ESRI

Working Paper No. 628

June 2019

The role of socio-economic characteristics in predicting peak period appliance use

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Abstract: Household appliances represent significant load demand within the domestic electricity market, and therefore present considerable challenges for grid managers, specifically during peak demand periods. This paper presents the results of a statistically representative study of Irish households, undertaken specifically to assess peak period domestic appliance use, with respect to time of use and the socio-economic characteristics of the users. Specific attention is devoted to both an analysis of appliance use patterns, and to the likelihood of individuals using such appliances during the evening peak period, with respect to socio-economic characteristics.

Results highlight the presence of potentially deferrable load associated with domestic appliances within the evening peak. Findings from both logit and zero-inflated negative binomial models provide insights into differences in appliance use patterns with regard to employment status, household size, the number of individuals present in the home during the day, and respondents' income. These results highlight the possibility of either targeted marketing campaigns to encourage appliance deferral to periods of lesser demand, or direct load control to reduce peak period appliance demand. In particular, both engagement in full time employment and number of household members present in the home during the day, are found to be significant predictors of whether or not a given household is a peak period appliance user. This suggests that there is scope for automated or remote appliance control to reduce peak period load without adversely impacting consumers. In contrast, household size and income emerge as predictors of the number of appliance use events that occur during the evening peak period.

Keywords: Domestic Appliances, Household Characteristics, Direct Load Control
Classification: D1 Household Behaviour and Family Economics

Acknowledgements: This project was funded as part of the CREDENCE Project (Collaborative Research of Decentralisation, Electrification, Communications and Economics), a US-Ireland Research and Development Partnership Program (centre to centre), funded by Science Foundation Ireland (SFI) and The National Science Foundation (NSF) under grant number 16/US-C2C/329

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1 Introduction and Background

This paper presents the results of research undertaken to gain a better understanding of domestic appliance use behaviour, specifically during the evening peak period. Specific attention is given to appliance loads that may have the ability to be shifted to periods when electricity demand is lower. Large domestic appliances, especially those such as washing and drying appliances that are characterised by discrete user initiated cycles, represent an opportunity to shift load out of peak demand periods without negatively impacting consumers. To understand the potential impact of shifting these loads, it is important to evaluate current levels of appliance use during the evening peak period, and also consider the lifestyle factors that drive such behaviours. This research therefore sets to advance the literature by identifying the relationship between potentially deferrable washing and drying appliance loads and the socio-economic characteristics of the households they belong to.

When assessing the impact of appliance use on domestic load demand, specific attention has been focused upon large washing and drying appliances cycle, and the potential to shift these loads away for the evening peak. Research from the Netherlands utilising load profile data has identified significant contributions from washing machines,tumble dryers, and dishwashers, in terms of increasing domestic electricity consumption [1], while a nationally representative study of UK households reported that appliance ownership and usage, in combination with household size, are the most significant predictors of domestic electricity consumption [3]. Research centred upon a study of the electricity consumption patterns of 183 houses in Leicester in the UK highlighted the increased odds of being defined as a what the study labelled a "high energy consumer" with increased computer usage, when undertaking five or more washing machine loads in a given week, and increased use of the tumble dryer [5]. In terms of the potential for load reductions, modelling work assessing the impact of real-time scheduling of domestic appliances on electricity load demand, examining washing machines, dishwashers, and electric ovens, noted the potential for an 8% reduction with respect to average load and a 41% reduction with respect to worst case scenario [2]. Similar research undertaken in Latvia suggests that deferring or shifting use of washing machines and dishwashers to other non-peak time periods can result in considerable reductions in domestic electricity demand during the peak period [7]. In contrast, research from urban Ghana highlights the impact of cultural and behavioural factors when considering appliance use deferral, as the majority of washing activities occur on Saturday mornings, washing activities were found to have no contribution to residential peak load [12]. When attempting to identify the most suitable domestic appliances for curtailment, a study in the eastern US suggests that tumble dryers are the most preferable of the large appliances for deferral, followed by space heating appliances, and finally by dishwashers and washing machines. This finding was mirrored by similar Dutch research which highlights dishwashers as the most suitable appliances for demand side management (DSM), compared to washing machines and tumble dryers [14], while Irish research has also noted the potential effectiveness of the rescheduling dishwashers away from peak periods to reduce domestic peak period demand [10].

