_i + \eta_i' z) \log \left\{ \frac{m_t}{m_0(z) a(p)} \right\} \tag{2}$$

where z represents a vector of r demographic variables, and following Ray (1983) $m_0(z) = 1 + \rho' z$ with ρ being a vector of parameters to be estimated. Following Poi (2012) the QUAIDS budget share equation excluding and including demographic variables are given by equations (3) and (4).

$$S_{it} = \alpha_i + \sum_{j=1}^{k} \gamma_{ij} \log p_{jt} + \beta_i \log \left\{ \frac{m_t}{a(p)} \right\} + \frac{\lambda_i}{b(p)} \left[\log \left\{ \frac{m_t}{a(p)} \right\} \right]^2 \tag{3}$$

$$S_{it} = \alpha_i + \sum_{j=1}^{k} \gamma_{ij} \log p_{jt} + (\beta_i + \eta_i' z) \log \left\{ \frac{m_t}{m_0(z) a(p)} \right\} + \frac{\lambda_i}{b(p) c(p, z)} \left[\log \left\{ \frac{m_t}{m_0(z) a(p)} \right\} \right]^2 \tag{4}$$

where functions $b(p)$ and $c(p, z)$ are the Cobb-Douglas price aggregators

$$b(p) + \prod_{i=1}^{k} p_i^{\beta_i} \text{ and } c(p, z) = \prod_{j=1}^{k} p_j^{\eta_i' z} \tag{5}$$

In model estimation we use each of the budget share equations (1)-(4) but specify two separate functional forms for the logarithm of the price function $a(p)$. Deaton and Muellbauer (1980) originally specified the transcendental logarithm function for the AIDS model.

$$\log (a(p)) = \alpha_0 + \sum_{i=1}^{k} \alpha_i \log p_i + \frac{1}{2} \sum_{i=1}^{k} \sum_{j=1}^{k} \gamma_{ij} \log p_i \log p_j \tag{6}$$

While in theory the parameter α_0 can be estimated, in reality its estimation proves difficult. Standard practice is to pre-assign a value, usually slightly less than the lowest value of $\log m_t$ observed in the data (Poi, 2012).

Deaton and Muellbauer also suggested approximating the translog with the Stone Price Index to overcome estimation difficulties with a non-linear price index. Moschini (1995) shows that, as the Stone Price Index is not invariant to the units of measurement of prices, it may affect the approximation properties of the model. He suggests the loglinear analogue of the Paasche index as a possible alternative that retains the properties of the Stone index, which Moschini ascribes as the 'corrected' Stone Price Index.

$$\log (a(p)) = \sum_{i=1}^{k} S_{it} \log \left(\frac{p_{it}}{p_i^0} \right) \tag{7}$$

where p_i^0 is the price in the base period. With modern computing capabilities the requirement to use the Stone approximation (7) is less. For example the 'quaids' command in Stata™, which facilitates estimation of (1)-(4), only uses the translog price index (6) without allowing other price index alternatives. However, because of limited degrees of freedom in the models we estimate, especially in the error-correction variants, we specify both (6) and (7) in the models we estimate. Estimation of (1)-(4) using (7) is implemented via the 'nlsur' command in Stata™ for estimating non-linear systems of equations.

Economic theory requires aggregation, homogeneity and symmetry conditions to hold. Within the AIDS/QUAIDS models these restrictions can be either imposed or tested and imply the following:

$$\sum_{i=1}^{k} \alpha_i = 1, \quad \sum_{i=1}^{k} \beta_i = 0, \quad \sum_{i=1}^{k} \gamma_{ij} = 0, \quad \sum_{i=1}^{k} \lambda_i = 0, \quad \sum_{j=1}^{k} \eta_{rj} = 0,$$
$$\sum_{j=1}^{k} \gamma_{ij} = 0, \quad \gamma_{ij} = \gamma_{ji} \tag{8}$$

Due to limited degrees of freedom and thus to improve the efficiency of our estimates these demand restrictions are imposed for the main model estimates. The adding-up conditions (e.g. Engel and Cournot aggregation) are imposed automatically by not estimating one of the equations in the system, whereas the remaining axioms are imposed by parameter restrictions. Negativity cannot be parametrically imposed.

3.2 *Elasticities*

The estimated model parameters are difficult to interpret and therefore not of direct interest. Instead the associated Marshallian price and expenditure elasticities are of policy relevance. The calculation of these elasticities differ depending on the combination of budget share equation (1)-(4) and price index (6)-(7) selected for estimation. The formulae are reported in Tables 1 and 2 where ε_{ij}^{M} refers to the uncompensated price elasticity of fuel i with respect to changes in the price of fuel j; θ_i is the expenditure elasticity for good i; and δ_{ij} is the Kronecker delta. Compensated price elasticities and Allen elasticities of substitution can be recovered via the Slutsky equation as $\varepsilon_{ij}^{C} = \varepsilon_{ij}^{M} + \theta_i S_j$ and $\sigma_{ij} = \varepsilon_{ij}^{M}/S_j + \eta_i$.

3.3 *Short-and Long-run Dynamics*

It is widely acknowledged that many demand time series present non-stationary dynamics. The models specified above are presumed to be long-run or equilibrium energy demand relationships and, to assess whether these relationships are economically meaningful or merely spurious, it is necessary to investigate the time-series properties of the data used in estimation. Augmented Dickey-Fuller unit root tests are used to detect the presence of non-stationarity (Dickey and Fuller, 1981). It is possible to have a co-integrated relationship even though the variables of interest have different time series properties and, thus, a different order of integration. Therefore, we ultimately test for long-run equilibrium co-integration relationships by using an augmented Dickey-Fuller test on the estimated model residuals. We follow the two step Engle-Granger procedure for co-integration modelling. The first stage of this method is to model the long-run relationship. The residuals from this first-stage regression are tested for stationarity. If they are stationary, a co-integrating relationship exists and we can proceed. The second stage is to estimate dynamic short-run relationships. The short-run regression includes the lagged residuals from the first step as the error correction term. The results of these short-run equations tell us the speed at which each variable adjusts to its long-run equilibrium value.

