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Essays in Energy Economics and Policy

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Abstract

The world is currently going through an 'Energy Transition' and it is changing how our economies, culture and society operate. The research presented in this thesis emanates from large scale changes and is investigated through three distinct research papers, with separate but interlinked themes. Research paper 1 (Chapter 2) profiles households that have adopted of micro renewable energy systems (micro-RES) and examines whether micro-RES installations have impacted energy consumption based on data from the Irish Household Budget Survey. Our findings indicate that some revision of energy policy is needed, as the presence of micro-RES doesn't affect total energy usage. Research paper 2 (Chapter 3) investigates how the success of solar PV has given rise to a positive feedback cycle in the residential electricity market, whereby increased customer adoption results in reduced demand from utility providers. This leads to price increases and further incentivises customers to adopt solar PV. Empirical findings indicate strong support for the idea of a positive feedback cycle using data from the UK, Australian and Irish Markets. This reinforces the need for stakeholders to consider this issue in framing future energy policies to ensure that the adoption of solar PV is supported in a sustainable way, while not punishing non-adopters with higher electricity rates. Research paper 3 (Chapter 4) employs a new multidimensional measurement to gauge the extent of fuel poverty in the USA. For the three coldest regions in the USA, we find that 12% (New England), 13% (East North Central) & 9% (West North Central) of households are fuel poor. Empirical findings show that the odds of being fuel poor are higher for households with elderly people and children present. These results have useful implications for policy formation and targeting appropriate supports to address this issue.

Declaration

I certify that this thesis, which I now submit for examination for the award of PhD (doctor of philosophy) is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for PhD of the Technological University Dublin has not been submitted in whole or in part for an award in any other institute or university. The work reported on in this thesis conforms to the principles and requirements of TU Dublin's guidelines for ethics in research.

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Signature ____________________________

Date ______________________

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List of Abbreviations

AHS	American Household Survey
AF	Appliance Factor
CER	Commission of Energy Regulation
CES	Chief Economic Supporter
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
ENC	East North Central
EV	Electric Vehicle
DF	Dwelling Factor
DG	Decentralised Generation
FiT	Feed-in Tariffs
GHG	Greenhouse gas
GWh	Gigawatt hour
HBS	Household Budget Survey
HDD	Heating Degree Days
kWh	Kilowatt hour
LIHC	Low Income High Costs Indicator
Micro-RES	Micro Renewable Energy Systems
MWh	Megawatt hour
NE	New England
NREAP	National Renewable Energy Action Plan
OECD	Organisation for economic co-operation and development
OLS	Ordinary Least Squares
PV	Photovoltaic
REC	Renewable Energy Certificates
SAP	Standard Assessment Procedure
SEAI	Sustainable Energy Association of Ireland
SEF	Socio-Economic Factor
WNC	West North Central
3SLS	Three Stages Least Squares

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Chapter 1

Introduction

1.1. Introduction

The research presented in this thesis emanates from large scale changes in the energy landscape, particularly in the context of energy generation and transmission. The 'Energy Transition' is in part due to environmental energy policies which is changing how our economies, culture and society operate (Sioshansi, 2016). The 'Energy Transition' involves the movement away from fossil fuels to renewable sources in the electricity generation sector but also a shift in the transportation fleet towards electric vehicles' (EVs) and housing sector towards heat pumps. The 'Energy Transition' involves a "vast expansion of renewables, a smarter and much more flexible electricity grid, and huge increases in the numbers of vehicles and other products and processes that run on electricity"(IRENA, 2019, p. 3). A centralised energy generation model is how the energy market operated over the last 100 years (Rochlin, 2016). Where a large scale thermal power station combusted fossil fuels, resulting in heat energy which is then converted into mechanical energy and used to turn turbines generating electricity. The electricity is then transmitted from the power station via a transmission network to the end users, the commercial and residential sectors. The centralised model was successful in that it delivered economies of scale and reliability however there was a cost associated with this system which is impacting the planet today, man-made climate change due to global warming caused by the emission of greenhouse gases (GHG) as a by-product of energy generation (Allen, Hammond, & McManus, 2008). The energy sector accounts for more than two-thirds of global GHG emissions, with about 40% of the emissions coming from power generation (Sioshansi, 2016).

To mitigate climate change, there has been a global effort to move towards a more sustainable method in the supply and consumption of energy in all sectors. To achieve this goal, many governments have implemented environmental energy policies; promoting the increased deployment of renewable energy systems (and more recently battery storage systems), higher energy efficiency standards in the construction of buildings and the production of more energy efficient products.

According to Pablo-Romero, Pozo-Barajas & Yñiguez (2017), residential energy policies are central in the reduction of emissions for two reasons, firstly, it represents around 25% of global energy consumption, and 17% of global CO2 emissions (IEA, 2016). The second reason is to do with emissions displacement, countries that have implemented policies aimed at reducing emissions have seen success however this achievement may be due to high polluting industries moving operations to developing countries with weaker regulations.

Residential environmental energy policies involve the promotion of energy saving features in the housing unit, for example energy saving appliances and upgrading housing insulation, and the installation of micro renewable energy systems (micro-RES)[1]. There are many different types of micro-RES, ones that generate electrical energy, solar photovoltaic (PV) panels and

[1] Micro-RES is used throughout this thesis to refer to energy produce at the residential scale usually measured in kilowatt (kW). Some of the literature refers to it as distributed energy recourses (DER's) or decentralised and dispersed. The definition of DER's includes any resource capable of providing energy services that is located in the distribution system which not only include that at the residential scale (kW) but commercial measuring at a scale of several hundred kW to several megawatts (MW), up to utility scale tens to hundreds (MW) (MIT Energy Initiative, 2016) .

micro wind turbines. Others that generate thermal energy, solar thermal water heaters and geothermal heat pumps. Micro-RES can benefit a household in two ways, firstly reducing the cost of their energy bills by generating their own energy therefore demanding less energy from the utilities. Secondly, households with a micro-RES that generate electricity, can sell their excess electricity to the utilities and become what is called a prosumer[2]. This transaction of utilities buying from the consumer and suppling it to another consumer, it is referred to as decentralised generation (DG).

To motivate households to adopt micro-RES, government regulators have used a range of policy instruments, two widely used instruments are, net metering and feed in tariffs (FiT). Net metering allows customers with micro-RES to reduce their electricity bills by offsetting their consumption with electricity generation, independent of the timing of the generation relative (Darghouth, Barbose, & Wiser, 2011). FiT, a household generating electricity can export excess electricity to the gird and receive payments at a fixed price per kilowatt hour (kWh), guaranteed by the government (Ramirez, Honrubia-Escribano, Gomez-Lazaro, & Pham, 2017). These instruments contribute towards the growing interest in micro-RES and play a role in jump starting the market, particularly solar PV, in the US, Australia and Europe (Darghouth et al., 2011; Nelson, Simshauser, & Kelley, 2011; J. Watson et al., 2008).

DG, particularity solar PV panels, may yield significant benefits in terms of energy efficiency and reduced carbon emissions, however there are costs associated with its increasing prevalence (Juntunen & Hyysalo, 2015). The growth of DG on many markets, particularly in parts of Australia and the US, has led some to suggest that the traditional electrical utilities

[2] Refers to consumers who are also producers.

have entered into a death spiral due to falling demand and increasing electricity tariffs (Felder & Athawale, 2014). However, some argue that the demise of these utilities is exaggerated(Laws, Epps, Peterson, Laser, & Wanjiru, 2017).

Indeed, many studies are arriving at the same conclusion, that electricity demand growth is slowing and in some cases falling in developed countries. The reasons for this vary from country to country, it is generally a result of several factors[3], with one such factor being the increased prevalence of DG. The falling demand due in part to the growth of DG will obviously have an impact on the electrical utilities business operations with studies estimating that by 2025, annual revenues of utilities in the US may be $48 billion lower than they would have been. The US is not alone, European utilities are estimated to see similar losses for the same reasons (Sioshansi, 2016).

Concurrently electrical utilities fixed costs are rising due the upgrading of an aging transmission and distribution infrastructure to accommodate the intermittency issues of increased share of renewable energies in generation portfolio. To recoup rising fixed costs and compensate for falling or stalling demand growth, electrical utilities raise prices. However higher electricity bills paired with decreasing costs of micro-RES make household self-generation an increasingly financial viable option (La Monaca & Ryan, 2017). Households that make the switch contribute to further falls in demand resulting in increased prices, creating a positive feedback cycle and threat of a death spiral (Laws et al., 2017). Thus, a positive feedback cycle and as some have theorised resulting in a death spiral. A scenario where every household eventually leaves the grid and generates its own energy resulting in a utility death

[3] The gradual deindustrialisation of advanced economies towards a less energy intensive tertiary sector, improvements in the energy efficiency of buildings and electrical devices.

spiral is highly unlikely according to Laws, et al. (2017). As most of these households with micro-RES will remain connected to the grid for reliability and backup (Costello & Hemphill, 2014).

The utility business is no longer viewed as a growth industry, with retail electricity prices that are flat or rising after adjusting for inflation (Sioshansi, 2016). Fuel poverty could become an issue, fuel poverty occurs when a household is unable to heat their home to a comfortable level due to a multitude of factors; lack of finances, low energy efficiency dwelling and high energy costs (Pereira, Freitas, & da Silva, 2011). There are several health and social effects associated with households living in fuel poverty (Hills, 2011).

1.2. Research Objectives

As discussed above the energy sector in the developed world is undergoing a transition driven by the combination of several factors resulting in economic and social issues. This thesis examines the consequences of the energy transition, particularly the role of environmental energy policies on the residential sector. Primarily the residential sector in developed countries with mature energy markets. The selection of countries was informed by literature and is detailed further in Chapters 2, 3 & 4. The examination was undertaken through three distinct research papers, with separate but interlinked themes. The following paragraphs details each papers' objectives.

The first research paper entitled, “Household Energy Consumption: A Study of Micro Renewable Energy Systems in Ireland” (Chesser, Hanly, Cassells, & Apergis, 2019). We examine if environmental energy policy aimed at promoting micro-RES in the residential sector has been effective. The literature on adoption of new energy technology in the residential sector and the determinants of residential energy use were reviewed. There was found to be a shortage of studies that investigate the determinants of energy use in the residential sector outside of the US and the UK according to Jones, Fuertes & Lomas (2015) and also there is limited research on the determinants of adoption of micro-RES in Ireland. Using data from the Irish Household Budget Survey (HBS) this paper bridges the gap between these two parts of the literature and sets the following objectives;

1. To establish a profile of a household that is adopting micro-RES.

2. How micro-RES affects energy use in the household.

To accomplish these objectives econometric analysis was undertaken, firstly a micro-RES ownership model was constructed and a logit regression was used to discover the main determinants of a household that are currently adopting micro-RES. For the second objective, several energies by fuel source consumption models were construction and regressed using ordinary least squares (OLS), to investigate whether the presence of micro-RES affects energy use in the household.

The second research paper, entitled “The positive feedback cycle in the electricity market: Residential solar PV adoption, electricity demand and prices”(Chesser, Hanly, Cassells, & Apergis, 2018) . Investigated another aspect of the energy transition, the feedback cycle in the residential electricity market due to the increasing penetration of solar PV panels. The literature investigating the existence of a positive feedback cycle which could possibly lead to a utility ‘death spiral’ is relatively new, with empirical studies mainly focus on the US market to date (Costello & Hemphill, 2014). This paper extends the ideas from the literature to a selected group of countries, Ireland, the UK and Australia, to investigate whether solar PV panel adoption in these countries has led to the existence of a positive feedback cycle in the residential market. The three countries can be seen to represent solar PV panels at three different stages of growth; infancy, intermediate and mature respectively. The objectives of this paper are as follows;

1. Construct an economic model that represents the positive feedback cycle.

2. To determine whether there is a positive feedback cycle is being experienced in the residential electricity market.

To accomplish these objectives firstly a simultaneous equations model was constructed to model the positive feedback cycle. Secondly a database was created with all the key variables for all the three countries under examination and a three stage least squares (3SLS) regression was used to discover if a positive feedback cycle was present.

The final research paper, entitled “Fuel Measurements in Residential America. Who are the Most Vulnerable?”. There are three different but related perspectives that make fuel poverty a distinct and serious problem: poverty and its reduction; health and well-being; climate change and the reduction of carbon emissions (Hills, 2011). However, there is debate in the literature about which measurement approach to use when attempting to quantify fuel poverty. A small group of new studies suggest using a new multidimensional measurement to gauge the extent of fuel poverty. This paper examines fuel poverty in the US using a multidimensional measurement as the research in this area is less prevalent as compared to European countries added to this that the existing US studies use the older debateable measurements (Thomson, Snell, & Bouzarovski, 2017). The objectives of the paper are as follows;

1. Assess US households in fuel poverty using a multidimensional measurement

2. What households are most at risk of living in fuel poverty.

To accomplish these objectives, firstly the paper outlines the dimensions used to construct its multidimensional measurement and how it addresses some of the shortcomings of the other approaches and gives a truer reflective of the problem. Secondly, using the American Household Survey (AHS) we determine the probability of a household being fuel poor, using a logistic regression to examine the major socioeconomic and dwelling characteristics of households that affect the odds of being fuel poor. These results have useful implications for policy formation and targeting appropriate supports to address this issue.

1.3. Thesis Structure

Chapter 1 contained an introduction to the topic of the 'Energy Transition' and its implications on the sector and research objectives. The three research papers are formatted into three separate chapters, Chapters 2, 3, and 4. Each of these chapters are structured as follows; Abstract, Introduction, Literature Review, Data & Methodology, Empirical Findings and Conclusion. Chapter 5, is the final chapter containing a summary and discussion about the main research findings, areas of future research are also discussed and a critical reflection of my PhD.

Chapter 2 - Paper 1

Household Energy Consumption Energy Consumption: A Study of Micro Renewable Energy Systems in Ireland.

2.1. Abstract

Irelands National Renewable Energy Action plan addresses how it will meet its environmental commitments. One element of the strategy is the use and promotion of micro renewable energy systems (micro-RES). This paper profiles households that have adopted micro-RES and examines whether micro-RES installations have impacted energy consumption by source, and total fuel usage and electricity, based on data from the Irish Household Budget Survey. Results indicate that the presence of micro-RES doesn't result in a reduction of electricity usage, rather the opposite. Furthermore, our findings indicate that some revision of energy policy is needed, as the presence of micro-RES doesn't result in a decrease in total energy usage.

2.2. Introduction

The Irish Government has stated its commitment to a low carbon energy future as part of its plan to support the wide scale deployment of renewable energy in the residential sector. Towards this end, several micro renewable energy systems (micro-RES) and energy efficiency schemes have operated in Ireland. Currently there is the solar PV grant offered by Sustainable Energy Association of Ireland (SEAI) that offers a grant of up to €3,800 for solar PV panels and battery storage systems. There is also a 'Solar Thermal Grant' with a value up to €1,200 (SEAI, 2017).

Households which integrate micro-RES could allow themselves to generate their own energy thus reducing energy demand from utilities, which in turn reduces the amount of new generation that needs to be built, resulting in lower costs to consumers. The promotion of micro-RES in Ireland could help it reach its environmental energy policy goals while also contributing to its future energy demand. For example Allen et al., (2008) references a study where it was predicted that electrical micro-RES could provide 30 to 40 per cent of the UK's electricity needs by 2050[4].

To support policymakers' decisions about how to reduce energy consumption and CO_2 emissions from the residential sector through the promotion of micro-RES, it is essential to know the profile of the average household that is currently adopting it. Also, it is worth

[4]The UK and Ireland share a similar climate, it would stand to reason that Ireland could reach these percentages as well.

investigating whether the adoption of micro-RES is successful in reducing residential energy consumption. This chapter addresses these issues by examining what are the common household determinants among adopters of micro-RES using a logit regression model. We also consider whether the growing number of micro-RES installations has had an impact on energy consumption, by total fuel usage and by electricity usage, for residential sector in Ireland. Our results can inform the next generation of environmental energy policy formulation and planning, particularly regarding micro-RES in the Irish energy landscape. This study is significant for two reasons; firstly, no study, to the best of our knowledge, has yet to investigate how the growth of micro generation has impacted on residential energy consumption. Secondly, according to Jones et al., (2015), there is a shortage of studies which investigate the effects of the three main factors on residential energy consumption in countries outside the US and UK.

The rest of the chapter is structured as follows, in Section 2.3 the literature on the determinants of adoption of new energy technology and the determinants of energy use in the residential sector are reviewed. Section 2.4 presents the data and methodology, followed by our empirical findings in Section 2.5. These findings are then discussed in the conclusion together with policy implications in Section 2.6.

2.3. Literature Review

This study is concerned with, firstly investigating what are the common household determinants that have led to the adoption of micro-RES and secondly whether the presence of micro-RES has an impact residential energy consumption. Because of this the literature review will be presented in two parts, the determinants of adoption of new energy technology and the determinants of energy consumption in the residential sector.

2.3.1. Adoption of New Energy Technology in the Residential Sector

There are several studies that examine the decision process for the adoption of a new energy technology in the home. A study by Islam (2014) investigated whether Canadian households prefer the attributes of the new technology, solar PV and whether they are going to adopt it? Results show that younger households with higher technology awareness and aren't as concerned with cost are more likely to be in the early solar PV adoption rates. Mills & Schleich (2009) found that the adoption of solar thermal in Germany is higher in newer houses and in houses with more modern heating systems. While Michelsen & Madlener (2016) found that knowledge, house size, rural households and threats resulted in households adopting renewable heating systems. Variables that inhibited adoption were house age, comfort, status quo and homeowner with a university degree. Sopha, Klockner, Skjevrak & Hertwich (2010) using Norwegian data found that households with younger occupants and occupants with higher education levels were more likely to adopt heat pump or wood pellet as their future heating systems.

