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The Determinants of Residential Gas Demand in Ireland

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Abstract

This paper examines the determinants of residential gas demand in Ireland using a micro econometric analysis of the daily gas consumption panel data from Ireland's Smart Metering Gas Consumer Behavioural Trial. It also investigates the effectiveness of the demand side management stimuli that were tested during the Smart Metering Trial. The analysis is based on a sample of 1,181 households over 539 days. The results provide evidence that weather, together with the structural characteristics of the dwellings and the socio-economic characteristics of the households, are significant factors in explaining residential gas demand. More specifically, weather is found to be the most influential factor on household's daily gas consumption. Finally, the demand side management stimuli employed in the Smart Metering Trial were found to reduce daily household gas use on average.

1 Introduction

Residential natural gas consumption in Ireland has grown considerably in recent years. According to the Sustainable Energy Authority of Ireland, natural gas as a share of total residential energy consumption increased from 5.2% to 20.1% over the period 1990-2011 (SEAI, 2012), while the penetration of natural gas fired central heating systems into Irish houses has grown from 4% in 1987 to 28% in 2005 (SEI, 2008). In 2011, the residential sector in Ireland used 569 kilo tonnes of oil equivalent (ktoe) of natural gas compared to just 117 ktoe in 1990 (SEAI, 2012). The remarkable growth in residential natural gas consumption in Ireland has been attributed to a number of factors including the large increase in the Irish housing stock since 1990, expansion of the gas network and a preference for natural gas on the part of residential users.

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Better understanding residential demand for natural gas can be of assistance to suppliers, policymakers and ultimately customers. Suppliers need accurate forecasting models of residential gas demand to support efficient purchasing of gas supplies and to plan future investment in the face of changing demographics, fuel prices, macroeconomic conditions and energy policy measures. Such models exist, but they tend to be based on analysis of aggregate data and there may be scope to improve them using microdata linking detailed household characteristics to gas use. Policymakers also have an interest in domestic fuel demand, because it contributes a significant proportion of national energy use and greenhouse gas emissions. The residential sector in Ireland emitted 1,359 kilo tonnes of CO_2 from natural gas consumption alone in 2011, a 13% share of the overall energy-related household CO_2 emissions for that year (SEAI, 2012). Residential heating, apart from that contributed by electricity, also falls outside the boundaries of the Europe's Emission Trading Scheme, in a segment where there is not (yet) a common, consistent set of economic measures to provide incentives for carbon abatement across Europe. Overlapping policies towards carbon abatement, energy efficiency and encouragement of renewable fuels complicate the policy space in this area.

To curb carbon emissions and increase energy efficiency, policymakers employ a range of measures intended to change aspects of consumer behaviour. This may include encouragement of fuel switching, increased energy efficiency or changes in other aspects of behaviour that lead to lower fuel use. Better understanding the determinants of gas demand should help with the development of more effective and efficient policy measures. Information about consumer behaviour is particularly important when designing demand side programmes. These are used in some jurisdictions to bring about behavioural change among consumers, aiming to reduce fuel consumption by either improving the information available to households on potential energy efficiency opportunities or by giving them a financial incentive to decrease their overall household gas use. To maximise the potential impact of a demand side management programme and change the behaviour of consumer's gas consumption, it is necessary to recognise the determinants of residential gas demand and incorporate them into programme design.

In this paper, the determinants of residential gas demand in Ireland are examined using a micro econometric analysis of the gas consumption panel data from Ireland's Smart Metering Gas Consumer Behavioural Trial (CER, 2011). It is highly unusual for studies of gas demand to have access to such high frequency usage data combined with socioeconomic micro data. With the majority of residential gas consumption in Ireland used for space and water heating, gas demand is expected to be determined to a large extent by the energy efficiency of gas using appliances and dwellings, as well as the socio-economic characteristics of the household. It is also anticipated that weather will have a significant role in determining household gas demand. For example, gas consumption reportedly experienced an unusual increase in 2010 as a result of two exceptionally cold spells at the beginning and end of the year.

This paper aims to provide evidence that the energy efficiency of the dwellings, together with the socio-economic characteristics of the households and the weather are indeed important factors in determining residential gas demand and should for that reason, contribute significantly to advances in gas demand forecasting. In addition, this paper explores some of the socio-economic impact on the household's consumption of gas and investigates the demand side management stimuli tested during the Smart Metering trial, demonstrating their effectiveness in reducing household gas consumption.

The paper proceeds as follows: the related literature is reviewed in Section 2, the data and variables used are described in Section 3, details of the models used for estimation are specified in Section 4, results are presented in Section 5, and Section 6 provides a conclusion.

2 Literature

There is a limited body of research which specifically examines the determinants of residential gas demand. For example, Brounen et al. (2012) examine the extent to which gas and electricity use in the Netherlands is determined by household and individual characteristics. They found that residential gas consumption was driven largely by dwelling characteristics, with older and bigger homes found to consume more gas. They also note that insulation had a significant effect on gas consumption by households and that "residents living in a well-maintained and insulated home consume about 12% less natural gas compared to the same home with a lower level of maintenance and insulation" (Brounen et al., 2012). Interestingly, it was found that each additional person in a household decreases the per capita gas consumption by roughly 26%. According to the authors, "this reaffirms the well documented economies of scale in residential energy consumption" (Brounen et al., 2012). On the other hand, single-parent and elderly households were found to use more natural gas per capita. This is consistent with findings from a study of demand for space and water heating by older households in the United States. In particular, Liao and Chang (2002) reported that most elderly households spend a significant amount of their income on space heating energy and as the household head becomes older more heating energy is required.

