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Preferences for curtailable electricity contracts: Can curtailment benefit consumers and the electricity system?

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ABSTRACT

Growth in energy demand together with the increased volatility from growing intermittent electricity production requires new sources of demand flexibility to maintain power system balance. End-use specific curtailable electricity contracts are one incentive-based Demand Response (DR) instrument that could help increase flexibility. This paper employs a choice experiment on a representative sample of electricity consumers in Ireland to elicit their preferences for these types of contracts on household appliances during peak load hours. A welfare analysis is then conducted to determine the compensating variation for different contract scenarios and examine the potential savings associated with a selection of scenarios from the perspective of the power system. The results suggest that there could be potential for flexibility from curtailable electricity contracts. On average, consumers are found to be mostly indifferent to curtailable contracts compared to their status quo contract. More specifically, the type of household appliance in these contracts has the most influence on preferences, while contracts at low event frequencies that include advance notice and an opt out are most preferred. In general, the net benefits to the system in curtailing the tumble dryer or dishwasher at low monthly frequencies are found to be positive, while net benefits are estimated to be negative for the other appliances.

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 2025 with the share of renewable generation predicted to be around 40% of electricity supply by 2030 (IEA, 2020). 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, sector integration 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

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these peak periods by either improving the information available on potential energy efficiency opportunities (Jessoe and Rapson, 2014; Delmas and Lessem, 2014) 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. A similar 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.

In this context, this paper examines consumer preferences for end-use specific 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 highly representative sample of 972 electricity consumers in Ireland, 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 in this paper controls for differences between two groups, those consumers that have all four appliances in their households (Own, $n = 427$) and those consumers that do not have all four appliances (Do not 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. Furthermore, in the context of consumers owning all four appliances, a welfare analysis is conducted to determine the compensating variation for 48 different hypothetical curtailable contracts. This helps to isolate the welfare loss or gain from different end-use specific curtailable contracts when compared to their baseline 'status quo' contract. Finally, using the estimated compensating variations and the choice probabilities from the experiment an additional welfare analysis is undertaken to examine the potential savings for the energy system or utility from the introduction of this type of DR.

Curtailable contracts could be valuable to the electricity grid in terms of reducing expensive generation capacity and avoiding investments in new energy infrastructure from the flexibility they provide grid operators for peak load reduction. These contracts could also benefit consumers in term of the financial incentives that they would receive to reduce their electricity consumption at the peak usage time between 5pm and 8pm in the evening. While interruptible/curtailable load contracts are relatively commonplace in the industry and commercial sectors, and to a lesser extent in the residential sector for Air Conditioning units (AC), there is very little penetration of such contracts in the residential sector for household appliances where a large potential for increased system flexibility could exist. 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. Moreover, given that Ireland is in a geographic location with a much lower requirement for AC relative to other jurisdictions, it provides a useful setting to examine whether end-use specific curtailable electricity contracts can be effective in areas without a lot of AC.

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 curtailment strategies and energy efficiency strategies are complements in a least cost policy, and a diversity of contract types is necessary for DR 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; Sundt et al., 2020) and, consequently, could play an important role in this type of DR.

The remainder of the paper proceeds as follows: Section 2 presents a review of the related work examining demand flexibility opportunities through curtailable electricity contracts, Section 3 provides a description of the choice experiment including the experimental design and the data collection. This section also presents details of the econometric analysis used for the analysis of the choice responses. Results are reported in Section 4, and a discussion and conclusion follow in Section 5.

2. Literature

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 utilities. 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 accept load reductions during peak conditions or system instability situations (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 that could also be seen as important attributes for a curtailment contract. 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. (2021), Richter and Pollitt (2018), Ruokamo et al. (2019) and Sundt et al. (2020). 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. (2021) 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, 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. (2021) 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. More recently, Ruokamo et al. (2019) investigate Finnish household's acceptance of contracts to offer flexibility through the remote control of their electricity and heating usage during specific time periods in the day. Their results show that respondents were much more sensitive to restrictions in their electricity usage which included restrictions on their dishwasher, washing machine or tumble dryer compared to restrictions on their heating. Moreover, they estimated that the required compensation for remote load control of electricity was much higher in the evening than in the morning.

Finally, in a choice experiment study in Germany to examine overall willingness to accept (WTA) for time of use tariffs that differ by peak times and by control of separate appliances during those times, Sundt et al. (2020) find that control of the washing machines' electricity consumption has a negative WTA, while control of the freezer or tumble dryer requires additional compensation. Furthermore, the external control of the dishwasher is shown to require no compensation in the study by a statistically insignificant marginal WTA. In addition to the above choice analyses, there are 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; Ma and Burton, 2016). Furthermore, there are also choice studies which investigate preferences for climate change mitigation policies directly related to residential energy use, for example, Alberini et al. (2018).