Studies on the adoption of renewable energy at household level in Ireland is limited, however there have been studies on Irish households' decisions to adoption of different fuel sources and the adoption determinants of household appliances that improve energy efficiency. A study by McCoy & Curtis (2018) investigated the determinants of natural gas in the Irish residential sector. They found that socio-economic factors (SEF) such as lower levels of education and out of work households had lower rates of connections to gas lines. Another study by Leahy & Lyons (2010) which examined the determinants of appliance ownership in the residential sector using the HBS. They modelled access to several appliances including double glazing windows. The authors' results were estimated using a logit regression with findings showing that urban households are more likely to have double glazing than rural households. Another result of interest is that of household disposable income which implies as income increases, so does the probability of having double glazing.

2.3.2. Determinants of Residential Energy Consumption

This subsection of the literature review presents studies that investigate the main determinants of residential energy consumption using econometric analysis with a focus firstly on global studies followed by Irish studies. Jones et al., (2015) compiled a comprehensive literature review of studies examining the variables that either have a significant or non-significant effect on residential energy consumption (table 2.1). They broke down the variables into three groups; socio-economic factors (SEF)[5], dwelling factors (DF)[6] and appliance factors (AF)[7]. The study found that 62 variables in the literature reviewed influence residential energy consumption.

[5] Includes variables such as; number of occupants, education level of head of household, income, tenure type, age of head of household, etc.
[6] Includes variables such as; type of dwelling, year of construction, size of dwelling, number of bedrooms, double glazing windows etc.
[7] Includes variables such as; total number of appliances, power demand appliances, etc.

These include; 13 socio-economic factors, 12 dwelling factors & 37 appliance factors.

However, there are mixed results in the global literature with regards to the direction of the relationship between these variables and residential energy consumption. Reviewing the variable 'household with children' from the socio-economic factors group, it was found to vary across the literature. Several studies found that it had a positive effect on household energy consumption; Mcloughlin, Duffy & Conlon (2012) and Wiesmann, Lima Avevedo, Ferrão & Fernández (2011). While Bartiaux & Gram-Hanssen (2005) and Gram-Hanssen, Kofod & Petersen (2004) found a negative effect. The following studies found no effect; Bedir, Hasselaar & Itard (2013) and Cramer, Miller, Craig & Hackett (1985).

There is also a debate on the direction of the relationship between several dwelling factors and energy consumption. For example, Brounen, Kok & Quigley (2012) and Leahy & Lyons (2010) find a positive effect with regards to the age of dwelling. A negative effect was found by Baker & Rylatt (2008) and Chong (2012), while Tso & Yau (2007) found no effect.

Finally, the literature on appliance factors again shows mixed findings. For example, looking at the relationship between the presence of tumble dryers in a home and energy consumption, a positive effect was found by Mcloughlin, Duffy & Conlon (2012) while Carter, Craigwell & Moore (2012) found no effect.

The following subsection details three Irish studies investigating the determinants of residential energy consumption. The first study to investigate the determinates of residential energy consumption is Leahy & Lyons (2010), which examined the determinants of energy consumption first by; electricity use and then all other energy use. Their studied used ordinary least squares (OLS) regression analysis on the 2004/2005 Irish HBS. Their energy use model's included variables from SEF, DF & AF. McLoughlin, Duffy & Conlon (2012), differed from Leahy & Lyons (2010) by using four different parameters as the dependent variable; total electricity consumption, maximum demand, load factor and time of use. Mcloughlin et al., (2012) used a multiple linear regression on each model, using a sample of 3,941 Irish households. Their models included variables from SEF, DF & AF. Lastly Harold, Lyons & Cullinan (2015) investigates the daily residential gas demand by employing random effects estimator on a panel data set of 1,181 households smart meter data. Their daily residential gas demand models included variables from SEF, DF and weather variables.

Table 2.1: Summary of Studies

Study		Country	Independent (s) variable studied		
			SEF	**DF**	**AF**
Parker	(2003)	USA	X	X	X
Larsen & Nesbakken	(2004)	Norway	X	X	X
Summerfield, Lowe, Bruhns, Caeiro, Steadman & Oreszczyn	(2007)	UK	X	X	
Leahy & Lyons	(2010)	Ireland	X	X	X
Wiesmann et al.	(2011)	Portugal	X	X	X
McLoughlin et al.	(2012)	Ireland	X	X	X
Bartusch, Odlare, Wallin & Wester	(2012)	Sweden	X	X	
Zhou & Teng	(2013)	China	X	X	X
Belaid	(2016)	France	X	X	X
Huebner, Shipworth, Hamilton, Chalabi & Oreszczyn	(2016)	England	X	X	X
Iwafune & Yagita	(2016)	Japan	X	X	X
Matsumoto	(2016)	Japan	X	X	X
Wallis, Nachreiner & Matthies	(2016)	German	X	X	X
Copiello & Gabrielli	(2017)	Italy	X	X	
Harold, Cullinan & Lyons	(2017)	Ireland	X	X	

Source: Jones et al.,(2015)

Common independent variables that had impact on energy consumption across all three studies where the following; the DF, number of rooms had a positive impact on energy consumed. Similar results were found for SEF, with households with a lower income or from a lower social group consume less energy. Also, a head of the household who attained a lower level of education were found to consume less energy. AF such as the presence of a tumble dryer and a dishwasher both result in more energy usage.

After reviewing the literature, the direction of the relationship of the main determinants of household energy consumption in global studies is still open to debate whereas for Ireland, the evidence is much clearer. Generally urban privately owned households consume more energy as compared with rented or rural households. A head of a household that has attained a lower level of education consumes less energy than those with degrees from third level institutions. Also, newly constructed housing units and apartments use less energy than their older counterparts. However, none of the Irish studies[8] examined whether the presence of a micro-RES whether would impacts energy usage and what household determinants that result in ownership of a micro-RES.

[8] Leahy & Lyons Leahy, E., & Lyons, S. (2010). Energy use and appliance ownership in Ireland. *Energy Policy, 38*(8), 4265-4279. included the variable renewable source for water heating only and no other forms of renewable used for electricity whereas this study accounts for both.

2.4. Data & Methodology

2.4.1. Data

This paper uses anonymized microdata collected from the Irish HBS 2010[9]. The HBS is a survey of a representative random sample of all private households in the Ireland. Surveys have been carried out periodically in Ireland since 1951 and generally every five years since 1994. The 2009-2010 HBS was undertaken between the months of August 2009 to September 2010 and covered 5,891 households.

The following SEF variables where included in our study according to the literature reviewed. Number of persons living in household, average weekly disposable household income, family composition whether a home was children or not, highest level of education of chief economic supporter (CES) completed, household tenure (owned or rented). DF variables are as follows; year accommodation was built, number of bedrooms and location of house (urban or rural). AF variables include are; dishwasher, tumble dyer, fridge-freezer, microwave, games console and number of televisions. Descriptive statistics are presented in appendix II –IV.

The HBS questionnaire survey doesn't ask what type[10] of micro-RES has been installed in the dwelling outright. However, through several energy questions asked in the survey about the dwelling, a dummy variable was constructed to represent households with a micro-RES

[9] This household survey is a number of years old is nevertheless the most up to date available in micro-RES installations. While a newer study was published in 2016 – it did not contain the necessary data on micro-RES as the relevant question was dropped from the survey.
[10] Thermal or Electrical

installed. These energy questions included what type of central heating system is used for space heating in the winter[11] where renewable source is a selectable answer. The other question relates to the method of water heating in the winter were source is a selectable answer. If a household answered renewable for any of these questions it was given the value of 1 in under our variable micro-RES and conversely a value of zero when it is not.

As noted by Leahy & Lyons (2010) the HBS doesn't do enough to address every aspect of household energy consumption. It lacks extensive information on several issues especially energy efficiency of dwellings and the frequency of appliances and heating usage. However, the HBS does report on the average weekly expenditure on energy by fuel use type; electricity, natural gas, liquid fuel, solid fuel and total fuel. Using the same method as Leahy & Lyons (2010), in order to evaluate the average household energy consumption by fuel use the following formula was employed (equation 2.1).

$$elecuse_i = \left(expenditure_i^{elec}/price^{elec}\right)(kWh^{elec}/q^{elec}) \qquad (2.1)$$

The estimated energy use from electricity is measured in kilowatt hours, where $expenditure_i^{elec}$ is the average weekly expenditure by household i on electricity. $Price^{elec}$ is the average unit price of electricity for the period in which the household was interviewed. Price data was obtained from SEAI (Appendix I)[12]. kWh^{elec}/q^{elec} is the kw/h of electricity

[11] The survey doesn't address the same question for any other season only winter.
[12] The use of price data was informed by Leahy & Lyons ((2010).

per unit and is known as the gross calorific values, for electricity this is 1. Similarly, for each form of the remaining fuels (natural gas, liquid heating oil, solid fuel and total fuel) the corresponding value for average weekly expenditure, price data and gross calorific value were inputted.

2.4.2. Micro-RES Ownership Model

The objective of the first part of this paper is to establish a profile of the average household that adopts micro-RES and we constructed a logit model for this purpose (Braun, 2010). We use a step wise depletion method of variables in order to estimate a leaner model which omits explanatory variables that are not significant (Leahy & Lyons, 2010). This model included many of the SEF, DF and AF variables that are significant according to the literature in the adoption of a new energy technology in the residential sector.

2.4.3. Energy Consumption Models

The second part of the analysis into micro-RES, investigates whether it has had an impact on the average weekly household energy consumption by fuel use type and an ordinary least square (OLS) regression method will be used. Two models will be used, the first model will have total fuel use as the dependent variable and the second model will have electricity use as the dependent variable. The models can be formulated using the following equation (2.2);

$$lnenergyuse = \beta_0 + \sum_i \beta_i X_i + \varepsilon_i \qquad (2.2)$$

where *lnenergyuse* indicates the natural log of average energy use by fuel type and X is a list of predicator variables and ε_i is the unobserved error term. For Model 1 the dependent variable will be the total fuel use and Model 2 the dependent variable will be electricity use. Again, previous literature directed the choosing of variables used for modelling residential energy use (Druckman & Jackson, 2008; McLoughlin et al., 2012; Wiesmann et al., 2011; Zhou & Teng, 2013).

2.5. Empirical Findings

2.5.1. Micro-RES Ownership Model

Results from the logit model are presented in table 2.2 below. Results reveal that households with higher weekly disposable income are more likely to have access to micro-RES. This is not surprising since micro-RES installations are very expensive and support schemes are not as favourable in comparison to other EU countries which results in longer payback period for Irish customers. Households in urban areas are less likely to have had availed of micro-RES than their rural counterpart. This may be a result the density of houses in urban areas and restrictive building regulations for some types of micro-RES, particularly micro wind turbines. If the household is owned by the occupant they are more likely to have micro-RES than those who rent their property. This stands to reason that an owner-occupied house is more willing to invest in the property than that of a renter.

The level of education acquired by the CES also plays a role on whether a household is likely to adopt micro-RES. Households where the CES has only acquired a primary school level of education or has no formal education are less likely than those CES in the reference category of acquiring education at a third level institution to have had adopted micro-RES. If the CES has attained an education at third level institution it would be understandable that firstly, they would have a career where they earned a larger salary in relation to the CES of the other categories which would result in a greater ability to purchase micro-RES. Secondly, due to attaining a higher education they may have a greater awareness of environmental issues and the benefits of micro-RES.

The results from the categorical variable, housing unit construction year, are all statistically significant bar housing units constructed pre-1918 and have a negative sign in relation to the reference category of housing unit built in the period 2006-2010. Inferring, for example that for the variable 1918-1945, housing units built during this time are less likely than those built between 2006-2010 to have had adopted micro-RES. It should also be noted that the size of the coefficient doesn't increase linearly in the housing units' construction year variables. We attribute this to higher installation costs when retrofitting some older units with micro-RES.

Table 2.2: Logit Regression Results for the Determinants of micro-RES Installation.

	Coef.	**P-Value**
Log of Household Disposable Income	0.4836**	0.025
Number of People	0.0018	0.986
Urban & Rural Household Location	-1.0766***	0.000
Ownership or Rental Household	2.0533***	0.001
Household with Children	0.4893*	0.081
Education Status of CES		
Primary School, No Formal Education, Other	-1.0794**	0.015
Secondary School	-0.4701*	0.091
Higher Institute	(R.C)	
House Construction Year.		
Pre 1918	-0.5795	0.152
1918-1945	-1.1769**	0.033
1946-1960	-1.8636**	0.012
1961-1970	-1.2947**	0.038
1971-1980	-1.341***	0.002
1981-1990	-2.5067***	0.001
1991-2000	-0.9924***	0.003
2001-2005	-1.38***	0.000
2006-2010	(R.C)	
Number of Bedrooms	0.315***	0.008
Constant	-8.7955***	0.000
R^2	0.172	
No of Observations	5,818	

Notes; * significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level, R.C. Reference Category.

2.5.2. Energy Consumption Models

Energy use was modelled by, total fuel use (model 1) and electricity use (model 2). As well as our main variable of interest, micro-RES, we studied the influence of several household characteristics; SEF, DF and AF. Using ordinary least squares (OLS), the estimated regression coefficients are presented in table 2.3 below.

Firstly, the presence of micro-RES was only statistically significant for electricity use, where the presence of micro-RES resulted in more electricity use compared to households without micro-RES. The cause of this may be a result of the rebound effect where improved energy efficiency in the household gives rise to a reduction in energy prices however, lower prices will increase energy consumption to some extent (Wang, Lu, & Wang, 2014). More specifically, this may be the income effect because of the direct rebound effect, "when improvement in energy efficiency reduces the cost of a particular goods or services, consumers need to spend less to get the same outcome as before. Thus an increase in real income allows to achieve higher utility by increasing consumption of the same goods or services, including the energy service" (Labidi & Abdessalem, 2018, p. 11).

Table 2.3: OLS regression results for the determinants of Total Fuel Use & Electricity Use.

	Model 1 Total Fuel Use		**Model 2 Electricity Use**	
	Coef.	**P-Value**	**Coef.**	**P-Value**
Micro-RES	-0.021	0.799	0.202***	0.00
Number of People in Home	0.057***	0.000	0.113***	0.00
Log of Household Disposable Income	0.082***	0.001	0.063***	0.00
Urban & Rural Household Location	-0.048	0.299	-0.04	0.33
Ownership or Rental Household	0.104	0.128	-0.01	0.85
Household with Children	0.098***	0.003	0.058*	0.06
Education Status of CES				
Primary School, No Formal Education, Other	(R.C.)		-0.122**	0.02
Secondary School	-0.007	0.828	0.00	0.99
Higher Institute	-0.030	0.504	(R.C.)	
Housing Unit Construction Year				
Pre 1918	0.094*	0.067	0.01	0.78
1918-1945	0.242***	0.000	-0.09	0.18
1946-1960	0.274***	0.003	-0.13	0.27
1961-1970	0.148*	0.051	-0.159*	0.09
1971-1980	0.162**	0.015	-0.03	0.69
1981-1990	0.139	0.195	-0.06	0.61
1991-2000	-0.021	0.704	-0.04	0.44
2001-2005	-0.016	0.806	-0.05	0.43
2006-2010	(R.C.)		(R.C.)	
Number of Bedrooms	0.129***	0.000	0.061***	0.00
Appliances				
Dishwasher	0.115***	0.000	0.172***	0.00
Tumble dryer	0.008	0.734	0.04**	0.05
Fridge-freezer	0.063**	0.038	-0.02	0.53
Microwave	0.085*	0.064	0.03	0.53
Console	0.040	0.142	0.056**	0.03
Number of TVs	0.044***	0.000	0.030***	0.00
Constant	4.419***	0.000	3.049***	0.00
R_2	0.184		0.21	
No of Observations	5,759		4,607	
Inverse Mills Ratio	-0.052	0.597	0.14	0.21
F-stat	53.97***	0.000	50.83***	0.00

Notes; * significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level, R.C. Reference Category.

Results across the SEF variables results were in line with the previous literature. A larger number of people living in a household, results in greater energy use both for total fuel, as well as for electricity. As expected a higher weekly disposable income results in an increase energy consumption for total fuels and electricity use. A household with children consumes more energy from both total fuel and electricity when compared to a household without children. In terms of education, it was found only significant in the case of electricity use where a CES with a primary school education or no formal education uses less than the reference category of a third level institution educated CES.

Results from the DF variables show that having an extra bedroom in a home will increase total fuel as well as electricity use which is in line with the literature. When investigating the variable year of housing unit construction, the reference category varied across each model. In general, the more recently constructed units use less energy than that of the reference categories.

To summarize, the results strongly support the finding that newer built housing units use less energy than older homes, indicating that Irish policy to increase energy efficiency in the residential sector through greater standards in energy efficiency buildings is having its desired impact.

Results from AF variables effecting energy consumption in a household results varied across both the models. Households that had access to a dishwasher were found to statistically significant in terms of increasing total fuel and electricity use. Households that had access to a tumble dryer were found to use more electricity while in terms of solid fuel use households with a tumble dryer use less. Households that had access to a fridge-freezer were found to statistically significant in terms of increasing total fuel use. Households that had a larger number of televisions were found to statistically significant in terms of increasing total fuel and electricity use.