When assessing the potential benefits arising from shifting domestic appliance loads from the evening peak, it is important to consider the factors that drive this appliance demand in the first place, and whether such factors have the potential to act as barriers to load shifting. While the majority of previous research in this area indicates that electricity consumption increases with respect to household size [4], a number of other socio-economic factors have been observed to be linked with consumption and appliance use. Findings from the Japanese domestic energy sector highlights links between both family income and household structure and domestic appliance use [9], while previous research undertaken in Ireland has demonstrated a link between education, employment status, the presence of children in the home and uptake of appliance energy efficiency measures [6]. Other studies have also highlighted the importance of factors such as property value, household income, and years domiciled at current address with an increased likelihood of possessing energy saving features [11]. Analysis of smart metre trials in Ireland reported relationships between factors such as dwelling type, number of bedrooms within the home, household consumption, and the age of the head of the household as being significant determinants of overall electricity consumption [10], while research from the United States found that lifestyle factors accounted for 40% of residential electricity consumption [13]. Overall, it is clear from the literature that a number of characteristics of a household must be considered when assessing its electricity consumption patterns, and, therefore, the resultant potential to alter such consumption patterns in order to achieve the desired reductions in peak load demand.

Therefore, this paper seeks to build upon the existing research and add to the literature by using a na-

tionally representative survey sample of Irish households to assess the role that socio-economic characteristics play in determining peak period use of large domestic washing and drying appliances, with specific attention being given to both overall appliance use patterns and the factors that impact use of specific appliances.

2 Methodology

This research sets out to investigate the relationship between peak period large domestic washing and drying appliance use and the socio-economic characteristics of households. The analysis presented in this paper was undertaken on data collected as part of a wider on-line survey questionnaire designed to examine issues of domestic appliance use in Ireland and potential methods of addressing peak period issues. The sample was specified to be representative of Irish households, as per the national census of 2016 in terms of age, gender, urban/rural split, and household size. The analysis undertaken for this study is composed of two distinct parts: Firstly a descriptive examination of stated appliance use habits of households, with regard to frequency of use and specific time periods during which such uses occur, and secondly an examination of evening peak period appliance use via the application of both logit models and zero-inflated negative binomial models incorporating socio-economic factors as predictor variables.

2.1 Appliance Use Data

In order to collect appliance use data, survey respondents were presented with a number of questions regarding their use of domestic appliances. The appliances of interest were large washing and drying appliances namely: washing machines, clothes/tumble dryers, and dishwashers. Data on electric oven use patterns are included for comparative purposes. These appliances were selected as they are characterised as having distinct discrete cycles, and unlike an appliance such as a refrigerator, these cycles generally have to be initiated through an action undertaken by the user, rather than beginning automatically. Survey respondents were asked how often they used the specific appliances during an average week and during which period of the day did this usage primarily occur. While this collection method may not have the accuracy level associated with methods such as smart metre data, it does have the advantage of allowing for the collection of a larger, and more importantly demographically representative sample, as respondents' demographic characteristics are key to understanding the role of socio-economic factors in appliance use patterns. While smart metres offer the potential to collect precise appliance load data, no information is available without collection of additional data such as that used in this study.

2.2 Evening Peak Modelling

The assessment of the factors that impact evening peak domestic appliance use forms the major contribution of this research. These loads represent demand that could potentially be shifted to another time period when demand is lower, without imposing a major loss of utility to the individual or household. Specifically, it is considered important to identify the washing and drying loads that are occurring during the evening period, as well as the characteristics of the users. To this end, the modelling presented in this paper links the stated appliance use data collected in the survey with the socio-economic characteristics of the respondents. Modelling was undertaken both for specific appliance types via logit models, and also for overall use of washing and drying appliances via a zero inflated negative binomial model.

2.2.1 Appliance Specific Modelling

In order to model the factors that are linked to households' use of the individual appliances a standard logit modelling approach was undertaken, whereby the value of 1 was assigned to any household that stated they used a given appliance predominately in evening peak and a 0 to households that selected another time period. Logit models are one of the most commonly used statistical methods and apply to circumstances were the dependent variable is binary in nature, such as respondents' yes/no responses to questions on evening period appliance use. Unlike a linear regression, logistic regression fits an "S" shaped curve from 0 to 1 indicating the probability of the respondent fitting into one of the two binary states. The general model of

the logistic regression equation is described as:

$$log(p_1) = log(\frac{p_1}{p_0}) = \alpha_0 + \beta_1 X_1 + ...\beta_k X_k \tag{1}$$