In another study, Leth-Peterson (2002) conducted a micro econometric analysis of household demand for natural gas for a cross-section of 2,885 Danish households. The year in which the house was built as well as the house type were found to be important determinants of gas demand. The consumption of natural gas in non-detached houses was found to be 4% lower than in detached houses. In an analysis of residential heating consumption in the Netherlands, Guerra-Santin and Itard (2010) found that the frequency of use of the heating system was a much stronger determinant than temperature settings in explaining energy consumption by households. Interestingly, they found that "households with a programmable thermostat were more likely to keep the radiators turned on for more hours than households with a manual thermostat or manual valves on radiators." Karjalainen (2007) found significant gender differences in thermal comfort, with females preferring a higher room temperature than males. However, males tend to use thermostats more often than females in their sample.

In contrast to residential natural gas demand, there is a widespread literature on energy demand for residential space and water heating more generally. For example, Rehdanz (2007) studies the determinants of household expenditure on space heating and hot water supply in Germany in an attempt to establish if different types of households respond differently to changes in energy prices. The analysis covers more than 12,000 households for the years

1998 and 2003. The author points out that energy price increases lead to higher expenditures for households in rented accommodation compared to households in owner occupied accommodation with the difference becoming smaller over time. This suggests that home owners are more likely to have invested in energy efficient heating and hot water systems and, furthermore, that landlords have very little incentive to improve the energy efficiency of rented accommodation as their tenants pay the energy bills. In a replica study for Great Britain, Meier and Rehdanz (2010) utilise panel data over 15 years from 1991-2006 on over 5,000 households and discover the opposite result. The study finds that heating expenditure for home owners tend to be higher than for renters. Heating expenditures are lowest for flats compared with households living in other house types and as the majority of rented accommodations in Britain are flats, this explains the contradicting result. In examining residential energy consumption for space heating in Norwegian households, Nesbakken (1998) confirms that house type, dwelling size and temperature (degree days) are important in explaining energy demand in households.

Another strand of literature in this area investigates if weather has a significant impact on demand for energy. For example, Conniffe (1996) developed a model to help explain how daily demand for fuel by the domestic and commercial sectors varies from day to day in response to different factors including meteorological variables. The author estimates the model for natural gas and establishes that temperature measured as degree days is non-linear in the demand for gas. He also found that wind speed and sunshine hours have substantial effects on gas demand, while the significance of rainfall is much less pronounced in the model. Tol et al. (2012) also find that energy use is non-linear in temperature and that it declines with rising temperatures due to the decreased demand for heating.

In the Irish context, Rogan et al. (2012) performed a decomposition analysis of residential gas consumption in Ireland from 1990 to 2008 and report that the change in the number of customers had the greatest effect on gas consumption. In the period of the examination, Bord Gáis Éireann was the only natural gas retailer to the residential sector in Ireland. They had 139,000 customers in 1990 and by 2008 their customer base had grown by 342% to 616,000 customers. The CER (2011) Gas Customer Behaviour Trial Findings Report found that the smart metering trial had a positive impact on the awareness of residential gas usage in Ireland, with 74% of households reporting that they became more aware of their gas consumption. It also reported that the deployment of the demand side stimuli reduced overall gas consumption by about 2.9%.

3 Data and Variables

3.1 Data

For the purpose of this paper, micro data which was collected as part of Ireland's Smart Metering Gas Consumer Behavioural Trial (CER, 2011) is used. The trial was run from 1st December 2009 to 30th May 2011 and had two distinct periods, the benchmark period and the treatment period. During the benchmark period (1st December 2009 to 31st May 2010), all participants were charged their normal tariff and received bi-monthly billing. Data collected during this period was for the purpose of establishing the benchmark level of use by households. During the treatment period (1st June 2010 to 30th May 2011), participants were divided into treatment and control groups. The treatment groups were placed on different demand side management stimuli while the control group remained on their normal tariff and had no changes to their bill. The demand side management stimuli tested in the trial included providing the household with additional information on their gas usage; a more frequent bill (monthly), the provision of an In House Display (IHD) unit; and the introduction of a variable tariff. Data was collected on a half hourly basis from 1,892 household meters over the complete course of the trial. At the end of the complete period, 1,576 household meters remained in the trial after attrition. Changes of tenancy and changes of supplier were cited as the main reasons behind the attrition.

While 103 of the remaining household meters have complete gas data, 1,473 had at least one missing half hour entry in the trial period. The meters with more than 8 weeks missing data were removed together with the data for 6 particular days, where more than 15% of the meters had missing values. Furthermore, the data for the 27th March 2011 (daylight savings time) was deleted as there were two additional half hour periods recorded on that day for which there was no obvious way to attribute gas use. The remaining meters with missing data had the missing values imputed by statisticians at the Commission for Energy Regulation (CER) using a method of multiple imputation. This involved estimating a mean value by calculating an average of six values, the two values immediately preceding and after the missing value; the values during the same half hourly period one week before and after; and the values for the same period two weeks before and after. The uncertainty associated with the imputed value is measured by the standard deviation of the six values. The multiple imputation process then replicates the data series for the missing meters and completes the data with values obtained by reference to the distributions given by the mean and standard deviation calculated. The imputation was carried out for 1,390 of the households with missing gas data. Consequently, complete gas data is available for 1,493 households with the imputed values accounting for just 0.5% of all values (CER, 2011).

Additionally, pre- and post-trial surveys were distributed to the participating households as part of the trial. These surveys explored the structural and socio-economic characteristics of the household as well as the attitudes of the respondents with regard to energy saving activities. The surveys also investigated the presence and use of gas appliances in the home. A further 311 households were dropped from the analysis for failure to answer some key socioeconomic and housing characteristic questions, such as the number of bedrooms or the year the house was built. Thus. the data used in the analysis in this paper includes the daily household gas consumption (kWh) for 1,181 households over the trial period of 539 days (546 days less the 7 days dropped), the socioeconomic and housing characteristic variables from the pre-trial survey for each of these households, along with daily weather data provided by Met Éireann's Dublin Airport weather station.