The results of our study support the finding that households that have adopted micro-RES are more likely to be wealthier households, taking advantages of support schemes designed to financially incentivise households that are tentative about the decision whether to adopt micro-RES. As these schemes are funded through consumer energy bills, this may relatively disadvantage poorer households. Given our findings that the presence of micro-RES doesn't result in a decrease in total energy use in the home, we suggest that this element of Irish energy policy around residential sector needs to be re-evaluated. While the promotion of micro-RES is an essential element as part of our energy policy goals, there is also a need to inform adopters to change their 'behaviour as usual' approach to address the rebound effect.

The inverse mills ratio variable was included in the regression to test for sample selection bias. In both models, total fuel use and electricity use, the inverse mills ratio variable was statistically insignificant meaning that there is no sample selection bias (Heckman, 1979).

2.6. Conclusion

Micro-RES, properly supported, could have the potential to significantly contribute towards Ireland's environmental energy policy goals. Governments worldwide have recognised this by implementing strategies to stimulate the growth of micro-RES in the residential sector. In Ireland, electrical micro-RES growth has been relatively slow which may be partially attributable to ineffective governmental support mechanisms as compared with other countries.

In this paper, we investigated firstly the common determinants of households that have adopted micro-RES using a logit regression and secondly whether the presence of such would impact energy consumption by fuel type using an ordinary least squares regression. Analysis was carried out on the Irish HBS dataset.

Although there are some financial incentives provided to Irish households to adopt micro-RES, these schemes mainly are availed by wealthier households. As results attained from our logit model, show that the average household that is most likely to adopt micro-RES is a large[13] housing unit that has been constructed recently and is owner-occupied. The owner is most likely to be highly educated and is wealthy. The results would suggest that the households adopting micro-RES and availing of the support schemes are the ones that need them the least and that for many installing a micro-RES is still a luxury purchase in Ireland. However, some of Ireland's energy policies seem to be working, improvements in housing energy efficiency

[13] Large in terms of number of bedrooms

standards has resulted in newly constructed housing units using less energy than older houses.

The second part of this study was to find the determinants of household energy consumption by fuel type and whether micro-RES has had an impact on this. It was found that the determinants of household energy consumption were in line with those of previous literature. Surprisingly, it was found that the presence of micro-RES was only statistically significant in the electricity use model, where the presence of micro-RES increased electricity use.

Ireland is one of eight EU member states with a renewable energy share that was below the anticipated trajectories as laid out in the NREAPs[14]. While Irish environmental energy policy papers continue to address the importance of Irish citizens in combatting climate change and meeting their environmental goals through the promotion of energy saving appliances and micro-RES, results from this analysis would suggest that these policies need adjustments (EEA, 2017).

[14] National renewable energy action plan (2015).

Chapter 3 - Paper 2

The Positive Feedback Cycle in the Electricity Market: Residential Solar PV Adoption, Electricity Demand and Prices

3.1. Abstract

Micro renewable energy systems (micro-RES) such as solar photovoltaic (PV) are an increasingly important element of National energy strategies. However, the success of these installations has given rise to a positive feedback cycle whereby increased customer adoption results in reduced demand from Utility providers. This leads to price increases and further incentives customers to adopt micro-RES. This paper investigates the existence of a positive feedback cycle by developing a theoretical model based on simultaneous equations and estimating it using the three stage least squares approach using data from the UK, Australian and Irish Markets. Results indicate strong support for the idea of a positive feedback cycle. This reinforces the need for stakeholders to consider this issue in framing future energy policies to ensure that the adoption of solar PV is supported in a sustainable way, while not punishing non-adopters with higher electricity rates.

3.2. Introduction

Micro renewable energy systems (micro-RES) are small scale energy systems which generate small amounts of energy when compared to traditional centralized power plants. Micro-RES has now made it possible for home owners to retrofit their premises to generate their own electricity and/or heat, thus becoming more self-sufficient. Allen et al.,(2008) references a study where it was predicted that electrical micro renewable energy systems could provide 30–40% of the United Kingdoms' electricity needs by 2050.

Governments worldwide have included strategies to stimulate the growth of micro-RES at the residential level as part of their overall environmental energy policy aimed at combatting climate change. Governments have used a variety of support mechanisms to achieve their targets which include Feed-in Tariffs (FiT), point of sales rebates including Renewable Energy Certificates (REC), and tax benefits. These policies have been successful in increasing the number installations particularly that of solar photovoltaic systems in the residential sector in countries like the United States of America, Australia and the UK (Allen et al., 2008; Chapman, McLellan, & Tezuka, 2016).

Though, the increasing popularity of residential solar PV systems in electricity markets has led some to suggest that it has created a positive feedback cycle or loop. Simply put a positive feedback cycle is a situation where, action A generates more of action B which in turn generates more of action A. In economics, a positive feedback cycle results in a systemic risk to the system (Cai, Adlakha, Low, De Martini, & Chandy, 2013; Rodrigues et al., 2016; Sahu, 2015).

There has been a vast amount of literature on the economic impact of renewable energy systems; however, the literature has mainly been focused on renewable energy systems at a macro level (Payne, 2010; Salim, Hassan, & Shafiei, 2014; Shafiei & Salim, 2014). A new line of literature has begun to investigate the economic repercussions of increasing number of micro-generators, particularly that of residential solar PV systems and the effects on countries electricity markets which may result in a positive feedback cycle which could possibly lead to a utility 'death spiral'. This scenario is a result of residential electricity customers adopting solar PV systems due to high electricity prices will therefore reduce their consumption from the electricity grid. In response to falling sales electrical utilities will have to raise their prices as the costs[15] associated with the generation of electricity do not decrease in proportion to the decrease in electricity demanded. The increase in price by electrical utilities thus incentivises more of the remaining electricity customers to adopt solar PV systems. Increasing the penetration levels of residential solar photovoltaic systems onto a grid could further accelerate the positive feedback cycle and could have several implications. The increasing electricity prices will be borne by low and medium income households who cannot afford solar PV system and in a worst case scenario where electricity price increases will be futile in raising sufficient revenues to cover their total costs could potentially force electrical utilities into a death spiral (Costello & Hemphill, 2014; Felder & Athawale, 2014).

Of the literature that empirically investigates the topic of a positive feedback cycle in the residential electricity market caused by an increasing number of solar PV, has thus far mainly focused on the American experience. Therefore, this paper will be the first to extend the ideas

[15] This is because utilizes must pay for transmission and distribution infrastructure and these fixed costs are recovered over decades.

from the existing literature on the American experience to a newly selected group of countries, Australia, Ireland and the UK. To address this issue, this paper firstly models the positive feedback cycle caused by consumers in the residential sector by deciding to adopt solar PV systems and the resulting implications on demand and pricing in the residential electricity market. Following this, a three stage least squares regression is performed for the panel of countries to investigate whether a positive feedback cycle is being experienced. Our findings show support for: (1) increasing residential electricity prices leading to higher installation rates of residential solar PV, (2) residential solar PV installations lead to higher residential electricity prices, (3) residential solar PV installations negatively affect residential electricity demand.

The results attained in this research paper will be used to inform and support policy makers as they consider potential changes to residential electricity rates that could affect solar PV role in advancing policy objectives and not to punish non-adopters with higher electricity rates.

The chapter is organised as follows: Section 3.3 reviews the literature that examines the significant and insignificant factors impacting residential energy demand/consumption. Section 3.4, is the data and methodology section providing details on the model development, the estimation technique, data specifications and a descriptive statistics subsection. In Section 3.5, the results of the three stage least squares regression of our simultaneous equation model are presented and discussed. Section 3.6 contains the concluding remarks and policy implications.

3.3. Literature Review

The earliest reference to the positive feedback cycle as a result of micro-RES the author could find was by Severance (2011), however these terms aren't used in the study. Severance notes that utility managers have an “unspoken fear” of a death spiral scenario due to “on-site power” and the collection of higher and higher rates from poorer and poorer customers. Others studies raise concerns about the impact of favourably tariffs for micro-RES are having (Nelson et al., 2011; T. Nelson, Simshauser, & Nelson, 2012).

The hypothesis of a positive feedback cycle induced by residential solar PV, has motivated a new line of research into the interactions between residential solar PV adoption rates, electricity prices and demand. Arthur (1990) first wrote about the influence of the positive feedback on economic systems. In his paper, the author saw the positive feedback cycle as the driving force in determining which of competing technologies would dominate a market. He concluded that at the start, markets are unstable and small increases to a new technologies market share can expand its growth exponentially (Ruth & Hannon, 2012).

Studies examining the impact of electricity retail rate structure on solar PV are not new, however, most of them have stopped short of investigating whether it would lead to a positive feedback cycle (Darghouth et al., 2011; McLaren, Davidson, Miller, & Bird, 2015; A. Mills, Wiser, Barbose, & Golove, 2008). In a paper by Chew, Heling, Kerrigan, Jin, Tinker, Kolb, Huang (2012) for Pacific Gas & Electric Company, the authors acknowledge that a positive feedback cycle is in effect and conclude that electric utilities must adapt their rate-making procedures to ensure that both solar PV adopters and non-adopters are fairly charged for their cost of service. To do this the authors presented a model that could be used by electrical utilities to estimate the impact of various policies proposals will have on cost shifts and residential solar PV systems. In Cai, Adlakha, Low, De Martini & Chandy (2013), the authors investigate how the adoption of solar PV systems by households leads to a positive feedback cycle via increasing electricity rates. They modelled solar PV adoption for a specific investor owned utility, subject to rate-of-return regulation in California. The results from their model illustrate that the feedback cycle reduces the time it takes for solar PV capacity to reach 15% of peak demand by up to 4 months and has a greater impact in later years. Costello & Hemphill (2014) investigate whether the 'death spiral' facing electrical utilities due to increases in decentralised generation (DG)[16] is a reality or overstatement. The authors conclude that electrical utilities are in for some tough times ahead, but it is due to several factors not just DG. Moreover, it is in the interests of policy makers to ensure electrical utilities avoid entering a death spiral as this outcome would hurt customers in the long run, since they will have to rely on the grid on occasions. A similar conclusion is presented by Laws et al., (2017) where they investigate how many electric utilities are changing their pricing structures to address the rapidly-growing market for residential solar PV systems. The authors note that there is little knowledge about how changes to utility pricing structures would affect the adoption rates of solar PV systems, as well as the ability of utilities to prevent widespread grid defection. Laws et al., (2017) carry out simulations on a system dynamics model to predict how changes to the retail price of electricity impact on the adoption rates of residential solar PV systems. A sensitivity analyses is also conducted to investigate the likelihood of a utility 'death spiral'. Their results indicate that a utility 'death spiral' requires a perfect storm of high intrinsic adoption rates, rising utility costs, and favourable customer financials. Eryilmaz & Sergici (2016), investigate the price

[16] Distributed generation refers to the generation of energy close to the place where energy issued. It can mean a range of generator sizes; from residential households to community or district-level.

responsiveness of the residential customers with increasing residential solar PV systems penetration and projected future electricity sales to the residential sector considering various future solar PV systems penetration scenarios. Their results show that increasing residential electricity prices are associated with an increase in residential solar PV systems installations and using their findings for the estimated elasticity values, they project the share of utility electricity sales reduction due to solar residential sector between 2013 and 2020. In a future scenario where there is a 25% residential solar PV systems penetration by 2020, about 1.2% of the projected growth of the electricity sales to the residential customers will be taken over by solar PV systems.

The literature published on the topic of a positive feedback cycle due to residential solar PV systems adoption to date has focused on the American experience. This paper extends the ideas from the literature to a selected group of countries, Australia, Ireland and the UK, to investigate whether residential solar PV systems adoption in these countries has led to the existence of a positive feedback cycle.

3.4. Data and Methodology

3.4.1. Data

We consider monthly data spanning the period from 2010 to 2015, for three countries: Australia, Ireland and the UK in this study. The three countries can be seen to represent micro-RES at three different stages of growth; infancy, intermediate and mature respectively. One reason for the different levels of penetration between the countries is government support mechanisms. A possible reason for the slow residential solar PV uptake in Ireland when compared to the other countries is weak government support mechanisms. In Ireland, the ESB networks and Electric Ireland (formally known as ESB Customer Supply) ran a ‘pilot scheme’ from 2009 till 2014 for micro generators of electricity. Under this ‘pilot scheme’, micro-generators where offered a support package of a free installation of an import/export meter and support payment of 10 cent/kW h for the duration of their contract (the last of these contracts expire in 2017). For micro-generators who missed the deadline of the ‘pilot scheme’, Electric Ireland offered an export payment of 9 cents per kWh, this offer ceased to on the 31st December 2016. There is currently no other electricity supplier in Ireland offering payment for electricity produced from microgeneration technologies (Electric Ireland, 2014).

Whereas in Australia and the UK the support mechanisms for residential solar PV are much more generous by comparison to the Irish experience. In the UK, residential solar PV systems are supported through several measures including; reduced VAT on systems, capital grants for householders and government policies, such as the Feed-in Tariff (FiT). In the first year of the FiT payment period (April 2010 to April 2011) for residential solar PV systems, the feed in price for systems at and below 10 kW ranged from 43 to 49 cents. In the following years, the price has been continuously reviewed and amended every several months. The price in January 2016 ranged between 12.03 and 5.73 cents for systems at or below 10 kW. In Australia, there is two forms of support for adopters of residential solar PV systems, firstly at the federal level there is an upfront grant to reduce the capital cost of a residential solar PV system. Secondly form of funding is a solar FiT, the price of the FiT is managed at a state and territory level. In 2010, the FiT price across the Australian states and territories ranged from 20 to 66 cents (Nelson et al., 2011; Zahedi, 2010).

It is important to note that the definition of micro-generation can vary from country to country, but generally refers to small-scale local energy generation[17]. To the empirical ends of this study, we define residential solar PV having a max rated capacity up to 10 kW (Balta-Ozkan, Yildirim, & Connor, 2015; CER, 2016; Z. Li, Boyle, & Reynolds, 2011). The solar PV data for the UK were obtained from the statistics portal on the UK's government website. The solar PV data for Ireland were collected from ESB Networks and for Australia they were sourced from the Australian Photovoltaic Institute. For each country, the variable solar PV uptake was constructed which represents the average capacity installed per system per month and is reported as the average rated capacity (kilowatt/kW) installed per month. Data on the cost of solar PV installations are collected from Open PV Project published by the National Renewable Energy Laboratory and is reported as the average euro per kW. The residential electricity demand variable for Ireland is obtained from the Commission of Energy Regulation (CER), the statistics portal on the UK's government website for the UK and the statistics portal on the

[17] In Ireland ESB Networks classify a generator as 'micro' when the electricity generating system has a maximum rated capacity of 11 kW while in the U.K it's any generating system with a capacity below 50 kW. In Australia the definition for micro generators, is a solar PV system with a rated capacity of no more than 100 kW.

website Office of the Chief Economist for Australia. The variable measurement is gigawatts hour (GWh). The Coal Share variable for Ireland is collected from the Central Statistics Office, for the UK from the UK's government website and for Australia the statistics portal on the website office of the Chief Economist. The variable is reported as the monthly percentage of coal used in electricity production (%). The monthly wholesale price of electricity for Australia Energy Market Operator and for Ireland it was sourced from the Single Electricity Market Operator. The monthly UK wholesale electricity price was sourced from Thomson Reuters DataStream. The monthly wholesale price of electricity is reported in megawatt hour (€/MWh). Atmospheric variables, average temperature and sunlight hours, all are sourced from Met Éireann for Ireland, the statistics portal on the UK's government website and the Met Office for the UK, and the Bureau of Meteorology for Australia. The Scheme variable is a dummy variable, when the Scheme variable equals 1 represents when a federal government micro-generation support scheme is in operation, 0 represents otherwise. Information to whether a scheme is in operation is sourced from each countries' department of the environment website. This study uses data at a monthly frequency, however, some of the variables are only reported on a bi-annually or annually frequency basis by their sources. A linear extrapolation[18] is applied in that case to acquire monthly values. Both Appendix V and VI have a table detailing each variables data source and description.

[18] We use "Ipolate" command with epolate option in Stata to conduct the linear extrapolation. We have sufficient historical data points to do the extra-polation.