Using an error correction representation of the AIDS model is one approach for incorporating short-run dynamics (Nzuma and Sarker, 2010; Eakins and Gallagher, 2003; Karagiannis *et al.*, 2000). An error correction model (ECM) (Engle and Granger, 1987) is a restricted form of a vector autoregression (VAR), which is commonly used to examine time series dynamics. The ECM specification allows for short-run disequilibrium by assuming that the estimation error associated with the long-run demand relationship is a disturbance from the equilibrium. The ECM for the QUAIDS model with demographics (4) is specified as

$$\begin{aligned}\Delta S_{it} = \Delta\varphi S_{it-1} + \sum_{j=1}^{k} \gamma_{ij}\Delta \log p_{jt} + (\beta_i + \eta_i' z)\, \Delta \log \left\{\frac{m_t}{m_0(z)a(p)}\right\} \\ + \frac{\lambda_i}{b(p)c(p,z)}\left[\Delta \log \left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]^2 + \psi_i \mu_{it-1} + \nu_i\end{aligned} \tag{9}$$

where Δ is the difference operator, μ_{it-1} are the lagged residuals from the estimated co-integration equation (in this case equation (4)). The coefficient ψ_i measures the speed of adjustment to the long-run equilibrium following a disturbance from the equilibrium budget allocation related to fuel i in period $t-1$. The ECM for the QUAIDS model (3) is nested within (9). The short-run elasticities can be recovered by substituting the estimated parameters from (9) into the appropriate formulae in Table (2).

3.4 *Data*

We estimate a demand system for the residential sector with four fuels and an aggregate non-fuel consumer good. Fuel quantity data are taken from sector energy balance sheets published by the Sustainable Energy Authority of Ireland (SEAI).[3] Fuel prices are sourced from the ESRI databank and supplemented with data from SEAI's Domestic Fuel Cost Archive.[4] Solid fuel is an aggregate

[3] www.seai.ie/Publications/Statistics_Publications/Energy_Balance.
[4] www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison.

fuel comprising sod peat, peat briquettes and coal, and its price calculated as a quantity-weighted average. Oil comprises kerosene, diesel, LPG and petroleum coke with its price also calculated as a quantity-weighted average. Data for the non-fuel aggregate consumer good are sourced from National Income and Expenditure Accounts of the Central Statistics Office (CSO) and its price is the consumer price index excluding energy products. Data on the number of households were linearly extrapolated from Census data, which occur at five-year intervals. The dataset covers the years 1970 to 2013.

Figures 1 and 2 display historical residential fuel demand and prices. The composition of demand has evolved over the period with oil, gas and electricity demand increasing over the period, whereas solid fuel demand has declined since the late 1980s. Nominal fuel prices have trended upwards, though price increases were most pronounced for electricity. Electricity prices increased quite dramatically in the early 1980s and again after 2000. By contrast, solid fuel prices increases were relatively moderate.