Where: p_1 is the probability of the state represented by the value 1 and p_0 is the probability state represented by the value 0, α_0 is the intercept, β is the coefficient estimated for k independent variables and X is the value the independent variable value. For the purposes of this analysis, the results are reported in terms of odds ratios. In the case of the individual appliance models this relates to the odds of using an appliance during the peak period over the odds of not using the same appliance. Odds ratio OR is the inverse log of the reported coefficient β or β raised to the power of the exponential e

$$OR = e^{\beta} \tag{2}$$

2.2.2 Combined Appliance Use

The second aspect of the modelling process centred around an examination of combined evening peak appliance use. Building upon the time period specific logit modelling, this aspect of the research utilised a zero-inflated negative binomial regression model, to account for both the factors that impact use of appliances, and also the frequency of appliance use during the evening period. Where the individual appliance models simply assessed use in binary terms, this modelling also accounts for how often these appliance are used.

Zero inflated negative binomial models are utilised for count data where the dependent variables are observed to be over dispersed and there are a very large number of zeros observed within the data [8]. Specifically it is assumed that there are two distinct processes leading to the observation of zeros, hence the requirement for the combination of two explanatory models. Therefore the model is composed of a two stage process, involving the combination of a standard logit model modelling the probability of the dependent value being a zero, and a negative binomial model predicting the count value observed. For the purposes of this research the logit component of the model accounts for whether or not the individual is likely to be an evening peak user, while the negative binomial model accounts for the frequency of use these appliances. In both components of the model the socio-economic characteristics of the household are included as the predictors of both being an evening user, and if so, the frequency with which the appliances under examination are used.

Assuming for this model that a response can either take the form of a zero or non zero outcome, with the probability of a zero outcome being π and the probability of a non zero outcome being $1 - \pi$, the probability density function associated with zero inflated negative binomial for a given dependent variable y_i is given as:

$$Prob(y_i = j) = \begin{cases} \pi_i + (1 - \pi_i)k(y_i = 0) & if\ j = 0 \\ (1 - \pi_i)k(y_i) & if\ j > 0 \end{cases} \tag{3}$$

Where π is the logistic function element of the model and $k(y_i)$ is the negative binomial distribution. This distribution is defined by:

$$Prob(Y = y_i) = \frac{\Gamma(y_i + \alpha^{-1})}{\Gamma(\alpha^{-1})\Gamma(y_i + 1)} * \Big(\frac{1}{1 + \alpha\mu_i}\Big)^{\alpha^{-1}} * \Big(\frac{\alpha\mu_i}{1 + \alpha\mu_i}\Big)^{y_i} \tag{4}$$

Where μ and α are the parameters of the negative binomial distribution, where μ is normal set to 1. The logit element of the model takes the form as described in the previous section.

3 Results

The results of this study are presented as follows: An outline of descriptive statistics highlighting the overall appliance use patterns within the sample with respect to time periods under examination, followed by an examination of the relationship between the socio-economic characteristics of the respondents and their peak period appliance use habits in terms of both appliance specific and combined appliance use models.

3.1 Sample Characteristics

The sample of households gathered for this study was designed to be statistically representative of the Irish population based upon age, gender, household size, as well as regional distribution. Table 1 provides an outline of the sample characteristics with a comparison to the Irish population as of the national census of 2016. Education levels presented in this table and subsequent analysis represent an amalgamation of the categories contained in the Irish census of 2016. This is done for the purposes of allowing an easier interpretation of results, as well as enabling comparisons to equivalent international educational standards. The category "Secondary" is roughly equivalent to international high school qualifications or below, the category "Tertiary" relates to post-high school but below honours degree education, while the "Honours/Postgraduate" category relates to to honours third level degree courses and higher qualifications such as masters degrees and Ph.D.s. Data on stated household income within the sample is also provided, however there is not an equivalent national reference to compare this to.

3.2 Appliance Ownership and Use

To enable appliance use frequency modelling, respondents were asked to state when they primarily use a given appliance, and also to estimate the average number of times per week they used it, by selecting the appropriate category from a pre-defined list. To allow for better analysis of the respondents' appliance use habits, the categorical responses collected in the questionnaire were to be transformed into numerical values using the mid interval values of the respective categories as outlined in Table 2. A value 0.5 being assigned to "less than once per week" and a value of 10 being assigned to "more than eight times per week".

