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

Keywords: Residential Solar PV, Electricity Price, Positive Feedback Cycle, Electrical Utility.

Abstract

The increasing popularity of residential solar PV systems in electricity markets has led some to suggest that it has created a positive feedback cycle. A positive feedback cycle is a result of residential electricity customers adopting solar PV systems due to high electricity prices. Thus producing their own electricity and reducing their net purchases from the electricity grid. However, the costs incurred by the electrical utility companies do not decrease in proportion to the decrease in electricity consumed. Electrical utilities will have to raise their price of electricity to make up for the loss of revenue and thus incentivise the remaining electricity customers to adopt solar PV systems. Increasing penetration levels of residential solar PV systems onto a grid could further accelerate the positive feedback cycle and potentially force electrical utilities into a death spiral. The purpose of this paper is to investigate whether a positive feedback cycle is in effect for a group of countries, by developing a theoretical model based on simultaneous equations and estimating it using the three stage least squares approach.

1.1 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 have 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, Hammond & McManus (2008) references a study where it was predicted that electrical micro-RES could provide 30 to 40% of the UK's electricity needs by 2050. There are many different types of micro-RES, however solar photovoltaic (PV) systems are the most popular, with strong uptake in places like Australia and the southern states in the United States of America. Though, the increasing popularity of residential solar PV systems in electricity markets has led some (Cai, Adlakha, Low, De Martini, & Chandy, 2013) to suggest that it has created a positive feedback cycle or loop. Simply put a positive feedback cycle or loop 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 (Rodrigues et al., 2016; Sahu, 2015).

This study is concerned with the existence of a positive feedback cycle in the electricity market as a result of residential electricity customers adopting solar PV systems due to high electricity prices whereby reducing their net purchases from the electricity grid; however, the costs incurred by the electrical utility companies do not decrease in proportion to the decrease in electricity consumed. This is because the electrical utilities have to pay for transmission and distribution infrastructure and these 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. Increasing penetration levels of residential solar PV systems onto a grid could further accelerate the positive feedback cycle and potentially force electrical utilities into a death spiral; where electricity price increases will be futile in raising sufficient revenues to cover its total costs (Costello & Hemphill, 2014).

The goal of this paper is to firstly model the positive feedback cycle caused by consumers in the residential sector to deciding to adopt solar PV systems and the resulting implications on demand and pricing in the residential electricity market. Following this, an econometric analysis is performed for the selected group of countries Australia, Ireland and the United Kingdom to investigate whether a positive feedback cycle is being experience in their electricity markets. Therefore, the objectives are: (1) to find if increasing residential electricity prices will lead to higher installation rates of residential solar PV panels, (2) whether residential solar PV installations lead to higher residential electricity prices, (3) whether residential solar PV installations negatively affect residential electricity demand.

The results attained in this paper are meant to inform policy makers and regulators as they consider potential changes to residential electricity rates that could affect PV's role in advancing policy objectives and customer choice.

The paper is organised as follows: Section 2, is the material and methods sections; provides details on the model development, the estimation technique, data specifications and a descriptive statistics subsections. In Section 3, the results of the three stage least squares regression of our simultaneous equation model are presented and discussed. Section 4 contains the concluding remarks and policy implications.

2. Literature Review

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. There is a notable gap in the literature when it comes to empirical studies on the impact that micro-RES, particularly residential solar PV systems, are having on countries electricity markets and whether this results in a positive feedback cycle which could possibly result in a utility 'death spiral' (Felder & Athawale, 2014). The idea that a renewable energy technology will contribute to increasing electricity rates is in conflict with renewable energy literature to date, with studies by Gil, Gomez-Quiles & Riquelme (2012), Ketterer (2014) and Woo, Horowitz, Moore & Pacheco (2011) concluding that renewable energy from wind turbines contribute to lower electricity prices. While Clo, Cataldi & Zoppoli (2015) found that electricity from solar and wind sources reduce wholesale electricity prices in Italy.