Figure 1: *Quantity of Residential Fuel Consumption*

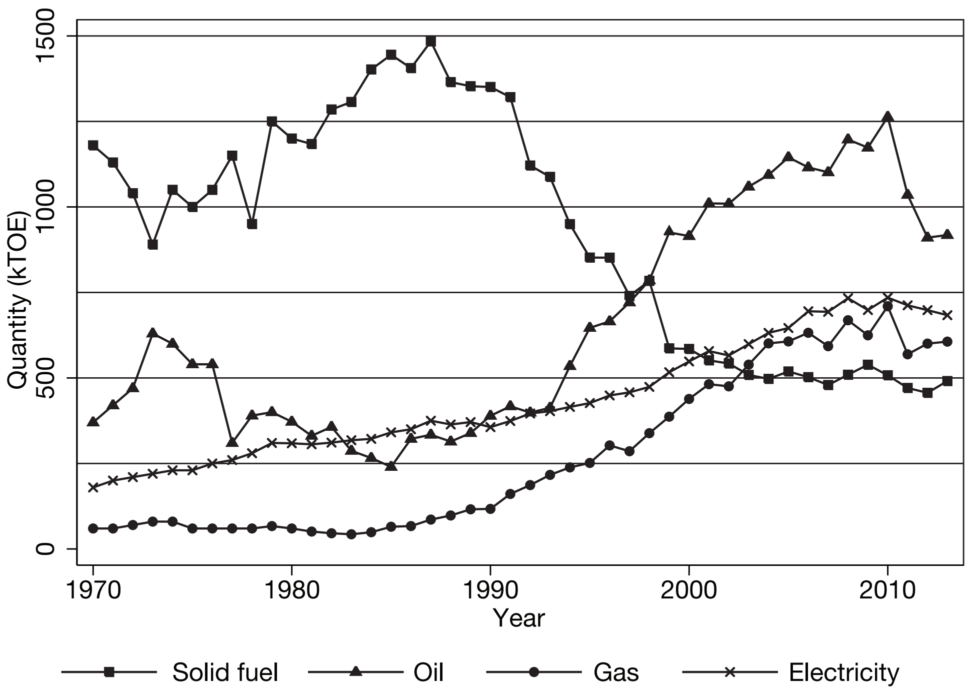

Figure 2: *Fuel Price per TOE*

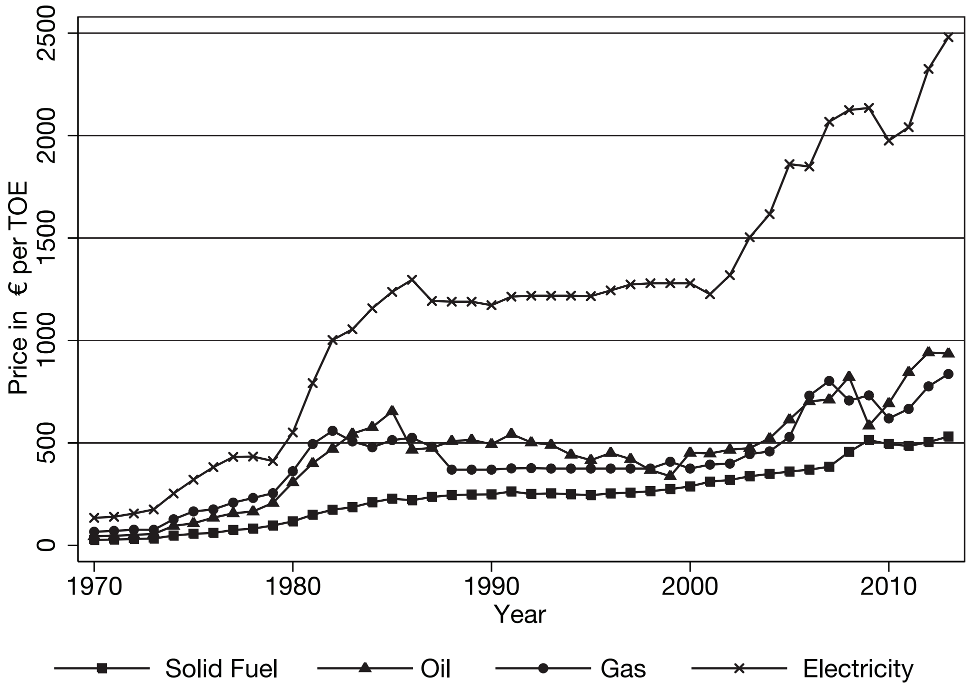

Table 1: *AIDS Model Elasticities*

Model		*Translog Price Index*	*Stone Price Index*
Excluding Demographics	ε_{ij}^{M}	$-\delta_{ij} + \frac{1}{S_i}\left[\gamma_{ij} - \beta_i\left(\alpha_j + \sum_k \gamma_{jk} \log p_k\right)\right]$	$-\delta_{ij} + \frac{1}{S_i}[\gamma_{ij} - S_j\beta_i]$
Excluding Demographics	θ_i	$1 + \frac{\beta_i}{S_i}$	$1 + \frac{\beta_i}{S_i}$
Including Demographics	ε_{ij}^{M}	$-\delta_{ij} + \frac{1}{S_i}\left[\gamma_{ij} - [\beta_i + \eta_i' z] \times \left(\alpha_j + \sum_k \gamma_{jk} \log p_k\right)\right]$	$-\delta_{ij} + \frac{1}{S_j}[\gamma_{ij} - S_j(\beta_i + \eta_i' z)]$
Including Demographics	θ_i	$1 + \frac{(\beta_i + \eta_i' z)}{S_i}$	$1 + \frac{(\beta_i + \eta_i' z)}{S_i}$

Table 2: *QUAIDS Model Elasticities*

Model		*Translog Price Index*	*Stone Price Index*
Excluding Demographics	ε_{ij}^{M}	$-\delta_{ij}+\frac{1}{S_i}\left[\gamma_{ij}-\left[\beta_i+\frac{2\lambda_i}{b(p)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]\right.$ $\times\left(\alpha_j+\sum_k\gamma_{jk}\log p_k\right)$ $\left.-\frac{\beta_i\lambda_i}{b(p)}\left[\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]^2\right]$	$-\delta_{ij}+\frac{1}{S_i}\left[\gamma_{ij}-\left[\beta_i S_j+\frac{2\lambda_i S_j}{b(p)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]\right.$ $\left.-\frac{\beta_j\lambda_i}{b(p)}\left[\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]^2\right]$
Excluding Demographics	θ_i	$1+\frac{1}{S_i}\left(\beta_i+\frac{2\lambda_i}{b(p)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right)$	$1+\frac{1}{S_i}\left(\beta_i+\frac{2\lambda_i}{b(p)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right)$
Including Demographics	ε_{ij}^{M}	$-\delta_{ij}+\frac{1}{S_i}\left[\gamma_{ij}-\left[\beta_i+\eta_i'z+\frac{2\lambda_i}{b(p)c(p,z)}\right.\right.$ $\left.\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]\times\left(\alpha_j+\sum_k\gamma_{jk}\log p_k\right)$ $\left.-\frac{(\beta_i+\eta_i'z)\,\lambda_i}{b(p)c(p,z)}\left[\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]^2\right]$	$-\delta_{ij}+\frac{1}{S_i}\left[\gamma_{ij}-S_j(\beta_i+\eta_i'z)\right.$ $-S_j\frac{2\lambda_i}{b(p)c(p,z)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}$ $\left.-\frac{(\beta_j+\eta_j'z)\,\lambda_i}{b(p)c(p,z)}\left[\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right]^2\right]$
Including Demographics	θ_i	$1+\frac{1}{S_i}\left(\beta_i+\eta_i'z+\frac{2\lambda_i}{b(p)c(p,z)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right)$	$1+\frac{1}{S_i}\left(\beta_i+\eta_i'z+\frac{2\lambda_i}{b(p)c(p,z)}\log\left\{\frac{m_t}{m_0(z)a(p)}\right\}\right)$

IV RESULTS

Our estimation procedure is to first estimate variations of long-run equilibrium AIDS/QUAIDS models using the two alternative price indices and compare the outcome of the various models. We report parameter estimates in Table 4. The restrictions implied by demand theory were imposed during estimation. However, when unrestricted models are estimated we find that the symmetry axiom generally holds, but not homogeneity.[5]

4.1 *Long-run Models*

The stationarity properties of our demand system are tested using the augmented Dickey-Fuller unit root test, with the test statistics reported in Table 3. While we generally fail to reject the existence of a unit root in the data levels, non-stationarity is rejected for the first differences. Given the rising trend in fuel quantities and prices, as shown in Figures 1 and 2, our tests also allow for a trend. Non-stationary time series may however be co-integrated because short-run deviations between dependent and explanatory variables may converge to an underling long-run co-integration relationship. We test for a co-integrating relationship using the residuals from the long-run equations reported in Table 4. We reject the null hypothesis of no co-integration in our demand system.

Residuals from the estimated models were examined to detect the presence of structural breaks. We inspected if the residuals were mean-reverting. In this respect the QUAIDS models incorporating demographic variables were the best fit for all four fuels. In the remaining models the residuals in the oil and gas equations exhibited a tighter mean-reverting behaviour than in the electricity and solid fuels equations. Across all the models estimated, the residuals were generally within two standard deviations, with the exceptions only occurring for at most a few periods (i.e. one to three years). Across the models there was no strong evidence of a structural break, and particularly so for the more flexible QUAIDS models incorporating demographic variables.

We use likelihood ratio tests to test model assumptions both on price index and model specifications. Regardless of price index specification, the hypothesis that the more flexible model specifications (e.g. QUAIDS or QUAIDS with demographics versus AIDS, etc.) are a better fit cannot be rejected ($p < 0.01$).

[5] While we proceed with the models as presented, the homogeneity result echoes the point that neoclassical economic theory is too narrow a framework to fully explain human behaviour (Sen, 1987).

Table 3: *Augmented Dickey Fuller Stationarity and Co-integration Tests*

Series	*Level Series*		*First Differences*		*Cointegration*
	No Trend	*Trend*	*No Trend*	*Trend*	*No trend*
Budget shares (S_i)					
Solid Fuel	–0.91	–1.56	–8.11	–8.01	–3.64
Oil	–2.32	–2.92	–7.34	–7.25	–4.48
Gas	–0.01	–1.81	–7.64	–7.91	–4.99
Electricity	–1.37	–1.64	–4.06	–4.01	–4.08
log price solid fuel	–4.48	–2.29	–3.74	–4.54	
log price oil	–2.91	–2.11	–5.27	–5.68	
log price gas	–2.69	–2.18	–4.30	–4.45	
log price electricity	–3.52	–2.20	–3.43	–3.86	
log total expenditure	–6.52	–0.36	–1.82	–3.19	
log households	2.50	0.13	–3.58	–3.91	
5% Critical values	–2.95	–3.52	–2.95	–3.52	–1.68

These test results reflect the fact that when demographic variables are incorporated in the models, the estimates of the associated parameters, η_i, which govern how demographics scale the expenditure function, are each generally significant. However estimates of ρ, which determines how demographics deflate household expenditure, are insignificant in the AIDS models but significant in the QUAIDS models. The test results also reflect that the quadratic parameters λ_i are mostly significant. The implication from the tests is that the more flexible models are better suited to estimating the energy demand system. We proceed by first discussing the estimates of all the long-run models. We subsequently report on the dynamic short-run model estimates, which are confined to estimates of the more flexible QUAIDS model.

