Working Paper No. 539

August 2016

Subsequently published in "Exploring the spacial and temporal determinants of gas central heating adoption", *Resource and Energy Economics*, Vol 52, May 2018, pp. 64-86, https://doi.org/10.1016/j.reseneeco.2017.12.004

The Timing and other Determinants of Gas Central Heating Adoption

Daire McCoy[a,b] and John Curtis[a,b]*

Abstract: In order to better understand the potential for both policy and technological improvements to aid carbon abatement, long-term historical information on the time-path of transition from more traditional to cleaner fuels is useful. Knowing how this varies by socio-economic, demographic and geographic factors is also crucial in designing targeted policies. This research examines the timing and determinants of residential gas connections at area level within Ireland. We merge a unique dataset on gas network roll-out over time, with other geo-coded data and employ an instrumental variables technique in order to simultaneously model supply and demand. Results indicate a non-linear relationship between the proportion of households using gas as their primary means of central heating and the length of time the network has been in place in each area. Proximity to the gas network, peat bogs, and areas which have banned the consumption of bituminous coal also affect gas connections. Variations in socioeconomic and dwelling characteristics at area level can also help explain connections to the gas network.

**Corresponding Author: daire.mccoy@esri.ie*

Keywords: Gas network; Residential heating; Spatial economics; Instrumental variables estimation

JEL Codes: Q40; C31; C36

Acknowledgements: This material is based upon works supported by the Science Foundation Ireland under Grant No. 12/RC/2302. The research was part funded by Gas Networks Ireland through the Gas Innovation Group and by Science Foundation Ireland (SFI) through MaREI - Marine Renewable Energy Ireland research cluster. Funding from the ESRI's Energy Policy Research Centre is also gratefully acknowledged. We are also grateful to the Central Statistics Office, Gas Networks Ireland and The Environmental Protection Agency (EPA) for providing data. Seminar participants at the 5th Annual ESRI-UCC Seminar on Energy Policy Research provided helpful comments. Any errors or omissions are the responsibility of the authors alone.

a The Economic and Social Research Institute, Dublin
b Trinity College, Dublin

1 Introduction

EU energy and climate targets require, through various policy mechanisms, an increase in energy efficiency and in renewable energy, resulting in a reduction in greenhouse gas emissions. Fuel switching away from carbon intensive fuels, such as peat and coal to less carbon intensive fuels, such as gas or renewables is one way member states can contribute to meeting nationally binding policy targets. An important element of this will be domestic fuel choice, given that in 2014 residential energy consumption constituted approximately one quarter of the total primary energy requirement within the EU28[1].

A body of research within development economics focuses on the so-called "energy ladder", in which households transition from traditional heating and cooking methods, such as biomass or wood, to more modern methods, such as LPG or electricity as their income levels increase (Hosier and Dowd, 1987)[2]. Fuel switching is also a feature of developed economies. For example, there has been a particular interest in recent years into the decision to adopt renewable or more efficient heating systems (Mahapatra and Gustavsson, 2008; Sopha and Klockner, 2011; Michelsen and Madlener, 2012).

A certain inertia appears to characterise this process and many households are reluctant to adopt more energy efficient options, even if it is financially advantageous for them to do so. This energy-efficiency gap also characterises the reluctance to adopt other types of energy efficient appliances that offer seemingly positive NPV. For examples see Blumstein et al. (1980); Jaffe and Stavins (1994); Golove and Eto (1996); Allcott and Greenstone (2012).

The reasons for a time-lag in diffusion of more modern heating methods are multiple, and could be a function of many factors. In some cases it could be misinformation or a lack of information; uncertainty about future energy prices coupled with the irreversible nature of the investment create an option value to waiting; certain households may value qualitative features, such as open-hearth fires highly, thus creating a reluctance to switch due to reasons of comfort despite the associated inefficiencies; heterogeneity of preferences in the population can also explain variations in the timing of adoption, even in cases where the new technology is qualitatively better than the existing one; the lack of a grid connection also constrains gas and electric heating adoption in certain areas.

Ireland provides a very interesting lens through which to examine the diffusion of a superior heating technology over time. The Irish economy has developed considerably in recent times. There is a cultural legacy of solid fuel usage, driven by plentiful local endowments of peat, creating a reluctance to switch to more modern heating systems. This contrasts with a strong policy push in recent years to encourage greater usage of renewable sources in electricity generation, and recent legislation prohibiting the sale and use of bituminous coal for domestic heating in urban areas.

Access to mains gas has been available in some locations in Ireland for a century, however its uptake can still be relatively low in areas adjacent to the gas network. It could be considered a more efficient alternative to many other fuels currently being consumed. Many households that are heavily reliant on peat, coal, or oil have the option to connect to mains gas but choose not to, even though it has historically been cheaper than oil, and is more efficient and cleaner than peat or coal[3].

This research examines the time path to adoption of gas central heating in Ireland. We exploit variation

[1]Measured in tons of oil equivalent. See http://ec.europa.eu/eurostat/web/energy/data/energy-balances for details.

[2]Others have argued that a multiple fuel model is more appropriate, as households will continue to use traditional fuels such as firewood along with modern fuels (Masera et al., 2000), switching back in response to relative prices and other factors (Wickramasinghe, 2011; Van der Kroon et al., 2013). This is similar to what we observe in Ireland as many households continue to use traditional fuels, such as peat as a secondary heating source.

[3]The Sustainable Energy Authority of Ireland (SEAI) hold comparable historical data for various domestic fuels, based on a delivered energy cost of cents/kWh. See http://www.seai.ie

in the proportion of mains gas connections at area level from the 2011 Population Census, combined with a unique GIS dataset on the timing and location of gas network infrastructure in Ireland over a period of 100 years. This is linked to information on the location of every residential dwelling in the country in 2011 to also examine the effect of distance to the network on the proportion of users in each area. We also examine at area-level, the socioeconomic and dwelling characteristics associated with higher adoption of mains gas. Further, GIS information on the location of peat bogs allows us to control, to a certain extent, for legacy fuel usage. While the timing and location of policy changes, such as the ban on sale and burning of bituminous coal, allow us to examine the impact this has had on gas connections in urban areas.

Suppliers are likely to extend the gas network to areas of high density, or those with a higher probability of adoption, and only those households in close proximity to the gas infrastructure can adopt. Not taking account of this could potentially bias our estimates. To account for this simultaneity, we estimate a two-stage least squares specification, allowing us to identify the time-path of network roll-out in the gas adoption equation.

Results indicate a non-linear relationship between the length of time the network has been in place and the proportion of gas users in each area. Each year the network has been in place is associated with a 3 percentage point increase in gas connections on average, and this effect decreases over time. Variation in distance to the network is a significant determinant of connections, even for areas in close proximity to the network. Proximity to peat sources, such as bogs is negatively associated with gas connections, while a ban on the sale and burning of bituminous coal which was in place in various urban locations in Ireland in 2011, is positively associated with gas adoption.

We find that areas with higher proportions of people in full-time employment, with third-level qualifications, and home owners are more likely to connect to mains gas. Dwelling characteristics also matter, areas with high proportions of flats and apartments are less likely to connect, and areas with high proportions of recently constructed dwellings (post 2006) and much older dwellings (pre 1945) have higher proportions of gas connections.

2 Fuel usage in Ireland

Ireland has a long history of solid fuel usage, and in particular peat usage in the residential sector. Mokyr (2013) cites reports from the 1830's describing the geographical ubiquity of peat and the intensity of its usage. While certain places, such as South Antrim and Limerick had depleted their reserves by this point, it was so plentiful throughout the rest of the country that it was taken for granted, and "people living as little as 4 miles away from a source of turf already considered themselves inconvenienced". Peat continued to be the primary source of fuel for home heating until relatively recently and the geographical relationship between the location of solid fuel resources and its usage persists (Fu et al., 2014).

As recently as 1990, the proportion of households using solid fuel as their primary means of space heating was as high as 60%. This had fallen to 16% by 2014[4]. However, 62% of households continue to use a stove, range or open fire as a secondary heating source, and the majority of these use solid fuel[5].

Comparable residential fuel usage trends in kilo tonnes of oil equivalent from 1990-2014 are demonstrated in fig. 1. The falling share of solid fuel is evident, which has been replaced by a rise in gas, oil and electricity usage primarily. Renewable energy has not yet established itself directly in domestic heating, however renewable sources accounted for 14.5% of energy inputs to electricity generation by 2014 (SEAI, 2015).

[4]http://statistics.seai.ie/

[5]Solid fuel in this case meaning peat, coal or wooden logs. 67% of those with open fires use solid fuel, and 36% of those with a stove or range continue to use solid fuel. See CSO (2016) for further details.