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 and 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, Barbose, & Wiser, 2011; McLaren, Davidson, Miller, & Bird, 2015; Mills, Wiser, Barbose, & Golove, 2008).

In a paper by Chew, Heling, Kerrigan, Jin, Tinker, Kolb, Buller & 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 rooftop solar PV systems. In Cai et al.(2013), the authors investigate how the adoption of solar PV systems by households leads to a positive feedback cycle via increasing electricity rates. They model solar PV adoption for a specific investor owned utility, subject to rate-of-return regulation in California. Their objective is to find the impact of the feedback cycle on the number of years it would take to reach 15% of peak demand. The results from their model illustrate that the feedback cycle reduces the time it takes for PV capacity to reach 15% of peak demand by up to 4 months and has a greater impact in later years. Costello and Hemphill (2014) investigate whether the 'death spiral' facing electrical utilities due to increases in distributed generation[1] is a reality or overstatement. The authors conclude that electrical utilities are in for some tough times ahead, but it is due to a number of factors not just distributed generation. 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, Epps, Peterson, Laser & Wanjiru (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. 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 and Sergici (2016), investigate the price-responsiveness of the residential customers with increasing residential solar PV penetration and projected future electricity sales to the residential sector considering various future solar PV penetration scenarios. Their results show that increasing residential electricity prices are associated with an increase in residential solar PV installations and in a future scenario where there is a 25% residential PV penetration by 2020, about 1.2% of the projected growth of the electricity sales to the residential customers will be taken over by rooftop solar PV.

[1] 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.

The literature published on the topic of a positive feedback cycle due in the residential electricity market due to residential solar PV 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 PV adoption in these countries has led to the existence of a positive feedback cycle.

3. Material and Methods

3.1. **Data Specifications**

We consider monthly data spanning the period from 2010 to 2015, for three countries: Australia, Ireland and the United Kingdom in this study. The countries are chosen as they retained sufficient records for monthly residential solar PV system installations and these installed solar PV systems rated capacities. 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.[2] To the empirical ends of this study, we define residential solar PV having a max rated capacity up to 10kW. (Balta-Ozkan, Yildirim, & Connor, 2015; CER, 2016; 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. Data from all three sources are reported in the number of installations and the installed capacity. For each country, the variable solar PV uptake is generated by taking the total installed capacity of residential solar PV systems in a month and divided by the number of installations in that month, thus, giving the average capacity installed per system per month. The variables measurement is reported as the average rated capacity (kilowatt / Kw) per system.

Data on the cost of solar PV installations are collected from Open PV Project published by the National Renewable Energy Laboratory. Data are downloaded for solar PV systems up

[2] In Ireland ESB Networks classify a generator as 'micro' when the electricity generating system has a maximum rated capacity of 11kW 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 100kW.

to a rated capacity 8 kW and the cost of solar variable is calculated by dividing rated capacity of systems by their cost to get the measurement of 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 U.K. and the statistics portal on the 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 price of natural gas at the Henry Hub is collected form Thomson Reuters DataStream and is measured in €/MCF[3].

The average monthly wage is sourced from the OECD website across all three countries and is reported in Euros (€). 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 Scheme equals to 1 if a federal government micro-generation support scheme is in operation, 0 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[4] is applied in that case to acquire monthly values. Both Appendix A and B have a table detailing each variables data source.

3.2. **Model Development**

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 impact residential electricity demand and this in turn affects residential electricity pricing. According to

[3] 1,000 cubic feet, a unit of measurement in the oil and gas industry for natural gas.
[4] We use "Ipolate" command with epolate option in Stata to conduct the linear extrapolation. We have sufficient historical data points to do the extrapolation.