Looking at the parameter estimates, there are noticeable differences between models depending on whether the translog or Stone price indices are used. The differences occur both in parameter magnitude and sign. As the elasticity formulae differ depending on whether a translog or Stone price specification is used, we would expect the underlying parameter estimates to differ and consequently specific parameters are difficult to interpret. Comparison of the associated elasticity estimates allows us to judge whether the translog or Stone price specification makes a practical difference in terms of policy inference.

4.2 *Long-run Elasticities*

Own-price elasticities are presented in Table 5. As expected, nearly all of the own-price elasticity estimates for fuels are negative but electricity is a notable exception. In a couple of the estimated QUAIDS models the electricity

Table 4: *Parameter Estimates for Long-run AIDS and QUAIDS Models*

Model:	*AIDS*	*AIDS*	*AIDS With Demo*	*AIDS With Demo*	*QUAIDS*	*QUAIDS*	*QUAIDS With Demo*	*QUAIDS With Demo*
Price Index:	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*
Coefficient								
α_1	–0.030***	0.252***	–0.025***	0.133*	–0.033***	0.507*	–0.017***	0.336*
	(0.005)	(0.019)	(0.005)	(0.069)	(0.005)	(0.269)	(0.004)	(0.197)
α_2	–0.002	0.065***	0.003	–0.053	0.008**	0.133	0.001	0.112
	(0.003)	(0.018)	(0.003)	(0.077)	(0.004)	(0.208)	(0.002)	(0.253)
α_3	0.007***	–0.034***	0.002	0.072***	0.007***	0.481***	0.002	0.193***
	(0.002)	(0.006)	(0.001)	(0.019)	(0.002)	(0.078)	(0.001)	(0.050)
α_4	–0.051***	0.042***	–0.046***	0.069	–0.057***	–0.186	–0.037***	0.158
	(0.004)	(0.011)	(0.003)	(0.047)	(0.004)	(0.202)	(0.003)	(0.212)
β_1	–0.012***	–0.012***	0.064*	0.002	–0.018***	–0.033	0.764***	–0.021
	(0.001)	(0.001)	(0.037)	(0.007)	(0.004)	(0.022)	(0.130)	(0.017)
β_2	–0.003***	–0.003***	–0.180***	0.009	0.013***	–0.008	–0.495***	0.007
	(0.001)	(0.001)	(0.035)	(0.008)	(0.004)	(0.017)	(0.157)	(0.021)
β_3	0.002***	0.002***	–0.049***	–0.010***	0.008***	–0.041***	–0.080	–0.016***
	(0.000)	(0.000)	(0.014)	(0.002)	(0.001)	(0.007)	(0.052)	(0.005)
β_4	–0.004***	–0.004***	0.150***	–0.006	–0.017***	0.015	0.471***	–0.024
	(0.001)	(0.001)	(0.018)	(0.005)	(0.002)	(0.017)	(0.065)	(0.017)
γ_{11}	0.008**	0.008**	0.007**	0.014***	0.008**	–0.006	0.008***	0.011
	(0.004)	(0.004)	(0.003)	(0.004)	(0.003)	(0.014)	(0.003)	(0.007)
γ_{12}	0.002	0.002	0.002	0.005***	0.002	0.004	–0.000	0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)	(0.001)	(0.002)
γ_{13}	0.003***	0.003***	0.002**	–0.001	0.002**	–0.012	0.002**	–0.004
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.010)	(0.001)	(0.002)
γ_{14}	0.003	0.003	0.002	0.003	0.003*	0.009	0.002*	0.004
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.007)	(0.001)	(0.003)
γ_{22}	0.002	0.002	0.004***	0.002	0.003*	0.001	0.005***	–0.005
	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.003)	(0.001)	(0.010)
γ_{23}	–0.000	–0.000	–0.000	–0.001***	–0.000	–0.005	–0.000	–0.005
	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.008)	(0.001)	(0.004)

Table 4: *Parameter Estimates for Long-run AIDS and QUAIDS Models (Contd.)*

Model:	*AIDS*	*AIDS*	*AIDS With Demo*	*AIDS With Demo*	*QUAIDS*	*QUAIDS*	*QUAIDS With Demo*	*QUAIDS With Demo*
Price Index:	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*
Coefficient								
γ_{24}	0.001	0.001	–0.001	0.002**	–0.000	0.004	0.000	0.003
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.005)	(0.001)	(0.004)
γ_{33}	0.000	0.000	–0.000	0.002***	–0.000	–0.019***	–0.000	–0.001
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.007)	(0.000)	(0.001)
γ_{34}	–0.002**	–0.002**	0.001	–0.002***	–0.000	0.007	0.000	–0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.009)	(0.001)	(0.003)
γ_{44}	0.022***	0.022***	0.020***	0.021***	0.022***	0.018***	0.018***	0.019***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.007)	(0.001)	(0.002)
λ_1					–0.002	0.000	0.029***	0.000
					(0.002)	(0.000)	(0.005)	(0.000)
λ_2					0.007***	0.000	–0.013**	0.000
					(0.002)	(0.000)	(0.006)	(0.000)
λ_3					0.002***	0.001***	–0.001	0.000***
					(0.001)	(0.000)	(0.002)	(0.000)
λ_4					–0.005***	–0.000	0.014***	–0.000
					(0.001)	(0.000)	(0.003)	(0.000)
η_1			–0.006**	0.011			–0.055***	0.000
			(0.003)				(0.009)	(0.000)
η_2			0.013***	–0.001**			0.035***	–0.002***
			(0.003)	(0.000)			(0.011)	(0.000)
η_3			0.004***	–0.001*			0.006	0.000
			(0.001)	(0.000)			(0.004)	(0.000)
η_4			–0.011***	0.000***			–0.034***	0.001***
			(0.001)	(0.000)			(0.005)	(0.000)
ρ			–0.018	0.000			–0.035***	–0.069***
			(0.012)	(0.000)			(0.002)	(0.000)

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

price elasticity is negative ranging between –0.05 and –0.23 but the estimate is not statistically significant.[6] Previous studies have estimated a negative price elasticity ranging between –0.07 and –0.31 (Hennessy and FitzGerald, 2011; Asche *et al*., 2008; Di Cosmo and Hyland, 2013).

