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Consumer preferences for end-use specific curtailable electricity contracts on household appliances during peak load hours

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Abstract: *Growth in energy demand together with the expansion of variable renewables has significant implications for the future electricity system. The increased volatility from growing intermittent production requires new sources of flexibility at a much greater scale to help maintain system balance. In particular, it is necessary to encourage demand reduction during peak load periods in order to avoid high cost capital investments in accommodating future peak capacity. Curtailable electricity contracts are one incentive-based Demand Response (DR) instrument that could help increase demand flexibility in the residential sector. Specifically, end-use specific curtailable contracts work by curtailing the household load directly related to the final energy service provided, for example a washing machine. To help understand consumer preferences for these types of contracts, this paper employs a discrete choice experiment on a large representative sample of electricity consumers to elicit their preferences for end-use specific curtailable contracts on different household appliances during the peak load hours between 5pm and 8pm in the evening. Furthermore, this paper estimates the compensations required by consumers to accept curtailable contracts and conducts a welfare analysis from the consumer's standpoint to determine the welfare effects for 96 different contract scenarios. In general, there is a large potential for demand flexibility from end-use specific curtailable contracts with consumers found to prefer curtailable contracts compared to their status quo electricity contracts on average. More specifically, the results show that the type of household appliance in these contracts has the most influence on consumer's preferences. The findings also suggest that consumers prefer contracts at low event frequencies that also include advance notice and an opt out. Overall, the compensations required for such contracts are estimated to be comparatively reasonable to other contract types examined in the literature.*

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1. Introduction

In efforts to combat climate change and to meet greenhouse gas emissions targets, there has been a worldwide expansion of variable renewable electricity generation. For instance, the International Energy Agency (IEA) expects that variable renewables will switch places with coal in the global power mix by 2040 with the share of renewable generation predicted to be around 40% (IEA, 2018). On the other hand, rising incomes, growing populations in developing countries, and a change in consumer tastes towards the electrification of heat and transport are expected to further push up global electricity demand. This growth in demand together with the expansion of variable renewables will have significant implications for the future electricity system. One main concern is how the system can maintain balance between supply and demand with growing intermittent production from renewable sources such as solar PV and wind power that result in volatility for the energy system's residual load. For this reason, there is an increasing demand for flexibility. At present, the power system's balance relies primarily upon traditional sources of flexibility on the supply side i.e. from the conventional power plants and the electricity grid, though with the transition underway to a more decarbonised system, new sources of flexibility are required and at a much greater scale. Specifically, this flexibility will be achieved through mechanisms including new interconnections, energy storage and demand response.

Demand response (DR) is a flexibility instrument increasingly employed by utilities and grid operators to promote behavioural change in the energy use of consumers and is considered to be an effective way to balance systems with large shares of intermittent electricity generation (Aghaei and Alizadeh, 2013; Lund et al., 2015; Stötzer et al., 2015; Feuerriegel and Neumann, 2016; Parrish et al., 2019). The main aim of DR is to encourage lower power usage during periods when the electricity system is imbalanced between supply and demand or when electricity market prices are unfavourable during peak load conditions. DR programmes allow consumers a greater role in reducing their energy consumption and shifting their demand for energy during these peak periods by either improving the information available on potential energy efficiency opportunities or by giving a financial incentive to decrease their overall energy use. The evolution of 'smart metering' and 'smart loads' as fundamental blocks of the 'smart grid' have made residential DR more effective (Strbac, 2008; Faruqui et al., 2010; Joskow, 2012; Goulden et al., 2014; Benetti et al., 2016) by increasing the frequency and availability of opportunities for flexibility in energy demand.

One incentive-based DR instrument that benefits significantly from the support of the 'smart grid' is so-called curtailable/interruptible electricity contracts (Woo et al., 2014), whereby utilities get access to a consumer's load to either interrupt it entirely or to curtail it to some degree during periods of system instability. Similarly, another form of curtailable contract is end-use specific in that the load curtailed is directly related to the final energy service provided, for example, a remotely operated power button on a washing machine. These types of contracts are valuable to the grid in terms of reducing expensive generation capacity from the flexibility they provide grid operators for peak load reduction, and to consumers, in term of the financial incentives that they would receive to reduce their peak consumption. While interruptible/curtailable load contracts are relatively commonplace in the industry and commercial sectors, there is very little penetration of such contracts in the residential sector where a large potential for increased system flexibility exists.

In the European Union (EU) alone, residential energy demand represents a significant share of overall energy consumption, accounting for a quarter of total energy consumption. As a consequence, it is a key priority area for EU policymakers concerned with the engagement of its citizens in a so-called ‘Energy Union’ that encourages consumers to take ownership of the energy transition to a low carbon and climate friendly European economy (European Commission, 2015). Since there is some evidence that residential consumers typically prefer curtailment strategies over energy efficiency strategies (Lesic et al., 2018), and a diversity of contract types is necessary for demand response to be appealing to a variety of consumers (He et al., 2013), there could be more engagement with a market for end-use specific curtailable contracts in the residential sector. In particular, for domestic ‘smart appliances’, which have the potential to provide significant load flexibility opportunities (D’hulst et al., 2015; Drysdale et al., 2015; Nistor et al., 2015; Li and Pye, 2018) and, consequently, could play an important role in this type of demand response.

In order to provide a meaningful estimate of the demand side flexibility of ‘smart appliances’, it is important to understand the value/utility that different electricity services provide to consumers using these appliances. This is because electricity is a derived demand, whereby consumers are not interested in the electricity itself but in the service they derive from it to run their household appliances. Within this context, this paper examines consumer preferences for curtailable contracts on different household appliances to be activated during the peak load hours of between 5pm and 8pm in the evening. Using a discrete choice experiment on a representative sample of 972 electricity consumers, each respondent is faced with a selection of hypothetical electricity contracts with varying attributes that include curtailment on separate household appliances, namely: the washing machine; the tumble dryer; the dishwasher; and, the electric oven. Respondents’ choices in the experiment reveal their preferences for peak hour curtailable contracts through their estimated loss or gain in utility from five important attributes of the contracts, which are: the appliance to be curtailed; maximum frequency of curtailment; whether or not there is advance notice of a curtailment event; whether or not there is an opt out available; and, the electricity discount received.

More specifically, to take into account the rates of household appliance ownership, the analysis is split between two samples, those consumers that have all four appliances in their households (Own, $n = 427$) and those consumers that don’t have all four appliances (Don’t Own, $n = 545$). Then, to help understand the incentives consumers need to become more flexible with their peak hour electricity demand in these types of contracts, compensations in the form of willingness to accept (WTA) estimates are calculated across the different non-monetary attributes of the contract for the full sample and both sub-samples. Furthermore, using the sample of consumers that own all four appliances, a welfare analysis is conducted to determine consumers’ compensating variation for 96 different hypothetical curtailable contracts. This helps to isolate the welfare loss or gain to consumers from different end-use specific curtailable contracts when compared to their baseline ‘status quo’ contract.

The remainder of the paper proceeds as follows: Section 2 presents a review of related work, Section 3 provides a description of the choice experiment, the experimental design and the data collection, together with the details of the econometric analysis used for the analysis of the choice responses. Results are presented in Section 4, and a discussion and conclusion follow in Section 5.

2. Related Work

Much of the literature examining demand flexibility opportunities in electricity contracts is focused on the dynamic pricing of electricity - see Dutta and Mitra (2017) for a comprehensive overview. Dynamic pricing is time-based and works by charging different prices for electricity at different times according to demand. The overall goal is to give consumers the monetary incentive to reduce their peak load and in turn, reduce peak capacity investments for the grid operators. In contrast to dynamic pricing, interruptible/curtailable contracts are incentive-based instruments where consumers receive a bill discount or credit in exchange for agreeing to reduce load during peak conditions or system instability (Aalami et al., 2010). Thus, curtailable contracts could be considered more flexible and dependable when compared to dynamic pricing contracts because they can be used in both market-based and reliability-based programmes. Curtailment is activated in market-based programmes by high market prices that generally occur during peak load. Whereas, curtailment is triggered in reliability-based programmes by system balancing emergencies (Ng'uni et al., 2006).

Somewhat related to interruptible/curtailable contracts, there is a very limited body of literature exploring variable capacity tariffs (Hayn et al., 2018; Simshauser, 2016; Hayn et al., 2015; Ruiz et al., 2014; Strauss, 1994; Woo, 1990). Rather than employing different price levels for the consumption of electricity like for dynamic pricing, variable capacity tariffs work by applying price differentiation to the electricity capacity limits. For example, Hayn et al. (2015) develop a set of four service level indicators for tariffs with variable capacity prices. These are: a guaranteed capacity limit; a defined duration of curtailment; a defined frequency of curtailment; and, an advance warning time.