Kaufmann and 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 (1):

$$\boldsymbol{P_t = \alpha + \beta_1 Load_t + \beta_2 RE_t + \beta_3 NRE_t + \beta_4 PFF_t + \beta_5 Dum_t + \varepsilon_t} \qquad \textbf{(1)}$$

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 (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. A simultaneous equations model is used when one or more of the explanatory variables is jointly determined with the 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:

$$\boldsymbol{lnPV_t = \propto_0 + \propto_1 lnPElec_t + \propto_2 Scheme_t + \propto_3 lnSunlight_t + \propto_4 lnAvrCostPV_t + D_y^{year} + D_m^{month} + \varepsilon_{1,t}} \qquad \textbf{(2)}$$

$$\boldsymbol{lnPElec_t = \beta_0 + \beta_1 CoalShare_t + \beta_2 lnPElec_{t-1} + \beta_3 lnPV_t^* + D_y^{year} + D_m^{month} + \varepsilon_{2,t}} \qquad \textbf{(3)}$$

$$\boldsymbol{lnE_t = \theta_0 + \theta_1 lnPElec_t^* + \theta_2 lnPV_t^* + \theta_3 lnNG_t + \theta_4 lnTemp_t + \theta_6 lnWages_t + D_y^{year} + D_m^{month} + \varepsilon_{3,t}} \qquad \textbf{(4)}$$

We start our simultaneous equation model of the positive feedback cycle with the residential solar PV uptake equation (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, et al. (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 first equation in the simultaneous equations model is the residential solar PV uptake equation (2). The dependent variable in equation (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. The next variable included is the average monthly sun light hours[5] (Sunlight), as it is an important 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 or not there is a support scheme in place for solar PV in a given 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 utilities pricing. This is represented by the residential electricity price equation (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 predicated residential solar PV uptake and time dummy variables for the Month and Year. It is expected that increasing levels of solar PV uptake will increase residential electricity prices, not only due to customer with solar PV demanding less electricity from the grid resulting in utilities charging more to remaining customers to meet its revenue requirements. But also due to the changing of the daily patterns of power supply and demand caused by solar PV. Traditionally the electric supply load graph for transmission system operators would have two moderate peaks in supply, in the

[5] Proxy for Solar radiation

morning and again in the afternoon with a slight dip in supply between the ‘working hours’ of nine to five. Increasing numbers of solar PV on the grid will result in greater production of electricity during the ‘working hours’. Resulting in a decrease in electricity supplied by utilities during this time. Where the problem arises is when the dip during the working hours deepens the more stress is put on ramping up and down of power plants in the afternoon to meet the rapid increase in demand as solar PVs stop generating electricity. There are some genuine implications for utilities for the cost of keeping the rest of the grid operating reliably. To manage the grids effectively, transmission systems operators and electrical utilities, need to invest in different power plants capable of effectivity ramping up and down to meet demand and require further maintenance of their network infrastructure to meet sudden changes in demand. Thus the financial cost will be covered by the customers of the utilities. (ISO, 2016; Lijesen, 2007).

The final part of the positive feedback cycle to be modelled is how the resulting increasing penetration of residential solar PV and rising residential electricity prices will lead to a decrease in residential electricity demand. The residential electricity demand equation (4) is the last equation in the simultaneous equations model. The residential electricity demand is a function of the predicated residential electricity price, the predicated residential solar PV uptake, the price of natural gas at the Henry Hub[6], the average monthly temperature and the average monthly wage (Fan & Hyndman, 2011; Holtedahl & Joutz, 2004; Krishnamurthy & Kristrom, 2015). A priori, higher predicated 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 wage increases they may buy more home appliances and therefore demand more electricity. However a higher wage could allow a person to purchase higher energy efficient appliances, which would demand less electricity. The price of natural gas at the Henry Hub (lnNG) is included as it is a substitute good for electricity. A household may decide to switch over to electricity if the residential price of natural gas exceeds that of the residential electricity price. Time dummies for the Month and

[6] Proxy for residential natural gas prices.