3.2 Variables

Figure 1 illustrates the frequency of daily gas consumption (kWh), our independent variable, in the sample. The distribution of daily gas consumption is skewed to the right with the high frequency of low consumption days reflective of the high seasonality of gas consumption.

The mean daily gas consumption in this sample is 47.8kWh* (see Table 1). The minimum daily gas consumption is as expected at 0kWh, though the maximum daily consumption gives some cause for concern at 530.49kWh. There are only 20 observations with daily gas consumption above 400kWh with 19 of these falling in late December and early January, a particularly cold period in the calendar. 15 of these observations are for households that own two or more gas fires along with their gas fired central heating system. Therefore, while the maximum of 530.49kWh is very high, it is possible.

[Insert Figure 1 and Table 1 about here]

The pattern of household gas consumption is represented in Figure 2. The histogram shows the frequency of the number of half hours in a day the gas is switched on across all households for the entire period. The high frequency of low gas use once again reflects the high seasonality in gas usage. The distribution of the usage of daily gas consumption becomes larger from one half hour to about 6 half hours with the distribution skewed to the right thereafter with a single bar spike at 48 half hours. It is not remarkable for a household to be much more likely to have gas on for just 6 half hours in a day in contrast to having it on for 35 half hours in a day. On the contrary, the high frequency of all day gas use is interesting and requires further analysis beyond the scope of this paper.†

[Insert Figure 2 about here]

In terms of explanatory variables, the data on the socioeconomic and building characteristics of the households was collected as part of a pre-trial survey conducted by Computer Assisted Telephone Interviewing (CATI) between April and May 2010 and just before the test period commenced. The summary statistics of the selected categorical and dummy variables important to this analysis are described in Table 2.

[Insert Table 2 about here]

At first glance,the 18-25 age group appears to be under represented in the sample at 0.4%; however, given that the CES's are gas bill payers it is expected that few respondents would fall into the 18-25 age category and therefore the fact that 0.4% is not representative of the national population of 18-25 year olds is not a problem for this analysis. For education, 76% of the sample has at the very least completed their Leaving Certificate examinations. As a direct result of dropping the 311 households for failure to answer key building characteristic

* The Smart Metering Gas Behavioural Trial reports an average daily gas usage of 38.8kWh; however, the higher average daily gas consumption in this analysis compared to the smart metering trial is to be expected as the complete sample period of 18 months is taken into account here, while the smart metering trial only accounts for the test period of 12 months. The additional 6 months in the sample includes a winter season when gas consumption tends to be at its seasonal peak and as a result the average daily gas consumption reported is higher.

† There may be some unobserved controls that are not contained in the data which would help explain such a high frequency. For example, it could be explained by a pilot light installed on some gas fires and gas central heating systems, which burns continuously and therefore results in gas usage being recorded for all half hour periods in a day. The average pattern of gas usage in the data is for a household to have gas turned on for about 16 half hours in a day (see Table 1). This is biased upwards though due to the high frequency of observations with all day gas usage. With these observations excluded, the average pattern of gas usage is a little over 12 half hours daily.

questions, the distribution of house types have changed compared to the Smart Metering Trial. 20% of the sample is now bungalows and 4% is terraced, compared to 4% and 21% respectively in the trial. 1-2 bedroom households account for just 9% of the sample, reflecting the fact that these smaller households are less likely to have gas central heating installed. This is backed up by the fact that apartments only account for 2% of households in the data. Houses built after 1980, when significant building thermal insulation requirements were introduced (1979), represent 51% of the sample.

In the pre-trial survey, details about the dwelling characteristics were also collected and respondents were asked to give the approximate proportion of windows in their house that are double glazed. For the purpose of this study, any household that answered any proportion apart from none was deemed to have double-glazing. Consequently, it is observed that 94% of households have some proportion of double-glazing. Households with attic insulation account for 91% of the sample. 2% of households were unaware whether or not they had attic insulation; this is not a significant share and does not highlight an unawareness issue. Conversely, 16% of households didn't know if they had external wall insulation, 11% do not have a lagging jacket on their hot water cylinder and surprisingly, 9% of households in the sample state that they have never had their boiler serviced. This could potentially signal an unawareness of certain energy efficiency measures. Nevertheless, there is not enough evidence here to draw conclusions in relation to any efficiency awareness issue. Almost half of all households have at least one fire effects gas fire and 40% have a booster button on their heating system which allows the household to switch on the space or water heating for an additional hour.

Because weather plays such an important role in energy demand generally, a more detailed discussion of the weather variables is relevant. The weather data that is used is from Met Éireann's Dublin Airport weather station and comprises variables on heating degree days, sunshine hours, mean cloud cover, daily rainfall and wind speed. The weather data is taken for Dublin as it is the area with the highest population density in Ireland and it also has the highest concentration of household gas meters in the whole country. The descriptive statistics for the weather variables are described in Table 3.

[Insert Table 3 about here]

The impact of temperature on the heating requirements of a house is provided for by heating degree days. Heating degree days is a measurement derived from outside air temperature; it is defined relative to a base temperature, the outside temperature above which a building needs no heating. The base temperature here is 15.5^{o}C in line with other studies. If the average daily temperature is one degree below the base of 15.5^{o}C, then this is referred to as one heating degree day. The larger the number of heating degree days, the colder it is and so the bigger the requirement on the heating system. In the sample, the average heating degree days based on the arithmetic mean is slightly over 8 heating degree days. This reports that on average the daily temperature is 8 degrees below the base of 15.5^{o}C and thus the average daily temperature in the sample is about 7.5^{o}C across the 539 days. Temperatures over and above the base are not deemed to have an effect on the heating requirement, with the outside base temperature of 15.5^{o}C equating to the satisfactory temperature for human thermal comfort indoors. The minimum heating degree days is 0 when the temperature is greater than or equal to 15.5^{o}C and the maximum in the data is 23 heating degree days, where a temperature of -7.5^{o}C was recorded at Dublin Airport during an unusually cold spell over Christmas 2010.