Labandeira *et al*. (2006) estimate a model for Spain that most closely resembles the model here and as such is potentially useful as an international benchmark, though their data comprise a panel across just three time periods. Their elasticity estimate is –0.79.[7] By contrast both Blázquez *et al*. (2013) and Asche *et al*. (2008) using alternative models for Spain estimate long-run price elasticities of –0.19 and –0.31 and both estimate short-run elasticities of –0.07. So while Labandeira *et al*.'s results are substantially different from our Irish estimate, it is not clear if that is a real difference or due to methodological reasons.

The price elasticity estimates for solid fuels is roughly –0.27 across the models estimated but none of the estimates are statistically significant. Di Cosmo and Hyland (2013) did not find a significant price effect for solid fuels either but much earlier work by Conniffe and Scott (1990) estimated a coal price elasticity of –1.39. So solid fuels do not appear to be very price responsive. However, there are significant cross-price elasticity estimates for solid fuels with respect to a change in the price of gas or electricity of roughly 0.2 and 0.3 respectively. Solid fuels are a substitute for gas and electricity but the cross-price elasticities are not symmetric. Cross-price elasticities for gas and electricity with respect to solid fuels are approximately 0.7 and 0.15 respectively.

The estimates of the own-price elasticity of oil roughly averages –0.8, ranging from –0.51 to –0.95, which is broadly consistent with an estimate of –0.52 by Conniffe and Scott (1990) and a –0.73 estimate by Hennessy and FitzGerald (2011) for non-electric energy in the residential sector. This contrasts with an insignificant price elasticity estimate for light fuel oil in Ireland by Asche *et al*. (2008).

Price elasticity estimates for gas are in the vicinity of –0.9, ranging from –0.64 to –1.11 (though in one case there is the implausible estimate of –13.04). Again these are consistent with earlier estimates by Conniffe and Scott (1990) and also similar in magnitude to estimates for Switzerland but substantially higher than those for Austria, Belgium, Denmark, Germany and the UK (Asche *et al*., 2008). Gas and electricity were found to be complementary fuels, which is consistent with previous Irish (Conniffe and Scott, 1990) and international

[6] Bootstrap methods were used to calculate confidence intervals for the elasticity estimates of the models that specified a Stone price index (6). For the translog specification the 'quaids' command in Stata returned standard errors.

[7] Labandeira *et al*. (2006) do not report standard errors on their elasticity estimates.

literature (Akmal *et al*., 2001). The cross-price elasticity of gas for a change in the price of electricity is –0.5 and of electricity with respect to gas prices is –0.1. The remaining cross-price elasticity estimates were statistically insignificant.

Expenditure elasticities are reported in Table 6. The estimates for solid fuels are negative and range from –0.35 to –1.74. These estimates are consistent with Conniffe (2000) who estimate expenditure elasticities for coal ranging from –0.43 to –0.56 for the residential sector. As expenditure (incomes) increases consumers substitute away from coal and peat as their consumption set expands. The estimated expenditure elasticities for oil range from 0.64 to 1.95 and for gas range from 0.92 to 1.98. Estimates for both fuels are broadly consistent with previous estimates by Conniffe (2000) and Labandeira *et al*. (2006) for Spain. Expenditure elasticity estimates for electricity vary between 0.29 to 0.84 across the models estimated.

4.3 *Error Correction Models*

Table 7 presents the results for the coefficient estimates of the QUAIDS error correction models. Due to limited degrees of freedom the error correction models are estimated using only the Stone price index (7). The error correction coefficient, ψ_i, captures the speed at which fuel demand adjusts to its long-run equilibrium. In the QUAIDS model the estimates of ψ_i imply that roughly up to one-third of the adjustment to long-run equilibrium occurs within one year across the four fuels. In the QUAIDS with demographics ECM model adjustment in oil and gas demand was estimated to occur much faster, with between 60-80 per cent adjustment within one year. This latter estimate compares favourably to a 72 per cent demand adjustment rate for an aggregate fuel product in a nine category AIDS model for Ireland estimated by Lyons *et al*. (2009).

4.4 *Short-run Elasticities*

The calculation of short-run own-price elasticities using the parameter estimates from Table 7 (including all insignificant parameter estimates) and the elasticity formulae in Table 2 yielded implausible estimates and are not reported. Instead, Table 8 reports elasticities calculated using only ECM parameter estimates in Table 7 that are statistically significantly different from zero. The short-run own-price elasticity estimates are smaller than their long-run equivalent, which is consistent with the hypothesis that households' full response to price changes is not instantaneous but instead take time to adjust. The short-run price elasticity estimate for solid fuel is –0.12, with the estimate from the QUAIDS with demographics model not credible. The short-run own-price elasticity for oil is roughly –0.3, gas roughly –0.25 and electricity –0.2. By

Table 5: *Long-run Own-Price Elasticities*

Model:	*AIDS*	*AIDS*	*AIDS With Demo*	*AIDS With Demo*	*QUAIDS*	*QUAIDS*	*QUAIDS With Demo*	*QUAIDS With Demo*
Price Index:	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*
ε^{M}_{11}: Solid Fuel	–0.28	–0.27	–0.31	0.12	–0.29	–2.26	–0.22	0.33
ε^{M}_{22}: Oil	–0.84***	–0.84[b]	–0.60***	–0.81	–0.74***	–0.95[b]	–0.51***	–0.97
ε^{M}_{33}: Gas	–0.87***	–0.87[b]	–1.11***	–0.44	–1.11***	–13.04[b]	–1.08***	–0.64[b]
ε^{M}_{44}: Electricity	0.19*	0.19[b]	0.05	0.27	0.18**	–0.23	–0.05	0.03

Note: *** $p < 0{:}01$, ** $p < 0{:}05$, * $p < 0{:}1$, [b] bootstrapped $p < 0{:}1$.

Table 6: *Long-Run Expenditure Elasticities*

Model:	*AIDS*	*AIDS*	*AIDS With Demo*	*AIDS With Demo*	*QUAIDS*	*QUAIDS*	*QUAIDS With Demo*	*QUAIDS With Demo*
Price Index:	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*	*Translog*	*Stone*
θ_1: Solid fuel	–0.14	–0.14	–0.35**	15.25	–0.12	–0.18	–1.74***	0.23
θ_2: Oil	0.71***	0.72[b]	1.28***	1.08	0.65***	0.64[b]	1.79***	1.95[b]
θ_3: Gas	1.55***	1.55[b]	1.98***	–4.28	1.41***	1.45[b]	1.98***	0.92[b]
θ_4: Electricity	0.79***	0.79[b]	0.57***	–6.52	0.84***	0.78[b]	0.29***	0.51[b]

Note: *** $p < 0{:}01$, ** $p < 0{:}05$, * $p < 0{:}1$, [b] bootstrapped $p < 0{:}1$.

contrast Lyons *et al*. (2009) estimate a short-run own price elasticity for an aggregate fuel product of –0.53 within a nine category AIDS model estimated for Ireland covering the period 1976–2003.