Based upon these mid-interval values, estimates of both total weekly and time period specific appliance uses can be estimated, and the descriptive statistic regarding these resultant values are outlined in Table 3. Estimates are provided in terms of weekly uses of each appliance. In addition, mean appliance use events for each of the respective appliances in each of the the four time periods under examination are provided. The combined appliance use figure represents a simple summation of the four appliances, either for the week as a whole, or within each of the specified time periods. Results show that the oven is the most frequently used appliance, with an average value of 4.87 uses per respondent per week. This is followed by washing machines which is used on average 3.53 times during the week, followed by the dishwasher with a value of 2.58 and the dryer with a value of 1.21. In terms of total appliance use, the mean value per respondent is observed to be 12.52 events per week. Nearly half of these (5.98) occur during the evening peak period. Although the majority of this use is accounted for by the electric oven, there are still significant contributions from the other less time period dependent appliances, specifically the dishwasher with 1.22 uses in this period per week.

Figure 1 provides a graphical illustration of the distribution of weekly appliance use events across the four time periods under examination. While outlining the high levels of oven use during the evening peak period, this figure also displays relatively high levels of use for the other domestic appliances in this period, with the highest levels of dishwasher use being observed in this period as well as the second highest level of washing machine use. This suggests the presence of a significant appliance load that may be suitable for curtailment or deferral to other periods.

Table 4 outlines the distribution of appliance uses across the time periods under examination expressed in terms of a percentage of the total uses of the respective appliances, so for example, 21% of dryer uses occur in the morning period. As expected, the majority of oven use events (78%) occur during the evening peak, however it is also observed that this is the period wherein the highest levels of dishwasher (51%) and dryer (36%) usage occur. The evening peak is also the period during which the second highest proportion of washing machine uses occur with a value of 26%.

Table 1: Sample Socio-Economic Properties

	Share	National*
Age Group		
18-24 years	10.12%	10.99%
25-34 years	16.91%	18.47%
35-44 years	21.11%	20.91%
45-54 years	18.77%	17.5%3
55-64 years	16.42%	14.25%
65+ years	16.67%	17.85%
Gender		
Male	44.94	48.88
Female	55.06	51.12
Residence		
Rural	36.42%	39.91%
Urban	63.58%	60.09%
Education		
Secondary	26.16%	48.65
Tertiary	35.43%	29.13
Honours/Postgraduate	38.41%	22.23
Household		
One or Two Members	51.48%	52.07%
Three Members	18.89%	17.48%
Four Members	18.89%	16.94%
Five Plus Members	10.74%	13.51%
Full Time Employed		
Yes	60.12%	53.43%
Other	39.88%	46.57%
Income		
Below €2000	26.86%	N/A
€2000–4000	56.63%	N/A
Over €4000	16.50	N/A
*Irish Census 2016		

Table 2: Mid Interval Values

Appliance Use Category	Assigned Value
Less than once per week	0.5
Once or twice per week	1.5
Three to five times per week	4
Six to eight times per week	7
More than eight times per weel	10

Table 3: Weekly Appliance Use Events By Time Period

	Oven	Dish Washer	Washing Machine	Tumble Dryer	Combined Total
Weekly Mean	4.40	2.58	3.53	1.21	12.19
Standard Dev..	3.27	2.92	2.64	1.92	7.22
Morning Mean	0.14	0.26	1.36	0.22	1.97
Standard Dev.	0.97	1.26	2.37	0.93	3.44
Afternoon Mean	0.73	0.24	0.7	0.35	2.02
Standard Dev.	2.05	1.2	1.89	1.21	3.75
Evening Mean	3.44	1.22	0.84	0.38	5.87
Standard Dev.	3.43	2.36	1.98	1.18	5.65
Nightly Mean	0.09	0.64	0.32	0.12	1.18
Standard Dev.	0.86	1.82	1.28	0.73	2.99