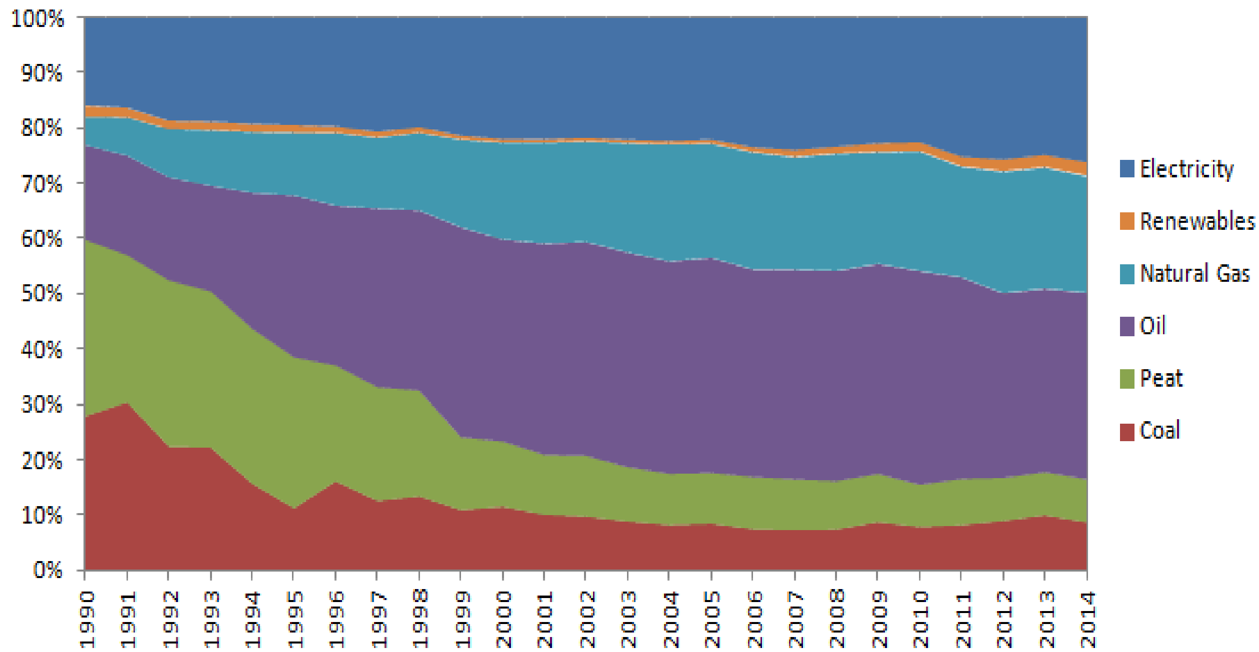

Figure 1: Fuel shares in Mtoe 1990-2014
Source: http://statistics.seai.ie/

In terms of CO2 emissions, even though final energy use in the domestic sector increased by 26% between 1990 and 2011, energy-related CO2 emissions fell by 2.7%, reflecting the decreasing share of solid fuel usage and the improved efficiency of oil and gas central heating boilers (SEAI, 2013).

2.1 The policy environment

Perhaps contributing to the falling share of solid fuel usage for domestic heating were a number of policy initiatives. A ban on the marketing, sale and distribution of bituminous fuel (or "smoky coal ban") was first introduced in Dublin in 1990[6]. This was introduced as a response to severe instances of winter smog. This ban was extended to towns with a population in excess of 15,000 people between 1990 and 2013, and a prohibition on burning was introduced in addition to the ban on marketing, sale and distribution.

A carbon tax of e15 per tonne of CO2 on fossil fuels was introduced in the 2010 budget. This was increased to e20 per tonne in 2012. It covers all non-ETS sectors so heating from electricity generation was exempt, however all other forms of non-renewable domestic heating were considered. New building regulations were introduced in 2008 and revised in 2011. These mainly apply to construction of new dwellings, but do require the installation of condensing boilers when existing gas or oil boilers are replaced[7].

The Sustainable Energy Authority of Ireland (SEAI) incentivise the improvement of the building stock through various schemes such as the "Better Energy Homes Scheme", "The Warmer Homes Scheme", "The Better Energy Communities Scheme" and others. These consist of a range of grants targeted at various groups within the population, aimed at encouraging households to improve the energy efficiency of their dwellings.

[6] See http://www.environ.ie/environment/air-quality/coal/smoky-coal-ban

[7] The MURE website (Mesures dâĂŹUtilisation Rationnelle de lâĂŹEnergie) can be accessed at http://www.measures-odyssee-mure.eu/, and provides detailed listing of these and all other energy efficiency policies introduced in all EU member states.

This could be through improved insulation, installation of new boilers, heating controls, lagging jackets, draught proofing and installation of solar panels amongst other measures[8].

2.2 Gas usage

Rogan et al. (2012) provide a comprehensive summary of gas network expansion and usage trends in Ireland between 1990 and 2008. The gas transmission infrastructure had extended to a number of large towns and cities by 1990, however 90% of gas customers were still resident in the two largest cities of Dublin and Cork. That decade saw an expansion of the transmission infrastructure outward from Dublin, along both northeast and southeast coasts and west to the fast-growing commuter towns in the greater Dublin area. The mid-2000ssaw an extension westwards linking Dublin with Galway, from here it was further extended to the northwest by the late 2000s. This extension resulted in a constant annual customer growth rate of 9% over the period 1990-2008. There is significant spatial variation however, and by 2014, natural gas customers were still as low as 5% in some western areas (CSO, 2016).

Over this period consumption increased by 470% (Rogan et al., 2012). This was mainly through a growing customer base, changes in the dwelling stock, and changing intensity of usage. Weather effects are also important. From a microeconometric point of view, Conniffe (1996) and Harold et al. (2015) also find weather a strong predictor of seasonal demand. This research also ties in with international research of gas consumption and more general space heating, which find that dwelling characteristics and the socioeconomic characteristics of inhabitants have a significant impact on demand (Rehdanz, 2007; Meier and Rehdanz, 2010; Wyatt, 2013).

The following section outlines our methodology and some empirical considerations one must consider when modelling adoption at arealevel.

3 Methods

The utility consumers receive from adopting gas central heating is likely to be a function of the relative price of gas compared with alternatives, along with their socioeconomicanddwellingcharacteristics. Physical constraints on adoption exist and will relate to each household's proximity to the gas infrastructure.

Economic theory suggests that households will adopt mains gas central heating if the benefits derived from adoption exceed the costs and there is an expected utility increase from doing so. However, innovations take time to diffuse, and households regularly make suboptimal choices. This can be related a range of factors, such as uncertainty about the relative costs or benefits of adoption, indifference, heterogeneity in consumer preferences or lack of access tofinancing.

In order to estimate the determinants of gas usage at a local area level, it is necessary to consider demand and supply simultaneously. Suppliers are likely to extend the gas network to areas with a higher probability of adoption, and only those households in close proximity to the gas infrastructure can adopt. Previous research has indicated that dwellings with piped gas in Ireland have higher incomes, partly due to their urban location (Watson et al., 2003). This endogeneity could potentially lead to our coefficients being biased if we simply estimate a demand equation. Therefore, we first estimate a supply equation in a two-stage least square regression. We use population per area, population per area squared, area size and area size squared as the instruments. This is because the economics of network roll-out will largely be driven by population density, and this will impact on the decision to extend the network to a particular area. However, the density of dwellings in an area will arguably only affect any individual household's decision to adopt gas central heating through the supply side.

[8] For more details on these schemes see SEAI report

This empirical strategy draws from Lyons (2014) in his estimation of the timing and determinants of local broadband adoption in Ireland.

As the network has been developed over a long period of time (approx 100 years) using population data from 2011 is not a perfect measure. However we do not have historical series for population at Small-Area level, and the geographic spread of population in the current period is likely to be highly correlated with past periods.

We assume that the proportion of gas users in any area j will be a function of the aggregate socioeconomic characteristics of that area X_j, aggregate dwelling characteristics D_j, spatial factors which will vary by location S_j and the length of time the gas network has been located in an area $t-t^0{}_j$. This can be summarised as follows:

$$\frac{\sum_{i=1} G_{ijt}}{N_j} = f(X_j; D_j; S_j; t - t^0_j) \quad (1)$$

3.1 Supply equation

As adoption might have a non-linear relationship with the length of time the network has been in place, we estimate two supply equations. In the first equation, the dependent variable is the length of time the network has been in place in each area, the second dependent variable is the squared length of time the network has been in place in each area.