3.4.2. Positive Feedback Cycle Model

The positive feedback cycle is centred on the idea that increasing electricity prices is a key variable in the decision-making process for solar PV adoption. Growing adoption levels of residential solar PV systems onto the residential electricity market will decrease residential electricity demand and this in turn will lead to increasing residential electricity prices. According to Kaufmann & Vaid (2016), empirical studies (Ballester & Furio, 2015; Gelabert, Labandeira, & Linares, 2011; Nicholson, Rogers, & Porter, 2010) examining the effects of renewable energy systems on electricity price have used some variants of the following equation (3.1) as a starting point:

$$P_t = \propto + \beta_1 Load_t + \beta_2 RE_t + \beta_3 NRE_t + \beta_4 PFF_t + \beta_5 Dum_t + \varepsilon_t \tag{3.1}$$

where P is the price of electricity at time period t, Load is the electricity load, RE is the quantity of electricity from renewable sources, NRE denotes electricity from traditional energy sources, PFF is the price of fossil fuels, Dum are dummy variables that represents time periods (year, month, etc.) and ε is the error term. Using equation (3.1) as a starting point, we can transform it into multiple equations, to treat simultaneously residential solar PV uptakes, residential electricity prices and residential electricity demand as endogenous[19]. A simultaneous equations model is used when one or more of the explanatory variables is jointly determined with the

[19] These are jointly dependent variables; or, those determined within the system of equations.

dependent variable. Given the nature of the positive feedback cycle, a simultaneous equation model would be best suited to model this relationship and to ensure the treatment of any endogeneity bias. The three equations that comprise our simultaneous equations model are shown below and explained in the following paragraphs:

$$lnP_t = \alpha_0 + \ \alpha_1 lnPElec_t + \alpha_2 Scheme_t + \alpha_3 lnSunlight_t + \alpha_4 lnAvrCostPV_t + D_y^{year} + D_m^{month} + \varepsilon_{1,t} \tag{3.2}$$

$$lnPElec_t = \beta_0 + \ \beta_1 CoalShare_t + \beta_2 lnPElec_{t-1} + \beta_3 lnPV_t^* + \beta_4 lnWPElec_t + D_y^{year} + D_m^{month} + \varepsilon_{2,t} \tag{3.3}$$

$$lnED_t = \theta_0 + \ \theta_1 lnPElec_t^* + \theta_2 lnPV_t^* + \theta_3 lnTemp_t + \theta_3 lnTemp_t + \theta_4 lnInc_t + D_y^{year} + D_m^{month} + \varepsilon_{3,t} \tag{3.4}$$

We start our simultaneous equation model of the positive feedback cycle with the residential solar PV uptake equation (3.2), which represents the residential electricity consumers' decision to adopt a solar PV system. Modelling the motivation of a consumers decision to adopt solar PV has been explored in studies such as Balcombe, Rigby & Azapagica (2013), Balta-Ozkan, Yildirim & Connor (2015) and Zhang, Song & Hamori (2011) where they concluded that the decision making process of solar PV is attributed to a number of factors, including environmental, financial and social interactions. The dependent variable in equation (3.2) is the residential solar PV uptake (PV) it is a function of the residential electricity price (PElec) for an average house and it is expected that when residential electricity prices increase, the incentive for people to adopt residential solar PV also increases as solar PV becomes financially feasible. The next variable included is the average monthly sun light hours[20] (Sunlight), as it is an important climatic variable in the decision-making process of adopting solar PV. It's expected that areas with a higher number of sunlight hours would have a higher penetration levels of residential solar PV. The monthly average cost of solar PV (AvrCostPV) is included and it is expected that falling costs of residential solar PV systems would result in a greater number of installations. The variable government support scheme (Scheme) is a dummy variable representing whether there is a support scheme in place for solar PV in each month. It's expected that when support schemes are in place, installation rates will be higher. Moreover, time dummies for both the Month and Year are included (Filippini, 2011).

The next part of the positive feedback cycle to be modelled is how this increase in the residential solar PV systems on the grid affects the residential electricity pricing. This is represented by the residential electricity price equation (3.3) in the simultaneous equations model. Residential electricity price is a function of the type of fuel used in the production of electricity (Coal Share), the previous time periods residential electricity price, the predicted residential solar PV uptake, the wholesale price of electricity (WPElec) and time dummy variables for the Month and Year. It is expected that increasing levels of solar PV uptake will increase residential electricity prices, due to an increasing number of customers' with solar PV systems demanding less electricity from the grid resulting in utilities charging more to remaining customers to meet its revenue requirements (ISO, 2016; Lijesen, 2007). The final part of the positive feedback cycle to be modelled is how the resulting increasing penetration

[20] Proxy for Solar Radiation

of residential solar PV and rising residential electricity prices will lead to a decrease in residential electricity demand. The residential electricity demand equation (3.4) is the last equation in the simultaneous equations model. The residential electricity demand (ED) is a function of the predicted residential electricity price, the predicted residential solar PV uptake, the average monthly temperature and the average monthly income (Fan & Hyndman, 2011; Holtedahl & Joutz, 2004; Krishnamurthy & Kristrom, 2015). A priori, higher predicted value for residential electricity price (PElec) will lead to a fall in residential electricity demand. A similar result is expected with an increasing residential solar PV uptake. The average monthly temperature (Temp) is expected to have a negative relationship with residential electricity demand, i.e. as the outside temperature starts to rise, the usage of clothes dryers and electric heating will decrease. The variable average monthly wage is included in the residential electricity demand equation. The relationship with demand could be either positive or negative, as a person's income (Inc) increases they may buy more home appliances and therefore demand more electricity. However, a higher income could allow a person to purchase higher energy efficient appliances, which would demand less electricity. Time dummies for the Month and Year are also included. Both Appendix VI and VII summarize the description of the variables used in the analysis, as well as the hypotheses on the sign of the coefficients for each equation.

Due to endogeneity, the residential electricity price equation is identified using instrumental variables of the percentage of coal used in electricity production (CoalShare) and the lagged electricity price ($PElec_{t-1}$). Coal is often used as a fuel in baseload generation due to its lower price when compared to other fuels. An increase in the percentage of coal used in generation reduces electricity bills, which would lead to an increase in electricity demand. Coal Share in the monthly generation mix can only affect electricity demand through the price of electricity, which is only determined by a shift in electricity supply. We expect to find a strong positive relationship between electricity price and the monthly lagged electricity price since the residential rates are fairly stable over time (Eryilmaz & Sergici, 2016). The model satisfies the order condition for identification, as the number of excluded exogenous variables from each equation (3.2 – 3.4) is at least as large as the number of right-hand side endogenous variables. The variables[21] are expressed in log-log (ln), so that the results can easily be expressed in percentage changes that identify elasticities.

Simultaneous equation models may be biased if estimated with ordinary least method due to the inherent correlation among the error terms and the explanatory variables in the specified equations. In this study, a three stage least square (3SLS) method (Eryilmaz & Sergici, 2016; Jeon & Moffett, 2010; Zellner & Theil, 1962) is employed. The assumptions associated with the 3SLS approach are: the error term is not correlated with the exogenous variables in the model Cov (εi,t,c|Xi,t,c)=0, where X represents the exogenous variables on the right-hand side of each of equation, i represents the number of equations (i=1,2,3), and t stands for each time period, considering the cross-equation correlation of error. The instrumental variables Z are correlated with the regressors' E [z′x] ≠ 0, while Z is also uncorrelated with the error term ε, E [z′ ε]=0 and Z is not a direct cause of the dependent variable y, cov[y, z | x]=0 (Wooldridge, 2010).

[21] PV, PElec, Sunlight, AvrCostPV, $PElec_{t-1}$, WPElec, Temp, Inc.

3.4.3. Descriptive Statistics

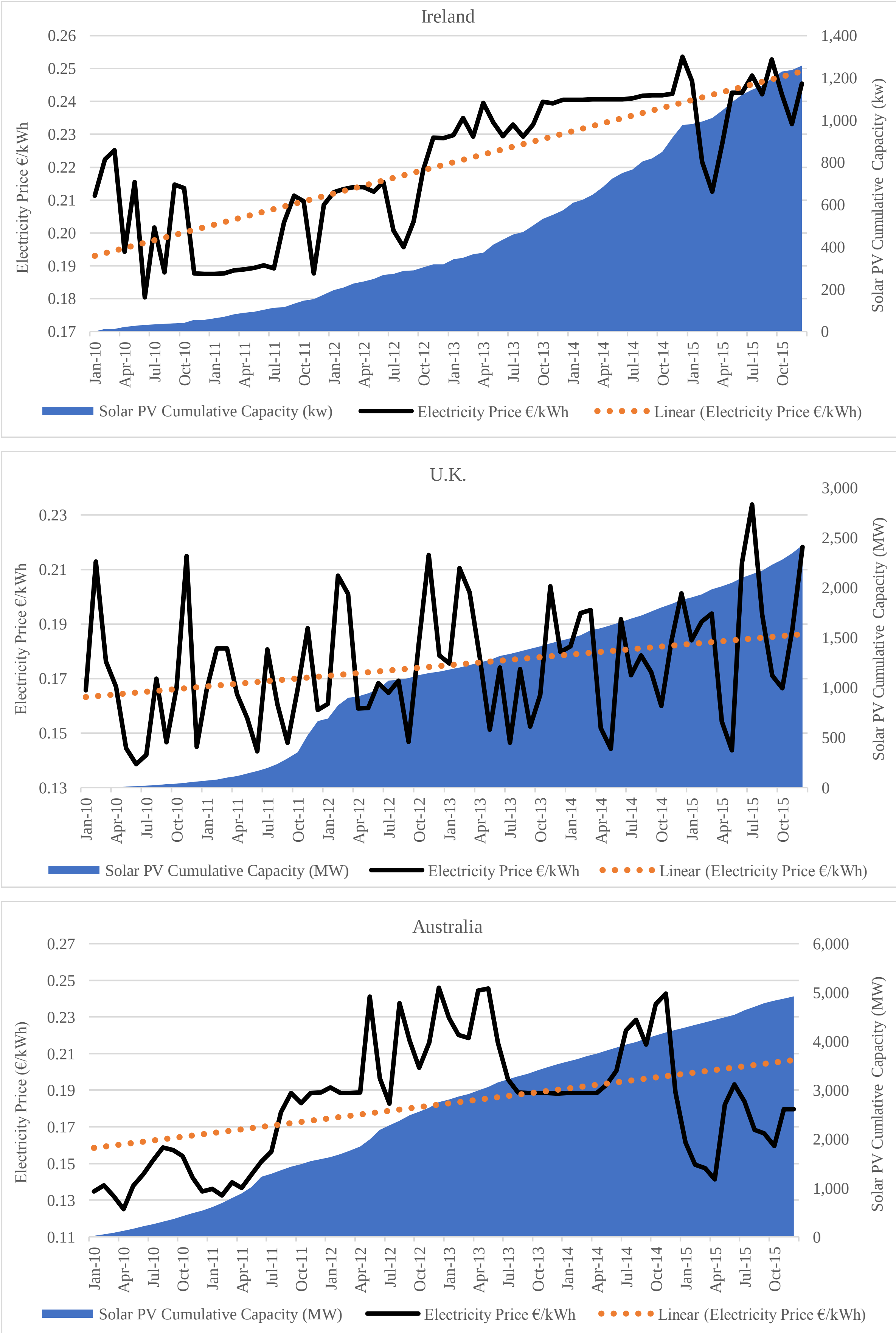
The three main variables of interest in our positive feedback cycle model are: residential solar PV uptake, residential electricity price and residential electricity demand. The following section highlights the associated descriptive statistics.

Table 3.1: Descriptive Statistics

Variable		**Mean**	**Std. Dev.**
Monthly residential solar PV installations	Panel	10,240	11,522
Average Residential Electricity Prices 2010 (€/kWh)	Panel	0.17	0.03
Average Residential Electricity Prices 2015 (€/kWh)	Panel	0.2	0.04
Average Residential Electricity Demand 2010 (GWh)	Panel	5,730	3,473
Average Residential Electricity Demand 2015 (GWh)	Panel	5,326	2,970

The average monthly residential solar PV installations over the period examined was 10,240. In terms of added electrical capacity to these three nations grids over the five-year period examined, Australia was the highest in terms of installed residential solar PV capacity with 4921 MW, followed by the UK at 2425MW and Ireland at 1.3 MW. The next variable of interest in the positive feedback cycle is residential electricity price. The average residential electricity price for the panel in 2010 was 0.17 €/kW h by 2015 the average electricity price had increased to 0.20 €/kWh. A similar price trend is seen in the individual countries with an increase in residential electricity over the time-period examined (Figure 3.1). The final variable of interest is the residential electricity demand, the demand for electricity decrease from an average of 5730 GWh in 2010 to 5326 GWh in 2015. The yearly demand figure for electricity is lower in all three countries for 2015 when compared to 2010. After analysing the summary statistics of the three variables of major interest, we can infer the positive feedback cycle or loop in existence across all countries, a rising cumulative capacity in terms of residential solar PV systems over the period, while the residential electricity prices have increased from 2010 to 2015 and residential electricity demand has decreased over the same period (Table 3.1).

Figure 3.1: Electricity price, linear electricity trend line & solar PV cumulative capacity.



3.5. Empirical Findings

Firstly, unit root tests are conducted to confirm whether the variables are stationary are not. The Im, Pesaran & Shin (2003) and Levin, Lin & Chu (2002) panel unit root tests were employed. The null hypothesis of the test is that each series in the panel dataset contains a unit root while alternatively, at least one of the individual series in the panel is stationary (no unit root). Hence, given the unit root results (Appendix VIII), we proceed by testing for the existence of cointegration. Table 3.2 presents the Pedroni cointegration statistics for the model, the null hypothesis of no cointegration is rejected therefore the pooled regression is estimated and the results are summarised in Table 3.3.

Table 3.2: Panel Cointegration Test Statistics.

	Equation 3.2		Equation 3.3	
	Panel	Group	Panel	Group
V-Stat	0.344		2.171**	
ρ-Stat	-7.836***	-9.288***	-8.477***	-9.569***
PP-Stat	-8.651***	-11.054***	-9.671***	-11.62***
ADF-Stat	-8.646***	-11.683***	-9.58***	-11.645***
	Equation 3.4			
	Panel	Group		
V-Stat	4.929***			
ρ-Stat	-6.042***	-4.972***		
PP-Stat	-7.728***	-7.094***		
ADF-Stat	-7.737***	-5.438***		

Note: V, non-parametric variance ratio statistic; ρ, non-parametric test statistic analogous to the Philips and Perron (PP) rho statistic; PP, non-parametric statistic analogous to the PP t-statistic; and ADF, parametric statistic analogous to the augmented Dickey-Fuller statistic. All statistics distributed as standard normal as T and N grow large. Null hypothesis: no cointegration. ***, **, * represent 1%, 5% and 10% significant levels respectively.

The key results from the simultaneous equation model are as follows, firstly the solar uptake equation (3.2) show that a 1% increase residential electricity price will significantly increase residential solar PV uptake by 0.55%. This result supports the theory of the positive feedback cycle, according to which, higher electricity prices lead to an increase in the installations of residential solar PV systems (see column 2 in Table 3.3 below).

Secondly, results (see column 3 in Table 3.3) from the residential electricity price equation (3.3) show that the other key variable in the positive feedback cycle, residential solar PV uptake, significantly affects the price of residential electricity with an increase of 0.41% in price given a 1% in solar PV uptake.

Finally, results from the residential electricity demand equation (3.4) show that the key variables, solar PV uptake and residential price of electricity, in the positive feedback cycle have a significant effect on residential electricity demand (see column 4 in Table 3.3). Results indicate that a 1% increase in the residential electricity price, will lead to a decrease in residential electricity demand by 3.55%. This result indicates significant electricity demand price elasticity and is in line with findings from Narayan, Smyth & Prasad (2007). In terms of Solar PV, we find that a 1% increase in residential solar PV uptake will decrease the amount of residential electricity demand by the residential sector by 1.45%.

Table 3.3: Three Least Squares Regression Results

Independent Variables	Equation 3.2 Solar PV Uptake Coef.	P-Value	Equation 3.3 Residential Electricity Price Coef.	P-Value	Equation 3.4 Residential Electricity Demand Coef.	P-Value
Price of Electricity	0.55***	0.000	–		−3.55***	0.000
Scheme	0.04	0.535	–		–	
Average Cost of Solar PV	−0.11	0.398	–		–	
Average Sunlight	0.06**	0.018	–		–	
Coal Share	–		−0.002***	0.000	–	
Lagged Price of Electricity	–		0.45***	0.000	–	
Solar PV Uptake	–		0.41***	0.001	−1.45**	0.040
Wholesale Price of Electricity	–		−0.01	0.708	–	
Temperature	–		–		−0.31**	0.003
Income	–		–		– 0.18	0.316
2011	0.24***	0.000	−0.07	0.122	0.51**	0.018
2012	0.20***	0.001	−0.01*	0.863	1.06***	0.000
2013	0.33***	0.000	−0.06	0.378	1.34***	0.000
2014	0.33***	0.000	−0.07	0.309	1.41***	0.000
2015	0.32***	0.000	−0.09	0.153	1.15***	0.000
February	0.07	0.304	0.03	0.393	0.26	0.125
March	0.01	0.927	0.01	0.830	0.2	0.229
April	0.07	0.33	−0.06*	0.078	0.06	0.752
May	0.02	0.734	−0.01	0.830	0.02	0.886
June	0.07	0.296	−0.02	0.599	0.17	0.326
July	−0.05	0.448	0.03	0.402	0.04	0.820
August	−0.01	0.895	0.02	0.513	0.22	0.210
September	0.07	0.285	−0.03	0.335	0.16	0.346
October	0.06	0.344	0.01	0.848	0.30*	0.080
November	0.07	0.295	0.04	0.237	0.50***	0.004
December	0.15**	0.025	−0.02	0.561	0.54***	0.005
Constant	1.68***	0.000	−1.20***	0.000	2.54	0.124
R2	0.49		0.7		0.45	

Note: Values in parentheses are the estimated P-values. * Significant at 10% level, ** Significant at 5% level, *** Significant at 1% level.

3.6. Conclusion

Residential solar PV systems, as well as other forms of micro renewable energy systems (micro-RES), have the potential to significantly contribute towards a country's climate change goals; however, they could also be a disruptive innovation to the traditional electrical industry. Currently, the adopters of micro-RES still rely on the national electricity grid for when their system stops producing electricity due to the lack of ideal atmospheric conditions. However, with residential battery storage options for electricity always improving and reducing in price, micro-RES and the traditional electricity industry could be akin to mobile telephones and the fixed land lines industry.