In terms of discrete choice experiments, there are a number of studies which employ this methodology to elicit consumer preferences for different types of electricity contracts. Most closely related to this analysis are the non-market valuation studies by Broberg and Persson (2016), Broberg et al. (2017) and Richter and Pollitt (2018). In examining people's preferences for load shifting in a hypothetical Direct Load Control (DLC) programme in Sweden, Broberg and Persson (2016) show that people place substantial value on not being controlled. Specifically, their results imply that people require much greater compensation to restrict their domestic electricity compared to their domestic heating and, that such compensation is unrealistic in a real-world policy setting. On the other hand, their results suggest that people will accept a relatively small compensation to allow their load be controlled remotely in extreme situations.

In a separate study, Broberg et al. (2017) elicit people's preferences for a softer load control that restricts load on a number of occasions during peak demand hours in the winter season in Sweden. The form that the 'soft' load control takes in their analysis is strongly connected with the variable capacity tariffs described above, in that temporary restrictions would be placed on the maximum possible load available to a household to provide their energy services. Similar to Broberg and Persson (2016), they find that this type of demand flexibility is expensive with the value to consumers of access to their electricity during peak hours being far above the marginal cost to provide electricity. Their results also point out that the stricter the restrictions on capacity, then the higher the compensations required by people, while an increase in the duration of control was also found to be associated with a higher compensation necessary. Additionally, Broberg et al. (2017) find that there is no statistical difference in people's preference for a flexible choice of appliances in soft load control versus a pre-determined choice of appliances.

Considering the key attributes that consumers might accept, Richter and Pollitt (2018) employ a choice experiment to analyse consumer demand for smart electricity services in Great Britain. Like the previous studies, they show that consumers in Britain also require statistically significant compensation to accept remote monitoring and load control by an external provider. Amongst their other notable findings, Richter and Pollitt (2018) suggest that consumers are willing to pay for technical support, whilst the compensation needed to share their usage and personal data is found to be quite substantial. In addition to the above choice analyses, there are also many studies which elicit consumer preferences for different electricity contracts based on related attributes. For example, power outages and reliability of electricity supply (Abdullah and Mariel, 2010; Pepermans, 2011; Carlsson and Martinsson, 2008; Hensher et al., 2014; Abrate et al., 2016; Ozbafli and Jenkins, 2016), electricity tariffs Goett et al. (2000); Buryk et al. (2015) and electricity mix (Amador et al., 2013; Huh et al., 2015).

3. Methodology

3.1. Choice Experiment

A discrete choice experiment is a stated preference survey method generally used to elicit consumer preferences and estimate monetary values for non-market goods. It usually works by presenting individuals with different choice sets and asking them to select their preferred alternative from each choice set by making trade-offs between all of the attributes that make up each alternative. The method is employed in this study to implicitly reveal consumer preferences for electricity contracts with curtailment on household appliances during peak hours. More specifically, a monetary compensation is included in the form of an electricity discount in each contract to be able to indirectly infer willingness to accept (WTA) estimates based on how respondents trade off the other attributes against the different compensations offered.

Attributes and levels were chosen for inclusion in this choice experiment following an extensive design process. First, a literature review was conducted reviewing non-market valuation studies exploring electricity contracts i.e. separate studies eliciting consumer preferences for load control, demand side management, electricity tariffs and power outages. This helped to identify a range of possible attributes and levels for the type of electricity contract with curtailment to be examined in this experiment. Following on from this, three separate focus group discussions were conducted between March and April 2018. Each focus group consisted of six people with participants recruited from a range of socio-demographic backgrounds based primarily on them being the bill payers for their current household electricity contract. Based on these discussions together with the findings from the related literature, five attributes were chosen to be included in the choice experiment. These attributes as well as their different levels are outlined in Table 1.

The first attribute in each hypothetical electricity contract is the type of household appliance to be curtailed in the contract. For this attribute, the levels chosen are based on the largest energy using white goods used in an Irish household in order to best provide the greatest energy demand reductions to the energy system through peak hour curtailment. These are: the electric oven; the tumble dryer; the washing machine; and the dishwasher. In cases where a respondent owned a combined washer/dryer appliance, they were asked to consider them as separate appliances for the purposes of this choice experiment. The second attribute is the maximum frequency of curtailment, which describes the maximum number of times per month that a curtailment event could take place as part of the terms of the contract. This attribute is presented with three levels. A curtailment event could take place up to three times per month, up to 6 times per month or up to 9 times per month. In this context, it is also important to note that the time of curtailment is fixed across all the hypothetical contracts and is between 5pm and 8pm in the evening. The third attribute is whether or not a consumer would receive advance notice before a curtailment event. The advance notice is specified to be at least 12 hours notice and it is presented with two levels, yes and no, to indicate whether it is or is not a feature of the contract.

During focus group discussions, it was revealed that participants were very concerned about a curtailment event occurring at the most inconvenient time, when for example, "a dinner party is planned" or "a shirt needs washed for an interview" and the requirement for the electric oven or washing machine is then indispensable. For circumstances such as this the fourth attribute is whether or not there is an opt out, where the contract would provide consumers with an opt out from one curtailment event per month. This attribute is also presented with two levels, yes and no. Finally, the fifth attribute is the monetary attribute which is required to indirectly estimate the welfare impacts. This is described as a discount on the respondent's bimonthly electricity bill and is the compensation for each hypothetical contract including curtailment.

To reflect a realistic discount, the attribute is defined by three levels between €10 and €30. In order to derive meaningful values for the discount, two different approaches were used. In the first approach, based on the assumed duration and frequency of curtailment in the study, the number of hours of curtailment in a bimonthly period was calculated (54-162h). Then, assuming that curtailment is most relevant during peak load, thus at peak price hours, the average Irish wholesale market price of the most expensive 54-162 hours was determined. Using standard capacities for the household appliances to calculate power and energy demand as well as to derive the market values of the curtailed load, the load values were found to range between €10 and €22. Note that these values only include energy market prices, while investment related costs and any compensation/premium for causing inconvenience to consumers are not considered. In a second approach, the full costs of the new peak load capacity are calculated using an open-cycle gas turbine as an example. Assuming 500€/kW as specific investment, an interest rate of 10% and an economic lifetime of 20 years, this approach leads to a discount of around €30 per bimonthly billing period. As a result, a discount in the range of €10-€30 bimonthly was deemed as most appropriate for the choice experiment.

3.2. Experimental Design

Respondent's time constraints and average cognitive abilities restrict the number of choices that they can credibly make on a single choice occasion, thus, a Bayesian efficient experimental design was employed to generate a careful selection of choice cards for the experiment. Unlike orthogonal designs, efficient designs aim to produce data that can generate coefficient estimates that are statistically efficient with standard errors that are as small as possible (Rose and Bliemer, 2009). If some prior information is available that allow prior coefficient values to be specified, then a design can always be improved since the asymptotic variance covariance (AVC) matrix can be determined and hence, standard errors can be predicted. Indeed, it could be argued that an orthogonal design is only most efficient when there is no prior information available. Further to this, to consider the potential uncertainty about these prior coefficients, Bayesian efficient designs make use of random priors instead of fixed priors and this means that the design can be made more robust to any misspecification of the priors as a direct result.

In this study, a Bayesian efficient experimental design that follows Bliemer et al. (2008) and minimizes the Bayesian D-error (Db-error) criterion was used. Moreover, a sequential experimental design was adopted in which prior coefficients are updated as more information about these priors becomes available. Initially, prior coefficients for the pilot study were obtained from the pre-pilot, focus group discussions and the previous literature (Bliemer and Collins, 2016). Whereas priors for the main field survey were based on Conditional Logit (CL) estimates of the coefficients from the pilot study ($n = 100$). Results from Scarpa et al. (2007) suggest that this type of design can deliver significant efficiency gains. In total, 24 choice cards are generated using this design approach with Ngene software. A sample choice card is presented in Figure 1. Each card consisted of a choice of three hypothetical electricity contracts, two contracts characterised by the different attributes that are discussed previously and a third contract indicating a respondent's 'status quo' contract (their current contract as it is today). In each case, respondents were asked to choose their preferred contract. In order to further reduce the burden for each respondent, the 24 choice cards were divided into three blocks, so that each respondent had only to complete a randomly selected block of eight choice cards. Furthermore, to help with any complexity in understanding what the different hypothetical contracts have to offer consumers, respondents were provided with a short animated tutorial video describing in plain language the different attributes of the alternative contracts. The video also explained how to complete the choice experiment[1].

[1]The Tutorial Video is available in Appendix A

Table 1: Discrete choice experiment attributes and levels

Attributes	Levels	Description
Appliance to be curtailed	Electric Oven, Tumble Dryer, Dishwasher, Washing Machine	The type of household appliance to be curtailed in the contract
Max frequency of curtailment	3/month, 6/month, 9/month	The maximum number of times per month a curtailment event could take place
Advance Notice	Yes, No	Whether or not you would receive advance notice of at least 12 hours before a curtailment event
Opt Out	Yes, No	Whether or not you have an opt out from one curtailment event per month
Electricity Discount	€10, €20, €30	Compensation for each contract including curtailment in the form of a discount on the bimonthly electricity bill.