Overall, the analysis in this paper contributes to the literature on demand side flexibility in several ways. First, it examines consumer preferences for curtailable electricity contracts at the household appliance level using a discrete choice experiment on a representative sample of Irish electricity consumers. Furthermore, it explores these preferences and the potential for this type of DR in a setting without a high penetration of AC, where AC is known to provide considerable flexibility in some jurisdictions. Second, while this paper examines preferences for the key attributes of appliance type and frequency of curtailment in an electricity contract, it also analyses preferences for some novel features that could be included in such a curtailable contract, such as whether or not consumers have an opt out from a curtailment event and whether or not they receive advance notice. Importantly, it also controls for the differences between the group that own all four appliances and the group that do not in the model specifications. Third, the paper includes a welfare analysis which estimates the compensating variation (CV) for different curtailable contract options in order to determine the overall welfare gain or loss to the average electricity consumer arising from their adoption of end-use specific curtailable contracts. Fourth, the paper provides an analysis of the overall potential savings to the system or utility from a selection of contract scenarios and based on the compensating variations and choice probabilities estimated from the experiment.

3. Methodology

3.1. Choice experiment

A discrete choice experiment is a stated preferences 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. For this attribute, the levels chosen are based on the most energy consuming 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

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 h 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.

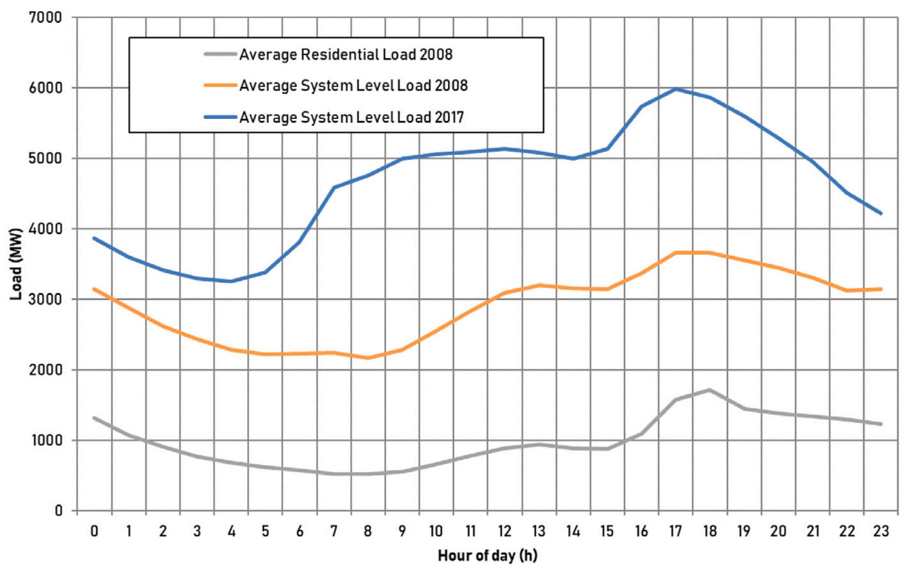

Fig. 1. Average daily load curves for Ireland.
Source: 2008 — Leahy and Tol (2011) and 2017 — SEMO/Eirgrid.

3 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. Fig. 1 illustrates that Ireland's system level load coincides with its residential load and that peak load occurs during these evening hours. 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 h 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 in the choice experiment 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 (18–54 h). 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 18–54 h 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 below €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 given that consumers' preferences may not be limited only to the market values. The suitability of this range of discounts was also tested in both the pre-pilot and pilot studies.

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 (Sándor and Wedel, 2001, 2005; Ferrini and Scarpa, 2007; 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 minimises 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, after employing constraints within the design to avoid dominant alternatives, 24 choice cards are generated using this experimental design approach with Ngene software. A dominant alternative arises where the attributes of one choice alternative has more preferable levels across all attributes relative to another alternative in a choice card.

A sample choice card and choice question is presented in Fig. 2. 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. The choice questions within each block were not randomised. 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]

Another important consideration for the choice experiment methodology is the issue of consequentiality, whereby an individual perceives a nonzero probability that their overall responses will influence decisions related to the final outcome and there is a vast literature concerned with this issue (Herriges et al., 2010; Poe and Vossler, 2011; Vossler et al., 2012; Vossler and Watson, 2013; Interis and Petrolia, 2014). It is significant in the context of making the experiment incentive compatible (Carson and Groves, 2007) and avoiding hypothetical bias where 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. To this end, the experiment design here aims to adopt a multinomial incentive compatible response format to help safeguard truthful preference revelation.