The gaining popularity of solar PV systems in the residential electricity market is not only due to the falling cost of systems, but also could be attributed to the positive feedback cycle. This is where residential electricity customers reduce their net purchases from the electric grid by adopting solar PV systems; however, the costs incurred by the electrical utility companies do not decrease proportionally to the decrease in electricity consumed. This happens because the electrical utilities must pay for transmission and distribution infrastructure expenses and such fixed costs are recovered over decades. Electrical utilities will have to raise their price of electricity to make up for the loss and thus incentivise the remaining electricity customers to adopt solar PV systems.

This study extended this line of research by examining the residential electricity markets in three countries: the UK, Ireland and Australia, to provide evidence of any positive feedback cycle. The empirical analysis used a simultaneous equation model to illustrate the interactions of residential solar PV uptake, residential electricity prices and demand, and to provide evidence of any positive feedback cycle in the market. To this end, a three stage least squares regression model was employed in relevance to the pooled panel data set of Australia, Ireland and the UK. The findings documented: a positive relationship between electricity prices and solar PV uptake, a positive relationship between solar PV uptake and electricity price, and finally, a negative relationship between electricity prices and electricity demand. Moreover, a negative relationship was found between solar PV and electricity demand. In other words, the findings indicated that a positive feedback cycle was in effect, as the adoption of residential solar PV systems was leading to a positive feedback cycle via increasing residential electricity prices and decreasing residential electricity demand.

The evidence of the positive feedback cycle in an electricity market could raise issues for electricity utilities, transmission system operators, and government energy departments, as some have suggested that it would result in a utility 'death spiral'. In our analysis, it seems that Australia and the UK would be more at risk due to the larger cumulative capacity of residential solar PV systems added to the grid in a short period of time. To tackle this issue, there needs to be a restructuring of current renewable energy policies for current and future adopters of micro-RES. If environmental goals are to be achieved, then stakeholders in the electricity market will have to support the adoption of solar PV in a sustainable way, while not punishing non-adopters with higher electricity rates.

Chapter 4 - Paper 3

Fuel Poverty Measurements in Residential America. Who are the Most Vulnerable?

4.1. Abstract

There is debate about which measurement approach to use when attempting to quantify fuel poverty. We employ a new multidimensional measurement to gauge the extent of fuel poverty in the US, where research in this country is less prevalent as compared to European countries. This measurement addresses some of the shortcomings of the other approaches, for the three coldest regions in the US, we find that 12% (New England), 12% (East North Central) & 9% (West North Central) of households are fuel poor. The odds of being fuel poor are higher; if a household is occupied by renters, is non-white, or has elderly people and children, for all regions. These results have useful implications for policy formation and targeting appropriate supports to address this issue.

4.2. Introduction

There are three different but related perspectives that make fuel poverty a distinct and serious problem: poverty and its reduction; health and well-being; climate change and the reduction of carbon emissions (Hills, 2011). Ever since Boardman's (1991) founding work on the concepts of fuel poverty and/or energy poverty, it has become a focus of public policy concern and the academic literature. However, there has been confusion around which term to use and whether there is a distinction between them. Li et al. (2014) found some overlap between the two terms after reviewing the literature but generally, "fuel poverty mostly occurs in relatively wealthy countries with cold climates whereas energy poverty occurs across all climates but mostly in poor countries" (K. Li et al., 2014, p. 480)[22].

Another concern that arises when investigating the topic of fuel poverty is should it be treated as a separate issue from income poverty, as it would stand to reason that households that are poor will be fuel poor? Watson & Maitre (2015) when investigating fuel poverty in Ireland argued that fuel poverty shouldn't be regarded as a distinct dimension of deprivation. While Charlier & Kahouli (2019) found when investigating fuel poverty in French households, that income poverty does not necessarily mean fuel poverty. Bosch, Palència, Malmusi, Marí-Dell'Olmo, & Borrell (2019), note that "fuel poverty is different from income poverty because both the causes and the policies to tackle these problems are distinct" (Bosch et al., 2019, p. 1379). Kerr, Gillard & Middlemiss (2019) note that fuel poverty is distinct from fuel poverty when related the three casual factors; low income households, low energy performance homes and high energy prices (Legendre & Ricci, 2015).

[22] For further detailed explanation regarding the definition of energy poverty and fuel poverty see Appendix IX.

As Moore (2012) notes, "the definition of fuel poverty is important for policy formulation; for determining the scale and nature of the problem, targeting a strategy and monitoring progress" (Moore, 2012, p. 19). There is still debate as to which approach to use when attempting to quantify fuel poverty; expenditure approach or consensual approach. A possible solution to this is to use a multidimensional framework that incorporates multiple attributes of poverty and energy efficiency. Additionally, Thomson et al., (2017) note that much of the academic and policy frameworks addressing fuel poverty are historically centred around the UK and Ireland (Healy & Clinch, 2002; Liddell, Morris, McKenzie, & Rae, 2012), with a growing research field in other European states (Welsch & Biermann, 2017). Currently, there is still a dearth of studies[23] on fuel poverty in the US.

This chapter addresses some of these issues and makes several contributions. Firstly, we focus on three regions[24] in the US that are most likely to be impacted by the adverse effects of fuel poverty as they are the highest in terms of heating degree days (HDD). Secondly, we compare some of the more traditional fuel poverty measurement, the 10% ratio, with our multidimensional measurement approach, highlighting how it overcomes some of the drawbacks of the traditional measurement. Finally, to determine the probability of a household being fuel poor, we use a logistic model to examine the major socioeconomic and dwelling characteristics of households that affect the odds of being fuel poor, using data from the 2017 American Household Survey (AHS).

[23] To our knowledge – only two studies have focused on the USA. Teller-Elsberg, Sovacool, Smith & Laine Teller-Elsberg, J., Sovacool, B., Smith, T., & Laine, E. (2016). Fuel poverty, excess winter deaths, and energy costs in Vermont: Burdensome for whom? *Energy Policy, 90*, 81-91. examined fuel poverty in the State of Vermont & Mohr Mohr, T. M. (2018). Fuel poverty in the US: Evidence using the 2009 Residential Energy Consumption Survey. *Energy Economics, 74*, 360-369. examined fuel poverty in the Northeastern States and South Atlantic States
[24] West North Central, East North Central (previously not studied) and New England.

The remainder of the chapter is structured as follows. Section 4.3 provides a critical review of the approaches used to measure fuel poverty in the literature. Section 4.4, Data & Methodology, presents the dimensions that define the multidimensional measurement and the logistic model used to explore the main drivers of fuel poverty for households. Section 4.5 discusses the results of a logistic model. Section 4.6 concludes and provides some policy recommendations as well as areas for future research.

4.3. Literature on Fuel Poverty Measurements

There are several approaches available for the measurement of fuel poverty which can be divided into three categories; the expenditure, the consensual and the multidimensional approaches. The following section details some of the advantages and disadvantages associated with the expenditure and consensual approach and how the literature suggests that the multidimensional approach can overcome these shortcomings.

4.3.1. Expenditure

The most widely used definition for fuel poverty under the expenditure approach is the 10% ratio indicator which defines households as fuel poor if their required fuel expenditure on energy services exceeds 10% of their income. This popular definition is considered to be reasonable based on its characteristics of straight forwardness, its objectivity and its responsiveness to major drivers of fuel poverty (Hills, 2011). The 10% ratio indicator was used by Teller-Elsber et al., (2016) in one of the two fuel poverty studies on American households to assess the extent and severity of fuel poverty in the American State of Vermont.

However recent literature is beginning question whether this measurement of fuel poverty is correct. Legendre & Ricci (2015) note a number of disadvantages with the use of the “10% ratio approach” to measure fuel poverty. Firstly, using a ratio to determine the extent of fuel poverty does not include a cut off for households with high income. As some wealthier households can overconsume their energy needs, leading them to be included in fuel poverty under this measure. The second issue with this indicator as Hills (2011) points out, is the use of income before deducting housing costs. The indicator uses a ‘full income’ definition, which counts all sources of income the household members receive. It is calculated net of income; it is not adjusted for housing costs or the size and composition of the household. The third issue is the use of actual domestic fuel costs instead of required domestic fuel costs. Actual fuel expenditure is easier to calculate, but is widely regarded as a poor indication of fuel poverty, especially as low income households often spend significantly less on fuel than would be required to maintain a warm home (Liddell et al., 2012; Moore, 2012; Thomson, Bouzarovski, et al., 2017).

In the Hills report (2011), the author proposes several other options for measuring fuel poverty. These options include: a fuel poverty ratio with income measured after housing costs; a fuel poverty ratio with a dynamic threshold based on twice median spending; using the fuel poverty ratio to measure a fuel poverty gap; after fuel costs poverty; low income and low SAP[25] rating

[25] Standard Assessment Procedure

overlap. Mohr (2018) which is the other American fuel poverty study, uses the twice the median proportion of income relative to others in their state[26] when assessing fuel poverty in two regions in Northeast states and South Atlantic states in America.

While all of these options have their advantages and disadvantages, ultimately Hills (2011) proposes using a new indicator to determine the extent of fuel poverty: the Low Income-High Costs (LIHC) indicator. It defines a household as fuel poor if they; firstly, have high energy costs above the national median[27] and secondly, low household income, which is defined as income below the 60% median poverty line[28]. Okushima (2017) notes that the LIHC indicator is not without its criticisms as well. Walker, Liddell, McKenzie, Morris & Lagdon (2014), point out the design of the relative energy costs component of the LIHC indicator for its failure to provide an accurate picture of the extent to which households can or cannot afford their energy costs. Heindl and Schuessler (2015) note that the LIHC indicator has counter-intuitive dynamic properties, which may cause false policy implications.

4.3.2. Consensual

An alternative to expenditure approach indicators are consensual approach indicators based on the research of Townsend (1979), Mack & Lansley (1985) and Gordon et al., (2000). The Hills Report (2011, p. 128) notes that the consensual approach "works on the basis of an objective assessment of energy need". Under this approach, a household is fuel poor if they reported

[26] Also uses the 10% ratio approach measurement.
[27] adjusted for household composition
[28] adjusted for household size and composition after energy costs are deducted

they could not stay reasonably warm for a variety of statements. For instance in studies by Healy & Clinch (2002), Thomson & Snell (2013) and Aristondo & Onaindia (2018) using a consensual approach, households were deemed poor; if they were in arrears on utility bills, had an absence of central heating, had an inability to keep a household warm and if there was a presence of a leaking roof, damp walls or rotten windows.

Criticisms of the consensual approach relate to the issue of subjectivity of the indicators due to their error of exclusion. When collecting the data, the household representative may report that they feel that the home is adequately warm however other members in the household may not feel the same. This can result in households being under reported as fuel poor (Thomson, Snell, et al., 2017) .

4.3.3. Multidimensional

Fizaine & Kahouli (2019, p. 1101) note, “how the use of one indicator over another can lead to the exclusion of some part of the affected population from being targeted by public policy measures devoted to fighting the problem”. To overcome the short comings associated with the expenditure and consensual approaches, recent literature uses a multidimensional framework to assess fuel poverty. Fuel poverty is multidimensional in nature as it is a result of a combination of factors; living in a low energy efficient house and being unable to heat it to a comfortable level due to a lack of finance (Pereira et al., 2011). The growth in multidimensional fuel poverty literature is a result of what Alkire & Foster (2011, p. 476) note as “unprecedented availability of relevant data”. Countries that have been studied using a multidimensional framework include Spain (Aristondo & Onaindia, 2018), India (Sadath & Acharya, 2017), Japan (Okushima, 2017) and African countries (Nussbaumer, Bazilian, & Modi, 2012).

4.4. Data & Methodology

4.4.1. Multidimensional Measurement

The following section explains our multidimensional measurement proposed by Okushima (2017) and Alkire & Foster (2011). Assuming a population with *n* households ($i = 1,\ldots,n$), and $d \geq 2$ dimensions of poverty ($j = 1, \ldots, d$). Subsequently, it can define the matrix of achievements in a multidimensional setting:

$$Y = [y_{ij}]_{n \times d'} \quad (4.1)$$

where y_{ij} is the achievement of household *i* in dimension *j*. A multidimensional poverty approach considers poverty as a shortfall from a threshold (cut-off) for each dimension. Let z_j denote a threshold of dimension *j*, and define dimension *j*'s specific poverty, that is, the deprivation of dimension *j*, of household *i* if $y_{ij} < z_j$. Following Alkire & Foster (2011), it can construct the 0 - 1 matrix of dimensional poverty, $\mathbf{g}_{ij} = [g_{ij}]_{nxd}$, whose elements are defined by $g_{ij} = 1$ when $y_{ij} < z_j$ and $g_{ij} = 0$ otherwise. In other words, $g_{ij} = 1$ means that household *i* is poor in dimension *j*, and $g_{ij} = 0$ and vice-versa. Subsequently, $\mathbf{g}_i$ means household *i*'s dimensional poverty (deprivation) vector and $c_i = |\mathbf{g}_i|$ counts the number of dimensional poverty of household *i*, which shows how many dimensions household *i* is poor in.

Next, we define the dimensions that can specify the condition of fuel poverty in developed countries. The first dimension, y_{i1}, is the share of energy cost to income in each household, age of housing is the second dimension represented by y_{i2} and the third dimension is income represented by y_{i3}. Consequently, after selecting dimensions, the threshold z_j for each dimension needs to be defined. In this study, the threshold for "energy" is defined as $z_1 = 0:1$; the threshold for "energy efficiency of housing", z_2, is whether their houses are built after 1970 or not[29]; the threshold for "income", z_3, is the boundary income between the third decile and the fourth decile.

Following the methodology used by Okushima (2017), an identification function $\rho(y_{ij};z_j)$ is used, which shows a households ***i***'s achievements, y_{ij} , and thresholds, z_j , to an indicator variable in such a way that $\rho(y_{ij};z_j) =1$ when household ***i*** is fuel poor. The intersection approach is used where household ***i*** is poor if and only if it's poor in all three dimensions (Alkire & Foster, 2011). Figure 4.1, below illustrates Okushima (2017) concept of multidimensional fuel poverty.

29 Reasons discussed in following Section 4.4.4.

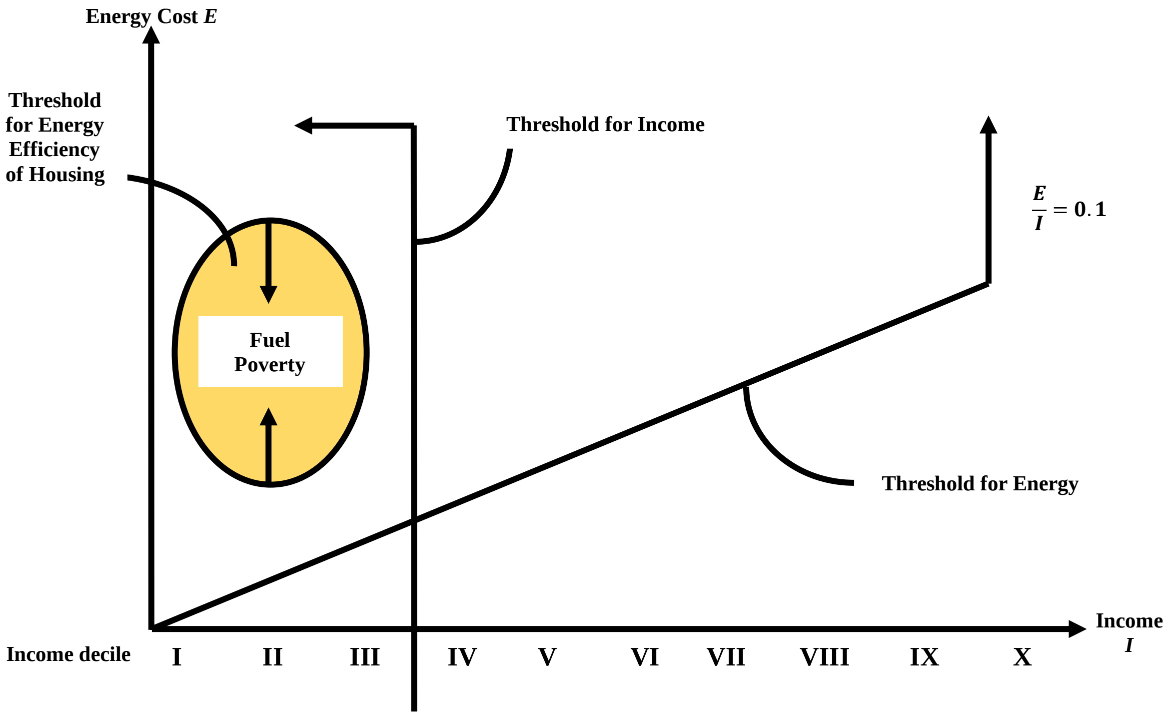


Figure 4.1: Concept of Multidimensional Fuel Poverty, Okushima (2017)

4.4.2. Data

To complete this papers' objectives, the 2017 American Household Survey (AHS) dataset was employed. The AHS was first conducted in 1973 with a sample size of 60,000 housing units. The survey was on an annual basis from 1973 to 1981 however due to budget constraints it became biennial. The AHS provides information on a wide range of core housing subjects, including size and composition of the nation's housing inventory, fuel usage, physical condition of housing units, characteristics of occupants, home improvements and other housing costs.

This study will focus on the following regions in America; West North Central (WNC), East North Central (ENC) and New England (NE). The region of WNC contains the following states; Iowa, Kanas, Minnesota, Missouri, Nebraska, North Dakota and South Dakota. ENC contains; Illinois, Indiana, Michigan, Ohio and Wisconsin. Lastly NE contains; Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. These regions where chosen as according to Li et al. (2014) fuel poverty is associated with cold climates and these regions are the coldest in the USA in terms of heating degree days (HDD)[30] and are like the climate of Northern European Countries in the literature (Figure 4.2).