	Contract A	Contract B	Contract C
Appliance to be curtailed	Tumble Dryer	Washing Machine	Current contract as it is today
Max frequency of curtailment	3 times per month	9 times per month	
Advance Notice (at least 12 hours)	No	Yes	
Opt Out (once per month)	No	Yes	
Electricity Discount (per bimonthly bill)	€20	€30	

Figure 1: Sample Choice Card

3.3. Data Collection

In general, the choice experiment survey comprised of four parts. The first part contained questions about the respondent, their electricity bill and household appliance use. The second part was the actual choice experiment where respondents first watched the animated tutorial video describing the hypothetical curtailment contracts and then afterwards were faced with eight different choice tasks. The third part involved a number of post choice debriefing questions, and the final part collected some further information on the respondent's background and attitudes. Pre-pilot and pilot studies were first conducted with electricity bill payers to establish the suitability of the attributes and levels as well as to test the questions, tutorial video and the overall layout of the survey. The pilot study involved 100 respondents and the results found that there were generally no difficulties for participants in understanding the questions or completing the eight choice cards presented to them. Moreover, CL models estimated using the choice responses from the pilot revealed that all coefficients conformed to a priori expectations and were statistically significant to the respondent's choice of electricity contract and, thus, no substantial changes to the design were made for the main survey.

A stratified random sample was selected for the main survey using a sampling frame from the 2016 Irish Census of Population aged 18 and over. The sample was stratified by geographic location (NUTS III region), gender, age and employment status. The main survey was conducted online using a representative panel (n=1,519) drawn from the panel book of Research Now, an international company with over 80,000 panelists across Ireland. The survey was conducted in July 2018. After a preliminary analysis, 539 respondent's observations were dropped due to their failure to correctly answer the two screening questions in the survey instrument. The screening questions were included to ensure data quality by determining whether respondents were paying adequate attention[2]. Also, in line with best practice, a further 108 respondent's observations were removed since they were contained in the top or bottom 5% of survey completion times. After their removal, the average completion time for the survey is just over 15 mins. The final sample comprised of n=972 respondents including the 100 respondent's responses from the pilot and this sample is representative of the population of Irish people aged 18 and over in terms of many demographic variables (see the descriptive statistics in Table 2).

One important explanation for any preference heterogeneity for the appliance attribute is household ownership of the individual appliances. In fact, it is argued that ownership of the appliance in the household will influence the respondents choice of contract in the experiment. While the ownership rates for the washing machine and the electric oven are very high in the sample at 99% and 90% respectively, the ownership rates for the tumble dryer and dishwasher are lower at 66% and 65% respectively[3] (see Table 2). For this reason, the analysis is split between two samples, those respondents that have all four appliances in their households (Own, $n = 427$) and those respondents that don't have all four appliances (Don't Own, $n = 545$). The reasoning for this follows a key assumption in discrete choice experiments that respondents are able to make relative tradeoffs between the different attributes in the choice cards presented. This assumption can be considered much more realistic for the respondents that own all of the appliances and hence, are able to make relative tradeoffs in all choice scenarios. In addition, the results from the analysis on the sample of respondents that don't have all four appliances in their households could provide an insight into the attributes that influence their choices across curtailment contracts. The descriptive statistics for both sub-samples are also reported in Table 2.

Table 2: Descriptive statistics and the representativeness of the sample

Variables	Sub-sample owning all appliances %	Sub-sample not owning all appliances %	Total Sample %	National Statistics† %
Gender				
Female	49.18	57.98	54.12	51.12
Male	50.82	42.02	45.88	48.88
Age				
18-24 years	10.30	9.54	9.88	10.99
25-34 years	15.22	17.80	16.67	18.47
35-44 years	19.67	22.75	21.40	20.91
45-54 years	17.33	17.98	17.70	17.53
55-64 years	16.86	15.23	15.95	14.25
65+ years	20.61	16.70	18.42	17.85

Continued on next page

[2]The screening questions used in the study are presented in Appendix A

[3]It is noteworthy that these sample ownership rates are representative of the population of electricity consumers according to the Irish Household Budget Survey (HBS) 2015-2016

Table 2 – continued from previous page

Variables	Sub-sample owning all appliances %	Sub-sample not owning all appliances %	Total Sample %	National Statistics† %
NUTS3 Region				
Border	8.67	6.79	7.61	8.14
West	8.90	12.11	10.70	9.55
Mid-west	11.94	7.89	9.67	9.93
South-east	8.67	7.89	8.23	8.76
South-west	14.99	16.33	15.74	14.62
Dublin	23.89	30.09	27.37	29.18
Mid-east	16.16	13.94	14.92	13.88
Midlands	6.79	4.95	5.76	5.94
Primary Economic Status‡				
Persons at work	55.27	60.37	58.13	53.43
Unemployed	5.62	5.69	5.66	7.92
Homemaker/Carer	9.60	6.61	7.92	8.14
Student	6.56	6.97	6.79	11.37
Retired	20.84	16.33	18.31	14.52
Unable to work	2.11	3.85	3.09	4.22
Other	0.00	0.18	0.10	0.40
Appliance Ownership				
Electric Oven	100.00	81.28	89.51	-
Dishwasher	100.00	37.25	64.81	64.70
Washing Machine	100.00	97.98	98.87	97.50
Tumble Dryer	100.00	39.82	66.26	64.80
Location				
Urban	59.48	67.16	63.79	60.09
Rural	40.52	32.84	36.21	39.91
Tenure				
Rented	16.86	42.57	31.28	27.67
Owned by mortgage	39.82	24.41	31.17	31.55
Owned outright	42.62	31.93	36.63	36.04
Other	0.70	1.10	0.93	1.62
Not stated	-	-	-	3.12
Dwelling Type				
Apartment	7.03	20.48	14.55	12.03
Terraced	10.77	15.50	13.42	16.76
Semi-detached	30.68	30.63	30.65	27.80
Detached & bungalow	51.05	32.65	40.77	42.12
Other	0.47	0.74	0.62	1.29
No. of Household Members				
One or two members	43.32	57.07	51.03	52.07
Three members	20.84	18.17	19.34	17.48
Four members	21.78	15.05	18.00	16.94
Five+ members	14.05	9.72	11.63	13.51

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Table 2 – continued from previous page

Variables	Sub-sample owning all appliances %	Sub-sample not owning all appliances %	Total Sample %	National Statistics† %
Market Share§				
Bord Gais	20.37	20.92	20.68	17.80
Electric Ireland	46.60	47.52	47.12	49.53
Energia	10.30	7.34	8.64	7.96
Panda Power	0.94	1.65	1.34	1.51
Pinergy	0.23	0.18	0.21	1.46
Prepay Power	5.85	5.14	5.45	5.99
SSE Airtricity	12.88	14.13	13.58	15.36
Don't Know	2.11	1.47	1.75	0.00
Other	0.72	1.65	1.23	0.39

† National statistics are taken from Ireland's Census of Population 2016 and from the Irish Household Budget Survey 2015-2016 where appropriate.
‡ National statistics for Primary Economic Status also include persons aged 15-17 years, while the sample in this study consists only of persons aged 18 and over.
§ National market shares are taken from Ireland's Commission for Regulation of Utilities 2017 Electricity and Gas Retail Markets Annual Report.

3.4. Econometric Analysis

The analysis of the responses to the choice experiment is based in random utility theory (McFadden, 1974), where individuals choose the electricity contract that provides them with the highest utility level. The theory states that the indirect utility U_{ni} for individual n from choosing contract i is assumed to be a linear function of the contract attributes X_{ni} and a random component ϵ_{ni}, such that:

$$U_{ni} = \beta' X_{ni} + \epsilon_{ni} \tag{1}$$

where β represents a vector of coefficient estimates corresponding to the contract attributes X_{ni} as well as to the alternative specific constant (ASC). To be consistent with demand theory (Louviere et al., 2000), one of the contracts in the choice experiment represents a status quo contract, a respondent's current contract as it is today. It is important to present this baseline contract so that respondents can understand and identify the consequences for their utility from the contract changes to be valued in the experiment by allowing them to express a preference for or against their current service contract (Johnston et al., 2017). These preferences are then captured in the models by the coefficient for the ASC.