Respondents are presented with their status quo electricity contract as well as the two alternative curtailable contracts to be evaluated in each choice card ($k = 3$) across a sequence of eight choice tasks under the assumption that they treat each choice set as independent from the others. The status quo is represented by the respondents' current electricity contract today and can be understood as a credible baseline in order for respondents to more accurately anticipate the likely effects that the changes in the hypothetical curtailment contracts might have on their welfare. Although a multinomial response format with $k > 2$ alternatives is generally associated with a loss of incentive compatibility compared to a single binary discrete choice format with $k = 2$ alternatives, such a format can still be viewed as incentive compatible when in reality $k - 1$ of the contracts can be provided instead of just one of the k contracts. This is the case for most private goods/contracts including those examined in this analysis. In this scenario, the likelihood that a respondent will choose an alternative that is not their favourite is reduced since if the respondent's first choice is the contract that is not provided, all other contracts would be provided and the respondent's second choice would be available. Thus, the respondent's optimal response is to always select their most preferred option — see (Carson and Groves, 2007, 2011) for a detailed explanation.

Similarly, to help enhance the policy consequentiality of the design, the introduction which contained a brief description of curtailment contracts also stated that "in the future, households could save money if they adapted their electricity consumption at peak times" to reflect that these types of demand flexibility contracts could become a reality.[2] In addition, to help ensure data quality and truthful preference revelation the survey included two data screening questions to determine whether respondents were paying adequate attention.[3] These type of validation questions aim to detect the respondents who are less careful in answering the questions and giving less reliable answers. Indeed, welfare estimates for respondents passing and failing these types of screening questions have been shown to differ significantly with estimates for respondents passing found to have smaller variances (Gao et al., 2016).

3.3. Data collection

In general, the choice experiment survey comprised of an introduction followed by four separate parts. For the introduction, respondents were provided with information about what curtailment means and how adapting their electricity consumption at peak times could save their household money. Then, 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

[1] The Tutorial Video is available in the Online Appendix.

[2] The full description provided to respondents in the introduction is presented in Appendix A.

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

Note: The time of curtailment is fixed across all contracts and is between 5pm and 8pm in the evening.

Choice Card 1

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

Please select which contract you prefer.

- Contract A
- Contract B
- Contract C

Fig. 2. Sample Choice Card and Question.

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. Also, to help mitigate the potential measurement error from survey 'speeders' (Zhang and Conrad, 2014) and very slow responders (Draisma and Dijkstra, 2004), 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 total sample at 99% and 90%, respectively (see Fig. 3), the ownership rates for the tumble dryer and dishwasher are lower at 66% and 65%, respectively.[4] For this reason, the analysis controls for differences between two groups, those respondents that have all four appliances in their households (Own, $n = 427$) and those respondents that do not have all four appliances (Do not 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. The descriptive statistics for both groups are also reported in Table 2.

3.4. Econometric analysis

3.4.1. Random parameters logit

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 for the status quo contract (ASC-SQ). 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-SQ.

[4] It is noteworthy that these sample ownership rates are representative in terms of the national statistics for the population of electricity consumers according to the Irish Household Budget Survey (HBS) 2015–2016.

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[a] %
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
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[b]				
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
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
Market share[c]				
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
Do not Know	2.11	1.47	1.75	0.00
Other	0.72	1.65	1.23	0.39

[a]National statistics are taken from Ireland's Census of Population 2016 and from the Irish Household Budget Survey 2015–2016 where appropriate.

[b]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.

[c]National market shares are taken from Ireland's Commission for Regulation of Utilities 2017 Electricity and Gas Retail Markets Annual Report.

While the conditional logit (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

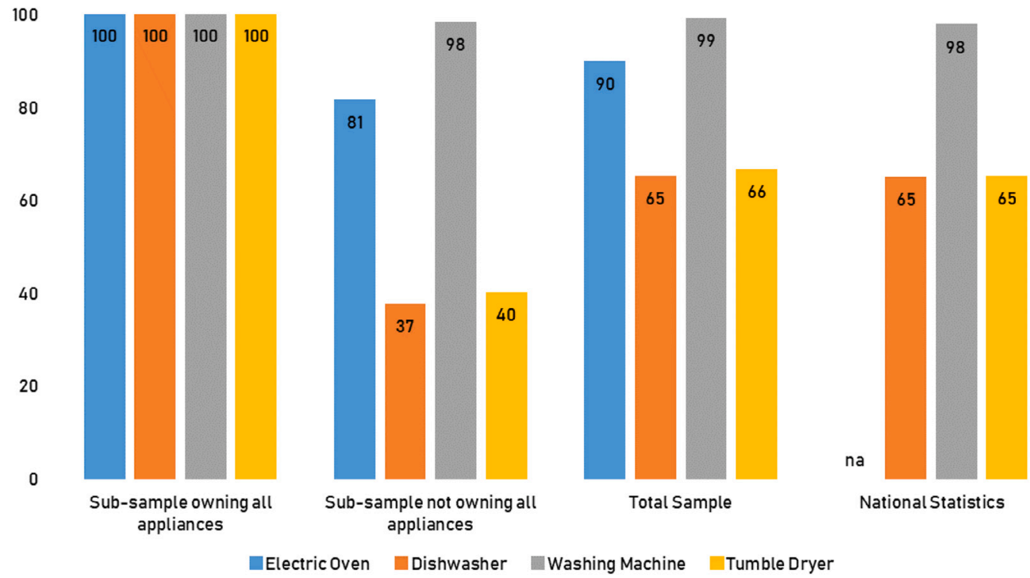

Fig. 3. Proportion of households appliance ownership across samples and compared to national statistics.