Year are also included. Both Appendix B and C summarize the description of the variables used in the analysis, as well as the hypotheses on 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 (lnPElec). 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 (2, 3 & 4) is at least as large as the number of right-hand side endogenous variables. The variables 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 (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 $\mathrm{Cov}(\varepsilon i,t,c \mid Xi,t,c) = 0$, 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, taking into account the cross equation correlation of error. The instrumental variables Z are correlated with the regressors' $E[z'x] \neq 0$, while Z is also uncorrelated with the error term ε, $E[z' \varepsilon] = 0$ and Z is not a direct cause of the dependent variable y, $\mathrm{cov}[y, z \mid x] = 0$ (Wooldridge, 2010).

3.3. **Descriptive Statistics**

The three main variables of interest in our positive feedback cycle model are the variables of residential solar PV uptake, the residential electricity price and the residential electricity demand. The following section details the current status of these three variables in the selected countries of this study over the same time period (2010-2015). Table 1 highlights the descriptive statistics associated with these variables.

Table 1 Descriptive statistics

Variable		Mean	Std. Dev	Min	Max
Monthly residential solar PV average capacity installed (kW)	Ireland	3.7	1.5	0	7.6
	UK	2.9	0.4	1.0	3.3
	Australia	3.6	0.6	2.6	4.5
Average Residential Electricity Demand 2010 (Gw/h)	Ireland	2,253	313	1,914	2,681
	UK	9,901	2,366	7,521	14,548
	Australia	5,036	28	4,994	5,081
Average Residential Electricity Demand 2015 (Gw/h)	Ireland	2,088	256	1,803	2,493
	UK	8,915	1,542	7,130	11,436
	Australia	4,975	48	4,857	5,038
Average Residential Electricity Prices 2010 (€/kWh)	Ireland	0.20	0.02	0.18	0.23
	UK	0.17	0.03	0.14	0.21
	Australia	0.14	0.01	0.13	0.16
Average Residential Electricity Prices 2015 (€/kWh)	Ireland	0.24	0.01	0.21	0.25
	UK	0.19	0.03	0.14	0.23
	Australia	0.17	0.02	0.14	0.19

The average rated capacity per installation in Ireland is the highest at 3.7 kW per system, followed by Australia at 3.6 kW and the UK 2.9 kW. Viewing the number of installations of residential solar PV systems per household in each country, again Australia is highest with 0.17 installed systems per household, next is the UK with 0.03 per household and lastly Ireland with 0.0002 per household. 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 4,921 MW added to the grid, followed by the UK at 2,425 MW and Ireland at 1.3 MW. The next variable of interest in the positive feedback cycle is residential electricity price. Ireland has the highest average residential electricity price for the period examined at 0.217 €/kWh, followed by Australia at 0.182 €/kWh and the UK at 0.175 €/kWh. When comparing the average residential electricity price for 2010 to 2015 for each country prices show a slight upward trend. The final variable of interest is the residential electricity demand, the yearly demand figure for electricity is lower in all three countries for 2015 when compared to 2010. The demand for electricity from decrease by 11.7% from 2010 to 2015, the UK the decrease was 11% and Australia experienced a decrease of 0.4%.

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 time period, while the residential electricity prices have increased from 2010 to 2015 and residential electricity demand has decreased over the same period.

4. Results and discussion

The following panel unit root tests were employed Im, Pesaran and Shin (2003) and Levin, Lin and Chu (2002) in this paper to test the stationarity property of each series, it was found that all the series are to be stationary in the level form. To investigate the linkages between solar PV systems, residential prices and demand for the panel of countries a three stage least squares regression is employed. The results of the pooled regression are summarised in tables 2-5 and the results are discussed below.