Sunshine hours are a measure of the duration of sunshine in a day. The average daily duration of sunshine across the period is a little over 4.5 hours. According to Met Éireann, Ireland normally gets between 1,400 and 1,700 hours of sunshine each year and the daily average of 4.5 hours here corresponds with this information. On a cloud covered day the minimum sunshine hours of 0 is documented, while on the summer solstice (21st June 2010) a maximum of 15.8 sunshine hours is observed. Mean cloud cover measures the average daily amount of cloud cover. Oktas are the unit of measurement for cloud cover. Oktas are estimated with respect to how many eighths of the sky are covered by cloud. They range in values from 0 to 8, with 0 representing a completely clear sky and 8 representing a completely overcast sky. The average daily cloud cover across the 539 days is almost 5.5 oktas. Irish skies are predominantly cloudy due to Ireland's position in the northwest of Europe close to the path of the Atlantic low pressure systems. As expected, sunshine hours and mean cloud cover are highly negatively correlated.

Daily rainfall is measured in millimetres (mm). The average daily rainfall is recorded at 1.67mm over the sample period in line with Met ireann's reported average daily rainfall for Ireland of between 1 and 2mm. The maximum daily rainfall of 28.4mm was recorded in December 2009 when Ireland suffered from a period of extensive flooding. The daily mean wind speed is measured in knots. A knot is a unit of speed equal to one nautical mile per hour, equivalent to 1.852km per hour. The average daily wind speed in the period for the analysis is over 9.8 knots (18.15km per hour) with the maximum of over 28 knots recorded in early February 2011.

In the analysis, dummy variables are added for weekends and bank holidays, together with dummies for each of the four seasons. In addition, dummies are also introduced for the treatment period, the treatment group and the interaction between treatment period and group.

4 Methodology

The main model for estimation assumes that the demand for gas depends on a range of variables, such that:

$$G_{it} = \alpha + \beta X_i + \gamma Y_i + \delta W_t + \tau D_{it} + \pi Z_i + \epsilon_{it} \tag{1}$$

where the dependent variable G_{it} denotes the daily natural gas demand of household i at time t, and X_i is a vector of the socio-economic characteristics of the chief economic supporter (CES) in the household, which includes gender, age, education, and employment status. Y_i is a matrix of household level characteristics, which include the number of household members, a dummy variable for whether the house is rented or owned, the house type, the number of bedrooms and the period in which the house was built. W_t represents the weather variables, D_{it} are the time and season dummies, together with the treatment period and group dummies. Z_i is a matrix of dwelling characteristics, which range from features that enhance the energy efficiency of the household such as attic insulation and double glazed windows, to devices that contribute to a household's greater energy use such as a booster button and a fire effects gas fire. The error term is denoted by ϵ_{it}. The model is estimated using a random effects estimator with cluster robust standard errors.

Conniffe (1996) identifies weather as the main determinant of natural gas consumption. Hence, the weather variables are an essential inclusion in the gas demand model. Heating degree days, which measure the temperature impact on the building's heating requirement, is expected to be a highly significant factor in the household's daily gas usage. The coefficient is predicted to be positive as a high number of heating degree days indicates a colder day and an increased requirement for gas energy use to preserve a satisfactory household thermal comfort. Sunshine hours and cloud cover are introduced in the model because of possible smaller impacts on a household's gas demand when compared with heating degree days. It is anticipated that the signs on the coefficients for sunshine hours and cloud cover will be positive and negative respectively, given the high negative correlation that exists between the two variables. An overcast day has no sunshine and is associated with cooler temperatures. In controlling for wind speed and rainfall, there is no a priori expectation. However, Conniffe (1996) finds that wind has quite a substantial effect on gas demand while rainfall has a less convincing significance.

Time dummies which account for the effects of weekends and bank holidays are added to control for the fact that a household's daily demand for gas would normally increase on these specific days due to the greater likelihood of household members being at home all day. Furthermore, dummies for the seasons, winter, spring, summer and autumn are included with summer as the reference season. This will assist in unravelling any additional impacts the seasons have on household gas demand over and above the usual weather effects.

In order to account for the treatment and control effects of the smart metering trial a differences in differences approach is used. In this approach, a dummy for the treatment period that switches on for observations in the test period from 1st June 2010 to 30th May 2011 is included. In addition, a dummy for the treatment group is necessary. The treatment group dummy should be insignificant as the households were randomly selected in the sample to take part in the different demand side stimuli. In order to measure the treatment effects on gas demand, an interaction term that marks observations from the treatment group in the treatment period is also included. If the demand side stimuli, such as the additional usage information on the gas bill or the installation of an In-House Display unit, were successful in reducing gas demand then the coefficient on the treatment period and the interaction term should be negative and significant.