Our first-stage supply equations are summarised below:

$$T_j = \alpha + \beta_Z Z_j + \beta_X X_j + \beta_D D_j + \beta_S S_j + E \quad (2)$$

$$T_j^2 = \lambda + \gamma_Z Z_j + \gamma_X X_j + \gamma_D D_j + \gamma_S S_j + \delta \quad (3)$$

We regress time and time squared on our instrument set Z_j consisting of population, population squared, area and area squared. This is because there is likely to be positive but diminishing economies of density in gas network roll-out.

This generates predicted values for time and time squared which we can use to identify the effect of these factors in our second-stage demand equation. All other variables from the second stage are also included in the first stage regression. We implement a two-stage, generalised method of moments specification (GMM), with common intercepts (α, λ) and errors (E, δ).

3.2 Demand equation

The dependent variable in this regression is the proportion of households in each area that use gas as their primary source of central heating. When completing the 2011 Census, households were asked to select from a range of options the one that best describes their primary means of central heating. This is summarised in table 1 in section 4.1.

The demand equation takes the estimated time and time squared from the supply equations, along with a range of socioeconomic and dwelling characteristics, some spatial variables representing the proximity to the gas network, proximity to alternate fuel sources and policy variables prohibiting the sale and burning of bituminous coal.

$$\frac{\sum_{j=1}^{N_j} G_{ijt}}{N_j} = \nu + \delta_{\hat{T}} \hat{T}_j + \delta_{\hat{T}^2} \hat{T}^2_j + \delta_X X_j + + \delta_D D_j + \delta_S S_j + \mu \tag{4}$$

We include a range of socioeconomic factors at area level, which might influence the decision to adopt gas central heating. These are related to economic status, age, education levels and tenure type. Dwelling characteristics include house type, a measure of energy efficiency (Building Energy Rating - BER), and dwelling age. All of these variables are expressed as proportions for each Small-Area.

4 Data

The data in this paper come from a range of sources. The proportion of natural gas users within each area, along with area proportions of socio-demographic and dwelling characteristics were obtained from the Central Statistics Office (CSO) Census of Population, Small-Area Population Statistics 2011.

Gas Networks Ireland provided detailed GIS maps, including the timing and geographic location of the high-pressure (HP), medium pressure (MP) and low pressure (LP) gas network. The Environmental Protection Agency's (EPA) website provide GIS maps of soil types in Ireland, from this we calculated the average distance to bogs for all dwellings in each location. The EPA also provide information on the timing and location of smoky-coal bans in Irish urban areas[9]. For descriptive statistics of all variables used in estimations, please see Appendix B.

The analysis is conducted at Small-Area level. This is the most disaggregated unit for which one can obtain publicly available Census data in Ireland. These range in population from 8 - 549 dwellings. There are over 18,000 Small-Areas in Ireland. Our sample consists of 9,638 Small-Areas which are all in close proximity to the gas network.

4.1 Dependent variable

The dependent variable is the proportion of gas users within each Small-Area. This was self-reported by households as per table 1. Natural gas usage accounted for almost a third of all primary central heating in 2011. This is concentrated in urban areas close to the network.

Table 1: Census 2011 primary central heating proportions

What is the main type of fuel used by the central heating in your accommodation?	Percentage
No central heating	1.6%
Oil	43.1%
Natural Gas	33.4%
Electricity	8.5%
Coal (including anthracite)	4.8%
Peat (including turf)	4.8%
Liquid Petroleum Gas (LPG)	0.6%
Wood (including wood pellets)	1.3%
Other	0.5%
Not Stated	1.4%

Notes: Author's calculations based on CSO Census 2011 data

[9] This can be accessed at http://gis.epa.ie/

However, even within these areas, considerable variation exists in the proportion of users. Figure 2 illustrates that even for areas in which the average distance of all households to the nearest point on the low or medium pressure network is less than 100m., a significant proportion do not use gas as their primary means of heating.

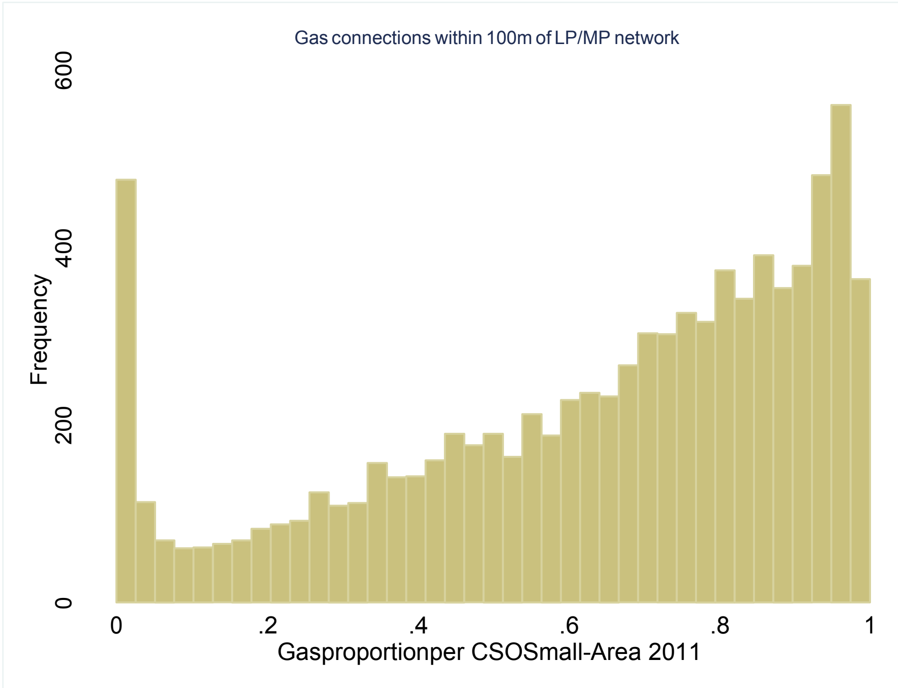

Figure 2: Proportion of households using gas as their primary fuel in close proximity to the low pressure gas network

This can be illustrated geographically. As examples we choose four metropolitan areas in Ireland, all of which have access to the gas network. Outside of Dublin, Cork has both the greatest number and highest proportion of households using natural gas as their primary means of central heating, however there is still significant local variation. Galway has a relatively low proportion of gas users in most areas, reflecting the recent extension of the network to this city.