Table 2 3SLS regression summary results

Equation	Obs	Parms	RMSE	"R-sq"	chi2	P
Solar PV Uptake	211	20	0.191	0.494	195.13	0.00
Residential Electricity Price	211	19	0.096	0.698	530.43	0.00
Residential Electricity Demand	211	21	0.451	0.448	234.06	0.00

Equation 2 Solar PV Uptake	Est.	T-stat	Equation 3 Residential Electricity Price	Est.	T-stat	Equation 4 Residential Electricity Demand	Est.	T-stat
PElec	0.46***	3.49	CoalShare	-0.003***	-7.06	PElec	-2.82***	-5.94
Scheme	0.08	1.27	$Pelec_{t-1}$	0.53***	10.16	PV	-1.6*	-1.37
AvrCostPV	-0.11	-0.82	PV	0.17**	2.05	NG	0.21	0.92
Sunlight	0.05**	1.81				Temp	-0.14*	-1.51
						Wage	-1.24**	-2.39
2011	0.24***	4.73	2011	-0.01	-0.4	2011	0.56**	1.71
2012	0.22***	3.4	2012	0.05*	1.58	2012	0.98***	2.53
2013	0.34***	4.37	2013	0.03	0.74	2013	1.21**	2.21
2014	0.35***	4.11	2014	0.03	0.69	2014	1.23**	2.16
2015	0.35***	4.13	2015	0.01	0.12	2015	1.26***	2.78
February	0.07	1.13	February	0.06**	1.78	February	0.3*	1.45
March	0.02	0.23	March	0.02	0.7	March	0.26*	1.41
April	0.07	1.07	April	-0.03	-0.99	April	0.10	0.51
May	0.03	0.45	May	0.02	0.54	May	-0.01	-0.02
June	0.08	1.18	June	0.02	0.49	June	0.10	0.45
July	-0.04	-0.63	July	0.03	0.97	July	-0.07	-0.38
August	0.00	0.04	August	0.04	1.24	August	0.08	0.41
September	0.08	1.17	September	-0.004	-0.12	September	0.07	0.33
October	0.07	1.05	October	0.04	1.15	October	0.24	1.13
November	0.08	1.17	November	0.08**	2.29	November	0.44**	2.01
December	0.16**	2.28	December	0.02	0.61	December	0.52**	1.94

Statistically significant at the 10% (*), 5% (**), 1% (***) level.

The first equation in our simultaneous equation model is the solar uptake equation (2), the variables included were the ones thought to be the main drivers behind the residential sectors uptake of solar PV systems. However, the variable that is of most importance to us in discovering whether a positive feedback cycle is in effect is the residential electricity price. The positive feedback cycle theorized that an increase in residential electricity price would lead to a higher uptake in solar PV. The main results from our regression of the solar PV uptake equation (2) are summarised in Table 3. They highlight that a 1% increase residential electricity price will increase residential solar PV uptake by 0.46%, while the variable is statistically significant at the 1%. This result fits into 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.

Table 3 3SLS regression summary results. Statistically significant at the 10% (*), 5% (**), 1% (***) level.

Equation 2 Solar Uptake	Coefficient	T-Statistics
Residential Electricity Price	0.46^{***}	3.49
Sunlight Hours	0.05^{**}	1.81

Other results from the solar uptake equation (Table 2) show that a 1% increase in the average monthly sunlight hours by 1%, will increase the monthly residential solar PV average uptake by 0.05%, while it is statistically significant at 5%. Surprisingly, the variables of government support scheme and the average cost of solar PV are statistically insignificant and do not influence the decision making process for residential solar PV. All dummy year variables are statistically significant and positive, indicating that every year since 2010 there has been an increase in the residential solar PV uptake. There is only one dummy month variable that is statistically significant, in December, where the residential solar PV average capacity installed is higher than that in January.

The next equation in our simultaneous equation model is the residential electricity price equation (3), included were the variables thought to be the drivers between residential electricity price changes. The variable of most interest is that of the residential solar PV uptake variable, where under the positive feedback cycle an increase in the uptake of residential solar PV will result in an increase in residential electricity prices. The price increase, as explained in section 3.2 early, is a result of falling demand and expenditure on infrastructure to deal with the rapid changes in the demand portfolio.

The main results from the regression of this equation are summarized in Table 4. These results are in line with the positive feedback cycle, with the residential solar PV uptake variable being statistically significant at the 5% level, while they indicate that a 1% increase in the residential solar PV uptake variable results in a 0.17% increase in the price of residential electricity.