In the standard conditional logit (CL) model, ϵ_{ni} is assumed to be independent and identically distributed extreme value type 1, so the probability P_{ni} that an individual n will choose contract i in the set of J alternatives is expressed by:

$$P_{ni} = \frac{exp(\beta' X_{ni})}{\sum_{j=1}^{J} exp(\beta' X_{nj})} \tag{2}$$

While the CL model is most generally used for the analysis of responses in a discrete choice experiment, it makes a number of very restrictive assumptions. First, it assumes that choices are independent from irrelevant alternatives (IIA). Second, it assumes that preferences are homogeneous across individuals and, finally, it makes the assumption that any unobserved heterogeneity is uncorrelated over the repeated panel of choices. Given these limitations, the random parameters logit (RPL) model is a more appropriate estimator for this analysis because it takes into account the panel nature of the data and considers unobserved heterogeneity explicitly in modelling the responses. More specifically, it assumes that the coefficient vector β_n varies across individuals in the population with density $f(\beta_n|\theta)$, where θ represents a vector of the true parameters of the taste distribution. For a sample with N individuals, each individual n has a choice of J alternative contracts on T choice occasions, such that the utility U_{njt} that individual n derives from choosing contract j on choice occasion t is:

$$U_{njt} = \beta_n' X_{njt} + \epsilon_{njt} \tag{3}$$

Here, if β_n is observable and the random component ϵ_{ni} is independent and identically distributed extreme value type 1, the conditional choice probability of contract i for individual n on choice occasion t is given by:

$$P_{nit}|\beta_n = \frac{exp(\beta_n' X_{nit})}{\sum_{j=1}^{J} exp(\beta_n' X_{njt})} \tag{4}$$

Since β_n is unobserved, the unconditional choice probability is defined as the integral of $P_{nit}|\beta_n$ for all possible values of β_n:

$$P_{nit} = \int \Big(\frac{exp(\beta_n' X_{nit})}{\sum_{j=1}^{J} exp(\beta_n' X_{njt})} \Big) f(\beta_n|\theta) d\beta_n \tag{5}$$

For the purposes of this analysis, a simulated maximum likelihood estimator based on 1,000 Halton draws is used to estimate the models due to the fact that the integral cannot be evaluated analytically. In addition to this, taste parameters are assumed to be correlated and so, RPL models with correlated coefficients (RPL-C) are also estimated to consider the likelihood that the random coefficients are related across the curtailment contract attributes. To this end, the starting values for the RPL-C model are taken from the standard estimated RPL model with uncorrelated coefficients and then, a simulated maximum likelihood estimator based on 2,000 Halton draws is used to estimate the final RPL-C models.

Also of importance to the employment of both the RPL and RPL-C models, is the choice of coefficients that should be allowed to be random and vary across individuals as well as the choice of the distribution that these coefficients should then follow (Hole, 2008). All coefficients in this study with the exception of the coefficient on the monetary attribute (electricity discount) are specified as random and the distribution of the taste variation is modelled with a normal distribution like in previous related studies (Carlsson and Martinsson (2008); Pepermans (2011); Buryk et al. (2015) and Broberg and Persson (2016)). On the other hand, the electricity discount coefficient is specified to be fixed (non-random) to avoid heavily skewed Willingness to Accept (WTA) distributions as described in Hole and Kolstad (2012).

The electricity discount attribute is included in order to derive a marginal value for the different contract attributes in the form of the Marginal Willingness to Accept (MWTA) for each of the separate attributes. For the estimation of this MWTA, a distinction is made between the monetary discount attribute, m_{njt}, and the non-monetary attributes, x^k_{njt} in Equation 3, such that:

$$U_{njt} = \lambda m_{njt} + \sum_{k=1}^{k} \beta^k_n x^k_{njt} + \epsilon_{njt} \tag{6}$$

where λ is the marginal utility of income represented by the coefficient for the monetary discount attribute and β^k_n are the coefficients for the non-monetary attributes as well as the coefficient for the ASC. Thus, to estimate the MWTA for an attribute k, the ratio of its coefficient β^k_n to that of the coefficient on the monetary attribute λ is calculated as follows:

$$MWTA = -\frac{\beta^k_n}{\lambda} \tag{7}$$

Overall, CL, RPL and RPL-C models are estimated for the full sample of respondents and RPL-C models are estimated for two separate sub-samples of respondents where the sub-samples were chosen for the reasons outlined in Section 3.3. The first sub-sample is made up of those respondents who have all four appliances in their households (Own, $n = 427$) and the second sample consists of those respondents that don't have all four appliances (Don't Own, $n = 545$). Then, the MWTA estimates are based on the coefficients from the RPL-C models for each of the samples.

Finally, to measure the economic welfare impact of different curtailment contracts on the consumers of electricity, the compensating variation (CV) which measures the consumers' minimum WTA for some level of appliance curtailment is also estimated for the sample of respondents that own all four appliances using the coefficients from the random parameters logit model with correlated coefficients. The CV is the monetary amount that needs to be added to the consumer's income to make him or her as well off as at his or her initial utility level. The welfare loss or gain experienced by the average consumer as a result of the difference between their new curtailment contract and their status quo contract is expressed as:

$$CV = -\frac{(V^0 - V^1)}{\lambda} \tag{8}$$

where V^0 is representative of the average individual's utility with the status quo contract and V^1 represents the average individual's utility with the new curtailment contract. In this study, the welfare impacts on an average individual is calculated under 96 different contract scenarios which are outlined in Section 4.4.

4. Results

4.1. Full Sample Econometric Results

The results for the full sample of respondents are presented in Table 3 from three separate models; the conditional logit (CL) model (1), the random parameters logit (RPL) model (2), and the random parameters logit model with correlated coefficients (RPL-C) (3). All attribute levels are dummy coded with the exception of both the electricity discount and the frequency of curtailment which are treated as continuous variables in the analysis.

In general across the three models, the parameters for all attributes conform to a priori expectations with the expected signs estimated for most of the attributes. Nevertheless, the parameters in the CL model are of lesser magnitudes than those in the other two models except for the parameter on the Alternative Specific Constant (ASC) which is of a larger positive magnitude and is also statistically significant at the 1% significance level. This suggests that, ceteris paribus, electricity consumers prefer to choose the status quo contract rather than any contract with curtailment. It is important to note, however, that the CL model assumes the independence of irrelevant alternatives (IIA) property, whereby the relative probabilities of choosing any two alternatives is independent of the availability of other alternatives. Estimated results from a CL model are biased if the IIA assumption is violated. The Hausman and McFadden (1984) test for IIA was performed on the CL model here and the IIA assumption is rejected at the 99% confidence level. Thus, the results from the CL model are biased and the alternative models are necessary.

Indeed, to overcome the limitation of the CL model and to also take into consideration consumers' preference heterogeneity, the results for both the RPL and the RPL-C are presented. In comparing the log-likelihood, the Akaike information criterion and the Bayesian information criterion across the three models it is also evident that both the RPL and the RPL-C are a much better fit statistically compared to the CL model, though it is not particularly clear which model between the RPL and the RPL-C performs best in terms of fit to the data. The log-likelihood improves slightly in the RPL-C model moving from $-5,853$ to $-5,774$ together with an improvement in the AIC which decreases from $11,735$ to $11,619$. On the other hand, the BIC which places more weight on the number of parameters in a model increases in the RPL-C model where the elements of the lower triangular Cholesky matrix are additional parameters for the model. Despite this, the RPL-C is chosen as the preferred estimator because it fits a model where coefficients are assumed to be correlated. Theoretically it could be argued that for electricity contracts with curtailment, consumers who like a particular attribute of a contract might also tend to like or dislike some other attributes in the contract, thus, for the purposes of the interpretation of the results the estimated parameters from the RPL-C in model (3) are used hereafter.

In contrast to the CL model, the mean estimate for the coefficient on the ASC is statistically insignificant in the RPL-C model. This indicates that, all other factors equal, respondents are indifferent to the status quo electricity contract (their current contract as

Table 3: Parameter estimates for the full sample from three separate estimators

	(1) (CL) Conditional Logit	(2) (RPL) Random Parameters Logit		(3) (RPL-C) RPL (Correlated Coefficients)	
Attributes	Coefficient	Coefficient	Std Dev	Coefficient	Std Dev
Electricity Discount	0.048***	0.092***		0.095***	
	(0.002)	(0.005)		(0.006)	
Electric Oven[1]	-0.774***	-1.857***	2.150***	-1.798***	2.168***
	(0.061)	(0.142)	(0.141)	(0.157)	(0.163)
Tumble Dryer[1]	0.210***	0.144	1.806***	0.121	2.192***
	(0.053)	(0.096)	(0.141)	(0.113)	(0.157)
Dishwasher[1]	0.077	-0.065	1.311***	-0.158	1.683***
	(0.050)	(0.087)	(0.131)	(0.107)	(0.150)
Frequency	-0.037***	-0.099***	0.179***	-0.109***	0.189***
	(0.007)	(0.013)	(0.018)	(0.013)	(0.018)
Advance Notice	0.207***	0.359***	-0.664***	0.428***	0.729***
	(0.029)	(0.049)	(0.088)	(0.058)	(0.093)
Opt Out	0.145***	0.271***	-0.141	0.349***	0.345***
	(0.026)	(0.043)	(0.112)	(0.052)	(0.084)
ASC	0.784***	0.357*	4.302***	0.296	4.371***
	(0.077)	(0.193)	(0.244)	(0.193)	(0.244)
No. of respondents	972	972		972	
No. of observations	23328	23328		23328	
Log-likelihood	-8080.779	-5852.679		-5773.514	
AIC	16177.558	11735.358		11619.028	
BIC	16242.017	11856.219		11909.094	
χ^2 Statistic	628.907	407.411		372.602	

Standard errors clustered at the individual level in parenthesis
[1]Reference category is the washing machine
*p<0.10, **p<0.05, ***p<0.01

it is today) on average. Though, turning to the estimated standard deviation for the coefficient on ASC, it is evident that there is large preference heterogeneity around the status quo contract given the large and highly statistically significant standard deviation estimate relative to the mean. As expected, this result suggests that the coefficient on ASC varies to a large degree across the respondents.