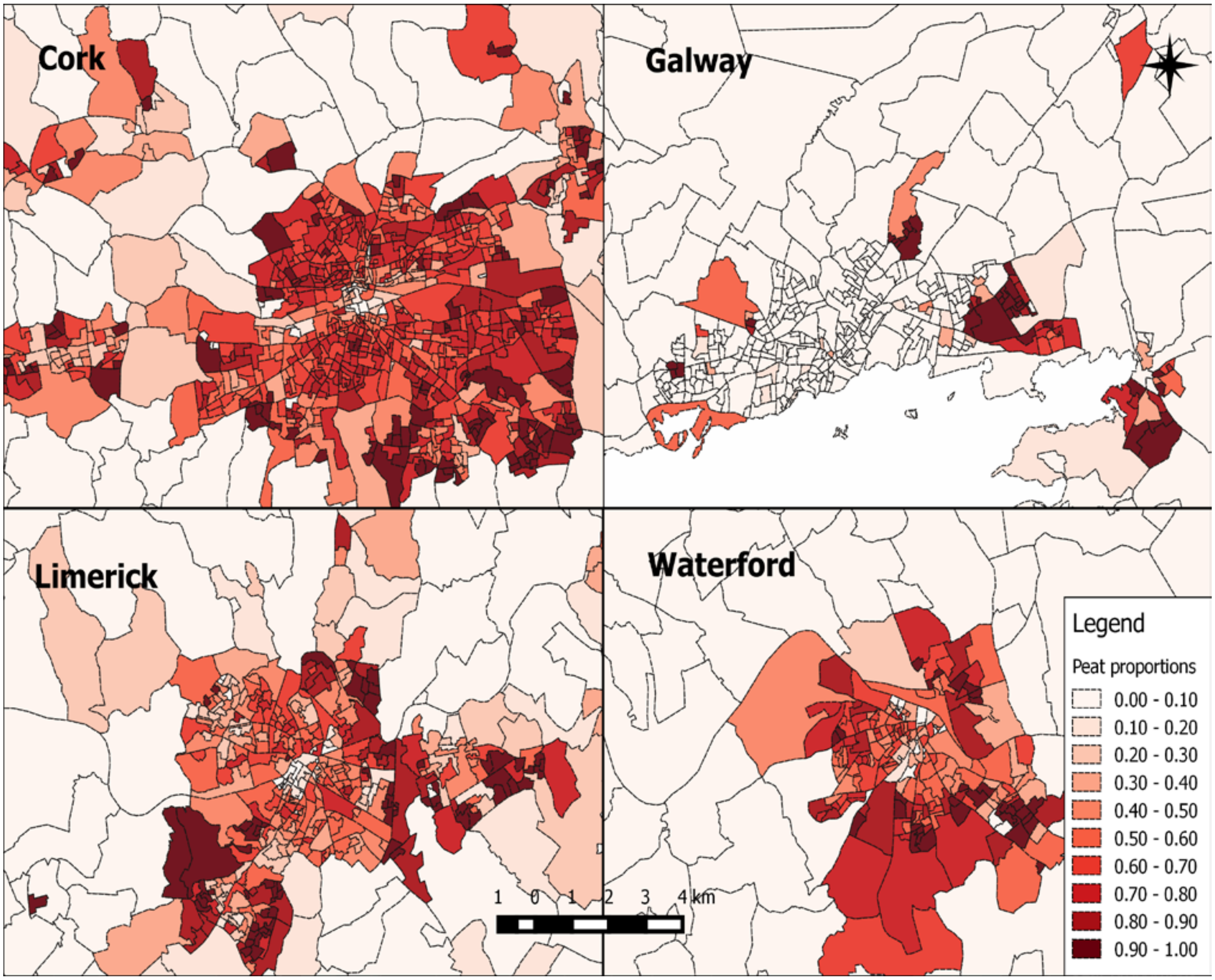

Figure 3: Spatial variation in gas connections at Small-Area level in four Irish metropolitan areas
Source: Author's calculation using Census 2011 data

4.2 Gas network

The location of the gas infrastructure in Ireland is displayed in fig 4. As described in Section 2.2, the network location was concentrated mainly in larger cities such as Dublin and Cork until relatively recently. The high-pressure network was expanded to link Limerick and Galway in the early 2000s.

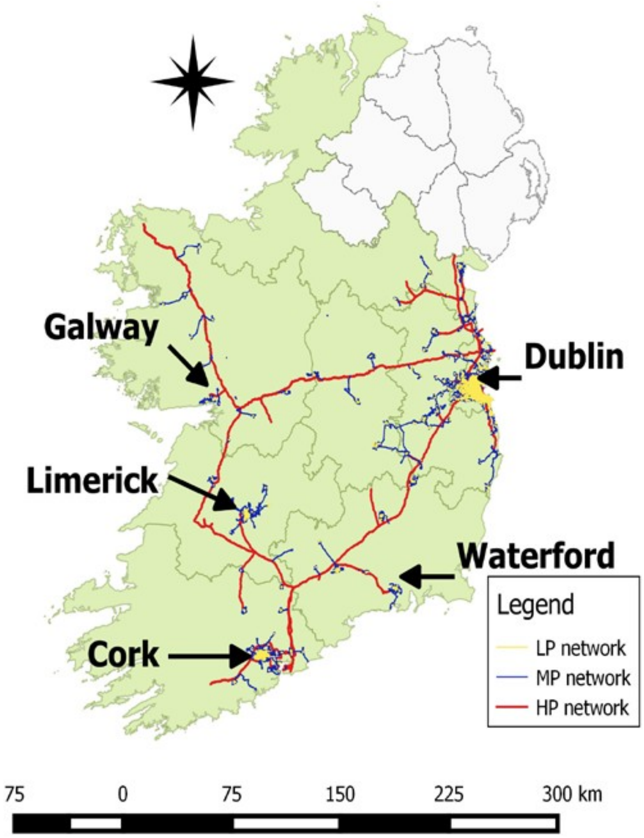

Figure 4: Location of Irish gas network infrastructure 2011
Source: Gas Networks Ireland - please see the disclaimer at the end of this document

Detailed network maps, which also contain the date each individual segment was laid, were obtained for each segment of the gas network. From this we calculate when the gas network was put in place for each Small-Area.

4.2.1 Mean distance to LP or MP network

This distance variable was generated by calculating the distance of every domestic residence in the CSO 2011 Census to the nearest point on the LP or MP gas network (Krah et al., 2016). We then aggregated by Small-Area, to calculate the average distance for each area. This variable will reflect the relative ease of connection for various areas. This can vary even within close proximity to the network - as can be seen from figure 5.

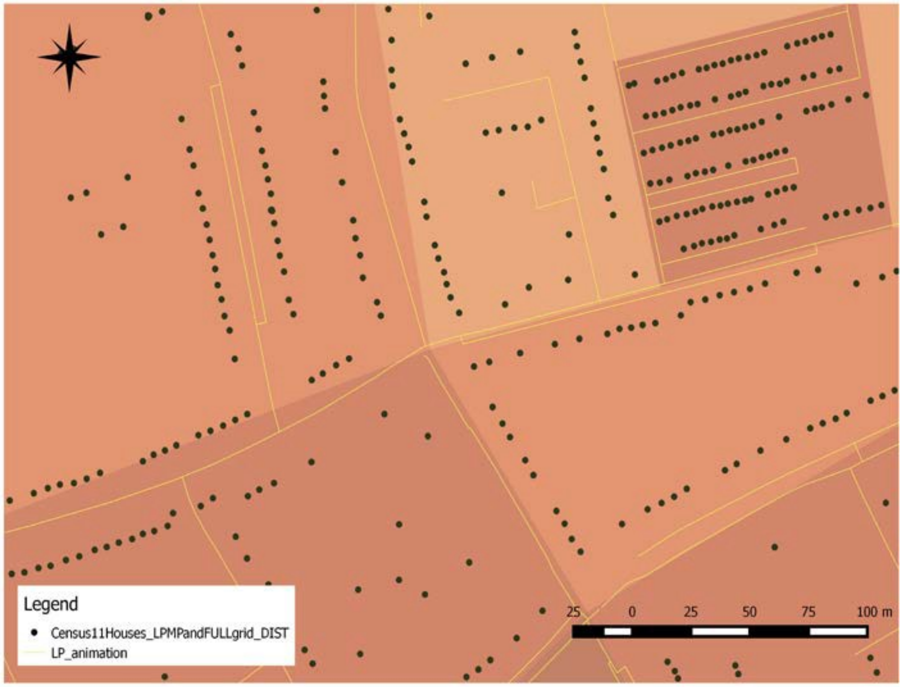

Figure 5: Variation in household density and location in close proximity to the low pressure gas network. Notes: The black dots denote residential dwellings from the 2011 Census. The red shaded areas represent proportions of gas users per area. The yellow lines are the low-pressure network. Source: CSO Population Census; Gas Networks Ireland - please see the disclaimer at the end of this document

4.2.2 Date network waslaid

Each segment of the gas network[10] has a date identifier marking the day that portion of the network was laid. Using GIS software, we map each network segment to any Small-Area it is fully within or intersects at any point, illustrated in figure 6. This generates a distribution of date variables for each Small-Area. As the 2011 Census (from which we take our gas proportions data) took place on April 10th 2011, we consider this as time t. From this we calculate the length of time in years since each segment was laid as $t - t_j^0$, where t_j^0 is the date each segment was laid. This generates a distribution of year-length variables for each Small-Area. As a proxy for the length of time gas was available to households in each area we choose maximum time length, i.e. the date the first segment was laid in each area. However we also run estimations with various other time variables, such as the average time and latest time gas became available in each area[11].

[10]The low pressure network contains 135,195 separate segments, the medium pressure network contains 123,048 segments.

[11]We are missing a date identifier on approximately 20% of the MP and LP networks. This may introduce some error into the estimation but we have reduced it substantially through aggregation. When we aggregate to area level, there remains only 3% of Small-Areas for which we have no date identifier.