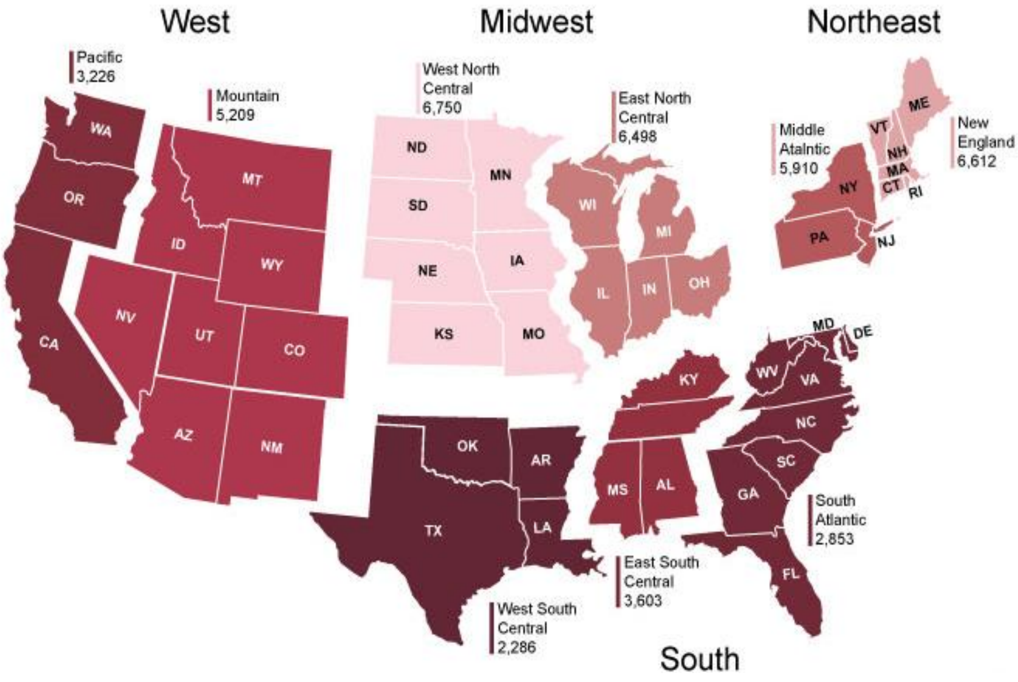


Figure 4.2: Heating degree days by census region. Source: U.S Energy Information Administration (2018)

30 Heating Degree Days are the measure of how cold the temperature was on a given day or during a period of days. For example, a day with a mean temperature of 40 degrees Fahrenheit (4.4oC) has 25HDD. Two such cold days in a row have a total of 50HDD for the two-day period.

4.4.3. Fuel Poverty Model

To explore the household factors that are likely to result in fuel poverty using our multidimensional approach, a logit model is developed. A household is only fuel poor under our multidimensional approach measurement if; they are equal or greater than 10% under the 10% ratio for fuel poverty; the household unit was constructed before 1970; and the household is in the first three deciles of household income. Letting Y_i represent Multidimensional Fuel Poverty with a binary response. We define Y_i equal to 1 when a household is deemed fuel poor and 0 when it is not. The outcome depends on explanatory variables, the following model is estimated for each of the regions New England (NE), East North Central (ENC) and West North Central (WNC) in our study;

$$Y_i = \beta_0 + \sum \beta_i X_i + \varepsilon_i \tag{4.2}$$

where X_i is the vector of covariates and ε_i is the error term. The X_i variables in our model were selected on previous fuel poverty literature and include; Tenure, Education, Heating System, Type of House, Kids, Elderly, Solar, Cooking Fuel, Housing Unit Structure and Race. Descriptions and descriptive statistics of the variables used in our models can be found in Appendix X-XIII.

4.4.4. Descriptive Statistics

The first dimension is 'energy', z_1, which is calculated using the 10% ratio for fuel poverty. To set the threshold for the second dimension 'Energy Efficient of Housing', z_2, we categorized households living in a housing unit built before 1970[31] as energy inefficient and therefore fuel poor in our multidimensional measurement approach. The paper follows the methodology of Okushima (2017), where their dimension for energy efficiency of housing was whether the house was built after 1980 or not for Japan. Their reasoning was that in 1980, Japan introduced energy conversion standards for housing. In the USA, energy building codes as ACEEE (2008) and Horowitz (2007) point out differ in both their stringency and enforcement across states and even counties. We chose 1970, as in Aroonruengsawat, Auffhammer & Sanstad (2012) the empirical measure they use to identify the effect of building codes in USA, are buildings constructed since 1970 for a similar reason as Okushima (2017). The last dimension in our measurement is 'income', z_3, households below the boundary of the third and fourth decile are classified as fuel poor.

[31] "yrbuilt" was the variable used in AHS to question the year unit was built. The respondent selected from a band of years Bands include 1919 (1919 or earlier), 1920 (1920-1929), 1930 (1930-1939), 1940 (1940-1949), 1950 (1950-1959), 1960 (1960-1969), 1970 (1970-1979), 1980 (1980-1989), 1990 (1990-1999), 2000 (2000-2009) & 2010 (2010-2017).

Figure 4.3: 10% Ratio and Multidimensional fuel poverty measurements by regions. (Black broken line represents the boundary between 3rd & 4th income deciles, the income dimension)

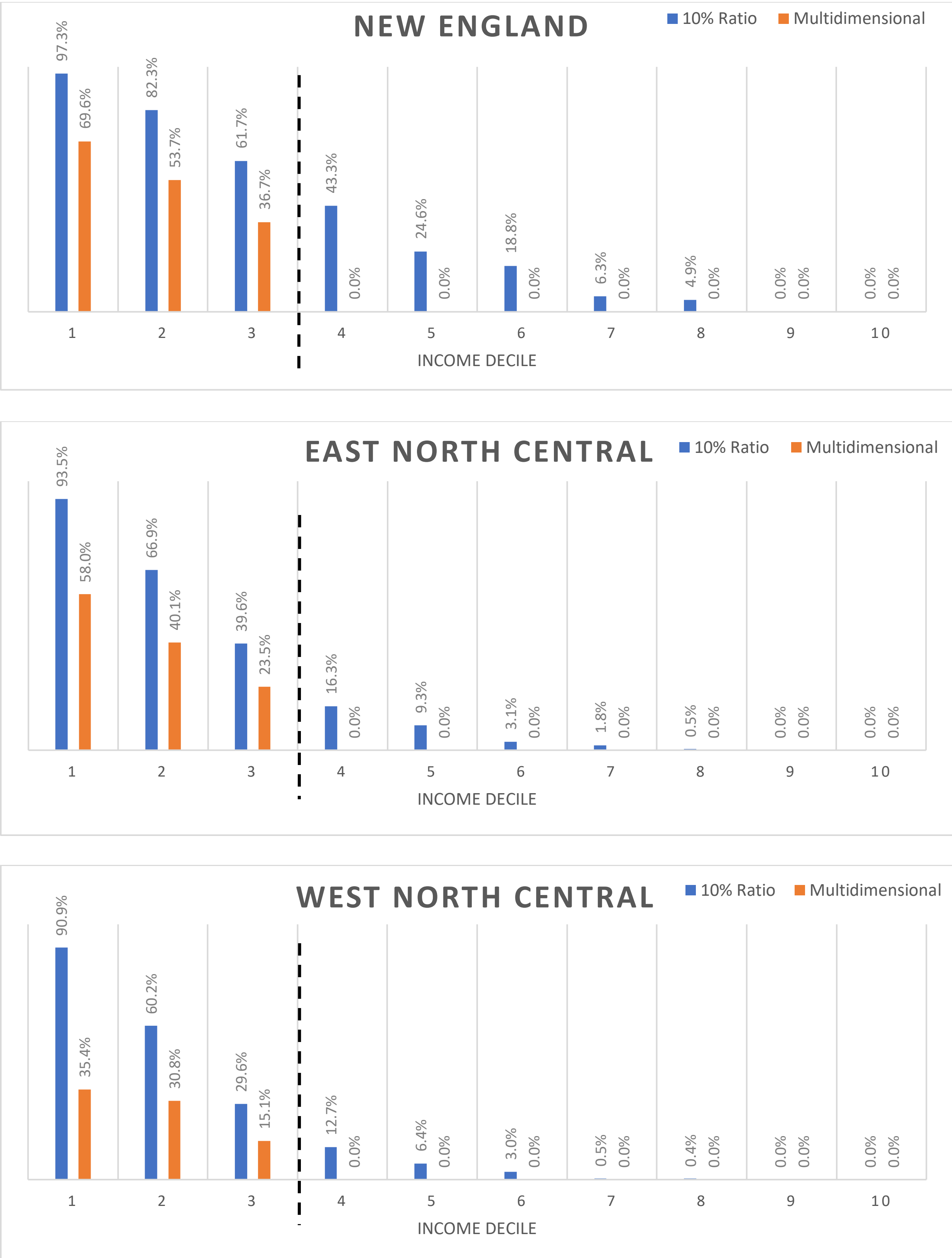
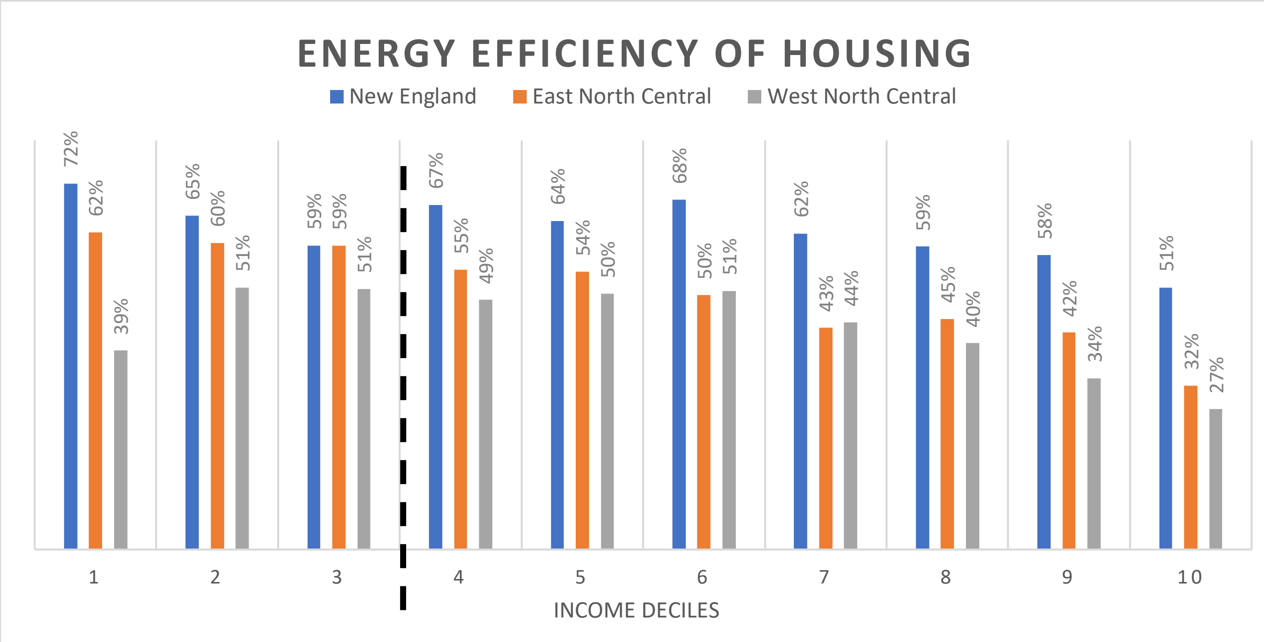


Table 4.1: Summary Statistics for overall fuel poor households by region. 10% ratio & multidimensional measurements

	New England	East North Central	West North Central
Fuel Poor 10% Ratio	26%	24%	20%
Fuel Poor Multidimensional	12%	12%	9%

Fuel poverty is a multidimensional concept, which is why using an expenditure or consensual approach is suboptimal as they are a single dimension approach, as can be seen from Figure 4.3. Under the dimension 'energy', the 10% ratio, doesn't have a cut off for high income households and therefore incorrectly accounts households with high income as fuel poor. This can be seen by viewing the 10% ratio in each region by income deciles, a percentage of NE, ENC &WNC households are classified as fuel poor up till the 8th decile. It would not be reasonable to assume, that households in these upper income deciles would be unable to heat their house to an adequate level and to therefore classify them as fuel poor. Viewing table 4.1, the 10% ratio, 26%, 24% and 20% of households overall are classified as fuel poor for NE, ENC and WNC regions respectively.

Figure 4.4: Energy Efficiency of Housing by region. (Black broken line represents the boundary between 3rd & 4th income deciles, the income dimension)



Unlike the ‘energy’ dimension, the percentage of households in fuel poverty doesn’t decrease as we move we move through the income deciles under ‘Energy Efficiency of Housing’. In the 10th income decile 51%, 32% and 27% of households classified as fuel poor under the second dimension. It wouldn’t be correct to classify these households as fuel poor. Even though the housing unit is very old and energy inefficient the residents can afford the energy expense to heat to a comfortable level (Figure 4.4).

‘Income’ is the third and final dimension used in our multidimensional measurement, in which households under the boundary between the third and fourth income deciles are classified as fuel poor. Taking this dimension together with are other two dimensions to form our multidimensional measurement, fuel poverty in households are at 12%, 12% and 9% for NE, ENC & WNC regions respectively (table 4.1). These overall fuel poverty statistics are down considerably from the 10% ratio for fuel poverty and this highlights the statistical variability among the different types of measurements. Our multidimensional measurement evaluates fuel poverty on its three core concepts[32], and overcomes one of the drawbacks associated with the traditional 10% fuel poverty ratio which is the inclusion of high income households in fuel poverty.

In this section, we have shown that when using a single dimension measurement approach to assess fuel poverty it often includes wealthy households as fuel poor and that when a multidimensional measurement is used it corrects for this error. In the next section, we investigate what are common household unit variables that lead to higher odds of being fuel poor.

4.5. Empirical Findings

The three regions we have chosen to represent the coldest regions, in terms heating degree days, in the US and are therefore households located there may be more susceptible to fuel poverty. The regression results from each region NE, ENC and WNC are presented in Table 4.2.

[32] Energy, Energy Efficiency of Housing and Income

Table 4.2: Logistic regression results for households in fuel poverty under the multidimensional measurement by each region.

	New England		East North Central		West North Central	
	Odds Ratio.	**P-Value**	**Odds Ratio.**	**P-Value**	**Odds Ratio.**	**P-Value**
Type Household						
Married Couple	(R.C.)		(R.C.)		(R.C.)	
Separated Household	2.647***	0.000	3.025***	0.000	2.098***	0.000
Living Alone	2.618***	0.000	2.036***	0.000	2.373***	0.000
Non-Family Household, multiple people	0.607***	0.000	1.210***	0.000	1.137***	0.000
Tenure	0.576***	0.000	0.554***	0.000	0.431***	0.000
Children	2.145***	0.000	1.990***	0.000	2.017***	0.000
Elderly	2.699***	0.000	1.760***	0.000	2.211***	0.000
Education						
No High School Education	(R.C.)		(R.C.)		(R.C.)	
High School Education	0.219***	0.000	0.402***	0.000	0.823***	0.000
College Education	0.108***	0.000	0.174***	0.000	0.257***	0.000
Race						
Non-White	(R.C.)		(R.C.)		(R.C.)	
White	0.872***	0.000	0.528***	0.000	0.687***	0.000
House Unit Structure						
Detached	(R.C.)		(R.C.)		(R.C.)	
Attached	1.077***	0.000	0.394***	0.000	0.468***	0.000
Small apartment Building	1.979***	0.000	0.910***	0.000	0.296***	0.000
Medium apartment Building	0.822***	0.000	0.307***	0.000	0.305***	0.000
Large apartment Building	0.878***	0.000	0.356***	0.000	0.163***	0.000
Solar						
No Solar	(R.C.)		(R.C.)		(R.C.)	
Solar Energy	0.493***	0.000	0.746***	0.000	0.905***	0.000
Heating System						
Furnace	(R.C.)		(R.C.)		(R.C.)	
Steam or Hot Water System	0.887***	0.000	1.791***	0.000	1.775***	0.000
Electric Heat System	0.821***	0.000	0.799***	0.000	0.622***	0.000
Others	1.173***	0.000	0.963***	0.000	1.438***	0.000
Cooking fuel						
Electric	(R.C.)		(R.C.)		(R.C.)	
Gas	0.824***	0.000	1.011***	0.000	0.772***	0.000
Constant	0.535***	0.000	0.563***	0.000	0.255***	0.000
Pseudo R^2	0.1561		0.1232		0.1211	
No. Of Observations	2,376		6,546		2,055	

Notes; * significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level, R.C. Reference Category.

Starting with the socio-economic variables in each of our models in Table 4.2 above. The first variable is household type which is a categorical variable, with a married couple household as our reference category. A separated household across all regions is more than twice as likely to be in fuel poverty as a married couple household. Similar odds are seen in the category of living alone. The only category that differs in odds across the regions is a non-family (multiple people) household where in NE they are nearly 40% less likely to be in fuel poverty than the reference category. In the other two regions, a non-family (multiple people) is more likely to be in fuel poverty than the reference category.