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:

$$U_{njt} = \beta_n' X_{njt} + \epsilon_{njt} \tag{2}$$

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:

$$P_{nit}|\beta_n = \frac{exp(\beta_n' X_{nit})}{\sum_{j=1}^{J} exp(\beta_n' X_{njt})} \tag{3}$$

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:

$$P(i^T)_{nt} = \int \prod_{t=1}^{T} \Big(\frac{exp(\beta_n' X_{nit})}{\sum_{j=1}^{J} exp(\beta_n' X_{njt})} \Big) f(\beta_n|\theta) d\beta_n \tag{4}$$

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[5] 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 to create an incentive to accept a curtailment contract as well as to derive a marginal value for the different contract attributes in the form of the marginal Willingness to Accept (WTA) for each of the separate attributes. For the estimation of this WTA, a distinction is made between the monetary discount attribute, D_{njt}, and the non-monetary attributes, X_{njt} in Eq. (2), such that:

$$U_{njt} = \alpha D_{njt} + \beta_n' X_{njt} + \epsilon_{njt} \tag{5}$$

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

$$WTA = -\frac{\beta_n^k}{\alpha} \tag{6}$$

3.4.2. Random Parameters Logit — WTP space

Alternatively, Train and Weeks (2005) and Scarpa et al. (2008) suggest estimating WTP or WTA directly by re-parameterising the model specification in preference space from Eq. (5) above and instead, estimating a model in WTP space using RPL. They point out that a fixed monetary coefficient implies that the standard deviation of unobserved utility, also known as the scale parameter, is the same for all observations and ignoring the variation in scale in this way might

[5] Alternative distributions could also be specified for the random parameters. For example, it could be argued that a log-normal distribution might have more credible distributional characteristics for the random parameter on the frequency attribute, where the attribute levels multiplied by −1 would imply a positive coefficient to suggest that respondents would always prefer lower frequencies of interruption. However, the RPL-C model failed to converge with this specified distribution since the reliance of maximum simulated likelihood on gradient methods to find a maximum imposes stronger restrictions on the choice of distribution (Train and Sonnier, 2005).

lead to this variation being attributed to variation in WTA in error. Similar to Eq. (5), a distinction is made between the monetary attribute and the non-monetary attribute; however, now the coefficient α_n on the discount attribute is individual-specific and specified to be random. It is modelled with a log-normal distribution, which implies that the coefficient is positive. The indirect utility of individual n choosing alternative j on choice occasion t is therefore:

$$U_{njt} = \alpha_n D_{njt} + \beta_n' X_{njt} + \epsilon_{njt} \tag{7}$$

where ϵ_{njt} is a Gumbel distributed random term with a variance equal to $\mu_n^2(\frac{\pi^2}{6})$, where μ_n is the individual-specific scale parameter. Dividing equation (7) by μ_n is shown not to affect behaviour and results in a new error term which is IID extreme value distributed with a variance equal to $\frac{\pi^2}{6}$ (Train and Weeks, 2005) such that:

$$U_{njt} = \lambda_n D_{njt} + c_n' X_{njt} + \epsilon_{njt} \tag{8}$$

where $\lambda_n = \alpha_n/\mu_n$ and $c_n = \beta_n/\mu_n$. Using the fact that WTP for the attributes is $\gamma_n = c_n/\lambda_n = \beta_n/\alpha_n$ equation (8) can now be rewritten and the utility function is specified in WTP Space as:

$$U_{njt} = \lambda_n [D_{njt} + \gamma_n' X_{njt}] + \epsilon_{njt} \tag{9}$$

Another advantage to this specification is that it avoids the necessity of specifying the distribution of the ratio of two random coefficients as would be the case for the model in preference space above (Eq. (5)) if the discount attribute was not specified to be fixed. By directly specifying the distribution of the WTP parameter γ_n in Eq. (9), heavily skewed WTA distributions can be avoided.

Overall, RPL, RPL-C and RPL-WTP Space models are estimated for the full sample of respondents with a model specification that includes interaction terms between the separate appliances and a binary variable, 'Own', indicating whether the respondent owned all four appliances (Own = 1), as well as an interaction term between ASC-SQ and Own. This specification is chosen for the important reasons outlined in Section 3.3 where the interaction terms control for any differences in preferences across the two groups (sub-samples). The first group is made up of those respondents who have all four appliances in their households (Own, n = 427) and the second group consists of those respondents that do not have all four appliances (Do not Own, n = 545). Also, a RPL model is estimated excluding these interaction terms for comparison. The final WTA estimates reported are based on the coefficients from the RPL-C and the RPL-WTP Space models.