Concerning the attribute for electricity discount, the marginal utility of income is assumed to be constant across individuals and so the estimated parameter for the electricity discount is specified as non-random in the RPL-C model. The results show a positive and highly statistically significant coefficient for the discount attribute. Ceteris paribus, respondents are shown to prefer higher discounts. This is in agreement with economic theory and also lends further support to the theoretical validity of the experiment itself.

In terms of the attributes; frequency, advance notice, and opt out, the signs of the coefficients also conform to prior beliefs and are statistically significant at the 1% level. Not surprisingly, the mean parameter on frequency is estimated to be negative, suggesting that respondents prefer electricity contracts with less frequent curtailment events on average. Whereas, the mean coefficients on both advance notice and opt out are found to be positive. This indicates that on average consumers have a preference for such contracts to include advance notice of at least 12 hours before an upcoming curtailment event together with an opt out from one event per month which can be used in a case of exceptional circumstance or otherwise. It is of particular note that the estimated standard deviations for the coefficients of these attributes are also highly statistically significant, indicating that preference heterogeneity is present and that the coefficients differ across respondents but not to the same extent compared to the ASC.

Most interestingly, the results for the attribute describing the household appliance to be curtailed in these types of electricity contracts show that a contract curtailing the electric oven at the peak evening times between 5 and 8pm is significantly less favoured compared to a contract curtailing the washing machine. This is evident from the large negative magnitude (absolute value) of the coefficient for the electric oven. Given that the electric oven is one such household appliance with the greatest use value for cooking during the evening peak, this result is as expected. In contrast, the coefficients on the tumble dryer and the dishwasher are of a much lesser magnitude and are found to be statistically insignificant to respondents' utility. Nevertheless, the estimated standard deviations for these appliance attributes are statistically significant, demonstrating the large taste heterogeneity across respondents for the inclusion of these different types of appliance in electricity curtailment contracts.

4.2. Sub-sample Econometric Results

To take into account the rates of household appliance ownership and to help satisfy a key assumption in discrete choice experiments that respondents are able to make relative tradeoffs between the different attributes in the choice cards presented to them, the analysis is split between two samples, those respondents who have all four appliances in their households (Own, $n = 427$) and those respondents that don't have all four appliances (Don't Own, $n = 545$). The estimated results from the RPL-C model for both sub-samples together with the results from the full sample for comparison are reported in Table 4. Reassuringly, in comparing across the three samples, the mean parameter estimates for frequency, advance notice, opt out and the ASC are very similar in terms of absolute values and statistical significance. Again, the mean coefficient for the ASC is insignificant across the different samples, indicating that respondents tend to be indifferent toward the status quo contract. Though the standard deviation on ASC is still significant with the largest absolute value for the sample of respondents that own all appliances. For the fixed parameter on electricity discount the estimate is also the same across the samples and provides additional confidence in the validity of the experiment.

Similarly, the mean estimate for the coefficient on the electric oven is consistent across samples with the electric oven being found to be much less preferred on average relative to the washing machine in this type of curtailment contract. On the contrary, there are large differences for the mean coefficients on the tumble dryer and the dishwasher across the separate samples. While the estimated mean parameters for both these attributes are insignificant for the full sample, they are significant for the sample of respondents that own all four appliances and the sample of consumers that don't. Furthermore, the mean estimates differ in their signs for both these sub-samples. In the sample of respondents that have all household appliances the coefficients are positive, which suggests that compared to the washing machine, respondents prefer contracts that curtail either the tumble dryer or the dishwasher. Whilst for the sample that don't have all appliances the opposite is found, where respondents are less likely to prefer contracts that curtail the tumble dryer or dishwasher rather than the washing machine.

Intuitively, this is expected with the sample of consumers that own all household appliances being the one that best matches the assumptions underlying the experimental methodology of discrete choice. In other words, this sample of respondents are best placed to make all the relative tradeoffs amongst the different attributes in an electricity contract with curtailment and so, the most confidence can be given to the parameter estimates here. Additionally, the specified RPL-C model for this sample is also the one with the best statistical fit, where the AIC and the BIC are lowest compared to the other samples. In this context, the results from model (2) in Table 4 show that for the different levels of household appliance, the most preferred appliance to be curtailed at the peak evening times is the tumble dryer, followed somewhat closely by the dishwasher when compared to the washing machine. While in contrast, respondents are revealed to have a very strong negative utility toward the electric oven being included in this type of curtailment contract.

Also of relevance are the results for the sub-sample of respondents that don't have all four appliances in their households. The negative and significant coefficients on the tumble dryer and dishwasher levels of the appliance to be curtailed could plausibly be explained by the fact that the respondents to the experiment are less likely to have either of these appliances in their households and therefore also much less likely to choose a contract which would curtail these appliance types rather than the washing machine on average. As a consequence, the respondents could be considered to have acted rationally in the experiment and again provides some further assurance for the theoretical validity of the methodology.

In addition, it is of particular note that the estimated standard deviations for the coefficients on the tumble dryer and dishwasher are a much larger magnitude compared to the mean estimates for the sub-sample of respondents that don't own all appliances (model

Table 4: Parameter estimates from the Random Parameters Logit (Correlated Coefficients) Model

Attributes	(1) Full Sample	(2) Own	(3) Don't Own
Non-random parameter			
Electricity Discount	0.095***	0.097***	0.094***
	(0.006)	(0.009)	(0.007)
Random parameters: Mean			
Electric Oven[1]	-1.798***	-1.787***	-1.817***
	(0.157)	(0.224)	(0.185)
Tumble Dryer[1]	0.121	0.842***	-0.483***
	(0.113)	(0.153)	(0.177)
Dishwasher[1]	-0.158	0.408***	-0.519***
	(0.107)	(0.134)	(0.146)
Frequency	-0.109***	-0.101***	-0.115***
	(0.013)	(0.020)	(0.018)
Advance Notice	0.428***	0.368***	0.423***
	(0.058)	(0.090)	(0.079)
Opt Out	0.349***	0.353***	0.311***
	(0.052)	(0.079)	(0.068)
ASC	0.296	0.438	0.218
	(0.193)	(0.375)	(0.313)
St Dev of random parameters			
Electric Oven	2.168***	2.064***	2.312***
	(0.163)	(0.233)	(0.223)
Tumble Dryer	2.192***	1.559***	2.585***
	(0.157)	(0.206)	(0.232)
Dishwasher	1.683***	1.003***	2.029***
	(0.150)	(0.213)	(0.193)
Frequency	0.189***	0.181***	0.201***
	(0.018)	(0.026)	(0.028)
Advance Notice	0.729***	0.957***	0.529***
	(0.093)	(0.122)	(0.139)
Opt Out	0.345***	0.367***	0.350***
	(0.084)	(0.123)	(0.123)
ASC	4.371***	5.009***	3.866***
	(0.244)	(0.389)	(0.309)
No. of respondents	972	427	545
No. of observations	23328	10248	13080
Log-likelihood	-5773.514	-2460.311	-3252.858
AIC	11619.028	4992.622	6577.715
BIC	11909.094	5253.076	6846.954
χ^2 Statistic	372.602	178.565	229.337

Standard errors clustered at the individual level in parentheses
[1]Reference category is the washing machine
*p<0.10, **p<0.05, ***p<0.01

(3)) and relative to the sample for model (2). This suggests that there is larger preference heterogeneity for these attributes for the model (3) sample and that some respondents would still have chosen contracts with appliance types that they did not have in their households. Also interestingly, the standard deviation estimate on the ASC is largest in absolute value for the sample in model (2), which would indicate a greater difference in tastes for the status quo contract amongst that sample. Despite this, on average the sample remains statistically indifferent to their current contracts as they exist today.

4.3. Marginal Willingness To Accept

To estimate a value for the trade-offs that respondents make between the different attributes in the experiment, the non-monetary coefficients are normalised with the fixed parameter on the monetary attribute. The monetary attribute here is the compensation received for each contract that includes curtailment. This compensation is provided in the form of a discount on the respondents bi-monthly electricity bill. These values reflect the mean marginal willingness to accept (WTA) for each attribute level and are estimated across the separate samples described before for the RPL-C models. The WTA values are directly relatable to the electricity discount levels indicated in the experiment and are stand alone estimates. In other words, they cannot be summed. Table 5 presents the WTA estimates together with their 95% confidence intervals for each sample using the estimated coefficients from the RPL-C models in Table 4. The confidence intervals are calculated using the Delta method.