The tenure of the household had the same outcome across all regions, with owners just over 40% less likely to be in fuel poverty in the NE and ENC and 57% less likely in the WNC than the reference category of renters. Similar results were found in Belaïd (2018) where families living in rented properties are more than twice as likely to be fuel poor than families living in owned properties.

Fuel Poverty, has serious effects on health of the people living in this situation, especially those of children and the elderly (Teller-Elsberg et al., 2016). In our model, the presence of children in a household shows that they are about twice as likely to be in fuel poverty as a household without children (reference category). While the presence of elderly people in the household results in a household being more likely to experience fuel poverty, the magnitude of the odds varies quite considerably across the regions. In NE the odds ratio was 2.7, followed by 2 in the WNC and lastly an odds ratio of 1.8 in the ENC. This finding of higher odds in NE could be attributed to its having the oldest housing stock out of the regions and it is also the second coldest in terms of HDD.

The level of education attained by the householder is in general a good indicator of household income and social status (Legendre & Ricci, 2015). In our model, we include the categorical variable, education, where the reference category is no high school education. If the householder has been educated at high school[33] they are 78%, 60% and 18% less likely to be fuel poor than those in the reference category in NE, ENC and WNC respectively. We also find that a householder with some college experience[34] are 89%, 83% and 74% less likely to be fuel poor than those in the reference category. These results were not surprising, as householders with higher levels of education earn more and are therefore less likely to suffer from fuel poverty. The interesting result is that a householder with a high school education in WNC is only 18% less likely to be fuel poor than a householder with no high school education which is much lower than the other regions. Unfortunately, this data set doesn't include the occupation of householders which could explain the difference between the regions.

A binary variable for race was included in our analysis, where race =1 is for a white household and race = 0 is a non-white household. In all regions, a white household is less likely to be fuel poor than a non-white household, at 13%, 47%, 31% in NE, ENC and WNC respectively.

[33] From 9th grade to at least a high school graduate
[34] Semester to full PhD.

There are several dwelling variables included in our model, including the structure of the housing unit, solar, heating system and cooking fuel. Analysing first the category variable house unit structure where the reference category is a detached house, results from the model vary across the regions. In NE, households in detached and small apartment buildings are more likely to be in fuel poverty, with households in medium and large apartment buildings are 18% and 12% less likely to be fuel poor than those in the reference category. Results in the other two regions are that a household in all categories are less likely to be fuel poor than those of the reference category. This ranges from households in ENC living in a small apartment building at the low end at 9% less likely and households in WNC living in a large apartment building at the high end at 84%.

Furnace is the reference category in our heating system category variable, electric heat system is the only variable that had the same outcome across each of the regions. With households with an electric heat system 18%, 20% and 38% less likely to be fuel poor in NE, ENC and WNC respectively. Electric heating systems are found to be more energy efficient and are therefore cheaper to operate meaning lower bills and less likelihood to be fuel poor (Belaid, 2018). Households with a steam or hot water system are less likely to be fuel poor in NE, however in the ENC and WNC a household with a steam or hot water system is more likely to be fuel poor. While for all other forms of heating systems, households in NE and WNC are more likely to be fuel poor and households in ENC marginally less likely to be fuel poor at 4% when compared to the reference category.

The model also includes another energy variable for a household, solar energy. Households in all regions are less likely to be fuel poor if they have some form of solar energy system installed on their unit, 51%, 25% & 10% for NE, ENC & WNC. It was found in Chesser et al., (2018) that the wealthier a household was the more likely they would have some form of a micro renewable energy systems[35] which may explain why households in this study are less likely to be fuel poor.

The last variable in the model is cooking fuel, with households in NE and WNC less likely to be fuel poor if they use gas to cook with instead of cooking with electricity. While cooking with gas in ENC means a household is more likely to be poor but only marginally with an odds ratio of 1.01.

In summary, we find that the variables that result in households having higher odds of being fuel poor are generally the same across the regions. Fuel poverty results in serious health problems for those that live in it, but especially for children and the elderly which our results show are the variables with some of the highest odds of a household being fuel poor (Teller-Elsberg et al., 2016).

[35] micro renewable energy systems include forms of solar energy.

4.6. Conclusion

This paper is noteworthy for two reasons; firstly, the topic of fuel poverty isn't as deeply researched in the US as it is in Northern Europe which is surprising given that the three US regions studied are far colder than that of Northern European countries, in terms of heating degree days. Secondly, where this study improves on previous studies of fuel poverty in the US, is in the measurement used. A multidimensional measurement is used to assess the extent of fuel poverty in three regions of the US where households are most at risk of fuel poverty. This measurement overcomes the issues associated with the single dimension measurement used in the previous studies, which fail to fully capture the multi-dimensional nature of fuel poverty and thus provide policymakers with imprecise statistics.

Our multidimensional measurement approach uses the following three attributes to define fuel poverty; Energy, Income and Energy Efficiency of Housing. In Section 5.1, we presented the descriptive statistics for each of the dimensions used in our measurement for each of the regions. We highlighted the fact that the 10% ratio approach to fuel poverty, reports households as fuel poor up to the 8th income decile which is one of the drawbacks to this single dimension approach. When using the multidimensional measurement, we see a dramatic decrease in those classified as fuel poor, over 10% in some cases.

After presenting the statistics on our multidimensional measurement, we conduct further analysis into the main determinants of those in fuel poverty to satisfy our second objective. A logistic model was used to analysis the impact of several socioeconomic factors and dwelling characteristics on the odds of being fuel poor on each region in our study. The purpose of this analysis is to inform policy makers as to which types of households to prioritise. Given that the adverse health effects of fuel poverty affect mostly children and the elderly and that households with the greatest risk of being fuel poor are ones with children or elderly people. These types of households should be at the top of a policy makers list when addressing fuel poverty.

There is a governmental policy that allows successful participants to avail of assistance in the weatherization of their homes which includes installing insulation, replacing or repairing windows and doors, sealing of air leaks, patching small areas of the roof, etc. Analysing the data set, housing units with these types of issues[36] only make up 26%, 33% & 35% of housing units in NE, ENC & WNC respectively under the multidimensional fuel poverty measurement so this policy could move some households out of fuel poverty. However, the guidelines and type of assistance varies state by state, with some states specifying that applicants must qualify first for the 'Low Income Home Energy Assistance Program'. This seems like an ineffective way to combat the fuel poverty issue, as the reason a low-income household is paying such high energy is that their home isn't energy efficient. This stipulation is like putting the cart before the horse, if the low energy efficiency households where made more efficient there would be less demand for the 'Low Income Home Energy Assistance Program'. Also, most of the criteria is based on income and number of occupants in the household when from our regression results it tells us that the type of occupants is more important in determining fuel poverty.

[36] Appendix X-XIII for description.

Future areas of research should examine, selecting different attributes of multidimensional fuel poverty measurement, for example, using a consensual measurement as an attribute. Also, an interesting finding that is worth further investigation, was that households living in medium and large apartment buildings are less likely to be fuel poor across all regions as compared to detached houses.

Chapter 5

Conclusions

5.1. Summary

The research presented in this thesis emanates from large scale changes in the energy landscape, particularly in the context of power generation and transmission. We began in Chapter 1 with the background on the 'Energy Transition' and how it is changing how economies, culture and society operate, particularly the residential sector. This thesis examines the consequences of the energy transition through several research papers which are detailed in Chapters 2, 3 & 4.

Chapter 2, examined the effectiveness of Irish environmental energy policy on the promotion of micro-RES in the residential sector and its desired outcome of reducing energy demand from the sector. The first objective was to establish a profile of the average household that is adopting micro-RES in Ireland using the Irish HBS. To achieve this objective a micro-RES ownership model was constructed. Our empirical findings show that the typical household adopting micro-RES is a large house that has been constructed recently and is owner-occupied. The owner is most likely to be highly educated and is wealthy. The second objective was to find if the presence of micro-RES in the household affects energy use. Our empirical findings showed that the presence of micro-RES was only statistically significant in the electricity use model, where it increased electricity use. Although there are some financial incentives provided to

Irish residents to adopt micro-RES, these schemes are mainly availed of by wealthier households. The results would suggest that the households adopting micro-RES and availing of the support schemes are the ones that need them the least and that, for many, installing a micro-RES is still a luxury purchase in Ireland. Ireland is one of eight EU Member States with a renewable energy share that was below the anticipated trajectories as laid out in the NREAPs. While Irish energy policy papers continue to address the importance of Irish citizens in combatting climate change and meeting their environmental goals through the promotion of energy saving appliances and micro-RES, results from this analysis would suggest that these policies need adjustment (EEA, 2017).

Chapter 3, focused on another area associated with the energy transition the positive feedback cycle in the residential electricity market. The positive feedback cycle is a result of increasing penetration of solar PV panels in the residential sector resulting in falling demand from the sector. In response to falling sales utilities increase prices to recoup fixed costs and thus incentivising more households to adopt solar PV panels. A cycle is created where falling demand is met with increasing prices that further suppress demand. The literature investigating the existence of a positive feedback cycle is relatively new, with empirical studies mainly focused on the US market to date. This paper extends the ideas from the literature to a selected group of countries, Ireland, the UK and Australia. The three countries represent solar PV installations at three different stages of growth; infancy, intermediate and mature respectively. The first objective was to construct an economic model that represents the positive feedback cycle. We started with an equation from the literature for examining the effects of renewable energy systems on electricity price. Using this as a starting point, we transformed it into multiple equations, a residential solar PV uptake equation, a residential electricity price equation and residential electricity demand equation. Given the nature of the positive feedback cycle, a simultaneous equation model is suited to model this relationship and to ensure the treatment of any endogeneity bias. The second objective to determine whether there is a positive feedback cycle is being experienced in the residential electricity market. To this end, a three stage least squares regression was employed in relevance to the pooled panel data set of Australia, Ireland and the UK. The findings indicated that a positive feedback cycle was in effect, as the adoption of residential solar PV panels was leading to a positive feedback cycle via increasing residential electricity prices and decreasing residential electricity demand. The evidence of the positive feedback cycle in an electricity market could raise issues for electricity utilities, transmission system operators, and government energy departments. To tackle this issue, there needs to be a restructuring of current renewable energy policies for current and future adopters of micro-RES. If environmental goals are to be achieved, then stakeholders in the electricity market will have to support the adoption of solar PV in a sustainable way, while not punishing non-adopters with higher electricity rates.

Chapter 4 examined the topic of fuel poverty, where a household is unable to heat their home to a comfortable level due to a multitude of factors; lack of finances, low energy efficiency dwelling and high energy costs. There is debate in the literature about which measurement approach to use when attempting to quantify fuel poverty. A small group of new studies suggest using a new multidimensional measurement to gauge the extent of fuel poverty. Thus, a country that has received little research in fuel poverty was chosen, the US, using a multidimensional measurement. The first objective was to assess US households in fuel poverty using a multidimensional measurement. Our multidimensional measurement consists of three dimensions; energy, energy efficiency of housing and income. After conducting statistical analysis on the AHS, it was found under the multidimensional measurement that 12%, 13% & 9% of households are fuel poor in New England, East and West North Central regions, respectively. These statistics are approximately 10% lower as compared to more commonly used 10% ratio measurement correcting some of the main criticisms of this measurement. Next, we conducted further analysis into the main determinants of those in fuel poverty to satisfy our second objective. While it was found that the variables that result in households having higher odds of being fuel poor are generally the same across the regions, the variables resulting in some of the highest odds of a household being fuel poor are households with children and households with elderly people. The purpose of this analysis is to inform policy makers as to which types of households to prioritise. Given that the adverse health effects of fuel poverty affect mostly children and the elderly and that households with the greatest risk of being fuel poor are ones with children or elderly people. These types of households should be at the top of a policy makers list when addressing fuel poverty. There is a governmental policy that allows successful participants to avail of assistance in the weatherization of their homes. However, the guidelines and type of assistance varies state by state, with some states specifying that applicants must qualify first for the 'Low Income Home Energy Assistance Program'. This seems like an ineffective way to combat the fuel poverty issue, as the reason a low-income household is paying such high energy is that their home isn't energy efficient. This stipulation is like putting the cart before the horse. If the low energy efficiency households where made more efficient there would be less demand for the 'Low Income Home Energy Assistance Program'. Also, most of the criteria is based on income and number of occupants in the household when from our regression results it tells us that the type of occupants is more important in determining fuel poverty.

Many environmental energy policies' aim to promote the adoption of micro-RES as well as other energy efficiency measures in residential sector. This is accomplished through several policy instruments, such as FiT and grants, which are funded through all consumers' energy bills. The purpose of these policy instruments is twofold, firstly consumers that adopt will generate and consume green energy. Secondly, it will make these technologies more financially feasible for more households. In our first paper in was found that it is generally wealthier households are more likely to adopt micro-RES. Highlighting that these policy instruments can be viewed as a form of regressive taxation. Add to this that when micro-RES reaches a significant penetration level, the residential market experiences a positive feedback cycle resulting in higher electricity prices as shown in Chapter 3. The situation now exists were lower income households are subsidising high income households adopting micro-RES and in return are faced with higher energy due to falls in demand from those households with micro-RES. Essentially, they are getting penalised twice. A recent study by Borenstein & Davis (2016) highlights this inequality caused by environmental energy policies, they found that since 2006, US households have received more than $18 billion in federal income tax credits for clean energy investments. These tax expenditures have gone predominantly to higher income Americans with the bottom three income quintiles have received about 10% of all credits. Lastly, as we discussed in Chapter 4 rising energy bills can push households into fuel poverty which can lead to serious health effects and social issues. As Sioshansi (2016) notes the future of the energy sector could become increasingly bifurcated between the haves and the haves nots. However, these issues can be overcome through proactive regulatory, policy, and market reform design enabling the efficient evolution of the energy system in the future (MIT, 2016).

5.2. **Future Research**

The promotion of micro-RES is very important in helping to mitigate climate change. However as seen in this thesis and the literature, that government schemes used to promote micro-RES seem to only benefit wealthier households. If environmental energy policy goals are to be achieved, then stakeholders in the energy market will have to support the adoption of micro-RES in a sustainable way, while not punishing non-adopters with higher prices. An area of research that could address some of the issues surrounding the energy transition, is rate design. A study by Burger, Knittel, Perez-Arriaga, Schneider & Scheidt (2019) examined efficiency and distributional effects of alternative residential rate design as a result of decentralised generation however they didn't investigate how this would affect household in fuel poverty.

5.3. **Critical Reflection**

The idea of doing a PhD. journey began when I was completing my masters' thesis, my supervisor asked me if I would be interested. Unfortunately, the funding for PhD research at NUIG at the time was in the area of environmental issues so I decide to decline the offer and look elsewhere. I came across a posting for PhD. applicants' in the area of energy economics on DIT website and submitted my interest for the position. I was contacted by the Head of Research at the College of Business Paul O'Reilly to discuss what a PhD. entailed. I then met with my supervisor Dr Jim Hanly and I explained my interest in the area of micro renewable energy systems (micro-RES) economics and policy.

Jim and I discussed submitting my own research proposal in this area of energy economics and policy for the Fiosraigh scholarship and that I would complete the thesis via the North American model which is three separate but thematically linked research papers. I began work on my application in the summer of 2015. My application was successful and was awarded the scholarship with a start date of my PhD. 1st of November 2015.

The first year of my PhD. was quite daunting as the learning curve was very steep. A requirement of the structured PhD. programme is the completion of a number of course modules relating to PhD. research and future work prospects. These modules were extremely beneficial to my work on the thesis. Some of the first modules I completed were Project Management, Business Research Methods, Econometrics (time series) and Econometrics (panel data) over the first year. The first two modules helped in laying down the foundation of how to complete my thesis improving my time management skills and research abilities. I had previously done an econometrics (cross sectional) module in my masters but I needed to strengthen this skillset further to achieve the research objectives in my thesis. Much of my time during my first year dealt with trying to manage the workload of the PhD, making sure assignments relating to the modules were completed and also conducting my own research. Each year of the PhD. programme involved an annual evaluation event usually in May/June, where I had to write an annual progress report for assessment and give a presentation on my progress for an assessment panel and they assessed the quality and progress of my research work to date. I was quite nervous heading into this in my first year as I thought I would have been further along in my research at this point.

My first paper (Chapter 3) had to go through several revisions from my initial project proposal after data availability concerns. My aim was to have a draft of my first paper to present at my first annual evaluation. However by June 2016, what I had accomplished was the completion of several of the required modules and a research paper consisting of an introduction, literature review and some descriptive statistics, no real empirical analysis had been done at this stage. The gathering of data took a substantial amount of time, between searching online databases and corresponding with several institutions from several countries by email. Despite my own concerns, my progress was deemed satisfactory to continue into my second year. Each one of these annual evaluations, was a small accomplishment as it offered some reassurance and gave me confidence that I could complete the PhD.

The second year of my PhD. was by far the most stressful as there was I number of milestones set that I had to achieve while at the time I began teaching. I finally got a draft of my first paper together towards the end 2016. The big milestone was to get the paper into a conference. We had selected several conferences were I could present my paper and began submitting it around February 2017. For me this was the first big test I faced in my PhD., whether or not my paper was approved by my peers and deemed to be at a conference standard. While not all of my applications were successful, to my relief my first paper got accepted to the International Symposium on Environment & Energy Finance Issues conference which took place in May 2017. Shortly after this, the paper also got accepted into another conference later in summer 2017. This validated my work thus far and gave me greater confidence in my abilities. After I presented my paper at these conferences I received lot of feedback which I then incorporated into the paper to get it ready for submission to a journal. Towards the end of the summer while finalising the first paper for a journal submission, I began work on the second paper (Chapter 2).