Figure 1: Appliance Use During Different Time Periods

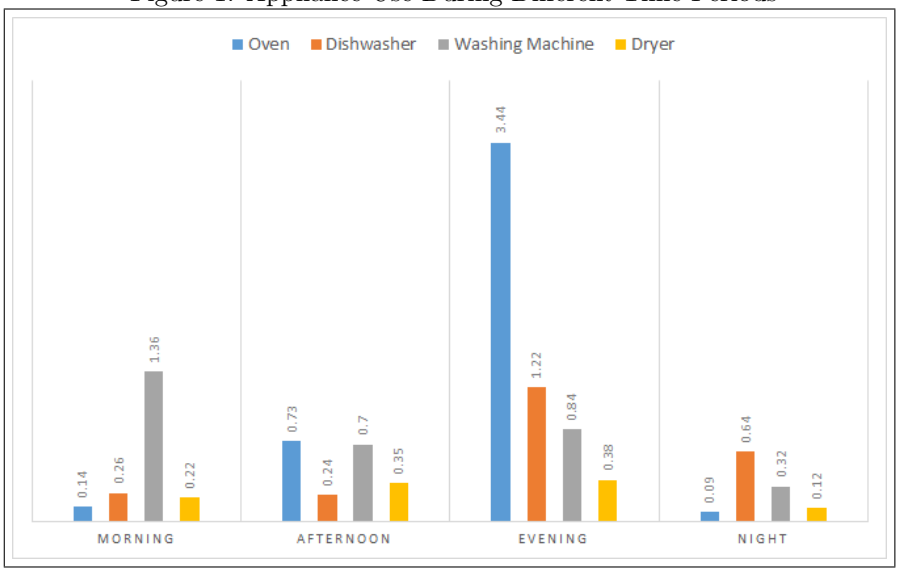

Table 4: Appliance Use Time Period Distribution

	Oven	Dishwasher	Washer	Dryer
Morning	3.18%	11.02%	42.24%	20.56%
Afternoon	16.59%	10.17%	21.74%	32.71%
Evening	78.18%	51.69%	26.09%	35.51%
Night	2.05%	27.12%	9.94%	11.21%

Finally, Table 5 outlines the percentage of respondents by the number of washing and drying appliances they use that they report during the evening peak. These results show that, while nearly half of the sample use at least one of the appliances during the evening peak, multiple peak period appliance users are not a very common occurrence, only with 11.42% of the sample using two appliances and only 5.66% of the sample using all three during the evening peak period at least per week.

Table 5: Evening Appliances Used

	Percent of Sample
Zero Appliances	53.4%
One Appliance	29.53%
Two Appliances	11.42%
Three Appliances	5.66%

3.3 Evening Peak Appliance Use Modelling

The principal aim of this study is to examine levels of domestic appliance use during the evening peak period and its relationship to the socio-economic characteristics of the respondents. Whereas the previous section outlined appliance use across the four time periods, the results presented in this section focus specifically on the evening period. This relationship is modelled in two ways: Firstly appliance specific peak period user identification logit models examining the factors that impact use of the three large washing and drying appliances under assessment. The second stage of the analysis involved the application of a zero-inflated negative binomial modelling approach to examine combined evening peak appliance use, and adds to previous modelling by also accounting for frequency of use during this period.

3.3.1 Specific Appliance Use Modelling

The first element of this research centred around appliance specific logit models assessing the role of socio-economic and household characteristics in predicting the use of large washing and drying appliances in the evening peak period. Table 6 outlines the results of the appliance specific logit models specified for use of the three cleaning appliances during the peak time period. A model is estimated for each of the respective appliances, with the dependent variable taking the value of 1 where the respondent is a peak period user of that appliance, and taking a value of 0 otherwise. Distinct differences are observed regarding the statistical significance of various dependent attributes for the three appliances.

With regard to age, the only significant difference with respect to evening appliance use is observed with respect to the dishwasher, where an odds ratio of 1.93 is observed for over 55s compared to the reference group of 18 to 34 year olds. Regarding the employment status of the respondents, increased levels of evening appliance use is associated with respondents being engaged in full time employment with odds ratios of 1.6 and 1.51 for the dishwasher and washing machine respectively with respect to those with the "Other" employment status. Employment status is not observed to be linked to evening period dryer use. No significant differences in evening appliance use is observed between urban and rural respondents or with regard to the highest level of education attained by the respondents.

With regard to the role of household size in determining peak period appliance use, significant differences are observed for each of the appliances under examination. For the dishwasher significantly higher levels of evening use occurs for households of four or more members. For the washing machine, for all cohorts other than two persons families, odds of double the reference group are observed, with regard to likelihood of appliance use. Finally, the most marked differences in evening peak appliance use are observed for the dryer where odds ratio values ranging 2.48 for the two person families to 8.77 for families with five plus members emerge. Regarding the numbers of household members present in the home during the day time, significant differences are observed for both the washing machine and the tumble dryer, but not for the dishwasher. In terms of washing machine use, odds ratios of between 0.23 and 0.36 are observed where one or more individual is present at home during the day, suggesting much lower odds of appliance use during the peak period if members of the household had been able to access these appliances during other periods. Results for the tumble dryer are less pronounced, although lower odds ratios are observed for households with one

or two members home, with respect to the reference group of zero individuals at home. Finally, with respect to income, statistically significant results are only observed for peak period use of the dishwasher, where increased levels of income are associated with increased use of this appliance, with odds ratios of 1.46 and 2.36 for the €2000-4000 and over €4000 cohorts respectively.