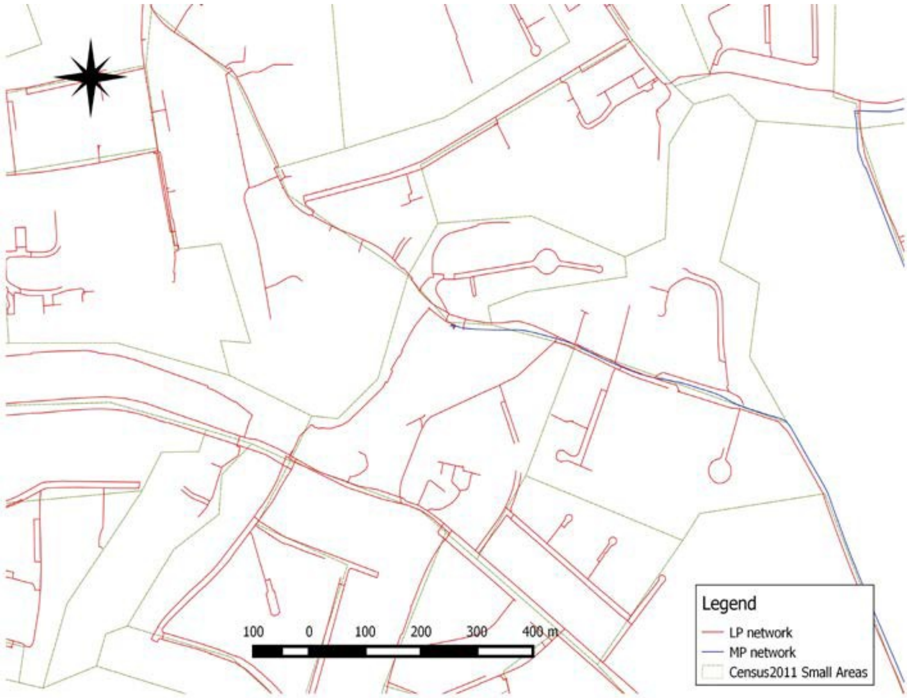

Figure 6: Example of Small-Area boundaries and gas network
Source: CSO Population Census; Gas Networks Ireland - please see the disclaimer at the end of this document

4.3 Spatial fuel source and policy variables

From Census 2011 4.8% of households in Ireland use peat as their primary heating source, however a sizeable proportion also have an open fire or peat burning stove as a secondary source. As can be seen from figure 7, this pattern is highly correlated with the location of peat bogs. Using GIS software we calculate the distance of every household to the nearest raised and blanket bog. Again, we aggregate these variables to Small-Area level, allowing us to determine the relative proximity of dwellings in each area to different bog types.

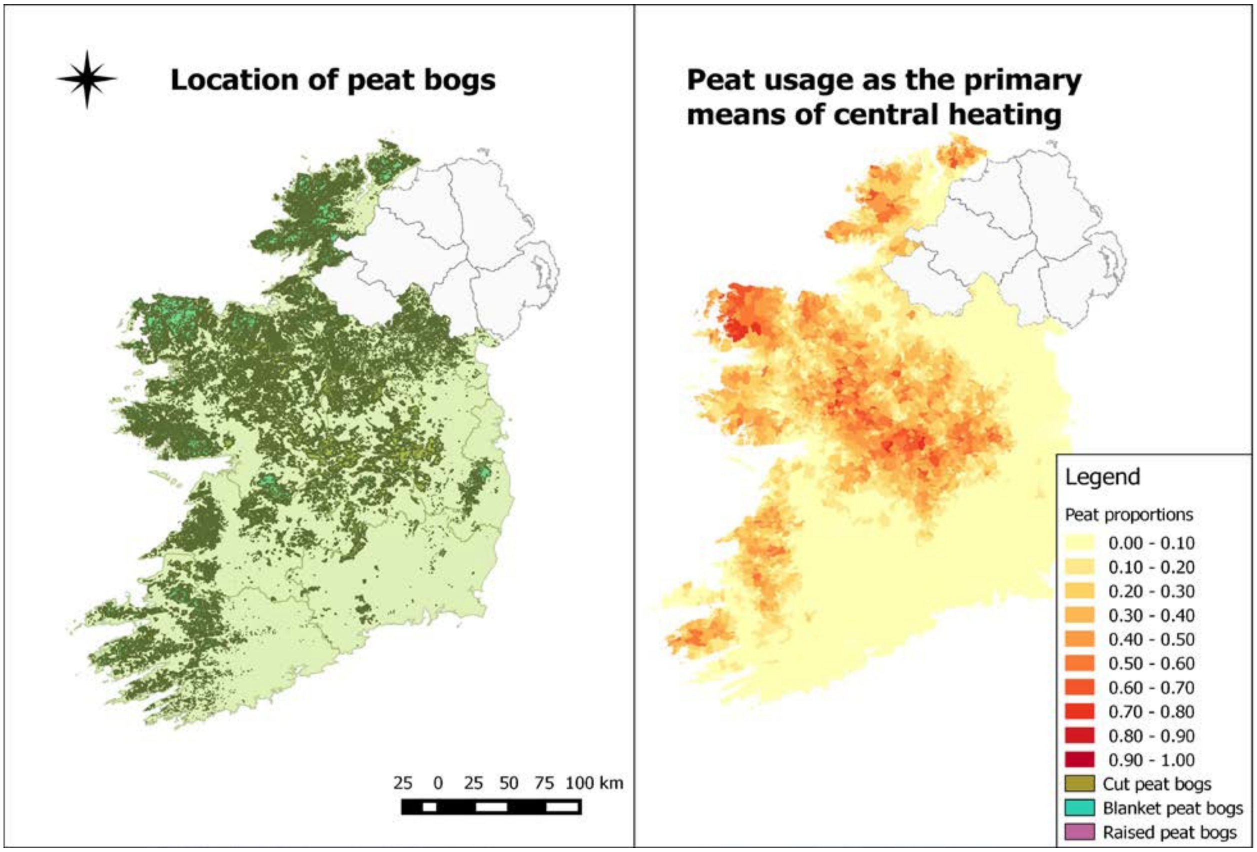

Figure 7: Location of peat bogs and areas where peat burning is the primary means of central heating. Source: CSO Population Census; EPA GIS portal

The ban on the sale and consumption of bituminous coal was in place in 19 towns in Ireland by 2011. Information on the location of these bans allow us to overlay this onto our Small-Areas. We then create a dummy variable for these areas. While we cannot infer a causal relationship between this policy and gas usage, we can examine the correlation, holding other factors constant.

4.4 Census and other data

Supplementing the spatial and temporal data on fuel sources and policy variables, we include a range of socioeconomic, demographic and dwelling variables from the Census in our estimations. These variables are all at Small-Area level and thus will reflect the aggregate characteristics of each area.

We also include information on the energy efficiency of dwellings. This data was estimated using the SEAI BER database and the Census of population 2011. For more information see Curtis et al. (2015). We use the proportion of low-rated (E,F,G) dwellings in each area.

5 Results

We estimate a generalised method of moments (GMM) instrumental variables specification, with population count, area and their squared terms as instruments. The length of time the network has been in place might affect the proportion of users in a non-linear manner. For example, to run mains gas to certain housing estates adjacent to the existing network GNI require a minimum proportion of households within that area to adopt immediately[12]. This would result in a large initial uptake which mitigates over time. Alternatively for one-off connections, certain households might be slow to switch to mains gas when it first becomes available, due to sunk costs related to their current heating system. This might result in a slow initial uptake, followed by more rapid switching. To accommodate this, we specify two first stage regressions, with time and time squared as the dependent variables. Standard errors are clustered at area level, to control for heteroskedasticity. Areas are weighted by population in all specifications. We restrict our analysis to areas in which the average distance of all dwellings is less than 1km from the nearest point on the low or medium pressure gas network. Other areas are not relevant for our analysis, as it would not be feasible for households within them to connect to mains gas[13].

We report the results from our first stage supply equations first, followed by the second stage demand equation.

5.1 Supply equations

These equations are primarily used to identify the length of time the network has been in place in our demand equation. The instruments are all significant and have the expected signs. The gas network was located first in areas of high density. We include all other covariates from our second stage in the first stage regressions, as there is no efficiency loss from doing this. However, as many of them, particularly those related to socioeconomic characteristics, reflect current factors and the gas network was constructed over many years, their interpretation is subject to caution. The results are reported in section B of the appendix.

One variable of interest though is the proportion of houses built in various time periods in each area. This will reflect changes in the housing stock over time. As one might expect the coefficients on these terms are highest for those areas with high proportions of pre 1945 dwellings, decreases for areas with higher proportions of building constructed between 1945-1980, and rises again for buildings constructed between 1980-2000. This effect is indicative of the outward sprawl of network infrastructure from areas of historically high density over time.

Regarding instrument relevance, Baum et al. (2007) suggest using Kleibergen-Paap rk statistic to test for underidentification when using a robust covariance estimator, and the corresponding Wald F statistic when testing for weak identification. In both cases the results of these tests fail to reject the null hypothesis that our instruments are underidentified and weakly identified, as per table B1. This is likely to be the case because we are including interactions of endogenous variables (linear and quadratic terms) in our estimations and these are highly correlated. Wooldridge (2010) suggests that when this is the case, one should check whether the most general linear version of the model is identified and if this is not the case, proceed with caution. In our case both the linear and quadratic endogenous variables are strongly identified when estimated separately, table B1, and we proceed on that basis.