Table 4 3SLS regression summary results. Statistically significant at the 10% (*), 5% (**), 1% (***) level.

Equation 3 Residential Electricity Price	Coefficient	T-Statistics
Coal Share	-0.003^{***}	-7.06
Lagged Electricity Price	0.53^{***}	10.16
Solar PV Capacity Installed	0.17^{**}	2.05

Other results from the residential electricity price equation (Table 2) show that a 1% increase in the price of the previous month's residential electricity price will increase this month's prices by nearly 0.53%. An increase in coal share used in electricity production is statistically significant at the 1% level, with an increase of 1% in this fuel source used in electricity production leading to a decrease in residential electricity prices by 0.002%. Only the dummy year variable 2012 is statistically significant, implying that residential electricity prices are higher in 2012 compared to those in 2010. There are only two dummy month variables that are statistically significant, i.e. in February and November, indicating that the residential electricity price in these months is higher than that in January.

The final equation in our simultaneous equations model is the residential electricity demand equation (4). Under the conditions of the positive feedback cycle theory, residential electricity demand will decrease as a result of increased solar PV uptake. The main regression results from this equation are presented in Table 5 and support the presence of a positive feedback cycle.

Table 5 3SLS regression summary results. Statistically significant at the 10% (*), 5% (**), 1% (***) level

Equation 4 Residential Electricity Demand	Coefficient	T-Statistics
Residential Electricity Price	-2.81^{***}	-5.94
Solar PV Capacity Installed	-1.59^{*}	-1.37
Average monthly Temperature	-0.14^{*}	-1.51
Average monthly Wage	-1.24^{**}	-2.39

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Using the regression results from Table 5, both the price elasticity of residential electricity demand and the residential solar PV uptake elasticity of residential electricity demand can be calculated. The theory suggests that electricity demand will fall as electricity prices increase, *ceteris paribus*. The residential consumer's sensitivity to price changes can be measured by the coefficient of price elasticity, i.e. the percentage change in electricity demand divided by the percentage change in price, *ceteris paribus* (Fan & Hyndman, 2011). Our model is specified in a log-log form and the estimated price elasticity of residential electricity demand can be obtained from the estimation of residential electricity demand in Equation (4). The estimated price elasticity of residential electricity demand is 2.81 and is statistically significant at the 1% level. The estimated figure indicates that a 1% increase in the residential electricity price, will lead to a decrease in residential electricity demand by 2.89%.

The residential solar PV uptake elasticity of residential electricity can be obtain directly from the results presented in Table 2: the residential solar PV elasticity of residential electricity demand is 1.59 and is statistically significant at the 10% level, indicating that a 1% increase in the residential solar PV uptake will decrease the amount of residential electricity demand by the residential sector by nearly 1.6%. Moreover, an increase in the average temperature variable by 1% will lead to a decrease in residential electricity demand by 0.14%, while an increase in the average wage by 1% will lead to decrease by 1.22% and is statically significant at the 5% level. Moreover, the negative relationship between the two variables suggests that higher earners can afford better quality electrical appliances with higher energy efficiency ratings, which generates less electricity demand from that household. The natural gas price variable (Table 2), which represents the substitution effect, is statistically insignificant. All dummy year variables are statistically significant and positive, indicating that the residential electricity demand is higher in each year than in 2010. Several of the dummy month variables are also statistically significant and positive, indicating that residential electricity demand is higher in these months than in January.

5. Conclusion and Policy Implications

Residential solar PV systems, as well as other forms of 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 storage options for electricity always improving, micro-RES and the traditional electricity industry could be akin to telephone and what happens to the telegraph industry.

The gaining popularity of solar PV systems in the residential electricity market is not only due to the falling cost of systems, but is also 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 have to 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. In the renewable energy literature, the consensus is that renewable energy systems contribute to lower electricity prices. However, there is a new line of literature investigating the effects of micro-RES, particularly solar PV systems, are having on the traditional energy industry.