As expected, most disutility is placed on having the electric oven curtailed at the peak evening hours between 5pm and 8pm with respondents requiring compensation of somewhere between €14.32 and €23.16 on their bi-monthly bill when compared to a contract that curtails their washing machine. The compensation range here is dependent on the separate samples. Again, it is important to highlight that the sample with the most reliable mean estimates for the tumble dryer and dishwasher attribute levels is for the sample of respondents that have all four appliance in their homes. Within this context, the mean marginal WTA estimates are found to be negative and therefore show that respondents are, on average, willing to pay €8.64 bimonthly to curtail the tumble dryer and €4.19 bimonthly to curtail the dishwasher, both relative to the washing machine. The willingness to pay (WTP) estimates are reflected in the negative WTA for these attributes and might be better described as the average amount less that respondents would need to be compensated compared to curtailing their washing machines. Moreover, the positive WTA estimates for the sample in model (3) need to be interpreted very carefully. It is necessary to bear in mind for these results that the estimates are most probably an implication of the fact that respondents were much less likely to choose contracts that curtailed either the tumble dryer and dishwasher because they did not own that particular appliance type rather than not choosing such contracts for any other reason.

In terms of the frequency of curtailment, the WTA results imply that respondents would require a discount of between 68 cents and €1.56 on their bimonthly electricity bill for each additional curtailment event per month. In scaling these estimates to the monthly rate, the results show that for each curtailment event, respondents would require, ceteris paribus, a compensation of between 34 cents and 78 cents per event. For advance notice, the WTA results are negative and quite similar across the samples with a negative coefficient indicating a willingness to pay (WTP) for the particular attribute. Thus, all else equal, respondents would expect to pay between €2.02 and €6.17 bi-monthly, dependent on the sample, to have advance notice for an upcoming curtailment event of at least 12 hours. Similarly, with regards to opt out, the results suggest that respondents have a negative bi-monthly WTA of between €1.85 and €5.25 to allow them an opt out from one curtailment event per month. Finally, the WTA estimates on the ASC are also found to be negative which could suggest that respondents would be willing to pay to remain with their status quo contracts, however, these estimates are not statistically significant. While the WTA estimates presented in Table 5 provide a useful measure of the value consumers place on the separate attributes of an electricity contract with curtailment, it does not provide estimates of the compensating variation for the contract alternatives. Thus, the results from a welfare analysis examining the CV across different contract alternatives are reported in the next section.

Table 5: Willingness to accept (WTA) (bimonthly) estimates for attributes of an electricity contract with curtailment from RPL (Correlated Coefficients) model

	(1) Full Sample		(2) Own		(3) Don't Own	
Attributes	WTA(€)	[WTA(€) 95% CI]	WTA(€)	[WTA(€) 95% CI]	WTA(€)	[WTA(€) 95% CI]
Electric Oven	18.92***	[15.82, 22.03]	18.33***	[14.32, 22.35]	19.26***	[15.35, 23.16]
Tumble Dryer	-1.28	[-3.61, 1.06]	-8.64***	[-11.95, -5.32]	5.12***	[1.49, 8.76]
Dishwasher	1.67	[-0.52, 3.86]	-4.19***	[-7.04, -1.34]	5.50***	[2.55, 8.46]
Frequency	1.14***	[0.90, 1.39]	1.03***	[0.68, 1.39]	1.22***	[0.88, 1.56]
Advance Notice	-4.50***	[-5.70, -3.31]	-3.77***	[-5.52, -2.02]	-4.49***	[-6.17, -2.80]
Opt Out	-3.68***	[-4.80, -2.56]	-3.62***	[-5.25, -2.00]	-3.30***	[-4.75, -1.85]
ASC	-3.11	[-7.03, 0.81]	-4.50	[-11.93, 2.94]	-2.31	[-8.75, 4.12]
No. of respondents	972		427		545	
No. of observations	23328		10248		13080	

*p<0.10, **p<0.05, ***p<0.01

4.4. Welfare Analysis

In order to estimate the average respondent's compensating variation (CV) for different curtailment contract options in relation to the 'status quo' baseline contract, the welfare loss or gain to the respondent is calculated (Hanemann, 1991; Birol et al., 2006). Table 6 presents the CV estimates for 96 different hypothetical contract types. The standard errors for each welfare estimate were computed using the Delta method and the statistical significance level is indicated by the stars on each estimate reported in Table 6. All 16 contract combinations of appliance type, advance notice and opt out are examined across different frequencies of curtailment (1 per month; 3 per month; 6 per month; 9 per month; 20 per month, and 30 per month). It is important to note that each of the welfare impacts are estimated relative to the base contract of the 'status quo', the respondent's current contract as it is today.

Not surprisingly, the CV estimates are largest for the electric oven at all frequencies of curtailment. For the hypothetical contracts examined, the welfare loss associated with the inclusion of the electric oven in the curtailment contract are estimated to range between €16.46 and €53.78 bimonthly with all losses found to be highly statistically significant. The welfare loss is smallest where there are both advance notice and an opt out available, and the frequency is only once per month, while the loss is largest where there are no advance notice nor opt out available and the frequency is 30 per month. In relation to the frequency of curtailment, when the frequency is increased for each of the 16 hypothetical contracts in Table 6, the welfare impact also increases considerably and helps demonstrate the large disutility found to be associated with a higher frequency of curtailment for each appliance. For example, Contract 1 curtails the household washing machine and contains both advance notice and an opt out. By moving from one curtailment event per month up to thirty events per month, the bimonthly welfare loss for contract 1 in Table 6 is estimated to start statistically indifferent to zero and then grow to a loss of €35.45 that is statistically significant at the 1% level.

Interestingly, contract 12 which curtails the tumble dryer once per month and includes both advance notice and an opt out is predicted to provide a welfare gain of €10.51 for the average respondent. This suggests that respondents might receive utility from having their tumble dryers curtailed at low frequencies per month, particularly in the instances where advance notice and an opt out are also available. Also, it is noteworthy that any hypothetical contract which curtails the tumble dryer or dishwasher is not expected to incur a significant welfare loss until at least after nine events per month and this could signal a large potential for demand flexibility from such appliances. In contrast, the results show that in certain cases, welfare losses from the curtailment of the washing machine could become significant beyond just six events per month and thus, the presence of advance notice or an opt out for this appliance in the contract may then play an ever more important role for a consumer's welfare at the margin.

Table 6: Attribute levels and compensating variation estimates for hypothetical contracts relative to the base contract with no curtailment

Contract	Appliance	Advance Notice	Opt Out	Compensating Variation (€ Bimonthly) By Frequency of Curtailment: 1 per month	3 per month	6 per month	9 per month	20 per month	30 per month
1	Washing Machine	✗	✗	-5.53	-7.59**	-10.69***	-13.78***	-25.13***	-35.45***
2	Electric Oven	✗	✗	-23.86***	-25.92***	-29.02***	-32.11***	-43.46***	-53.78***
3	Tumble Dryer	✗	✗	3.11	1.04	-2.05	-5.15	-16.50***	-26.82***
4	Dishwasher	✗	✗	-1.34	-3.40	-6.50*	-9.59**	-20.94***	-31.26***
5	Washing Machine	✓	✗	-1.75	-3.82	-6.91*	-10.01***	-21.36***	-31.68***
6	Washing Machine	✓	✓	1.87	-0.19	-3.29	-6.38*	-17.73***	-28.05***
7	Washing Machine	✗	✓	-1.90	-3.97	-7.06*	-10.16***	-21.51***	-31.83***
8	Electric Oven	✓	✗	-20.09***	-22.15***	-25.25***	-28.34***	-39.69***	-50.01***
9	Electric Oven	✓	✓	-16.46***	-18.52***	-21.62***	-24.72***	-36.07***	-46.38***
10	Electric Oven	✗	✓	-20.23***	-22.30***	-25.39***	-28.49***	-39.84***	-50.16***
11	Tumble Dryer	✓	✗	6.88*	4.82	1.72	-1.37	-12.72***	-23.04***
12	Tumble Dryer	✓	✓	10.51***	8.44**	5.35	2.25	-9.10*	-19.42***
13	Tumble Dryer	✗	✓	6.73*	4.67	1.57	-1.52	-12.87**	-23.19***
14	Dishwasher	✓	✗	2.44	0.37	-2.72	-5.82	-17.17***	-27.49***
15	Dishwasher	✓	✓	6.06*	4.00	0.90	-2.19	-13.54***	-23.86***
16	Dishwasher	✗	✓	2.29	0.22	-2.87	-5.97	-17.32***	-27.64***

*p<0.10, **p<0.05, ***p<0.01

5. Discussion and Conclusion

This paper employs a discrete choice experiment to reveal consumer preferences for electricity contracts with curtailment on household appliances during peak load hours. An econometric analysis of the responses to the experiment is based on a statistically representative sample of 972 Irish electricity consumers. More specifically, the sample is split between households that have all four appliances (washing machine, tumble dryer, dishwasher and electric oven) and households that don't have all four appliances. An analysis on the former sub-sample facilitates a key assumption for a choice experiment that respondents are able to make relative tradeoffs between all attributes across different alternatives. While an analysis on the latter sub-sample is undertaken to provide an insight into consumer preferences in households that don't own all appliances and helps provide some evidence for the theoretical validity of the methodology.