Table 7: *Parameter Estimates for Error Corrected QUAIDS Models*

Model:	*QUAIDS*	*QUAIDS With Demo.*		*QUAIDS*	*QUAIDS With Demo.*
Price Index:	*Stone*	*Stone*		*Stone*	*Stone*
Coefficient			*Coefficient*		
α_1	–0.268***	–0.233***	λ_1	–0.005	–0.215***
	(0.100)	(0.079)		(0.079)	(0.057)
α_2	–0.030	0.116	λ_2	0.072	0.038
	(0.126)	(0.129)		(0.092)	(0.074)
α_3	0.015	0.174*	λ_3	–0.003	0.021
	(0.101)	(0.103)		(0.020)	(0.017)
α_4	0.080	0.109*	λ_4	0.053	0.003
	(0.058)	(0.059)		(0.037)	(0.031)
β_1	–0.016***	–0.076***	η_1		2.867***
	(0.006)	(0.018)			(0.845)
β_2	–0.008	0.005	η_2		–0.273
	(0.007)	(0.024)			(1.119)
β_3	0.001	0.008	η_3		–0.373
	(0.002)	(0.005)			(0.236)
β_4	–0.009***	–0.020**	η_4		0.493
	(0.003)	(0.010)			(0.441)
γ_{11}	0.010***	0.016***	ρ		1.367***
	(0.004)	(0.003)			(0.229)
γ_{12}	0.003**	0.001	ψ_1	–0.223**	–0.281**
	(0.001)	(0.001)		(0.104)	(0.111)
γ_{13}	0.002**	–0.000	ψ_2	–0.310***	–0.614***
	(0.001)	(0.001)		(0.098)	(0.133)
γ_{14}	–0.000	0.001	ψ_3	–0.369***	–0.795***
	(0.001)	(0.001)		(0.096)	(0.129)
γ_{22}	0.008***	0.006***	ψ_4	–0.322***	–0.367***
	(0.002)	(0.002)			
γ_{23}	–0.000	–0.000			
	(0.000)	(0.000)			
γ_{24}	0.001	0.001*			
	(0.001)	(0.001)			
γ_{33}	0.002***	0.003***			
	(0.000)	(0.000)			
γ_{34}	–0.001	–0.001			
	(0.001)	(0.001)			
γ_{44}	0.016***	0.015***			
	(0.001)	(0.001)			

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

Table 8: *Short-run Own-Price Elasticities*

Model:	*QUAIDS ECM*	*QUAIDS ECM with Demo*
Price Index:	*Stone*	*Stone*
ε_{11}^{M}: Solid fuel	–0.12	a
ε_{22}^{M}: Oil	–0.24	–0.36
ε_{33}^{M}: Gas	–0.30	–0.21
ε_{44}^{M}: Electricity	–0.18	–0.20

Note: a: Calculated elasticity was not plausible.

V DISCUSSION

It was clear from the existing literature that energy price elasticities are likely to be country-, sector- and fuel-specific. Additionally, in a meta-analysis study Menegaki (2014) concludes that elasticity estimates are not independent of econometric analysis. On that basis it is likely that there will not be consensus on the magnitude of an elasticity estimate. Depending on the policy application for which the elasticity is required, a particular methodological approach or dataset may be most useful, rather than the most recent estimate.

5.1 *Solid Fuels*

For the equilibrium models there are a number of general conclusions that can be drawn. Solid fuel is an 'inferior' fuel, with less demanded as total expenditure increases. While most of the models indicated a negative own price elasticity none of the estimates were statistically significant. Our solid fuel category comprises products such as coal, sod peat, and peat briquettes and potentially our implicit assumption that these goods could be treated as a homogeneous product was not reasonable. However, we did find evidence that solid fuels can be considered as substitutes for gas and electricity. An analysis by specific residential fuels (i.e. not aggregated) may be more appropriate but an alternative to AIDS/QUAIDS models may be necessary due to insufficient estimation degrees of freedom.

5.2 *Oil*

Estimates of the own-price elasticity of oil ranged between –0.51 and –0.95, so demand is moderately inelastic. The short-run response is more muted with the elasticity estimate roughly –0.3. There was a wide spread in the expenditure elasticity estimates from 0.64 to 1.95 with several of the estimates above one. The least restrictive QUAIDS models, which were the best fit models on the basis of the likelihood ratio tests discussed earlier, yield expenditure elasticity estimates of 1.79 and 1.95. On that basis if we view oil predominantly as a heating fuel (it is also used for cooking), as levels of residential expenditure increase households will spend proportionately more on additional home comfort.

5.3 *Gas*

The findings for gas are surprisingly similar to those of oil. Surprising because mains gas is an urban fuel whereas oil is the predominant fuel in rural areas and previous research indicated differences in fuel preferences by urban/rural location (Conniffe, 2000). Own-price elasticity estimates ranged from –0.64 to –1.11. The least restrictive QUAIDS models yielded estimates at the two extremes so there is no guidance on which might be closer to the true value. The variation in expenditure elasticity estimates was somewhat similar, ranging from 0.92 to 1.98, though with the exception of one model all estimates exceeded one. The short-run price elasticity was roughly –0.25, quite similar to that for oil. Short-run responses to price shocks are likely to be quite small but over time have the potential to be significantly greater. Similar to oil, as expenditure grows households are likely to spend proportionality more on gas.

5.4 *Electricity*

There was no clear conclusion across the models estimated on the long-run own price elasticity. In the models where there is a statistically significant estimate, its sign is positive. Where estimates have a negative sign they are statistically insignificant. Regardless of sign it is reasonable to conclude that its value is close to zero. A recent estimate by Di Cosmo and Hyland (2013) is –0.07. The short-run elasticity estimates are approximately –0.2, so short-run responses to price shocks may be more dramatic. Such a finding may be reconciled with the fact that electricity is such a critical part of everyday life that households find it difficult to maintain short-run changes in behaviours associated with price changes.

5.5 *Implications for Climate and Energy Policy*

Climate and energy policy ambitions are for lower but more efficient fossil energy use with the objective of reducing greenhouse gas emissions. Carbon or energy taxes are potential policy instruments to achieve such a goal but on the basis of the estimates in this paper it is likely that achieving substantial reductions in energy (or ultimately emissions) would require quite large additional taxes on energy or carbon. Furthermore, the full effect of such a policy mechanism would take several years to be realised. The implication is that any new policy measures focusing on the residential sector should not rely solely on a price effect.