3.4.3. Compensating variation

To measure the economic welfare impact of different curtailment contracts on the consumers of electricity, the compensating variation (CV) which measures the minimum WTA for some level of appliance curtailment can also be calculated for the sample of respondents using each respondent's individual level posterior coefficients conditional on the pattern of their observed choices. The expected value of the parameter for each attribute k for each respondent n, given the observed sequence of T choices y and the estimated parameters from Eq. (4), can be approximated by simulation as follows:

$$\hat{E}[\beta_{x,n}] = \frac{\frac{1}{R}\sum_{r=1}^{R} \beta_n^{[r]} \prod_{t=1}^{T}\prod_{j=1}^{J}\left(\frac{exp(X_{njt}'\beta_n^{[r]})}{\sum_{j=1}^{J} exp(X_{njt}'\beta_n^{[r]})}\right)^{y_{njt}}}{\frac{1}{R}\sum_{r=1}^{R} \prod_{t=1}^{T}\prod_{j=1}^{J}\left(\frac{exp(X_{njt}'\beta_n^{[r]})}{\sum_{j=1}^{J} exp(X_{njt}'\beta_n^{[r]})}\right)^{y_{njt}}} \tag{10}$$

where $\beta_n^{[r]}$ is the rth draw for individual n from the estimated distribution of β.

Once the posterior conditional parameters for each respondent are computed the welfare effects of specific curtailment contracts can be examined by computing the CV log-sum formula, described by Hanemann (1984), for determining the expected welfare loss or gain associated with the difference between the new curtailment contract and the status quo contract and expressed as:

$$CV = -\frac{1}{\alpha}\left[ln\sum_{j=1}^{J} exp(V_j^0) - ln\sum_{j=1}^{J} exp(V_j^1)\right] \tag{11}$$

where V_j^0 and V_j^1 represent the deterministic part of the indirect utility function for the status quo contract and the new curtailment contract scenario, and α represents the marginal utility of income. In this study, the welfare impacts are calculated under 48 different contract scenarios which are outlined in Section 4.3. Finally, it is important to note that this welfare analysis explores welfare in the context of owning all four household appliances and 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. Thus, using the compensating variation values together with the predicted choice probabilities estimated from the RPL-C model, the overall potential savings to the system or utility are then calculated under a selection of contract scenarios in Section 4.3.2.

4. Results

4.1. Random parameters logit in preference space

The econometric results from three separate models; the random parameters logit (RPL) model (1), the random parameters logit (RPL) with interactions model (2), and the random parameters logit model with interactions and correlated coefficients (RPL-C) (3) are presented in Table 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. Given that the frequency attribute was presented as the maximum number of curtailment events per month, some respondents could form an expectation that there might be fewer events than the maximum indicated, thus, the frequency of curtailment was also dummy coded in an alternative specification with no interactions to investigate for any non-linearities in marginal utility across the frequency range.[6]

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.[7] However, in contrast to a priori expectations the mean coefficients on the tumble dryer and the dishwasher attributes are found to be statistically insignificant in the RPL model. As described in Section 3.3, it is likely that the sample of consumers that own all household appliances could best match the assumptions underlying the experimental methodology of discrete choice. Specifically, this particular group of respondents are best placed to make all the relative tradeoffs between the different attributes in the choice cards presented to them. Thus, the most confidence can be given to the parameter estimates in specifications that control for this group's differences. To take into account these rates of household appliance ownership and to

[6] The parameter on the attribute for a max frequency of six times was found to be statistically indifferent to the parameter on the attribute for of a max frequency of three times, while the parameter on the attribute for a max frequency of nine times was shown to have a higher marginal disutility relative to a frequency of three times. However, the preferred specification treats the frequency of curtailment as a continuous variable since this was the specification employed at the experimental design stage of the choice experiment.

[7] As a robustness check, model specifications were also estimated which included interaction terms between the appliance type and the other attributes in the choice experiment in order to help explore the possibility that respondent's preferences for the other attributes could be related to the specific appliance included in the contract. These interaction terms were all found to be statistically insignificant and this provides some evidence that there were no labelling effects from the appliance type.

Table 3
Parameter estimates for the full sample from three separate Random Parameters Logit (RPL) models.