5 Results

Table 4 presents the results of the random effects regressions examining the factors influencing the daily gas consumption of households in the sample. The table presents the estimated coefficients from three models, the first model includes the CES's socio-economic and household level characteristics. The second model includes the independent variables from the first model together with the weather variables, time dummies and treatment controls and finally the third model includes the energy efficiency dwelling characteristics. An examination of the estimated coefficients across all three models tests the robustness of the findings. The reference category for each of the categorical explanatory variables act as a baseline against which the household's different characteristics can be compared. The final model has an R-squared of 0.585 and accordingly explains almost 60% of the variation in daily residential gas consumption with the estimated coefficients confirming robustness across the models

[Insert Table 4 about here]

In terms of the results, the gender of the chief economic supporter (CES) has no significant effect on the daily gas consumption by households. This is in contrast to Karjalainen's (2007) finding that females prefer higher room temperatures to males. However, as the data collected for the smart metering trial is focused on households rather than individuals, no relevant inference can be made here about the gender differences in daily gas consumption. Households with the CES aged 26 to 35 years consume less gas daily than households with the CES in the age reference category 36 to 45 years. Households with the CES over 65 years old consume more gas relative to those in the 36 to 45 years age category in both the first and second model, though when the dwelling characteristics are incorporated in the third model the significance is less. This finding is in agreement with Liao and Chang's (2002) discovery that as the household head becomes older more heating energy is required.

In terms of education, our prior expectations were that education may be a signal of an increased awareness of energy efficiency concerns and that higher education could possibly be associated with a decrease in gas consumption. However, contrary to this expectation, we find the opposite, with households with lower levels of CES educational attainment using less gas daily on average. However, this may be capturing an income effect, with higher education being correlated with higher income; highly educated households have the means to consume more gas than the lower educated households. In addition, households with a self-employed CES with employees consume significantly more gas in a day than households with an employed CES. Self employed people with employees tend to earn more than employees and as a result have a greater resource to consume more gas. Thus, this significance may also be explained by an income effect.

As expected, the number of household members has a highly significant effect on the daily gas consumed by households. Relative to the reference category of 2-3 household members, a single person household consumes considerably less gas daily and a household with 4-5 members consumes moderately more. The households with 6 plus members are too few in the sample to make any inference. The additional members in a household reveal a reduction to the per capita gas consumption of the household; this result gives further evidence to Brounen et al's (2012), well documented economies of scale in residential energy demand.

The results also suggest that homeowners consume significantly more natural gas in a day than their renting counterparts. This result is consistent with Meier and Rehdanz (2010), who found that renters use more gas than owners, primarily because the highest proportion of renters are inclined to occupy flats or apartments which by nature are much more energy efficient. However, the same cannot be said here. In our sample nearly 37% of renters live in semi-detached houses, compared to less than 9% in apartments. The significant result could instead be due once again to an underlying income effect. Over 38% of homeowners own their homes outright in the sample and as a result may have the disposable income to increase their daily gas consumption, whereas renters after rent is paid may have less disposable income to spend on natural gas.

Households living in detached houses and bungalows demand comparatively more gas daily than those in semi-detached houses. As discussed in Wyatt (2013), this may be due to both detached houses and bungalows having more external walls, resulting in an extra requirement for natural gas because of the additional heat loss. Semi-detached houses on the other hand benefit from the additional insulation afforded them from not having all their walls exposed to the elements. Thus, Leth-Peterson's (2002) finding that house type is an important determinant of gas demand is confirmed by this analysis. The number of bedrooms provides additional information in this regard. Households living in four and five bedroom houses consume more gas than those in three bedroom houses, while alternatively, households in one and two bedroom houses consume a relatively smaller amount of gas when compared to households in three bedroom houses. As the number of bedrooms increases, the household daily gas consumption increases notably and therefore, in line with expectations, house size is a highly significant determinant in daily residential gas demand.

Households in houses built pre 1981 consume considerably more natural gas daily than those in houses built in the period from 1981-2000. Interestingly, the thermal insulation requirements for buildings in Ireland were introduced in 1979. It is possible that the standards of energy efficiency in the new housing stock improved substantially from 1979 onwards and this effect is picked up in the analysis as a reduction in daily household gas demand post 1980. This result reaffirms Brounen et al's (2012) finding that residential gas consumption is driven largely by the period in which the house was built. It is noteworthy that the older the house relative to the 1981-2000 period, the greater the household daily gas consumption, with houses built pre 1900 exhibiting the most gas use.

All the weather variables are found to be highly significant determinants of residential natural gas consumption in Ireland, this echoes Conniffes's (1996)findings from his analysis. Of the weather variables, heating degree days have the largest positive association with household daily gas consumption. The results reveal that large heating degree days indicate colder temperatures and a considerable increase in daily residential gas demand. It would be interesting to model heating degree days following Conniffe's (1996) method and perhaps establish the effect of heating degree days on gas consumption when taking into account the long run degree days and the nonlinearity of temperature; however, this is beyond the scope of this study.

The results find that sunshine hours have a negative effect on residential gas demand. The more sunshine observed in a day, the less gas consumed by households. The sunshine effect may be a supplementary effect to heating degree days, where a household on a cold day with lots of sunshine would consume less gas than a household on a cold day with no sunshine, as a direct result of the sunshine having a strong association with warm temperatures. In contrast, cloud cover has the opposite effect with the model producing a positive coefficient.

On a cloudy day households consume more gas. These results reiterate the strong negative correlation between both sunshine hours and cloud cover.

While Conniffe (1996) finds little effect of rainfall on gas demand, rainfall proves to be highly significant and increases the demand for natural gas by households. The reason for this impact of rainfall on daily residential gas demand is not particularly clear, however; it may be subjective in that rain gives individuals the feeling of cold or quite possibly rain gives rise to an increased requirement to dry clothes indoors. Like Conniffe's (1996) model, wind is an important determinant for residential gas demand with increased wind speeds culminating in greater daily gas consumption by households.