5.2 Demand equation

Predicted values for length of time and length of time squared are generated from the first stage estimation. The proportion of gas connections in each area is then regressed on these and other variables. The results indicate that each additional year the network has been in place results in a 3 percentage point increase in the proportion of households within that area who use gas as their primary fuel. This effect mitigates over time, as indicated

[12]See for details http://www.cer.ie/document-detail/Gas-Networks-Ireland-Connections-Policy-Review/1007

[13]We test the sensitivity of this parameter to various distances from 100m upwards, and the results remain stable.

by the negative effect on the squared term. We can graphically illustrate the time-path to adoption including both linear and squared terms, as per the left-hand panel of figure 8. Both of these effects are highly statistically significant. On average, for all areas in our estimation there is an increasing adoption up to about 25 years. The limiting factor is due to certain areas having had access to the gas network for up to a century, but which still do not have a very high proportion of connections. When the analysis is restricted to more recent periods the rate of adoption appears to be much faster. This is graphed in the right-hand panel of figure 8. When the sample is restricted to the previous 20 years, each additional year is associated with approximately a 12 percentage point increase in gas customers, again this effect appears to reduce over time. This is broadly in line with Rogan et al. (2012), who reported an annual increase of 9% between 1980 and 2010. On average, penetration rates are reaching about 50% after 8-10 years.

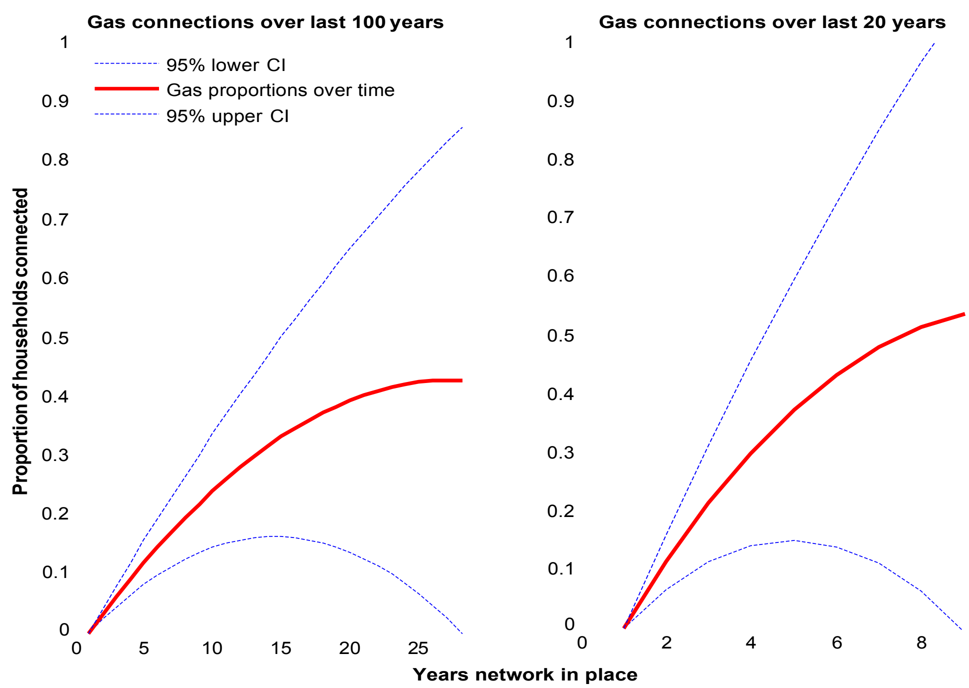

Figure 8: Proportion of gas adopters at Small-Area level over time

The distance to the gas network also is significant at the 1 percent level. Even in areas that are relatively close to the network, distance still matters. The coefficient on this variable indicates that a 1 percent increase in average distance to the network is associated with a 12 percentage point reduction in the proportion of users in an area. This reflects the cost of domestic connections. For houses within 15m of the network connection costs are e250, with a charge of e50 for each additional metre beyond this.

The distance to a cut bogs (this includes both raised and blanket bogs) has a positive coefficient, indicating that the further away an area is from a cut bog, all else being equal, the higher the proportion of gas users in that area. The coefficient on uncut blanket bogs is negative, but not significant[14]. This is likely to be the case

[14] A number of blanket bogs are located in the Wicklow mountains, in close proximity to Dublin, which has the largest concentration

because the current proportion of households using solid fuel in an area will reflect past incentives in that area. Therefore proximity to cut bogs might be a better indicator of fuel usage as this will reflect areas where peat has been harvested over manyyears.

The ban on the sale and burning of bituminous fuel appears to also have had an effect. All else being equal, these areas have a 6 percentage point higher proportion of gas users. We can not infer causality however.

Considering the socioeconomic and dwelling variables next, our reading of the coefficients changes. For each set of variables, we interpret the effect relative to the reference category. All of these variables are area proportions. The employment status variable indicates that, all else equal, compared to areas with higher proportions of people in employment, all other categories have reduced gas connections, although not all coefficients are statistically significant. Taking the "EconUnemployed" variable as an example, our interpretation is that all else equal, a 10 percent increase in the proportion unemployed, relative to the reference category (those in employment), is associated with a 4.27 percentage point decrease in the proportion using natural gas.

Areas with high proportions of young families and elderly people are also associated with greater gas connections, compared to those with high proportions of 25-44 year olds. Considering tenure type next, those areas with higher proportions of mortgage holders and private renters are less likely to have gas connections than those with high proportions of outright owners. However, local authority areas have higher proportions of gas connections.

Areas with high proportions of houses, as opposed to flats or bedsits are more likely to use gas. This reflects the large proportion of electrical heating in apartment complexes in Ireland. The proportion of low-rated BER dwellings in an area is strongly negatively associated with gas connections.

Finally we can see that both very new (post 2000) and very old (pre 1960) constructed houses are more likely to have high proportions of gas connections. This likely reflects the urban location of a high proportion of the older buildingstock.

There is a high degree of collinearity between some of the socioeconomic and demographic variables. For example, areas with high proportions of retired people also have high proportions of people aged over 65, and have a high proportion of owner occupiers without any remaining mortgage obligations. While each of these variables is compared with the reference category in each class, caution is advisable in interpreting some of these coefficients. For example, the results indicate that areas with greater proportions of retired households are less likely to have high connections to the gas network than areas with greater proportions employed. However, areas with greater proportions aged over 65 are more likely to have high gas connections than areas with greater proportions of 25-44 year olds. This result seems contradictory, but is driven by the reference category changing in each case, and a small number of areas, with very high gas connections, which also have households aged over 65 on average, that are not in retirement.

of gas users. This is likely to be driving the negative coefficient of this variable.

Table 2: Second stage demand equation

	Dep Var: Proportion of gas users by SA in 2011		
Variable category	**Variable**	**Coefficient**	**Robust SE**
Spatial fuel and policy variables	Maxlengthyears hat	0.032***	(0.004)
	Maxlengthyears squared hat	-0.001***	(0.000)
	log(mean distance to gas network)	-0.120***	(0.006)
	log(distance to cut bog)	0.019***	(0.004)
	log(distance to bkt bog)	-0.006	(0.005)
	Coalban dummy	0.063***	(0.011)
Socioeconomic	**EconWorking**	**[REF]**	
	EconLooking for first job	-0.289	(0.313)
	EconUnemployed	-0.427***	(0.123)
	EconStudent	-0.398***	(0.130)
	EconHome	-0.303*	(0.155)
	EconRetired	-0.774***	(0.198)
	EconDisabled	-0.710***	(0.175)
	EconOther	-0.150	(0.198)
	Age 25-44	**[REF]**	
	Age 0-14	0.560***	(0.117)
	Age 15-24	0.188	(0.156)
	Age 45-64	-0.293***	(0.099)
	Age 65 plus	1.046***	(0.239)
	EduSecondary	**[REF]**	
	EduPrimary	0.187**	(0.082)
	EduTechnical	-0.124	(0.100)
	EduDegreeplus	0.253***	(0.059)
	EduRefused	-0.029	(0.128)
	TenOwnmortgage	**[REF]**	
	TenOwnnomortgage	-0.351***	(0.064)
	TenRentland	-0.153***	(0.044)
	TenRentlocal	0.119**	(0.049)
	TenRenvol	-0.009	(0.081)
	TenRentfree	-0.252	(0.203)
Dwelling	**DwellHouse**	**[REF]**	
	DwellFlat	-0.219***	(0.026)
	DwellBedsit	-0.192	(0.358)
	DwellOther	-0.317**	(0.133)
	Proportion EFG	-0.499***	(0.036)
	AgePost2000	**[REF]**	
	AgePre1945	0.446***	(0.075)
	Age 1945-60	0.363***	(0.056)
	Age 1960-80	-0.126***	(0.033)
	Age 1980-2000	-0.126***	(0.025)
	constant	0.840***	(0.097)
Diagnostics	N	9638	
	F(34, 9603)	461.38	(0.00)
	Overid - Hansen J	1.341	(0.512)

Notes: Results from IV-GMM specification. Cluster-robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1.