This study extended this line of research by examining the residential electricity markets in three countries: the U.K., 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. If environmental goals are to be achieved as well, 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.

Appendix A. Data sources

Variable	Ireland	Britain	Australia
Solar PV Uptake	ESB	gov.uk	Australian Photovoltaic Institute
Cost of Solar PV	The OpenPV Project by National Renewable Energy Laboratory	The OpenPV Project by National Renewable Energy Laboratory	The OpenPV Project by National Renewable Energy Laboratory
Residential Electricity Demand	CSO	GOV.UK	Office of Chief Economist
Coal Share	CSO	GOV.UK	Office of Chief Economist
Price of Natural Gas	Thomson Reuters DataStream	Thomson Reuters DataStream	Thomson Reuters DataStream
Residential Price of Electricity	Eurostat	Eurostat	Australian Energy Market Commission
Wage	OECD Database	OECD Database	OECD Database
Temperature	Met Eireann	GOV.UK	The Bureau of Meteorology
Sunlight Hours	Met Eireann	GOV.UK	The Bureau of Meteorology
Government Support Scheme	ESB	GOV.UK	australia.gov.au

Appendix B. 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	E	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	^{O}C
Lagged Residential Price of Electricity	LPElec	Lagged Price of residential electricity	€
Sunlight Hours	Sunlight	Average monthly duration of Sunlight	Hours
Government Support Scheme	Scheme	Dummy Variable for years that a support scheme was operational	1 = scheme open, 0 = scheme closed

Appendix C. 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.

References

Allen, S. R., Hammond, G. P., & McManus, M. C. (2008). Prospects for and barriers to domestic micro-generation: A United Kingdom perspective. *Applied Energy, 85*(6), 528-544.

Arthur, W. B. (1990). POSITIVE FEEDBACKS IN THE ECONOMY. *Scientific American, 262*(2), 92-&.

Balcombe, P., Rigby, D., & Azapagica, A. (2013). Motivations and barriers associated with adopting microgeneration energy technologies in the UK. *Renewable & Sustainable Energy Reviews, 22*, 655-666.

Ballester, C., & Furio, D. (2015). Effects of renewables on the stylized facts of electricity prices. *Renewable & Sustainable Energy Reviews, 52*, 1596-1609.

Balta-Ozkan, N., Yildirim, J., & Connor, P. M. (2015). Regional distribution of photovoltaic deployment in the UK and its determinants: A spatial econometric approach. *Energy Economics, 51*, 417-429.

Cai, D. W. H., Adlakha, S., Low, S. H., De Martini, P., & Chandy, K. M. (2013). Impact of residential PV adoption on Retail Electricity Rates. *Energy Policy, 62*, 830-843.

CER. (2016). Eligible systems. Retrieved 22 August, 2016, from http://www.cleanenergyregulator.gov.au/RET/How-to-participate-in-the-Renewable-Energy-Target/Choosing-a-system/Eligible-systems

Chew, M., Heling, M., Kerrigan, C., Jin, D., Tinker, A., Kolb, M., et al. (2012). *Modelling Distributed Generation Adoption Using Electric Rate Feedback Loops.* Paper presented at the 31st USAEE/IAEE North American Conference

Clo, S., Cataldi, A., & Zoppoli, P. (2015). The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy, 77*, 79-88.

Costello, K. W., & Hemphill, R. C. (2014). Electric utilities''death spiral': hyperbole or reality? *The Electricity Journal, 27*(10), 7-26.

Darghouth, N. R., Barbose, G., & Wiser, R. (2011). The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California. *Energy Policy, 39*(9), 5243-5253.

Eryilmaz, D., & Sergici, S. (2016). Integration of residential PV and its implications for current and futureresidential electricity demand in the United States. *The Electricity Journal, 29*, 41-52.

Fan, S., & Hyndman, R. J. (2011). The price elasticity of electricity demand in South Australia. *Energy Policy, 39*(6), 3709-3719.