In terms of time of use, households consume more gas at the weekends and on public holidays. This is because houses are much more likely to be occupied on these days when adults are off work and children are off school. The augmented requirement for space and water heating leads to an increase in household gas consumption on these particular days. In winter, spring and autumn households consume relatively more gas daily than they do in summer. The most gas is consumed by households in winter as would be expected. The seasons capture the additional unobserved seasonal effects on residential gas demand that are not accounted for in the weather variables.

The coefficient on the treatment group dummy is insignificant, verifying that the households were selected at random to take part in the demand side management stimuli and that there are no important underlying differences between the treatment group and the control group. The coefficient on the treatment period dummy and the coefficient on the interaction term representing the observations from the treatment group in the treatment period are both negative and significant. This provides strong evidence that the demand side stimuli, incorporating the increased frequency of billing, the additional usage information made available and the provision of an In House Display unit and the introduction of a variable tariff, are effective in reducing household daily gas consumption, echoing the conclusions of the cost benefit analysis conducted as part of Ireland's Smart Metering Gas Consumer Behavioural Trial (CER, 2011). It is important to note that the individual treatments in the demand side stimuli were also included as dummies in an earlier model and none of the dummy coefficients registered any significance. However, this is most likely due to a sample size issue with each individual treatment having comparatively less observations in the sample than the treatments combined. Furthermore, as the treatment was randomly assigned, it is fair to state that the combined treatment causes a reduction in daily gas consumption by households.

Somewhat surprisingly, households with no attic insulation were found to consume less natural gas per day relative to households with attic insulation more than 5 years old. According to O'Doherty et al. (2008) households with higher incomes tend to have more energy saving features and an increase in a household's income is also associated with higher potential energy use. Therefore, as this analysis cannot control for income, it is likely that the omitted variable income is biasing the coefficients on the categories of attic insulation. It is more likely that high income households have attic insulation, though they also consume more natural gas. Households without external wall insulation consume significantly more gas compared to households with external wall insulation, highlighting the success of external wall insulation as an energy saving measure and reiterating Brounen et al's (2012) result that insulation is a significant factor in gas consumption.

Households that never service their boilers or only service them every 2-3 years use less gas in a day than those that service their boilers every year. This is an unexpected result with a well serviced boiler likely to be more efficient and requiring less gas. On the other hand, it could be a result of reverse causality. A household that consumes a large amount of gas daily may need to have their boiler serviced more often and this would fully explain the unexpected result. The other energy saving measures (double glazed windows and a lagging jacket on the cylinder) are found not to have a statistically significant effect on household gas demand. Household ownership of a fire effects gas fire results in an increase in household daily gas use, while households that have a booster button on their gas heating system also use more gas, its significance is much less convincing.

6 Conclusion

This paper used a micro econometric analysis of the high frequency gas consumption panel data from the Smart Metering Gas Consumer Behavioural Trial (CER, 2011) to examine the determinants of residential gas demand in Ireland. Half hourly gas consumption data collected from 1,181 household meters over 539 days was aggregated into daily gas use data and together with the socio-economic and household level characteristics from the pre-trial survey and the weather variables provided by Met Éireann, this formed a balanced panel dataset on which the analysis was conducted. A random effects estimator with cluster robust standard errors was used to estimate the overall model.

The number of household members and the age of the house are found to have a strongly positive association with residential gas demand in Ireland. Residents of detached houses and bungalows are found to use more gas relative to semi-detached houses which may be due to the fact that their building walls are external. The size of the house as controlled for by the proxy of number of bedrooms is also a key determinant, with larger houses in Ireland consuming significantly more gas daily. Additionally, tenure is revealed to be a factor in Irish household gas demand. The interpretation from the analysis is that homeowners consume more gas than renters; however, this may be as a result of an underlying income effect as a large proportion of the homeowners in the sample own their houses outright and as a result have more disposable income to spend on gas.

All the weather variables controlled for in the analysis are found to be highly significant in determining residential gas demand. As expected, heating degree days, a measurement of the impact of temperature on the heating requirement, is proven to have the largest positive association with household daily gas consumption. Dummy variables for the four seasons, which capture any additional seasonal effects not accounted for by the weather variables, are also significant determinants, with the most household gas consumed in the winter season relative to the summer season as expected. Moreover, it is found that more gas is consumed on public holidays and weekends. This is probably because there are more people at home on these days.

The demand side stimuli tested as part of the Smart Metering Trial's demand side management programme to influence consumers to use less gas are found overall to be effective at reducing household daily gas consumption and reaffirms the conclusion of the **?** report. These stimuli were essentially informational in nature: households in the treatment groups were given more information about their gas use, some were given monthly rather than bi-monthly bills and others were provided with extra information through in-home electronic displays. Reductions in demand due to improved information may suggest that households better understood their energy use, and thus could optimise it better, or that the measures made the costs of use more salient. Unfortunately, due to limited sample sizes we could not test the effectiveness of each individual stimulus.

Unexpectedly, households who reported that their dwellings had no attic insulation consumed less gas than households with attic insulation. However, this does not imply that having attic insulation causes a household to use more gas and the outcome may instead be as a result of the high correlation between household income and the households ownership of attic insulation, which may lead to a bias in the result as income is an omitted variable here. In addition, possession of a fire effects gas fire and a booster button are confirmed to be positive factors in residential gas demand with the latter having a less convincing effect on the households gas demand. External wall insulation is found to have a negative effect on household gas consumption and the high frequency of boiler servicing is found to have a positive effect on consumption. While it is expected that a well maintained boiler would use less gas, the result could be interpreted as, households that in general consume a lot of gas may require their boiler serviced more regularly.

Overall, this paper has shown that the dwelling characteristics, together with the household size and other socio-economic characteristics of households, are highly significant determinants of residential gas demand in Ireland. Weather is found to be a very influential factor on the households daily gas consumption and for that reason is a necessary inclusion in any gas demand forecasting model. Furthermore, we found evidence that the demand side management stimuli employed in the Smart Metering Trial reduced household gas use on average, although the sample size was not sufficient for us to test individual stimuli with much confidence.