3.3.2 Zero Inflated Negative Binomial Regression

The second stage of the modelling process centres around the examination of a combined appliance use variable, taking into account both the use of appliances, as explored in the logit models, while also considering the frequency of use of these appliances during the evening peak. The dependent variable for this analysis was the combined use of the three appliances during the evening peak period, with the dependent variable having a mean of 2.6 appliance uses per week, with a standard deviation of 4.1 appliance uses and an observed minimum of 0 and an observed maximum of 27.

Table 7 outlines the results of the zero inflated negative binomial model, in terms of both the logit (Appliance Users) and the negative binomial (Appliance Uses) components of the models, as well as the resulting marginally effects associated the negative binomial component.

First considering the zero inflation element of the model, it can be seen that a number of factors are statistically significant. For the purposes of model interpretation, where coefficients are observed to be negative in sign, higher variable values (or taking the value of 1 in the case of binary terms) signifies a higher probability of using the appliances in the evening peak period. The results of this model indicate that engagement in full time employment and the number of appliances (i.e. washing machines, dishwashers, tumble dryers) present in the house are significant predictors of evening appliance use. Conversely, households with members home during the day are approximately twice as likely to have no appliance uses in the evening.

Considering the negative binomial element of the model, it is observed that a number of factors are significant predictors of the frequency of appliance use in the peak period. Specifically, household size and income emerge as being associated with appliance use at $p< 0.05$, while age and rural/urban divide are significant at a level of $p< 0.1$. Increases in household size, with respect to the reference category of one member, is linked to an increase in evening appliance use. In addition, it is seen that with each increase in the number of a household members there is a corresponding increase in the likelihood of evening washing and drying appliance use. Income also emerges as a significant factor, with levels of appliance use increasing with respect to increases in stated household income. Additionally, urban households are observed to have a greater likelihood of increased peak period appliance use, but at a significant of $p< 0.1$ rather than 0.05.

Considering the marginal effects associated with the negative binomial element of the model results show that engagement in full time employment is associated with approximately an extra 0.7 appliance uses compared to the reference group. In addition, increases in household size are associated with increased appliance use, ranging from 0.87 extra uses for a two person family to 3.19 extra uses for a household of five or more, in comparison to a single person household. Marginal effects estimates relating to the number of household members present in the home during the day show quite consistent results, with three of the four cohorts displaying roughly one to one and a half fewer peak period appliance uses than those households with no one home during the day. Finally, considering the stated income of the household, it is observed that there are a 0.95 additional peak period appliance uses associated with the highest income group, in comparison to the reference group of lowest earners.

4 Discussion and Conclusions

The research presented in this paper was undertaken to better understand domestic appliance use habits of households during the evening peak, as well as the relationship between use of these appliances and the defining socio-economic characteristics of the households. Specific attention is given to large washing and drying appliances defined by discrete cycles which need to be initiated by the individual, and that have the potential to be shifted to other periods of decreased demand. Using a nationally representative sample of Irish households, this research provides insight into the factors associated with the use of such appliances during the peak period.

An examination of overall weekly appliance use patterns identifies that a considerable proportion of washing and drying activities occur during the evening peak, a period when load demand is at its highest

Table 6: Non Cooking Evening Appliance Use

Observations	Dishwasher 926		Washer 922		Dryer 926	
	Odds	P>z	Odds	P>z	Odds	P>z
Age						
18-34	Ref	Ref	Ref	Ref	Ref	Ref
35-54	1.02	0.92	1.31	0.19	0.94	0.78
55 Plus	1.93	0.00	0.68	0.12	1.40	0.18
Employment						
Other	Ref	Ref	Ref	Ref	Ref	Ref
Full Time	1.60	0.01	1.51	0.05	1.26	0.27
Location						
Rural	Ref	Ref	Ref	Ref	Ref	Ref
Urban	1.08	0.64	1.15	0.42	1.14	0.48
Education						
Level 1	Ref	Ref	Ref	Ref	Ref	Ref
Level 2	1.10	0.64	0.98	0.91	1.57	0.06
Level 3	0.90	0.61	0.82	0.40	1.08	0.74
Household Members						
One	Ref	Ref	Ref	Ref	Ref	Ref
Two	1.62	0.07	1.52	0.16	2.48	0.02
Three	1.29	0.39	2.03	0.03	6.02	0.00
Four	2.17	0.01	2.33	0.01	5.56	0.00
Five Plus	1.98	0.05	2.12	0.05	8.77	0.00
Members Home						
Zero	Ref	Ref	Ref	Ref	Ref	Ref
One	0.84	0.39	0.31	0.00	0.57	0.02
Two	0.87	0.56	0.36	0.00	0.39	0.00
Three	1.03	0.93	0.31	0.01	0.49	0.09
Four	1.04	0.83	0.20	0.00	0.75	0.53
Income						
Below €2000	Ref	Ref	Ref	Ref	Ref	Ref
€2000–4000	1.46	0.05	1.20	0.41	0.90	0.65
Over €4000	2.36	0.00	1.25	0.43	0.90	0.73
Constant	0.12	0.00	0.24	0.00	0.06	0.00