	(1)		(2)		(3)	
	RPL		RPL Interactions		RPL-C Correlated Coefficients	
Attributes	Coefficient	Std Dev	Coefficient	Std Dev	Coefficient	Std Dev
Electricity Discount	0.092***		0.093***		0.098***	
	(0.005)		(0.005)		(0.006)	
Electric oven[a]	−1.857***	2.150***	−1.733***	2.142***	−1.894***	2.469***
	(0.142)	(0.141)	(0.169)	(0.159)	(0.316)	(0.374)
Electric oven[a] × Own			−0.396	0.786	0.054	1.164***
			(0.242)	(0.504)	(0.344)	(0.356)
Tumble dryer[a]	0.144	1.806***	−0.332**	1.785***	−0.534***	2.724***
	(0.096)	(0.141)	(0.138)	(0.145)	(0.169)	(0.245)
Tumble dryer[a] × Own			1.117***	0.123	1.378***	1.547***
			(0.194)	(0.138)	(0.229)	(0.400)
Dishwasher[a]	−0.065	1.311***	−0.395***	1.328***	−0.502***	2.156***
	(0.087)	(0.131)	(0.127)	(0.129)	(0.156)	(0.223)
Dishwasher[a] × Own			0.691***	0.145	0.847***	1.345***
			(0.171)	(0.105)	(0.199)	(0.443)
Frequency	−0.099***	0.179***	−0.101***	0.184***	−0.111***	0.203***
	(0.013)	(0.018)	(0.013)	(0.018)	(0.015)	(0.020)
Advance Notice	0.359***	0.664***	0.362***	0.711***	0.390***	0.813***
	(0.049)	(0.088)	(0.051)	(0.091)	(0.063)	(0.131)
Opt Out	0.271***	0.141	0.272***	0.185	0.337***	0.414***
	(0.043)	(0.112)	(0.043)	(0.124)	(0.062)	(0.097)
ASC-SQ	0.357*	4.302***	0.422*	4.278***	0.424	4.128***
	(0.193)	(0.244)	(0.232)	(0.265)	(0.289)	(0.497)
ASC-SQ × Own			−0.317	1.485***	−0.127	3.332***
			(0.393)	(0.425)	(0.362)	(0.756)
No. of respondents	972		972		972	
No. of observations	23328		23328		23328	
Log-likelihood	−5852.68		−5821.58		−5714.09	
AIC	11735.36		11689.16		11584.18	
BIC	11856.22		11874.48		12212.66	
χ^2 Statistic	407.41		417.65		336.15	

Standard errors clustered at the individual level in ().
*p<0.10, **p<0.05, ***p<0.01
[a]Reference category is the washing machine.

help satisfy the above key assumption, the specifications in both model (2) and (3) include interactions between the separate appliances and a binary variable, 'Own', indicating whether the respondent owned all four appliances (Own = 1), as well as an interaction between ASC-SQ (where no appliances are curtailed) and Own.

In comparing the log-likelihood and the Akaike information criterion (AIC) across the three models, there is evidence that the RPL-C is a better fit statistically compared to the other models. The log-likelihood improves across the three models moving from $-5,853$ in the RPL model to $-5,714$ in the RPL-C model together with an improvement in the AIC which decreases from 11,735 to 11,584. On the other hand, the Bayesian information criterion (BIC) which places more weight on the number of parameters in a model increases in the RPL with interactions model relative to the RPL model, where the coefficients of the interaction terms are 8 additional parameters for the model, and is largest in the RPL-C model where the elements of the lower triangular Cholesky matrix are 55 additional parameters for the model.[8] Despite this, the model including the interactions for the joint sample is the preferred specification to control for the group differences and 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. The full variance–covariance matrix as well as the correlation matrix related to the unobserved heterogeneity are also reported in Tables A.1 and A.2 respectively.

In examining the results from the RPL-C model, the mean coefficient on the ASC-SQ, which indicates the preferences of the sub-group that do not own all appliances for the status quo contract, is found to be statistically insignificant. This suggests that, ceteris paribus, this group of consumers are indifferent to the status quo contract (their current contract as it is today) on average compared to a contract curtailing their washing machine. Furthermore, for the sub-group that own all appliances the coefficient on the ASC-SQ × Own is shown to be negative implying that this group relative to their counterparts could be less likely to choose the status quo electricity contract on average compared to a contract curtailing their washing machine. Though, this coefficient is not statistically significant either. It is also worth highlighting that the share of respondents that chose the status quo contract on all eight choice occasions in the experiment is 16.67%. Of these, 58.02% were individuals that did not own all appliances, while 66.05% indicated that they did not want to limit their appliance use or that they did not like any of the options presented to them as reasons for choosing the status quo.

In turning to the estimated standard deviations for the coefficients on ASC-SQ and ASC-SQ × Own, 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 these coefficients vary to a very large degree across the respondents. Concerning the attribute for electricity discount, the marginal utility of income is assumed to

[8] For parsimony, a model was also estimated constraining the 45 insignificant elements of the lower triangular Cholesky matrix from the RPL-C model to zero; however, these elements were found to be jointly significant in a likelihood ratio test which gives a $\chi^2_{45} = 2 \times (5750.97 - 5714.09) = 73.76$ with a p-value of 0.004.

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 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 h 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-SQ.

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 considerably less favoured compared to a contract curtailing the washing machine with no differences across the two groups examined. This is evident from the large negative magnitude (absolute value) of the mean coefficient for the electric oven and the non-significant parameter on the electric oven interaction term. 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 mean coefficients on the tumble dryer and the dishwasher are of a much lesser magnitude and there are large differences across both groups. In the context of the group owning all appliances, the mean coefficients are estimated to be positive which suggests that compared to the washing machine respondents prefer contracts that curtail either the tumble dryer or the dishwasher. In fact, the results 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.