6 Conclusion

We have examined the determinants of gas central heating adoption at Small-Area level in Ireland, simultaneously modelling supply and demand in order to account for potential endogeneity in network infrastructure roll-out and adoption.

We explicitly model the time-path in diffusion, which is important in order to better understand the potential for both policy and technological improvements to aid carbon abatement. Ireland is interesting from an international perspective as we have a legacy and culture of peat usage for home heating. The gas network has been in place in the two largest cities for a century, but only recently extended to other parts of the country. Much research looks at more recent time trends in adoption, however our unique time and location coded data allow us to examine this over an extended period.

On average the results show that over the past century, each year the network has been in place is associated with a 3% rise in connections. When more recent periods are examined, the connection rate is much higher, about 12% rise per year over the past twenty years. There appears to be a non-linearity in these estimates and this effect diminishes over time. Proximity to the network is also an important determinant of connections, and reflects the cost of connection for all dwellings in that area.

The widespread availability of peat as a source of fuel has clearly inhibited the transition to cleaner fuels. As peat usage is highly correlated geographically with the location of peat bogs, it is useful to see how gas network roll-out interacts with the proximity of other fuel sources in determining gas central heating adoption. Proximity to previously cut peat bogs is negatively associated with gas connections.

Recent policy developments such as the ban on the sale and consumption of bituminous coal is associated with a 6 percentage point higher proportion of gas connections in these areas, all else being equal. We can't attribute causality here however, as this ban was first introduced in urban areas, which would already have had higher proportions of gas connections before the bans were introduced.

Variations in the aggregate socioeconomic and dwelling characteristics can also significantly predict the proportion of natural gas users in an area. This information may be useful for network planners in deciding where to next extend the network, and also for commercial suppliers of gas in determining why certain areas in close proximity to the network have low levels of connections. Grid expansion into low-income areas for climate reasons may need subvention is it is likely to have a longer pay-back period than expansion into higher-income areas with a greater propensity to connect to the network.

These results point to certain features of domestic energy consumption in Ireland. Households in retirement and in unemployment, along with those in lower quality housing are less likely to use natural gas central heating. We know that solid fuel usage is particularly prevalent amongst these groups. Gas consumption is more difficult to budget for, without a pre-paid meter, possibly leading to lower income households choosing solid fuel. The inefficiency of using such fuels for central heating, along with the poor quality of the dwelling stock in many of these areas is likely to exacerbate fuel poverty and has the potential to affect air quality. These issues are more likely to be pronounced in areas without policy intervention, such as the ban on sale and consumption of bituminous coal, and in areas close to peat bogs.

To fully examine the factors influencing the choice of home-heating system, we would ideally have had access to individual household level data, as even aggregating to Small-Area level can mask important heterogeneity. Also, aside from the network roll-out data, we only have data for one point in time. A panel dataset on how gas proportions and various characteristics change over time, would have given us greater ability to identify effects. Similarly, the inclusion of other spatially coded information, such as relative prices of alternate fuels, or the location of kerosene suppliers, for example, would have significantly benefited this paper. This data is not available however.

Disclaimer

"Gas Networks Ireland (GNI), their affiliates and assigns, accept no responsibility for any information contained in this document concerning location and technical designation of the gas distribution and transmission network ("the Information"). Any representations and warranties express or implied, are excluded to the fullest extent permitted by law. No liability shall be accepted for any loss or damage including, without limitation, direct, indirect, special, incidental, punitive or consequential loss including loss of profits, arising out of or in connection with the use of the Information (including maps or mapping data). NOTE: DIAL BEFORE YOU DIG Phone 1850 427 747 or e-mail digatgasnetworks.ie. The actual position of the gas/electricity distribution and transmission network must be verified on site before any mechanical excavating takes place. If any mechanical excavation is proposed, hard copy maps must be requested from GNI re gas. All work in the vicinity of the gas distribution and transmission network must be completed in accordance with the current edition of the Health and Safety Authority publication, "Code of Practice For Avoiding Danger From Underground Services" which is available from the Health and Safety Authority (1890 28 93 89) or can be downloaded free of charge at www.hsa.ie."

References

Allcott, H. and Greenstone, M. (2012). Is there an energy efficiency gap? *Journal of Economic Perspectives*, 26(1):3–28.

Baum, C. F., Schaffer, M. E., Stillman, S., et al. (2007). Enhanced routines for instrumental variables/GMM estimation and testing. *Stata Journal*, 7(4):465–506.

Blumstein, C., Krieg, B., Schipper, L., and York, C. (1980). Overcoming social and institutional barriers to energy conservation. *Energy*, 5(4):355–371.

Conniffe, D. (1996). Modelling seasonal energy demand in the domestic and commercial sector. Technical report, ESRI mimeo.

CSO (2016). Central Statistics Office. QNHS module on household environmental behaviours, Quarter 2 2014. Available: http://www.cso.ie.

Curtis, J., Devitt, N., and Whelan, A. (2015). Using census and administrative records to identify the location and occupancy type of energy inefficient residential properties. *Sustainable Cities and Society*, 18:56–65.

Fu, M., Kelly, J. A., and Clinch, J. P. (2014). Residential solid fuel use: Modelling the impacts and policy implications of natural resource access, temperature, income, gas infrastructure and government regulation. *Applied Geography*, 52:1–13.

Golove, W. H. and Eto, J. H. (1996). Market barriers to energy efficiency: A critical reappraisal of the rationale for public policies to promote energy efficiency. *LBL-38059. Berkeley, CA: Lawrence Berkeley National Laboratory*.

Harold, J., Lyons, S., and Cullinan, J. (2015). The determinants of residential gas demand in Ireland. *Energy Economics*, 51:475–483.

Hosier, R. H. and Dowd, J. (1987). Household fuel choice in Zimbabwe: An empirical test of the energy ladder hypothesis. *Resources and energy*, 9(4):347–361.

Jaffe, A. B. and Stavins, R. N. (1994). The energy-efficiency gap what does it mean? *Energy Policy*, 22(10):804–810.

Krah, K., Glynn, J., and O Gallachoir, B. (2016). Assessing the opportunity for residential fuel switching: Spatial analysis to inform strategic development of the gas network. Available: http://www.esri.ie/pubs/3.-KKrah-ESRI-pres-June-7.pdf.

Lyons, S. (2014). Timing and determinants of local residential broadband adoption: Evidence from Ireland. *Empirical Economics*, 47(4):1341–1363.

Mahapatra, K. and Gustavsson, L. (2008). An adopter-centric approach to analyze the diffusion patterns of innovative residential heating systems in Sweden. *Energy Policy*, 36(2):577–590.

Masera, O. R., Saatkamp, B. D., and Kammen, D. M. (2000). From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World Development*, 28(12):2083–2103.

Meier, H. and Rehdanz, K. (2010). Determinants of residential space heating expenditures in Great Britain. *Energy Economics*, 32(5):949–959.

Michelsen, C. C. and Madlener, R. (2012). Homeowners' preferences for adopting innovative residential heating systems: A discrete choice analysis for germany. *Energy Economics*, 34(5):1271–1283.

Mokyr, J. (2013). *Why Ireland starved: a quantitative and analytical history of the Irish economy, 1800-1850*. Routledge.

Rehdanz, K. (2007). Determinants of residential space heating expenditures in Germany. *Energy Economics*, 29(2):167–182.

Rogan, F., Cahill, C. J., and O'Gallachoir, B. P. (2012). Decomposition analysis of gas consumption in the residential sector in Ireland. *Energy Policy*, 42:19–36.

SEAI (2013). Sustainable Energy Authority of Ireland. Energy in the residential sector, 2013 Report. Available: http://www.seai.ie.

SEAI (2015). Sustainable Energy Authority of Ireland, Energy in Ireland key statistics 2015. Available: http://www.seai.ie.

Sopha, B. M. and Klockner, C. A. (2011). Psychological factors in the diffusion of sustainable technology: A study of Norwegian households' adoption of wood pellet heating. *Renewable and Sustainable Energy Reviews*, 15(6):2756–2765.

Van der Kroon, B., Brouwer, R., and Van Beukering, P. J. (2013). The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. *Renewable and Sustainable Energy Reviews*, 20:504–513.

Watson, D., Williams, J., et al. (2003). Irish national survey of housing quality 2001-2002. *Economic and Social Research Institute (ESRI) Research Series*.

Wickramasinghe, A. (2011). Energy access and transition to cleaner cooking fuels and technologies in Sri Lanka: Issues and policy limitations. *Energy Policy*, 39(12):7567–7574.

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data*. MIT press.

Wyatt, P. (2013). A dwelling-level investigation into the physical and socio-economic drivers of domestic energy consumption in England. *Energy Policy*, 60:540–549.