Solid fuels, whether peat or coal, are the most emissions intensive fuels. What also distinguishes solid from the other fuels in the analysis in this paper are negative expenditure elasticities. Demand for solid fuels will decline with rising incomes. However, that is not useful information for designing policy to curtail emissions in the short term. But it does point to the fact that there may be an income effect preventing households switching from coal or peat to cleaner fuels, such as gas. For instance, initial capital costs of gas using equipment may be prohibitive. If that is the case a grant scheme supporting low income, solid fuel using households to switch to alternative fuels may accelerate the long-term trend away from solid fuels as expenditure (or income) increases.

VI CONCLUSIONS

This is the first attempt in an Irish context to estimate an energy demand system for individual fuels within residential sector. The methodology follows Deaton and Muellbauer's AIDS model incorporating both quadratic expenditure and demographics terms. We also estimate error-correction models to recover short-run as well as long-run equilibrium elasticity estimates. The estimated results complement and extend demand elasticity estimates for the Irish residential sector.

A brief review of the energy demand literature finds that there is little consensus on the magnitude of demand elasticities, even within countries or sectors. Different methodological approaches appear to yield widely different estimates for what is nominally the same parameter. Nonetheless, there is an ongoing need to update and inform policy decisions. The paper's contribution is that it is the first paper to estimate demand system for individual fuels in Ireland for the residential sector, complementing earlier single equation estimates.

With respect to price elasticities, we find that residential energy products are rather price inelastic. Oil and gas demand are most responsive to price changes, whereas solid fuels and electricity are not very responsive. In the case of electricity that may reflect how reliant modern life is on electricity. Our treatment of solid fuels as a homogeneous product may have concealed information on price responsiveness. However, there is evidence that solid fuels are substitute fuels for gas and electricity.

The policy implications are relatively straightforward. With demand for energy products by the residential sector being quite price inelastic it is likely that any policy measures intended to reduce demand (and thereby reduce associated greenhouse gas emissions) by increasing price are likely to be relatively ineffective for marginal changes in prices. If emissions reduction is the objective, a policy ambition might be to switch residential fuel demand away from carbon intensive solid fuels. Based on negative expenditure elasticities it may be reasonable to assume that there is an income effect preventing households switching away from solid fuels. Policy schemes that address barriers to fuel-switching, such as the capital costs of conversion, may be quite successful but require further research.

More generally, future research on energy demand should consider how energy demand is constrained by the energy using equipment installed within homes, i.e. path dependency, as well as focusing on more narrowly defined rather than aggregated fuel types.

REFERENCES

AGOSTINI, P., M. BOTTEON and C. CARRARO, 1992. "A Carbon Tax to Reduce CO_2 Emissions in Europe", *Energy Economics*, Vol. 14, No. 4, pp. 279-290.

AKMAL, M. and D.I. STERN, *et al*., 2001. "The Structure of Australian Residential Energy Demand", *Working Papers in Ecological Economics*.

ALBERINI, A., W. GANS and D. VELEZ-LOPEZ, 2011. "Residential Consumption of Gas and Electricity in the US: The Role of Prices and Income", *Energy Economics*, Vol. 33, No. 5, pp. 870-881.

ALSTON, J. M., K. A. FOSTER and R. D. GREEN, 1994. "Estimating Elasticities with the Linear Approximate Almost Ideal Demand System: Some Monte Carlo Results", *The Review of Economics and Statistics*, pp. 351-356.

ASCHE, F., O. B. NILSEN and R. TVETERÅS, 2008. "Natural Gas Demand in the European Household Sector", *The Energy Journal*, pp. 27-46.

AZGUN, S., 2011. "A Structural VAR Analysis of Electrical Energy Consumption and Real Gross Domestic Product: Evidence from Turkey", *International Journal of Economics and Finance*, Vol. 3, No. 5, p. 161.

BANKS, J., R. BLUNDELL and A. LEWBEL, 1997. "Quadratic Engel Curves and Consumer Demand", *Review of Economics and Statistics*, Vol. 79, No. 4, pp. 527-539.

BLACKLOW, P., A. NICHOLAS and R. RAY, 2010. "Demographic Demand Systems With Application to Equivalence Scales Estimation and Inequality Analysis: The Australian Evidence", *Australian Economic Papers*, Vol. 49, No. 3, pp. 161-179.

BLÁZQUEZ, L., N. BOOGEN and M. FILIPPINI, 2013. "Residential Electricity Demand in Spain: New Empirical Evidence Using Aggregate Data", *Energy Economics*, No. 36, pp. 648-657.

CHALFANT, J. A., 1987. "A Globally Flexible, Almost Ideal Demand System", *Journal of Business & Economic Statistics*, Vol. 5, No. 2, pp. 233-242.

CONNIFFE, D., 2000. "Household Energy Expenditures: Policy Relevant Information from the Household Budget Survey", Policy Research Series, No: 37, Dublin: The Economic and Social Research Institute.

CONNIFFE, D. and S. SCOTT, 1990. "Energy Elasticities: Responsiveness of Demands for Fuels to Income and Price Changes", General Research Series, No. 149, Dublin: The Economic and Social Research Institute.

DAVIS, L. W. and L. KILIAN, 2011. "Estimating the Effect of a Gasoline Tax on Carbon Emissions", *Journal of Applied Econometrics*, Vol. 26, No. 7, pp. 1187-1214.

DEATON, A. and J. MUELLBAUER, 1980. "An Almost Ideal Demand System", *The American Economic Review*, pp. 312-326.

DERGIADES, T. and L. TSOULFIDIS, 2008. "Estimating Residential Demand For Electricity in the United States, 1965–2006", *Energy Economics*, Vol. 30, No. 5, pp. 2722-2730.

DI COSMO, V. and M. HYLAND, 2013. "Carbon Tax Scenarios and Their Effects on the Irish Energy Sector", *Energy Policy*, Vol. 59, pp. 404-414.

DICKEY, D. A. and W. A. FULLER, 1981. "Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root", *Econometrica: Journal of the Econometric Society*, pp. 1057-1072.

EAKINS, J. M. and L. A. GALLAGHER, 2003. "Dynamic Almost Ideal Demand Systems: An Empirical Analysis of Alcohol Expenditure in Ireland", *Applied Economics*, Vol. 35, No. 9, pp. 1025-1036.

ENGLE, R. F. and C. W. J. GRANGER, 1987. "Co-integration and Error Correction: Representation, Estimation and Testing", *Econometrica*, Vol. 55, No. 2, pp. 251-276.

EUROPEAN COMMISSION, 2011. *Energy Efficiency Plan 2011, Communication from The Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions*. Number COM(2011) 109. European Commission. Available online: http://ec.europa.eu/clima/policies/roadmap/docs/ efficiency_plan_en.pdf.

EUROPEAN COMMISSION, 2014. *A Policy Framework for Climate and Energy in the Period from 2020 To 2030, Communication from The Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions*. Number COM(2014) 15 final. European Commission. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0015&from=EN.