For future research, it would be interesting to incorporate the non-linearity of the weather variables into the model by following Conniffe's (1996) method, together with establishing the impact of the long run weather on residential gas demand. It is also important to include household income in future surveys to separate out the income effect and remove any bias to other coefficients arising from its omission. Much research also remains to be done on other household factors that may determine residential gas demand, for which there was incomplete data in the Smart Metering Trial, i.e. the energy efficiency characteristics of households' dwellings, the heating controls employed in each household and the efficiency of the appliances used. Finally, there is a need for research to verify the effectiveness of different individual stimuli in demand side management programmes so that any future implemented programmes can be tailored to be made more efficient.

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Table 1: Descriptive statistics for daily gas consumption.

	Mean	St. Dev.	Min	Max	T	N
Daily Gas Usage (kWh)	47.8	45.2	0	530.49	539	1181
Daily Duration of Gas Usage (1/2 hour)	16.1	14.1	0	48	539	1181

Table 2: Proportion of households in the different variable categories.

		%			%
Female		47.0	**Number of Bedrooms**		
			1-2 Bedrooms		9.0
Age			3 Bedroom	*Ref*	50.6
18-25 years		0.4	4 Bedrooms		34.5
26-35 years		14.6	5+ Bedrooms		5.9
36-45 years	*Ref*	27.9			
46-55 years		23.9	**Period House Built**		
56-65 years		16.0	Pre 1900		3.6
65+ years		16.3	1901-1940		9.6
Refused		0.9	1941-1960		11.5
			1961-1980		24.0
Education			1981-2000	*Ref*	32.0
None		1.4	2001-2008		19.3
Primary		6.9			
Junior Cert		11.9	**Dwelling Characteristics:**		
Leaving Cert		22.5	**Double Glazing**		94.3
Third Level	*Ref*	53.3			
Refused		4.0	**Attic Insulation**		
			<5 years		27.3
Employment Status			>5 years	*Ref*	63.7
Employee	*Ref*	60.0	None		6.7
Self-employed (employees)		5.3	Don't Know		2.3
Self-employed (no employees)		6.4			
Unemployed		6.6	**External Wall Insulation**		
Retired		20.7	Yes	*Ref*	49.4
Care Giver		1.0	No		34.9
			Don't Know		15.7
Number of Household Members					
1 Person		16.1	**Boiler Service**		
2-3 People	*Ref*	50.6	Never		9.2
4-5 People		29.3	Every 2-3 years		36.5
6+ People		4.0	Every year	*Ref*	54.3
Tenure (Rented)		5.8	**Lagging Jacket**		89.1
House Type			**Booster Button**		40.1
Apartment		2.2			
Semi-Detached	*Ref*	56.2	**Fire Effects Gas Fire**		47.3
Detached		17.7			
Terraced		20.2			
Bungalow		3.7			

Note: *Ref* is the omitted reference category.

Table 3: Descriptive statistics for the weather variables.

	Mean	Std. Dev	Min	Max	T
Heating Degree Days	8.07	5.14	0	23.3	539
Sunshine Hours (hours)	4.54	3.8	0	15.8	539
Cloud Cover (oktas)	5.48	1.56	0.54	8	539
Rainfall (mm)	1.67	3.25	0	28.4	539
Wind Speed (knots)	9.84	4.11	2.33	28.8	539

Table 4: Estimated coefficients from the random effects models of daily gas usage

VARIABLES	(1) Daily Gas Usage	(2) Daily Gas Usage	(3) Daily Gas Usage
Female	-0.0788	-0.0506	0.0215
Age			
18-25 years	-6.846	-7.146	-5.482
26-35 years	-5.075***	-5.081***	-4.945***
36-45 years	*Ref*	*Ref*	*Ref*
46-55 years	2.502*	2.531*	2.2
56-65 years	2.412	2.469	1.9
65+ years	5.833**	5.841**	5.197*
Refused	9.377**	9.588**	7.608
Education			
None	-5.773	-5.744	-5.015
Primary	-4.347**	-4.354**	-4.947**
Junior Cert	-0.365	-0.384	-0.608
Leaving Cert	-1.069	-1.089	-1.351
Third Level	*Ref*	*Ref*	*Ref*
Refused	0.579	0.459	0.766
Employment Status			
Employee	*Ref*	*Ref*	*Ref*
Self-employed (employees)	8.108***	8.217***	8.731***
Self-employed (no employees)	3.824	3.912	4.357*
Unemployed	-0.186	-0.0932	-0.3
Retired	2.322	2.309	2.096
Care Giver	6.346	6.257	6.92
No. of Household Members			
1 Person	-7.465***	-7.528***	-7.608***
2-3 People	*Ref*	*Ref*	*Ref*
4-5 People	2.510**	2.516**	2.690**
6+ People	3.565	3.439	3.829
Tenure (Rented)	-7.585***	-7.678***	-7.013***
House Type			
Apartment	-6.910*	-6.975*	-5.762
Semi-Detached	*Ref*	*Ref*	*Ref*