At the beginning of my third year, I was in a much better place, I was effectively managing my workload of, undertaking the required modules as part of the structure PhD. programme, teaching commitments and research milestones. My supervisors and I decided to submit my first paper (Chapter 3) to Energy Economics in the autumn of 2017 however my application was unsuccessful. Looking back on it now it was understandable, as it was my first attempt at a research paper there was a lot of avoidable mistakes.

I received the report from the Energy Economics journal, the report was five pages long and included an overall summary of the paper, major and minor comments. I was advised to start by addressing the minor comments (grammatical errors, etc.) first which took about a day to complete and after that move onto the major comments which took several weeks. The first three comments from Energy Economics were about the literature review. I understood the comments that they made and I incorporated these changes into my paper. There was some comments about the econometrics in the paper, choice of model and the variables, with these comments I conversed with my supervisor and a colleague as to what would be the best course of action.

After taking on board the comments from the Energy Economics submission, in January 2018, we submitted the paper to Energy Policy. I received the editors' and the three reviewers' comments in April, and was informed by the editor to address each of the comments made by the reviewers' and resubmit. The comments addressed revisions to all sections of the paper, many of these comments surrounded the choice of model used to investigate the presence of the feedback cycle. The comments I received from the reviewers were similar to those I received from the examiners. The process of defending my work was rigorous and robust and took me about three weeks to complete. Again I started by addressing the minor comments from the three reviewers which took about a day. Some of the major comments again questioned the choices of variables in the model. For example, I had a variable representing natural gas prices in the model. The reviewer suggested using price data from another source. Per the reviewers request I sourced the price data from the source they requested and reran the model. Another comment from a reviewer asked to include wholesale price of electricity my model which I did as instructed. We resubmitted again in May and felt confident we would get a positive result. However, one of the reviewers disagreed with some of my responses to their comments on the paper. One such comment addressed the size magnitude of some of the variables in the results, which prompted me to search the literature and found another study which found similar sized magnitudes. Again I took the comments on board were I could and defended my position on some of the other comments. Upon reflection, throughout the journal review process and the Viva, there were good comments made by the reviewers & examiners about some aspects of the paper with regards to variables included/excluded from the model and on country selection. While I understand these comments and recognise their validity. I believe the work and research done in the paper is valid. Granted if sometime in the future I got access to all the data I wanted, I would take on board the comments made and present a more robust paper.

In June, we resubmitted and the paper was accepted by Energy Policy in July. I spent a lot of time on my first paper (Chapter 3) and learnt a lot about researching and the writing of a research paper which helped in my second and third papers. While going through the review process of the first paper, I was refining my second paper by submitting and attending conferences. In the summer of 2018 I began work on my third paper.

In the fourth year of my PhD, I had finished all of the required modules and was only focused on my second and third paper, finalising my thesis and my teaching commitments. I had my second paper (Chapter 2) ready for submission at the end of 2018. One concern I had about my second paper was that the data set was from 2010. When I started the paper it was a few months before the release of the 2016 household budget survey (HBS) dataset so I worked with the 2010 dataset while I waited for the release. To my disappointment, upon release of the 2016 dataset the questions relating to energy sources in the home were dropped from the survey which resulted in using the 2010 dataset for this paper. I was worried this could be an issue however I did see recent papers in the literature that used older datasets then mine which eased my concerns around this potential issue. After a discussion with my supervisor we decided to submit to The Economic and Social Research Journal. Similar to the experience with Energy Policy, we received an email form the editor asking us to address the comments from the reviewers and resubmit. Again, these comments were similar to that of the ones raised during the viva. One comment discussed the issue of selection bias and suggested running a Heckman type selection model. This required the construction of inverse mills ratio variable that could control for the potential sample selection bias and then include this as a new independent variable. Comments also were raised with the construction of total fuel use variable and electricity use variable and the inclusion of PSO levies, standing charges, etc. I could only work with the data that was given in the HBS. Another drawback of using the HBS is that I had to construct a variable to represent micro-RES, this I couldn’t differentiate between the different types of systems and examine their effect on energy use. While I do understand the importance of the comments that were raised, I was guided by the past literature and the data available, and this supporting my use of these variables.

At the time of thesis submission my third research paper (Chapter 4) had been accepted and presented at two conferences, one being the international conference for International Association of Energy Economics (IAEE). After presenting at these conferences and taking on board criticisms, we submitted the paper to Energy Journal were it was currently under review at the time of my Viva. Unfortunately the submission was unsuccessful. I feel like this can be my best paper to date after I incorporate the feedback I received from the journal, the comments from my Viva and the lessons I had learnt from my previous two papers.

Looking back on the PhD. the biggest decision was made at the very start when we decided to undertake the North American model to complete the thesis. While this was beneficial in a number of ways, first and foremost being I got two publications before the end of my PhD. It did have some drawbacks, the issues around data, which were brought up in comments from journal reviewers and Viva examiners. We had set the goal of having some of my work published before my Viva and the timeline for the North American model meant I worked with secondary data sets and not doing a survey. The option of selecting a sample and constructing and undertaking a survey for each individual paper would have been too time consuming. I feel that if I had undertaken a survey I could have attained some of the variables that were lacking from the secondary data sets I used. I also feel that undertaking a survey would have not only developed a new skillset but would have addressed many of the comments raised by reviewers during the journal submission process and Viva. I would have to believe that household surveys in coming years will ask more detailed questions around this topic of energy and energy efficiency in the household not only because it’s a very timely and important issue but could greatly benefit researchers in the future. In conclusion, while there are always ways to improve on previous research and I will try to incorporate all the comments I have gotten in future work. The work I have done has been peer reviewed on several occasions and been through a robust and rigorous review process where I had to the defend my work exhaustively. As a researcher, I can only be guided by the literature and put my faith in the journal review process, that my work is of publication standard. Im only still at the beginning of my research career and still of the mind-set that I can always learn and improve.

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Appendix I Gross Calorific value (kWh/ unit) by fuel type. Quarterly average fuel price per unit.

Fuel Type	Gross Calorific Value	Price Q3 2009	Q4 2009	Q1 2010	Q2 2010	Q3 2010
Heating Oil	10.6	0.66	0.63	0.7	0.76	0.86
Gas	1	0.06	0.05	0.05	0.05	0.05
Electricity	1	0.17	0.15	0.15	0.15	0.15
Wood	4.8	0.22	0.22	0.22	0.22	0.22

Appendix II. Descriptive Statistics

Variable	Mean	Std. Dev.
Electricity Use (Estimated energy use from electricity kWh)	15.82	11
Total Fuel Use (Estimated energy use from total fuel kWh)	34.49	23.99
Disposable Income (€ weekly)	905.31	674.18
Number of Persons	2.72	1.49
Number of Bedrooms	3.22	1.05
Number of TVs	2.2	1.33

Appendix III. Descriptive Statistics

Variable	Mean	Variable	Mean
Children In household		*Location of household*	
Children	30.5%	Urban	68.00%
No Children	69.5%	Rural	32.00%
Ownership status of household		*Appliance Ownership*	
Own	68.5%	Micro-RES	1.50%
Rent	31.5%	Dishwasher	64.10%
Education level attained by CES		Tumble Dryer	66.60%
Primary Education only	21.3%	Fridge Freezer	81.20%
Secondary Education only	31.9%	Microwave	91.40%
Higher Institution	46.8%	Console	39.90%
Period in which accommodation was built			
Pre 1918	8.5%		
1918-1945	7.8%		
1946-1960	7.3%		
1961-1970	6.0%		
1971-1980	12.5%		
1981-1990	9.6%		
1991-2000	14.7%		
2001-2005	20.0%		
2006-2010	13.6%		

Appendix IV Descriptive Statistics

Variable	Mean	Variable	Mean
Children In household		*Location of household*	
Children	30.5%	Urban	68.00%
No Children	69.5%	Rural	32.00%
Ownership status of household		*Appliance Ownership*	
Own	68.5%	Micro-RES	1.50%
Rent	31.5%	Dishwasher	64.10%
Education level attained by CES		Tumble Dryer	66.60%
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1971-1980	12.5%		
1981-1990	9.6%		
1991-2000	14.7%		
2001-2005	20.0%		
2006-2010	13.6%		

Appendix V Data Sources

Notation	Ireland	UK	Australia
PV	ESB	gov.uk	Australian Photovoltaic Institute
AvrCostPV	The OpenPV Project by National Renewable Energy Laboratory	The OpenPV Project by National Renewable Energy Laboratory	The OpenPV Project by National Renewable Energy Laboratory
ED	CSO	gov.uk	Office of Chief Economist
CoalShare	CSO	gov.uk	Office of Chief Economist
PGas	Thomson Reuters DataStream	Thomson Reuters DataStream	Thomson Reuters DataStream
PElec	Eurostat	Eurostat	Australian Energy Market Commission
wage	OECD Database	OECD Database	OECD Database
Temp	Met Eireann	gov.uk	The Bureau of Meteorology
Sunlight Hours	Met Eireann	gov.uk	The Bureau of Meteorology
Support Scheme	ESB	gov.uk	australia.gov.au

Appendix VI. Variables Description.

Variable	Notation	Description	Unit
Solar PV Uptake	PV	Monthly solar PV average capacity installed	kw
Cost of Solar PV	AvrCostPV	Monthly per watt cost of PV.	€/kw
Residential Electricity Demand	ED	Monthly electricity consumed by residential sector	Gw/h
Coal Share	CoalShare	Percentage of Coal used in Electricity Production	%
Price of Natural Gas	PNG	Monthly Price of natural gas at the Henry Hub	€/MCF
Residential Price of Electricity	PElec	Price of residential electricity, Band DC : 2,500 kWh < Consumption < 5,000 kWh. All taxes and levies included.	€
Wage	wage	Average Monthly wage	€
Temperature	Temp	Monthly Average Temperature	oC
Lagged Residential Price of Electricity	LPElec	Lagged Price of residential electricity	€
Sunlight Hours	Sunlight	(Proxy for solar radiation) Average monthly duration of Sunlight	Hours
Government Support Scheme	Scheme	Dummy Variable for months that a support scheme (eg. Feed in Tariff) was operational	1 = scheme open, 0 = scheme closed

Appendix VII Investigated Hypotheses

Estimated Equation	Variable	Expected Sign	Hypothesis
Equation 1 Solar Uptake	Residential Electricity Price	+	Increase in electricity price increases solar PV uptake
	Government Support Scheme	+	Months in which the government support schemes are in operation should result in higher uptake
	Sunlight Hours	+	Countries with higher average sunlight hours should have a higher solar PV uptake
	Cost of Solar PV	-	Lower solar PV costs, increases solar PV uptake
Equation 2 Residential Electricity Price	Coal Share	-	Increase in coal generation, decreases electricity prices
	Lagged Electricity Price	+	Increase in previous months prices, increases price of electricity
	Solar PV Uptake	+	Increase in solar PV uptake, increases price of electricity
Equation 3 Residential Electricity Demand	Residential Electricity Price	-	Increase in electricity price , decreases the electricity demanded
	Solar PV Uptake	-	Increase in solar PV uptake, decreases the electricity demanded
	Natural Gas price at the Henry Hub	+	Increases in the price of natural gas, increases electricity demanded (substitution effect)
	Temperature	-	Higher Temperatures decreases electricity demanded
	Wage	+/-	A higher wage could have either a positive or negative effect on Electricity demand.

Appendix VIII Panel Unit Root Tests

Variable	Method	Statistic	P-Value	Conclusion
Pelec	IPS	-5.79***	0.000	Stationary
	LLC	-7.339***	0.000	Stationary
Sunlight	IPS	-3.667***	0.000	Stationary
	LLC	-5.742***	0.000	Stationary
Wage	IPS	-3.993***	0.000	Stationary
	LLC	-6.103***	0.000	Stationary
ED	IPS	-4.408***	0.000	Stationary
	LLC	-6.51***	0.000	Stationary
CoalShare	IPS	-1.568*	0.058	Non-Stationary
	LLC	-4.023**	0.024	Non-Stationary
Temp	IPS	-2.343**	0.010	Stationary
	LLC	-4.728***	0.005	Stationary
PV	IPS	-12.546***	0.000	Stationary
	LLC	-0.919***	0.000	Stationary

Appendix IX Principal Elements of Energy and Fuel Poverty Frameworks in Traditional Understandings of the Two Concepts (Bouzarovski & Petrova, 2015).

Element	Developing World Energy Poverty	Developed World Fuel Poverty
Recognition	Explicitly acknowledged in isolated documents during the early 1970s. Subsequent debates mainly focused on technological expansion. More recent research addresses participation and governance challenges.	First mentions date back to the late 70s and 80s, principally referring to rising energy costs and 'the right to fuel' in countries like the UK. Later research allowed for a wider understanding of the problem.
Driving forces	Primarily low levels of electrification and other forms of networked energy provision due to economic under-development and non-functional institutions.	High or rising energy prices vs. low household incomes. Inefficient housing, heating systems and appliance stocks.
Expression	Lack of access to adequate facilities for cooking, lighting and electric appliances, but also other services such as space cooling and heating.	Mainly inadequate heating in the home; importance of other services (particularly space cooling, lighting, appliances, IT) is increasingly recognized in recent years.
Consequences	Detrimental impacts on health, gender inequality, education and economic development more generally.	Long and short-term mental and physical health, inadequate participation in society.
Principal policies	Support for transitions to 'modern' energy fuels, investment in power grid expansion or micro-scale renewables; income support.	Combination of income support, provision of energy at lower costs, and energy efficiency investment.

Appendix X Descriptive Statistics

Variable	Categories		Description	New England	East North Central	West North Central
					Frequency	
Tenure	Owner	1	Household unit is owner occupied	71%	71%	69%
	Rent	0	Household unit is rented	29%	29%	31%
Education	No High School Education	1	Education level of householder; below 9th Grade	2%	2%	3%
	High School Education	2	Education level of householder; 9th Grade to High School Graduate - High School Diploma or equivalent	23%	33%	31%
	College Education	3	Education level of householder; some college experience to Doctorate degree	75%	64%	67%
Heating System*	Furnace	1	Forced warm-air furnace; Floor, wall, other pipe less furnace	46%	88%	85%
	Steam or Hot Water System	2	Steam or hot water system	43%	6%	5%
	Electric Heat System	3	Electric heat pump; Built-in electric baseboard, electric coils; Potable electric heaters	9%	6%	9%
	Others	4	Vented & Unvented room heaters; Wood burning, pot belly, Franklin stove; Fireplace with inserts & without inserts; cooking stove used for heating; Other	3%	1%	1%

Appendix XI Descriptive Statistics

Variable	Categories		Description	New England	East North Central	West North Central
				Frequency		
Type of Household	Married Couple	1	Married-couple family household	52%	48%	50%
	Separated Household	2	Other family household: Male householder, no wife present; Other family household: Female householder, no husband present	16%	18%	16%
	Living Alone	3	Nonfamily household: Male householder, living alone; Nonfamily household: Female householder, living alone	23%	28%	27%
	Non Family Household, multiple people	4	Nonfamily household: Male householder, not living alone; Nonfamily household: Female householder, not living alone	9%	6%	7%
Kids	Kids in the housing unit	1	Household children under the ages 6 & ages 6-17	30%	30%	32%
	No Kids	0	No Children in Household	70%	70%	68%
Elderly	Elderly people in the housing unit	1	Household with persons age 65 and over	31%	30%	27%
	No Elderly	0	No persons age 65 and over	69%	70%	73%
Race	White	1	Household race white	86%	80%	87%
	Non-White	0	Household race non- white	14%	20%	13%

Appendix XII Descriptive Statistics

Variable	Categories		Description	New England	East North Central	West North Central
				Frequency		
Solar*	Housing unit has a renewable energy system present	1	Solar is the most used fuel for heating this unit; Solar is the most used fuel for hot water; House unit has solar panels.	4%	1%	1%
	No renewable energy system	0		96%	99%	99%
Cooking Fuel	Electric	1	Electric is the most used fuel for cooking	49%	51%	28%
	Gas	0	Piped Gas or LP gas is the most used fuel for cooking	51%	49%	72%
Housing Unit Structure	Detached	1	One-family house, detached	64%	74%	75%
	Attached	2	One-family house, attached	6%	8%	7%
	Small apartment Building	3	2 to 4 apartments in the building	18%	6%	5%
	Medium apartment Building	4	5 - 19 apartments in the building	7%	8%	7%
	Large apartment Building	5	20 and above apartments in the building	6%	4%	5%

Appendix XIII Descriptive Statistics

Variable	Categories		Description	New England	East North Central	West North Central
					Frequency	
Housing Issues	Has Housing Issue	1	Housing issues variable represents a housing unit reported yes to any of the following; roof has holes; foundation has holes, etc; outside walls have missing siding, bricks,etc; windows broke; windows are boarded up; inside walls or ceilings have open holes or cracks; floor has holes; outside water leaks in last 12 months; ranked the housing adequacy as severely inadequate; number of upkeep problems, 5 or more; a rating of less than 5 for the unit as a place to live on scale 1-10; mold present in any room over the last 12 months; watering leaking into the unit from the outside in the last 12 months; unit was uncomfortably cold for 24 hours or more last winter due to inadequate insulation; unit was uncomfortably cold for 24 hours or more last winter due to inadequate heating capacity	21%	24%	26%
	Doesn’t have housing issue	0		79%	76%	74%

Publications and Conferences

Publications

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