For the group that do not own all appliances the opposite is found, respondents are estimated to be less likely to prefer contracts that curtail the tumble dryer or dishwasher relative to the washing machine. 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 in this group 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 ignored irrelevant alternatives on average in the experiment and this might provide some further assurance for the theoretical validity of the methodology.

In addition, it is of particular note that the estimated standard deviation coefficients on the tumble dryer and dishwasher are statistically significant and of a much larger magnitude compared to the mean estimates and most particularly for the sub-group of respondents that do not own all appliances. This demonstrates the large taste heterogeneity across this group for the inclusion of these separate appliances in electricity curtailment contracts and that some respondents would still have chosen contracts with appliance types that they did not have in their households. This might be explained by some respondents justifying their acceptance of compensation since they consider themselves to be already doing a good thing for the electricity system by not owning such appliances.

Table 4
Parameter estimates from the Random Parameters Logit (WTP Space) Model.

	(1)	
Attributes	RPL WTP Space Coefficient	Std Dev
Electricity Discount	0.267***	0.436**
	(0.064)	(0.209)
Electric oven[a]	−17.123***	19.916***
	(1.090)	(1.030)
Electric oven[a] × Own	−6.947***	1.415
	(2.694)	(2.079)
Tumble dryer[a]	−3.637**	17.843***
	(1.522)	(0.977)
Tumble dryer[a] × Own	12.524***	0.657
	(2.130)	(2.531)
Dishwasher[a]	−5.225	13.460***
	(1.115)	(1.754)
Dishwasher[a] × Own	7.076***	2.290**
	(2.188)	(1.167)
Frequency	−1.138***	1.668***
	(0.127)	(0.127)
Advance Notice	3.529***	6.008***
	(0.473)	(0.511)
Opt Out	2.230***	2.520***
	(0.413)	(0.980)
ASC-SQ	0.378	43.803***
	(1.682)	(3.974)
ASC-SQ × Own	2.578	18.362***
	(0.083)	(2.344)
No. of respondents	972	
No. of observations	23328	
Log-likelihood	−5777.55	
AIC	11603.10	
BIC	11796.48	
χ^2 Statistic	2859.38	

Standard errors clustered at the individual level in ().
*p<0.10, **p<0.05, ***p<0.01
[a]Reference category is the washing machine.

It is also worth highlighting that reassuringly, the mean parameter estimates for the electric oven, frequency, advance notice, opt out and ASC-SQ are very similar in terms of absolute values and statistical significance across the three separate models. Similarly, the fixed parameter on the electricity discount attribute is the same across the models and this helps provide additional confidence in the validity of the experiment.

4.2. Willingness to accept and random parameters logit in WTP space

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 post-estimation. 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 based on the coefficients from the RPL-C model. Their 95% confidence intervals are calculated using the Krinsky and Robb method with 2,000 replications. The WTA values are directly relatable to the electricity discount levels indicated in the experiment. Table 5 presents these WTA estimates and for comparison, the WTA estimates from the RPL-WTP Space model.

In relation to the RPL-WTP Space model results which are reported fully in Table 4, the non-monetary coefficients are normalised with the random parameter on the electricity discount attribute and, unlike the RPL-C model, are computed in the model directly to give direct WTA

Table 5
Willingness to accept (WTA) (€'s bimonthly) estimates for attributes of an electricity contract with curtailment.

	(1) RPL-Correlated		(2) RPL-WTP Space	
Attributes	WTA (Std Dev)	[WTA 95% CI]	WTA (Std Dev)	[WTA 95% CI]
Electric oven	19.28 (25.19)	[13.86, 24.95]	17.12 (19.92)	[14.98, 19.26]
Electric Oven × Own	−0.55 (11.88)	[−7.27, 6.48]	6.95 (1.42)	[1.67, 12.23]
Tumble dryer	5.44 (27.80)	[1.99, 8.81]	3.64 (17.84)	[0.65, 6.62]
Tumble dryer × Own	−14.02 (15.79)	[−18.70, −9.27]	−12.52 (0.66)	[−16.70, −8.35]
Dishwasher	5.10 (22.00)	[1.85, 8.32]	5.23 (13.46)	[3.04, 7.41]
Dishwasher × own	−8.62 (13.72)	[−13.03, −4.48]	−7.08 (2.29)	[−11.36, −2.76]
Frequency	1.13 (2.07)	[0.85, 1.44]	1.14 (1.67)	[0.88, 1.39]
Advance notice	−3.97 (8.30)	[−5.25, −2.84]	−3.53 (6.01)	[−4.46, −2.60]
Opt Out	−3.43 (4.22)	[−4.61, −2.24]	−2.23 (2.52)	[−3.04, −1.42]
ASC-SQ	−4.32 (42.12)	[−9.63, 1.63]	−0.38 (43.80)	[−3.67, 2.92]
ASC-SQ × own	1.29 (34.00)	[−5.95, 8.75]	−2.58 (18.36)	[−9.60, 4.44]
No. of respondents	972		972	
No. of observations	23328		23328	