Continued on next page

Table 4 – continued from previous page

VARIABLES	(1) Daily Gas Usage	(2) Daily Gas Usage	(3) Daily Gas Usage
Detached	4.001**	3.983**	4.230***
Terraced	-1.892	-1.865	-1.89
Bungalow	5.590**	5.553**	6.573***
Number of Bedrooms			
1-2 Bedrooms	-3.611*	-3.512*	-3.173*
3 Bedrooms	*Ref*	*Ref*	*Ref*
4 Bedrooms	10.55***	10.60***	10.27***
5+ Bedrooms	20.30***	20.37***	20.98***
Period House Built			
Pre 1900	13.52***	13.42***	12.62***
1901-1940	9.606***	9.532***	8.353***
1941-1960	5.856***	5.823***	4.308**
1961-1980	7.468***	7.424***	6.336***
1980-2000	*Ref*	*Ref*	*Ref*
2001-2008	-0.818	-0.779	0.26
Weather			
Heating Degree Days		4.699***	4.699***
Sunshine Hours		-1.039***	-1.039***
Cloud Cover		0.817***	0.817***
Rainfall		0.138***	0.138***
Wind Speed		0.947***	0.947***
Time			
Weekend Day		0.661***	0.661***
Public Holiday		3.041***	3.041***
Treatment Period		-1.344**	-1.344**
Treatment Group		-0.0798	-0.117
TreatmentGroup*TreatmentPeriod		-1.537**	-1.537**
Winter		22.06***	22.06***
Spring		10.69***	10.69***
Autumn		3.394***	3.394***
Dwelling Characteristics			
Double Glazing			-0.104
Attic Insulation			
<5 years			-2.196*
>5 years			*Ref*
None			-4.319**
Don't Know			-1.129
External Wall Insulation			
Yes			*Ref*
No			4.537***
Don't Know			1.17
Boiler Service			
Never			-4.218**
Every 2-3 years			-2.266**
Every year			*Ref*
Lagging Jacket			-1.051

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Table 4 – continued from previous page

VARIABLES	(1) Daily Gas Usage	(2) Daily Gas Usage	(3) Daily Gas Usage
Booster Button			1.903*
Fire Effects Gas Fire			2.555**
Constant	38.19***	-18.11***	-18.09***
Observations	636,559	636,559	636,559
Number of ID	1,181	1,181	1,181
R^2	0.069	0.58	0.585
***p<0.01, **p<0.05, *p<0.1			

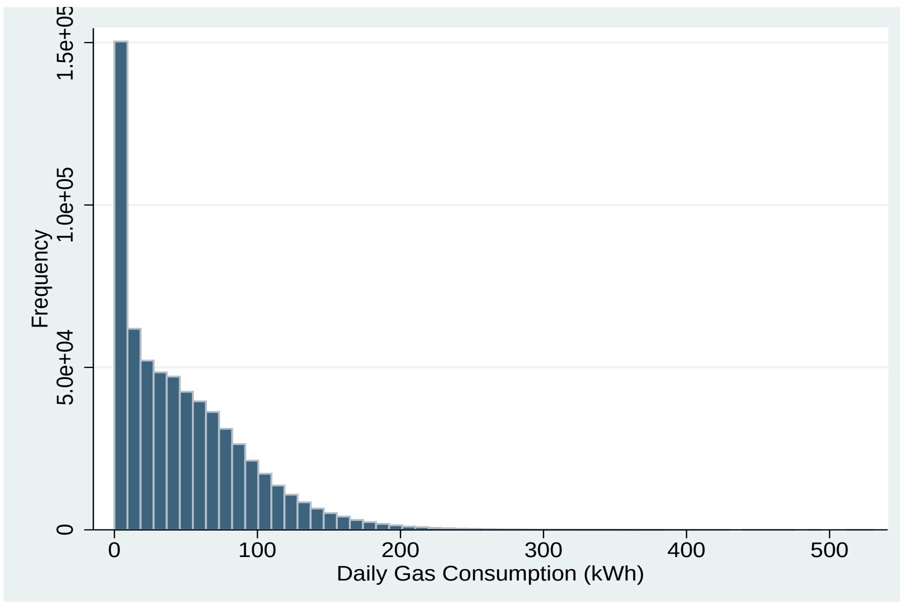

Figure 1: Frequency of daily gas consumption (kWh).

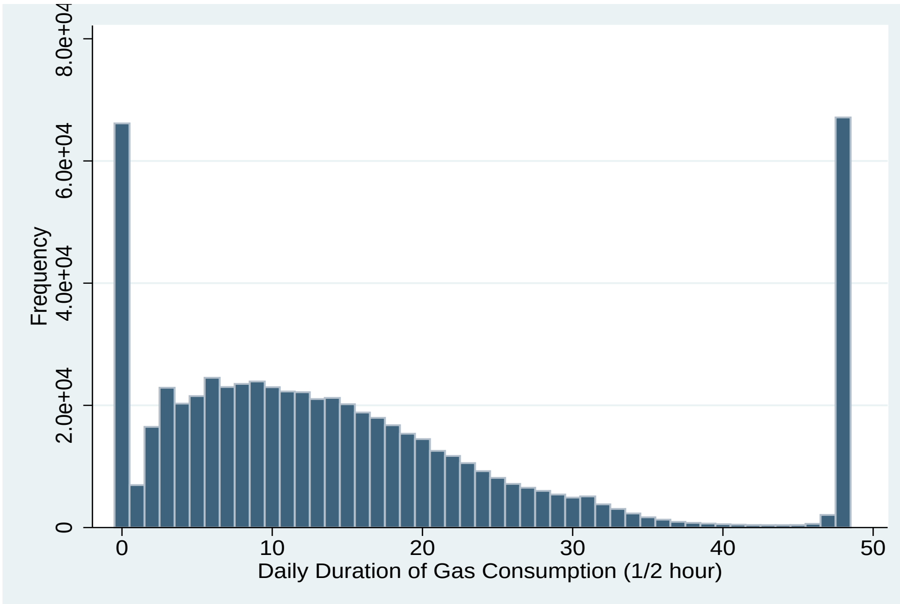

Figure 2: Frequency of daily duration of gas consumption ($\frac{1}{2}$hour).