All the attributes examined in the choice experiment are found to be important factors for consumer preferences for contracts including curtailment. Specifically, the results from all the samples analysed show that, all other factors equal, consumers are on average indifferent to their status quo electricity contract and this might suggest a strong potential for acceptance of contracts including curtailment on household appliances. Nevertheless, there is a large preference heterogeneity around the status quo contract given the large and statistically significant standard deviation estimated in the study.

In terms of the attribute for electricity discount, the parameter estimate is found to be consistent across the samples and models used in the analysis and this provides assurance regarding the validity of the overall experiment. This parameter represents the marginal utility of income and in line with economic theory is estimated to be positive and highly statistically significant, suggesting that consumers prefer higher discounts as one might expect. Moreover, the frequency of curtailment events in these types of contracts is also revealed to be a significant factor for consumer preferences with fewer events preferred to more. In examining the coefficient estimates on the attributes for advance notice and opt out across samples, the results show that these are also very important features for consumers' choice of curtailment contract. On average, consumers are found to have stronger preferences for contracts that contained both an advance notice of at least 12 hours for an upcoming event and an opt out from one event per month to be used when necessary. While the findings demonstrate that consumers prefer contracts at low frequencies with advance warning and an opt out, their preferences are shown to be largely dominated by the type of appliance in the end-use specific curtailable contract.

Concerning the household appliances attribute, the results show that during peak load hours between 5pm and 8pm, consumers are less likely to choose a contract that curtails the electric oven when compared to the washing machine. On the other hand, the findings from the full sample suggest that consumers are on average indifferent to curtailing their tumble dryer or dishwasher relative to their washing machines. It is important to note that household ownership of the separate appliances is an important factor for any preference heterogeneity for the appliance attribute in the choice experiment. In this regard, the full sample is divided between respondents that have all four appliances and respondents that don't. The estimated parameters for the sample of respondents that own all four appliances suggest that consumers prefer contracts that curtail either the tumble dryer or dishwasher. Whereas, the respondents that don't own all appliances are found to be less likely to choose contracts that curtail the tumble dryer or dishwasher. Since these respondents are also much less likely to own these appliances, this provides evidence for the validity of the choice experiment with respondents observed to be acting rationally by choosing contracts that curtail appliances that they actually own. More generally, the tumble dryer was the most preferred appliance in these types of end-use specific curtailable contracts.

Furthermore, this paper indirectly infers monetary values for the trade-offs made between different attributes in the form of marginal willingness to accept (WTA) estimates. Not surprisingly, with most disutility placed on having the electric oven curtailed, the WTA estimates are highest for this particular attribute and the results show that consumers require compensations of between €14.32 and €23.16 extra per bi-monthly bill relative to the curtailment of the washing machine. On the contrary, consumers are found to be much more flexible with their tumble dryers or dishwashers. For example, using the sample of consumers that owned all four appliances, respondents are willing to accept less bimonthly compensation on average for a contract that curtailed their tumble dryer (€8.64 less) or dishwasher (€4.19 less) relative to curtailing their washing machine. Moreover, consumers are found to require a discount of between 34 cents and 78 cents per curtailment event and are willing to pay €4.50 towards their bi-monthly bill for advance notice and €3.68 for an opt-out on average.

Related to the WTA estimates, this paper also conducts a welfare analysis where the average respondent's compensating variation (CV) is calculated across 96 different curtailment contract options. It is important to note that the welfare analysis here explores welfare from the consumer's standpoint only. Despite this, it is also likely that there are welfare effects from deploying curtailable contracts at the energy systems level, for example from the requirement for less peaking capacity, and future research could address this issue. At an overall level, the bimonthly welfare loss from including the electric oven in the contract is substantial and ranges between €16.46 and €53.78 dependent on the frequency of curtailment events. Apart from the electric oven, contracts that curtailed the other appliances at low frequencies are found to have either a welfare loss that was statistically indifferent to zero or a small welfare gain. On the other hand, at higher event frequencies, the mean welfare loss grew to a statistically significant loss of between €26.82 and €35.45 dependent on the appliance. Interestingly, contracts that curtail the tumble dryer at low frequencies are estimated to provide consumers with a moderate welfare gain. This would suggest that there is considerable utility associated with the occasional curtailment of the tumble dryer on average and thus, compensation might not be needed for the deployment of rare curtailment on this appliance type to the benefit of energy system operators. In addition, it is also worth highlighting that welfare losses are found to be at their smallest across household appliances when the contract includes both advance notice and an opt out.

There are a number of limitations associated with this analysis. One concern for stated preference methodologies is so-called 'hypothetical bias', whereby respondents' stated values could be different from their real values and thus, any welfare measures based on their stated values could be overestimated as a result of such bias. With this in mind, the choice experiment is designed using a multinomial incentive-compatible response format, where respondents are presented with their status quo electricity contract as well as the two alternative curtailable contracts to be evaluated in each choice card. This should help to satisfy the incentive compatibility requirements for truthful preference revelation.

Another concern related to this analysis is the survey mode used to elicit consumer preferences for electricity contracts with curtailment on household appliances. Online surveys can sometimes be less representative as a result of improper population coverage. They may also lead to poorer data quality due to the risk that some respondents might not fully understand the experiment and cannot seek clarification from a trained interviewer. To mitigate against these factors, this study adopts a number of different approaches. Firstly, a stratified random sample was selected from a reputable panel provider using a sampling frame from the most recent Irish Census (2016) which was based on geographic location, gender, age and employment status. This helps to ensure that the sample is representative of the population of Irish people aged 18 and over. Secondly, the survey includes two screening questions to ensure data quality by determining that the online respondents were paying adequate attention. The observations from respondents failing the screening questions together with the observations from respondents in the top and bottom 5% of survey completion times are removed from the analysis to help maintain good data quality. Thirdly, to assist with any complexity in understanding the experiment, the survey also includes a short and engaging animated video describing curtailment contracts in plain language as well as explaining what was required of respondents to complete the task.

In terms of the policy and market implications of this study, the results suggest that there is a large potential for end-use specific curtailable contracts. Consumers are generally found to prefer the alternative curtailable contracts presented to them, whilst being indifferent to their current electricity contracts. This could present policymakers and grid operators with much greater flexibility in balancing electricity systems that have larger shares of intermittent renewable generation and help achieve greenhouse gas emissions targets more effectively. Moreover, the monetary compensations required by consumers to accept these types of end-use specific curtailable contracts are much lower and more realistic compared to compensations estimated in other studies that aim to elicit compensations for direct load control and soft load control, for example in Broberg and Persson (2016) and Broberg et al. (2017) respectively. This might suggest that this type of demand side flexibility could be more favourable to both consumer welfare and the electricity market more generally.

In addition, this analysis helps policymakers and utilities to understand the value that different electricity services provide to consumers by presenting them with meaningful estimates of the flexibility of so-called 'smart appliances'. For example, it is apparent in this study that consumers are very flexible with their tumble dryers and dishwashers during peak evening hours, while they are more resolute with respect to their electric ovens. Indeed, the results indicate that for curtailable contracts on the tumble dryer or dishwasher, there is no significant welfare loss to consumers until at least after nine curtailment events per month.

Also of relevance to the acceptance of curtailable contracts is the availability of user friendly controls such as the provision of advance notice or an opt out. The presence of these type of controls are found to be very important to consumer welfare at the margin and as a result, such features should be given consideration by those utilities and grid operators interested in pursuing this type of demand flexibility. A further consideration for policy and the market is the large preference heterogeneity for the individual attributes in the experiment. All the estimated standard deviations of the random parameters are found to be statistically significant across the attributes and it would be important for future research to explore the different factors that might help to explain this heterogeneity.

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References

Aalami, H., M. P. Moghaddam, and G. Yousefi (2010). Demand response modeling considering interruptible/curtailable loads and capacity market programs. *Applied Energy 87*(1), 243–250.

Abdullah, S. and P. Mariel (2010). Choice experiment study on the willingness to pay to improve electricity services. *Energy Policy 38*(8), 4570–4581.

Abrate, G., C. Bruno, F. Erbetta, G. Fraquelli, and A. Lorite-Espejo (2016). A choice experiment on the willingness of households to accept power outages. *Utilities Policy 43*, 151–164.

Aghaei, J. and M.-I. Alizadeh (2013). Demand response in smart electricity grids equipped with renewable energy sources: A review. *Renewable and Sustainable Energy Reviews 18*, 64–72.