Felder, F. A., & Athawale, R. (2014). The life and death of the utility death spiral. . *The Electricity Journal, 27*(6), 9-16.

Filippini, M. (2011). Short- and long-run time-of-use price elasticities in Swiss residential electricity demand. *Energy Policy, 39*(10), 5811-5817.

Gelabert, L., Labandeira, X., & Linares, P. (2011). An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. *Energy Economics, 33*, S59-S65.

Gil, H. A., Gomez-Quiles, C., & Riquelme, J. (2012). Large-scale wind power integration and wholesale electricity trading benefits: Estimation via an ex post approach. *Energy Policy, 41*, 849-859.

Holtedahl, P., & Joutz, F. L. (2004). Residential electricity demand in Taiwan. *Energy Economics, 26*(2), 201-224.

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics, 115*(1), 53-74.

ISO, C. (2016). *Flexible Resources Help Renewables - Fast Facts*.

Kaufmann, R. K., & Vaid, D. (2016). Lower Electricity Prices and Greenhouse Gas Emissions due to Rooftop Solar: Empirical Results for Massachusetts. *Energy Policy, 93*, 345-352.

Ketterer, J. C. (2014). The impact of wind power generation on the electricity price in Germany. *Energy Economics, 44*, 270-280.

Krishnamurthy, C. K. B., & Kristrom, B. (2015). A cross-country analysis of residential electricity demand in 11 OECD-countries. *Resource and Energy Economics, 39*, 68-88.

Laws, N. D., Epps, B. P., Peterson, S. O., Laser, M. S., & Wanjiru, G. K. (2017). On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage. *Applied Energy, 185*, 627-641.

Levin, A., Lin, C. F., & Chu, C. S. J. (2002). Unit root tests in panel data: asymptotic and finite-sample properties. . *Journal of econometrics, 108*(1), 1-24.

Li, Z., Boyle, F., & Reynolds, A. (2011). Domestic application of solar PV systems in Ireland: The reality of their economic viability. *Energy, 36*(10), 5865-5876.

Lijesen, M. G. (2007). The real-time price elasticity of electricity. *Energy Economics, 29*(2), 249-258.

McLaren, J., Davidson, C., Miller, J., & Bird, L. (2015). Impact of rate design alternatives on residential solar customer bills: increased fixed charges, minimum bills and demand-based rates. *The Electricity Journal, 28*(8), 43-58.

Mills, A., Wiser, R., Barbose, G., & Golove, W. (2008). The impact of retail rate structures on the economics of commercial photovoltaic systems in California. *Energy Policy, 36*(9), 3266-3277.

Nicholson, E., Rogers, J., & Porter, K. (2010). The relationship between wind generation and balancing-energy market prices in ERCOT: 2007–2009. . *Contract, 303*, 275-3000.

Rodrigues, S., Torabikalaki, R., Faria, F., Cafofo, N., Chen, X. J., Ivaki, A. R., et al. (2016). Economic feasibility analysis of small scale PV systems in different countries. *Solar Energy, 131*, 81-95.

Ruth, M., & Hannon, B. (2012). *Positive Feedback in the Economy. In Modeling Dynamic Economic Systems* Springer US.

Sahu, B. K. (2015). A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. *Renewable & Sustainable Energy Reviews, 43*, 621-634.

Woo, C. K., Horowitz, I., Moore, J., & Pacheco, A. (2011). The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. *Energy Policy, 39*(7), 3939-3944.

Wooldridge, J. M. (2010). *Econometric Analysis of Cross Section and Panel Data* (2nd ed.): MIT Press.

Zellner, A., & Theil, H. (1962). Three-stage least squares: simultaneous estimation of simultaneous equations. *Econometrica Journal of the Econometric Society*, 54-78.

Zhang, Y., Song, J. H., & Hamori, S. (2011). Impact of subsidy policies on diffusion of photovoltaic power generation. *Energy Policy, 39*(4), 1958-1964.