7 Appendix

A Descriptive statistics for all variables includedin estimations

Table A1: Descriptive Statistics

Variable category	Variable	Obs	Mean	Std. Dev.	Min	Max
Gas variables	Gas	9,638	0.565	0.328	0	1
	Max length years	9,638	14.523	13.134	0	111
	log(mean distance to gas network)	9,638	3.252	1.074	0.732	6.906
Peat proximity	log(distance to bkt bog)	9,638	8.772	1.167	-3.037	10.638
	log(distance to cut bog)	9,638	9.315	0.639	6.147	10.786
Coalban areas	Coalban dummy	9,638	0.829	0.377	0	1
Density	Household count	9,638	94.853	22.256	21	252
	Area km	9,638	3.691	13.026	0.0163	417.358
Socioeconomic	EconWorking	9,638	0.516	0.141	0	0.942
	EconLooking for first job	9,638	0.010	0.012	0	0.489
	EconUnemployed	9,638	0.110	0.064	0	0.440
	EconStudent	9,638	0.117	0.083	0	0.980
	EconHome	9,638	0.084	0.036	0	0.297
	EconRetired	9,638	0.116	0.090	0	0.727
	EconDisabled	9,638	0.042	0.037	0	0.494
	EconOther	9,638	0.003	0.016	0	0.595
	Age 0-14	9,638	0.195	0.090	0	0.594
	Age 15-24	9,638	0.353	0.140	0	0.873
	Age 25-44	9,638	0.133	0.077	0	0.987
	Age 45-64	9,638	0.209	0.090	0	0.662
	Age 65 plus	9,638	0.110	0.094	0	0.780
	EduPrimary	9,638	0.128	0.109	0	0.722
	EduSecondary	9,638	0.344	0.105	0	1
	EduTechnical	9,638	0.183	0.063	0	0.5
	EduDegreeplus	9,638	0.296	0.179	0	1
	EduRefused	9,638	0.049	0.054	0	1
	TenOwnmortgage	9,638	0.347	0.192	0	0.953
	TenOwnnomortgage	9,638	0.275	0.196	0	0.808
	TenRentland	9,638	0.249	0.215	0	0.985
	TenRentlocal	9,638	0.091	0.165	0	0.987
	TenRenvol	9,638	0.011	0.043	0	0.688
	TenRentfree	9,638	0.011	0.020	0	0.890
Dwelling	DwellBungalow	9,638	0.798	0.292	0	1
	DwellFlat	9,638	0.176	0.280	0	1
	DwellBedsit	9,638	0.006	0.025	0	0.746
	DwellOther	9,638	0.021	0.031	0	0.982
	Proportion EFG	9,638	0.326	0.292	0	1
	AgePre1945	9,638	0.138	0.221	0	0.988
	Age 1945-60	9,638	0.088	0.171	0	0.954
	Age 1960-80	9,638	0.214	0.275	0	1
	Age 1980-2000	9,638	0.247	0.268	0	0.990
	AgePost2006	9,638	0.248	0.318	0	1

B Results from first stage supply equation

Table B1: First stage supply equation

Dep Var: Max length in years since network in place

Variable	Linear		Quadratic	
	Coefficient	**Robust SE**	**Coefficient**	**Robust SE**
Household count	0.102***	(0.028)	6.332***	(1.790)
Household count sq	-0.000**	(0.000)	-0.022***	(0.008)
Areakm	0.162***	(0.016)	2.773**	(1.079)
Areakm sq	-0.000***	(0.000)	-0.000**	(0.000)
log(distance to cut bog)	0.972***	(0.087)	44.660***	(6.365)
log(distance to bkt bog)	0.399***	(0.140)	8.285	(10.992)
log(mean distance to gas network)	-3.899***	(0.129)	-91.128***	(9.847)
Coalban dummy	2.319***	(0.216)	98.124***	(15.353)
EconWorking	**[REF]**		**[REF]**	
EconLooking for first job	-6.700	(16.052)	-181.729	(1166.800)
EconUnemployed	-7.628**	(3.704)	-542.257*	(301.803)
EconStudent	-6.209	(4.497)	-423.807	(359.568)
EconHome	9.683*	(5.359)	382.041	(442.248)
EconRetired	-4.277	(6.972)	-708.001	(560.839)
EconDisabled	2.635	(5.257)	-614.494	(413.031)
EconOther	9.977	(8.273)	241.815	(686.109)
Age 25-44	**[REF]**		**[REF]**	
Age 0-14	3.929	(3.868)	23.942	(331.530)
Age 15-24	16.346***	(5.366)	706.930	(430.658)
Age 45-64	6.820**	(3.219)	-2.660	(269.857)
Age 65 plus	14.968**	(7.520)	1291.967**	(639.143)
EduSecondary	**[REF]**		**[REF]**	
EduPrimary	-2.259	(2.866)	-147.458	(237.319)
EduTechnical	-5.784*	(3.271)	-331.153	(264.163)
EduDegreeplus	5.392***	(1.917)	283.807*	(158.999)
EduRefused	9.252**	(3.887)	589.154*	(338.634)
TenOwnmortgage	**[REF]**		**[REF]**	
TenOwnnomortgage	-0.600	(2.191)	-45.547	(184.580)
TenRentland	2.843**	(1.381)	90.053	(114.931)
TenRentlocal	3.347**	(1.415)	279.572**	(113.928)
TenRenvol	0.160	(2.666)	93.094	(202.774)
TenRentfree	11.902*	(6.710)	321.387	(517.277)
DwellHouse	**[REF]**		**[REF]**	
DwellFlat	0.513	(0.859)	21.788	(72.837)
DwellBedsit	8.401	(10.856)	1315.792	(1011.618)
DwellOther	8.870*	(4.635)	151.917	(369.691)
Proportion EFG	0.160	(1.163)	66.561	(95.703)
AgePost2000	**[REF]**		**[REF]**	
AgePre1945	9.851***	(1.721)	652.140***	(145.094)
Age 1945-60	4.592***	(1.577)	359.113***	(125.876)
Age 1960-80	5.355***	(0.943)	227.464***	(76.441)
Age 1980-2000	6.254***	(0.615)	235.929***	(48.380)
constant	-5.484*	(3.266)	-662.089**	(262.435)
N	9638		9638	
Weak id (Kleibergen-Paap rk Wald F)a	63.2		7.72	
Weak id (Kleibergen-Paap rk Wald F)b	95.18		20.73	
Underid (Kleibergen-Paap rk LM)a	0.001		0.001	
Underid (Kleibergen-Paap rk LM)b	203.642		30.82	

Notes: Results from IV-GMM specification. Cluster-robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1.
(a) Linear and quadratic first stage estimated jointly. (b) Linear and quadratic first stage estimated separately

Year	Number	Title/Author(s) ESRI Authors/Affiliates *Italicised*
2016		
	538	The Efficient Frontiers and Fiscal Stability: An Ex-ante and Ex-post Application to the Irish Public Finances *Kieran McQuinn* and Maurice Roche
	537	The Impact of Taxes on the Extensive and Intensive Margins of FDI Ronald B. Davies*, Iulia Siedschlag and Zuzanna Studnicka*
	536	The Surplus Identification Task and Limits to Multi-Attribute Consumer Choice *Peter D. Lunn, Marek Bohacek and* Féidhlim McGowan
	535	Evidence, Drivers and Sources of Distortions in the Distribution of Building Energy Ratings prior to and after Energy Efficient Retrofitting *Matthew Collins and John Curtis*
	534	The Impact of Free GP Care on the Utilisation of GP services in Ireland : An Evaluation of Different Approaches *Paul K Gorecki*
	533	An Examination of the Abandonment of Applications for Energy Efficiency Retrofit Grants in Ireland *Matthew Collins and John Curtis*
	532	An Examination of Energy Efficiency Retrofit Depth in Ireland *Matthew Collins and John Curtis*
	531	Use it or Lose it : Irish Evidence *Irene Mosca* and Robert E Wright
	530	Exporting under Financial Constraints: Firm-level Evidence from EU Countries Gavin Murphy and *Iulia Siedschlag*
	529	Fisheries Management for Different Angler Types *John Curtis and Benjamin Breen*
	528	Poorest made Poorer? Decomposing Income Losses at the Bottom of the Income Distribution During the Great Recession *Michael Savage*
	527	Profile of Second-level Students Exempt from Studying Irish *Emer Smyth* and *Merike Darmody*
	526	Modelling the Vietnamese Economy Pho Chi , *John FitzGerald*, Do Lam , Hoang Ha , Luong Huong, Tran Dung

For earlier Working Papers see http://www.esri.ie