Table 7: Evening Peak Appliance Use: Zero Inflated Negative Binomial Model

	Appliance User	Appliance Uses	Appliance Uses
	Odds Ratio	Odds Ratio	Marginal effects
Age (ref = 18–34)			
35–54	0.828	0.983	0.154
	(0.160)	(0.092)	(0.281)
55 Plus	0.915	1.198*	0.577
	(0.199)	(0.125)	(0.353)
Employment (ref = not full-time)			
Full Time	0.673**	1.112	0.696**
	(0.120)	(0.101)	(0.272)
Location (ref Rural)			
Urban	0.781	1.143*	0.597**
	(0.126)	(0.088)	(0.236)
Education (ref = Secondary)			
Tertiary	0.839	0.923	-0.023
	(0.165)	(0.088)	(0.326)
Honours/Postgraduate	1.106	0.853	-0.513
	(0.225)	(0.087)	(0.326)
Household size (ref = one member)			
Two	0.636*	1.426**	0.871***
	(0.172)	(0.218)	(0.242)
Three	0.771	2.123***	1.619***
	(0.233)	(0.345)	(0.357)
Four	0.685	2.537***	2.336***
	(0.217)	(0.417)	(0.439)
Five Plus	0.613	3.019***	3.195***
	(0.220)	(0.539)	(0.648)
Number at home during day (ref = zero)			
One	2.065***	0.906	-1.150***
	(0.451)	(0.087)	(0.369)
Two	1.784**	0.765**	-1.380***
	(0.447)	(0.090)	(0.408)
Three	1.860	0.928	-0.970
	(0.714)	(0.157)	(0.633)
Four	1.146	0.668**	-1.285**
	(0.552)	(0.136)	(0.623)
Income (ref = Below €2000)			
€2000–4000	1.214	1.263**	0.355
	(0.236)	(0.127)	(0.264)
Over €4000	1.093	1.492***	0.949**
	(0.286)	(0.187)	(0.411)
Number of appliances	0.455***		
	(0.050)		
Constant	7.562***	2.158***	
	(3.206)	(0.426)	
α		0.328***	
		(0.047)	
Number of observations	926		

$*p < 0.1,\ **p < 0.05,\ ***p < 0.01$. Standard error in parenthesis

across the grid. This suggests that there is the potential to defer or move such appliance loads into periods when demand from other loads is less pronounced, and thereby reducing stress on the network. Specifically, nearly half of respondents undertake some form of washing or drying activity at least once per week during the peak. However, this activity appears to be spread across the three appliances under examination, with only slightly more than one in twenty respondents using all three appliances during the peak period.

The second part of the research focuses on examining the socio-economic characteristics associated with peak period appliance use. Analysis of the relationship between the socio-economic factors and appliance use patterns via the individual appliance level logit models highlights that peak period appliance use is associated with factors including household size, the number of individuals in a given household who are present during the daytime, and whether or not the respondent is engaged in full time employment. Notably, the presence of individuals home during the day is found to be significantly negatively linked to use of the washing machine and tumble dryer during the peak period, with odds reductions of roughly one half being observed in some cases. This suggests that the individuals present in the home during the day may be undertaking the washing and drying cycles for the household, however this difference was not observed to be significant for the dishwasher. In contrast, the respondents' employment status was observed to positively and significantly linked to increased peak period use of dishwashers and washing machines, again suggesting that lack of daytime access to these appliances is a driver of peak period use, however this was not observed to be the case for tumble dryers.