Amador, F. J., R. M. González, and F. J. Ramos-Real (2013). Supplier choice and WTP for electricity attributes in an emerging market: The role of perceived past experience, environmental concern and energy saving behavior. *Energy Economics 40*, 953–966.

Benetti, G., D. Caprino, M. L. D. Vedova, and T. Facchinetti (2016). Electric load management approaches for peak load reduction: A systematic literature review and state of the art. *Sustainable Cities and Society 20*, 124–141.

Birol, E., K. Karousakis, and P. Koundouri (2006). Using a choice experiment to account for preference heterogeneity in wetland attributes: The case of cheimaditida wetland in greece. *Ecological Economics 60*(1), 145–156.

Bliemer, M. C. and A. T. Collins (2016). On determining priors for the generation of efficient stated choice experimental designs. *Journal of Choice Modelling 21*, 10–14.

Bliemer, M. C., J. M. Rose, and S. Hess (2008). Approximation of bayesian efficiency in experimental choice designs. *Journal of Choice Modelling 1*(1), 98–126.

Broberg, T., R. Brännlund, and L. Persson (2017). Consumer preferences and soft load control on the swedish electricity market. *CERE Working Paper, 2017: 9*.

Broberg, T. and L. Persson (2016). Is our everyday comfort for sale? preferences for demand management on the electricity market. *Energy Economics 54*, 24–32.

Buryk, S., D. Mead, S. Mourato, and J. Torriti (2015). Investigating preferences for dynamic electricity tariffs: The effect of environmental and system benefit disclosure. *Energy Policy 80*, 190–195.

Carlsson, F. and P. Martinsson (2008). Does it matter when a power outage occurs? — a choice experiment study on the willingness to pay to avoid power outages. *Energy Economics 30*(3), 1232–1245.

D'hulst, R., W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, and K. Vanthournout (2015). Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in belgium. *Applied Energy 155*, 79–90.

Drysdale, B., J. Wu, and N. Jenkins (2015). Flexible demand in the GB domestic electricity sector in 2030. *Applied Energy 139*, 281–290.

Dutta, G. and K. Mitra (2017). A literature review on dynamic pricing of electricity. *Journal of the Operational Research Society 68*(10), 1131–1145.

European Commission (2015). *A framework strategy for a resilient energy union with a forward-looking climate change policy.* Number COM(2015) 80 final. Brussels.

Faruqui, A., S. Sergici, and A. Sharif (2010). The impact of informational feedback on energy consumption—a survey of the experimental evidence. *Energy 35*(4), 1598–1608.

Feuerriegel, S. and D. Neumann (2016). Integration scenarios of demand response into electricity markets: Load shifting, financial savings and policy implications. *Energy Policy 96*, 231–240.

Goett, A. A., K. Hudson, and K. E. Train (2000). Customers' choice among retail energy suppliers: The willingness-to-pay for service attributes. *The Energy Journal*, 1–28.

Goulden, M., B. Bedwell, S. Rennick-Egglestone, T. Rodden, and A. Spence (2014). Smart grids, smart users? the role of the user in demand side management. *Energy Research & Social Science 2*, 21–29.

Hanemann, W. M. (1991). Willingness to pay and willingness to accept: how much can they differ? *The American Economic Review 81*(3), 635–647.

Hayn, M., V. Bertsch, and W. Fichtner (2015). A concept for service level indicators in residential electricity tariffs with variable capacity prices. *Advances in Service Research*, 1–10.

Hayn, M., A. Zander, W. Fichtner, S. Nickel, and V. Bertsch (2018). The impact of electricity tariffs on residential demand side flexibility: Results of bottom-up load profile modeling. *Energy Systems 9*(3), 759–792.

He, X., N. Keyaerts, I. Azevedo, L. Meeus, L. Hancher, and J.-M. Glachant (2013). How to engage consumers in demand response: A contract perspective. *Utilities Policy 27*, 108–122.

Hensher, D. A., N. Shore, and K. Train (2014). Willingness to pay for residential electricity supply quality and reliability. *Applied Energy 115*, 280–292.

Hole, A. R. (2008). Modelling heterogeneity in patients' preferences for the attributes of a general practitioner appointment. *Journal of Health Economics 27*(4), 1078–1094.

Hole, A. R. and J. R. Kolstad (2012). Mixed logit estimation of willingness to pay distributions: a comparison of models in preference and WTP space using data from a health-related choice experiment. *Empirical Economics 42*(2), 445–469.

Huh, S.-Y., J. Woo, S. Lim, Y.-G. Lee, and C. S. Kim (2015). What do customers want from improved residential electricity services? evidence from a choice experiment. *Energy Policy 85*, 410–420.

IEA (2018). World energy outlook. Technical report, International Energy Agency.

Johnston, R. J., K. J. Boyle, W. V. Adamowicz, J. Bennett, R. Brouwer, T. A. Cameron, W. M. Hanemann, N. Hanley, M. Ryan, R. Scarpa, R. Tourangeau, and C. A. Vossler (2017). Contemporary guidance for stated preference studies. *Journal of the Association of Environmental and Resource Economists 4*(2), 319–405.

Joskow, P. L. (2012). Creating a smarter u.s. electricity grid. *Journal of Economic Perspectives 26*(1), 29–48.

Lesic, V., W. B. de Bruin, M. C. Davis, T. Krishnamurti, and I. M. L. Azevedo (2018). Consumers' perceptions of energy use and energy savings: A literature review. *Environmental Research Letters 13*(3), 033004.

Li, P.-H. and S. Pye (2018). Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective. *Applied Energy 228*, 965–979.

Louviere, J., D. Hensher, and J. Swait (2000). Stated choice methods—analysis and application, Cambridge University Press, New York.

Lund, P. D., J. Lindgren, J. Mikkola, and J. Salpakari (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews 45*, 785–807.

McFadden, D. (1974). Conditional logit analysis of qualitative choice behaviour. In: Zarembka, P. (Ed.), Frontiers in Econometrics. Academic Press, New York. pp. 105–142.

Ng'uni, A. et al. (2006). Interruptible load and demand response: worldwide picture and the situation in sweden. In *2006 38th North American Power Symposium*, pp. 121–127. IEEE.

Nistor, S., J. Wu, M. Sooriyabandara, and J. Ekanayake (2015). Capability of smart appliances to provide reserve services. *Applied Energy 138*, 590–597.

Ozbafli, A. and G. P. Jenkins (2016). Estimating the willingness to pay for reliable electricity supply: A choice experiment study. *Energy Economics 56*, 443–452.

Parrish, B., R. Gross, and P. Heptonstall (2019). On demand: Can demand response live up to expectations in managing electricity systems? *Energy Research & Social Science 51*, 107–118.

Pepermans, G. (2011). The value of continuous power supply for flemish households. *Energy Policy 39*(12), 7853–7864.

Richter, L.-L. and M. G. Pollitt (2018). Which smart electricity service contracts will consumers accept? the demand for compensation in a platform market. *Energy Economics 72*, 436–450.

Rose, J. M. and M. C. J. Bliemer (2009). Constructing efficient stated choice experimental designs. *Transport Reviews 29*(5), 587–617.

Ruiz, N., B. Claessens, J. Jimeno, J. A. López, and D. Six (2014). Residential load forecasting under a demand response program based on economic incentives. *International Transactions on Electrical Energy Systems 25*(8), 1436–1451.

Scarpa, R., D. Campbell, and W. G. Hutchinson (2007). Benefit estimates for landscape improvements: Sequential bayesian design and respondents' rationality in a choice experiment. *Land Economics 83*(4), 617–634.

Simshauser, P. (2016). Distribution network prices and solar PV: Resolving rate instability and wealth transfers through demand tariffs. *Energy Economics 54*, 108–122.

Strauss, T. (1994). Perspectives on interrruptible electric tariffs. *Utilities Policy 4*(2), 165–172.

Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy 36*(12), 4419–4426.

Stötzer, M., I. Hauer, M. Richter, and Z. A. Styczynski (2015). Potential of demand side integration to maximize use of renewable energy sources in germany. *Applied Energy 146*, 344–352.

Woo, C., P. Sreedharan, J. Hargreaves, F. Kahrl, J. Wang, and I. Horowitz (2014). A review of electricity product differentiation. *Applied Energy 114*, 262–272.

Woo, C.-K. (1990). Efficient electricity pricing with self-rationing. *Journal of Regulatory Economics 2*(1), 69–81.

Appendix A

Screening Questions

Question 1

Question:	This question is only about the data quality. Please select B as your answer choice.
Answer Options:	1: A, 2: B, 3: C, 4: D

Question 2

Question:	How much do you agree with the following statement:
Statement:	It’s important that you pay attention to this study, please tick ”Strongly disagree”.
Answer Options:	1: Strongly agree, 2: Agree, 3: Neither agree or disagree, 4: Disagree, 5: Strongly disagree