EUROPEAN COUNCIL, 2014. *European Council (23 and 24 October 2014) Conclusions*. Number EUCO 169/14. European Council. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0015&from=EN.

GREEN, R. and J. M. ALSTON, 1990. "Elasticities in AIDS Models", *American Journal of Agricultural Economics*, Vol. 72, No. 2, pp. 442-445.

HAAS, R. and L. SCHIPPER, 1998. "Residential Energy Demand in OECD-countries and the Role of Irreversible Efficiency Improvements", *Energy Economics*, Vol. 20, No. 4, pp. 421-442.

HENNESSY, H. and J. FITZGERALD, 2011. "The HERMES Model of the Irish Energy Sector", Working Paper Series, No. 396, Dublin: The Economic and Social Research Institute.

HOWLEY, M. and M. HOLLAND, 2013. *Energy in Ireland 1990-2012*. The Sustainable Energy Authority of Ireland. www.seai.ie/Publications/Statistics_Publications/Energy_in_Ireland/Energy_in_Ireland_1990_-_2012_Report.pdf.

IMF STAFF, 2011. *World Economic Outlook, April 2011: Tensions from the Two-Speed Recovery Unemployment, Commodities, and Capital Flows*. International Monetary Fund. www.imf.org/ external/pubs/ft/weo/2011/01/pdf/text.pdf.

IPCC, 2014. *Climate Change 2014, Synthesis Report – Summary for Policymakers*. Intergovernmental Panel on Climate Change. Available online: www.ipcc.ch/pdf/assessment-report/ar5/syr/ SYR_AR5_SPMcorr1.pdf.

JAMIL, F. and E. AHMAD, 2011. "Income and Price Elasticities of Electricity Demand: Aggregate and Sector-Wise Analyses", *Energy Policy*, Vol. 39, No. 9, pp. 5519-5527.

KARAGIANNIS, G., S. KATRANIDIS and K. VELENTZAS, 2000. "An Error Correction Almost Ideal Demand System for Meat in Greece", *Agricultural Economics*, Vol. 22, No. 1, pp. 29-35.

KOURIS, G., 1983. "Energy Consumption and Economic Activity in Industrialized Economies – A Note", *Energy Economics*, Vol. 5, No. 3, pp. 207-212.

KRISHNAMURTHY, C. K. B. and B. KRISTRÖM, 2015. "A Cross-country Analysis of Residential Electricity Demand in 11 OECD-countries", *Resource and Energy Economics*, No. 39, pp. 68-88.

LABANDEIRA, X., J. M. LABEAGA and M. RODRÍGUEZ, 2006. "A Residential Energy Demand System for Spain", *The Energy Journal*, pp. 87-111.

LESER, C. E. V., 1962. *Demand relationships for Ireland,* General Research Series, No. 4, Dublin: The Economic and Social Research Institute.

LESER, C. E. V., 1964. "A Further Analysis of Irish Household Budget Data, 1951-52", General Research Series, No. 23, Dublin: The Economic and Social Research Institute.

LYONS, S., K. MAYOR and R. S. TOL, 2009. "Convergence of Consumption Patterns During Macroeconomic Transition: A Model of Demand in Ireland and the OECD", *Economic Modelling*, Vol. 26, No. 3, pp. 702-714.

MADDALA, G. S., R. P. TROST, H. LI and F. JOUTZ, 1997. "Estimation of Short-Run and Long-Run Elasticities of Energy Demand from Panel Data Using Shrinkage Estimators", *Journal of Business & Economic Statistics*, Vol. 15, No. 1, pp. 90-100.

MCCARTHY, C., 1977. "Estimates of a System of Demand Equations Using Alternative Commodity Classifications of Irish Data, 1953-1974", *The Economic and Social Review*, Vol. 8, No. 3, pp. 201-211.

MENEGAKI, A. N., 2014. "On Energy Consumption and GDP Atudies: A Meta-Analysis of the Last Two Decades", *Renewable and Sustainable Energy Reviews*, No. 29, pp. 31-36.

MOSCHINI, G., 1995. "Units of Measurement and the Stone Index in Demand System Estimation", *American Journal of Agricultural Economics*, Vol. 77, No. 1, pp. 63-68.

MURPHY, D. C., 1976. "1973 Household Budget Survey: Special Features and Results", *Journal of the Statistical and Social Inquiry Society of Ireland*, Vol. XXIII, No. III, pp. 135-191.

NZUMA, J. M. and R. SARKER, 2010. "An Error Corrected Almost Ideal Demand System for Major Cereals in Kenya", *Agricultural Economics*, Vol. 41, No. 1, pp. 43-50.

OECD, 2013. *Taxing Energy Use*, Paris: OECD Publishing. http://dx.doi.org/10.1787/9789264183933-en.

O'RIORDAN, W. K., 1975. "Consumer Response to Price and Income Changes", *Journal of the Statistical and Social Inquiry Society of Ireland*, Vol. XXIII, Part II, pp. 65-83.

POI, B. P., 2012. "Easy Demand-system Estimation with QUAIDS", *Stata Journal*, Vol. 12, No. 3, pp. 433-446.

PRATSCHKE, J. L., 1969. "Income-expenditure Relations in Ireland, 1965-1966", General Research Series, No. 50, Dublin: The Economic and Social Research Institute.

RAY, R., 1983. "Measuring the Costs of Children: An Alternative Approach", *Journal of Public Economics*, Vol. 22, No. 1, pp. 89-102.

REILLY, B., 1986. "A Note on Demand Elasticities for Energy Imports", *Economic and Social Review*, Vol. 17, No. 2, pp. 147-158.

SCOTT, S., S. LYONS, C. KEANE, D. MCCARTHY and R. S. TOL, 2008. "Fuel Poverty in Ireland: Extent, Affected Groups and Policy Issues", Working Paper Series, No. 262, Dublin: The Economic and Social Research Institute.

SEALE JR, J. L. and A. A. SOLANO, 2012. "The Changing Demand for Energy in Rich and Poor Countries Over 25 Years", *Energy Economics*, Vol. 34, No. 6, pp. 1834-1844.

SEN, A., 1987. *On Ethics and Economics*, Blackwell.

SMYTH, M., 1996. "The Dynamics of United Kingdom Regional Energy Demand", *International Journal of Energy Research*, Vol. 20, No. 2, pp. 93-106.

SWAN, L. G. and V. I. UGURSAL, 2009. "Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques", *Renewable and Sustainable Energy Reviews*, Vol. 13, No. 8, pp. 1819-1835.

TAYLOR, L. D., 1977. "The Demand for Energy: A Survey of Price and Income Elasticities" in W. D. Norhaus, (ed.), *International Studies of the Demand for Energy*, pp. 3-43, Amsterdam: North-Holland.