Results of the zero inflated negative binomial model of combined appliance use indicate that the factors associated with whether or not an individual uses an appliance during the peak period are not the same as those associated with how often they use such appliances. Engagement in full time employment, household members present in the home during the day, and the number of appliances owned by the household were found to be significantly associated with peak users, reflecting the results of the appliance specific logit models, however the frequency of appliance use is linked to factors such as stated income, the number of individuals in the household, and whether it is located in an urban or rural setting. For example, urban households have a mean number of evening peak appliance uses of roughly one and a half times that of rural households, while large sized households of five or more people use their appliances three times more on average than single person households in the evening peak.

Overall, both the descriptive statistics and the results of the respective logit and zero inflated negative binomial models indicate there is a considerable amount of potentially deferrable load, comprised of washing and drying appliances present within the evening peak period, and that this load can be related to the socio-economic characteristics of the households. As increased levels of peak period appliance use is observed to be correlated with full time employment and inversely correlated with the presence of individuals home during the morning and afternoon periods, this suggests there may be the potential for a combination of smart appliances and direct load control measures to enable such households to shift there appliance use to other periods.

Acknowledgements

This project was funded as part of the CREDENCE Project (Collaborative Research of Decentralisation, Electrification, Communications and Economics), a US-Ireland Research and Development Partnership Program (centre to centre), funded by Science Foundation Ireland (SFI) and The National Science Foundation (NSF) under grant number 16/US-C2C/3290.

References

[1] Merve Bedir, Evert Hasselaar, and Laure Itard. Determinants of electricity consumption in dutch dwellings. *Energy and buildings*, 58:194–207, 2013.

[2] Davide Caprino, Marco L Della Vedova, and Tullio Facchinetti. Peak shaving through real-time scheduling of household appliances. *Energy and Buildings*, 75:133–148, 2014.

[3] Gesche Huebner, David Shipworth, Ian Hamilton, Zaid Chalabi, and Tadj Oreszczyn. Understanding electricity consumption: A comparative contribution of building factors, socio-demographics, appliances, behaviours and attitudes. *Applied energy*, 177:692–702, 2016.

[4] Rory V Jones, Alba Fuertes, and Kevin J Lomas. The socio-economic, dwelling and appliance related factors affecting electricity consumption in domestic buildings. *Renewable and Sustainable Energy Reviews*, 43:901–917, 2015.

[5] Rory V Jones and Kevin J Lomas. Determinants of high electrical energy demand in uk homes: Appliance ownership and use. *Energy and Buildings*, 117:71–82, 2016.

[6] Amir Kavousian, Ram Rajagopal, and Martin Fischer. Ranking appliance energy efficiency in households: Utilizing smart meter data and energy efficiency frontiers to estimate and identify the determinants of appliance energy efficiency in residential buildings. *Energy and Buildings*, 99:220–230, 2015.

[7] Ilze Laicane, Dagnija Blumberga, Andra Blumberga, and Marika Rosa. Reducing household electricity consumption through demand side management: The role of home appliance scheduling and peak load reduction. *Energy procedia*, 72:222–229, 2015.

[8] Jerald F Lawless. Negative binomial and mixed poisson regression. *Canadian Journal of Statistics*, 15(3):209–225, 1987.

[9] Shigeru Matsumoto. How do household characteristics affect appliance usage? application of conditional demand analysis to japanese household data. *Energy Policy*, 94:214–223, 2016.

[10] Fintan McLoughlin, Aidan Duffy, and Michael Conlon. Characterising domestic electricity consumption patterns by dwelling and occupant socio-economic variables: An irish case study. *Energy and buildings*, 48:240–248, 2012.

[11] Joe ODoherty, Sean Lyons, and Richard SJ Tol. Energy-using appliances and energy-saving features: Determinants of ownership in ireland. *Applied Energy*, 85(7):650–662, 2008.

[12] Marriette Sakah, Stephane de la Rue du Can, Felix Amankwah Diawuo, Morkporkpor Delight Sedzro, and Christoph Kuhn. A study of appliance ownership and electricity consumption determinants in urban ghanaian households. *Sustainable Cities and Society*, 44:559–581, 2019.

[13] Thomas F Sanquist, Heather Orr, Bin Shui, and Alvah C Bittner. Lifestyle factors in us residential electricity consumption. *Energy Policy*, 42:354–364, 2012.

[14] MR Staats, PDM de Boer-Meulman, and WGJHM van Sark. Experimental determination of demand side management potential of wet appliances in the netherlands. *Sustainable Energy, Grids and Networks*, 9:80–94, 2017.