estimates. In further contrast to the RPL-C model, the discount parameter is assumed to be random and this implies that, more realistically, the scale parameter (standard deviation of unobserved utility) could be different across observations. Furthermore, the discount parameter is specified to be log-normally distributed indicating that consumers will always prefer higher discounts on their electricity bill. For the correlated specification in WTP space, the model complexity meant that the model failed to converge. Thus, the WTP space model is estimated under the assumption that coefficients are not correlated. In this case, the model in WTP space does not account for forms of correlation beyond scale heterogeneity and the variation in the discount parameter could also reflect other sources captured by this variation (Hess and Train, 2017). Hence, the RPL-C model in preference space is still the preferred estimator for this analysis.

Further to this, a comparison of the log-likelihood, AIC and BIC between the RPL-C in preference space model and the RPL in WTP space model suggests that statistically the RPL-C model is a better fit to the data based on the log-likelihood and AIC measures, while the WTP space model is a better fit according to the BIC measure. However, these comparisons have to be interpreted with some caution since it is assumed that coefficients are correlated in the RPL-C model which introduces many more parameters to be estimated.

As expected, the WTA estimates from both models in Table 5 show that 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 €13.86 and €24.95 on their bimonthly bill when compared to a contract that curtails their washing machine. In the event of households owning all four appliances these compensations can range between €7.27 less to €12.23 more compared to their counterparts that do not own all appliances. The compensation ranges here are dependent on the separate models (RPL-C vs. RPL-WTP Space) and groups (Own vs. Do not Own). The mean marginal WTA estimates for the tumble dryer and dishwasher attribute levels are found to be negative in the case of owning all appliances and therefore show that respondents are, on average, willing to pay €8.58 (5.44–14.02) bimonthly to curtail the tumble dryer and €3.52(5.10–8.62) 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. In general, the RPL-C model in preference space has higher WTA estimates in absolute values compared to those estimated in WTP space, while the standard deviations which indicate the existence of taste heterogeneity are generally found to be larger in preference space also. This finding is aligned with that of previous studies examining RPL in both preference and WTP space (Train and Weeks, 2005; Scarpa et al., 2008; Hole and Kolstad, 2012).

In terms of the frequency of curtailment, the WTA results imply that respondents would require a discount of between 85 cents and €1.44 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 43 cents and 72 cents per event. For advance notice, the WTA results are negative and similar across the two models with a negative coefficient indicating a willingness to pay (WTP) for the particular attribute. Thus, all else equal, respondents would expect to pay between €2.60 and €5.25 bi-monthly, dependent on the sample, to have advance notice for an upcoming curtailment event of at least 12 h. Similarly, with regards to opt out, the results suggest that respondents have a negative bi-monthly WTA of between €1.42 and €4.61 to allow them an opt out from one curtailment event per month. Finally, the WTA estimates on the ASC-SQ are also found to be negative which could suggest that respondents would be willing to pay to remain with their status quo contracts; however, they are not statistically significant given their confidence interval. 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.

4.3. *Welfare analysis*

In this section, the Compensating Variation (CV) estimates which measure the minimum WTA for some level of curtailment from a multiple of contract scenarios are presented. Then, based on these estimates, the overall potential savings to the utility are calculated for a selection of these contract scenarios. It is important to point out that the overall analysis here is focused on the results from the RPL-C model with CV estimates computed in the context of owning all four household appliances.

4.3.1. Consumers — compensating variations

In order to estimate the CV for different curtailment contract options in relation to the ‘status quo’ baseline contract, the welfare loss or gain is calculated (Hanemann, 1991; Birol et al., 2006). Posterior conditional parameters are computed for each respondent and then, the welfare effects of specific curtailment contracts can be examined using the log-sum approach outlined in Hanemann (1984). This provides a complete distribution of the CV across all respondents in the context of them owning all appliances and Table 6 presents the mean and median estimates from this distribution for 48 different hypothetical contract types. The standard errors for each welfare estimate were calculated by the bootstrapping 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: 3 per month; 6 per month; and, 9 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 mean and median CV estimates are largest in absolute terms for the electric oven at all frequencies of curtailment. For the hypothetical contracts examined, the mean welfare loss associated with the inclusion of the electric oven in the curtailment contract are estimated to range between €12.18 and €31.66 bimonthly with all losses found to be highly statistically significant. The mean welfare loss is smallest where there are both advance notice and an opt out available, and the frequency is only 3 per month, while the mean loss is largest where there are no advance notice nor opt out available and the frequency is 9 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 neither advance notice nor an opt out. By moving from three curtailment events per month up to nine events per month, the bimonthly mean welfare loss for contract 1 in Table 6 is estimated to start at a loss of €6.37 and then grow to a loss of €13.12, both statistically significant at the 1% level. Overall, median welfare losses(gains) are estimated to be lower(higher) compared to the mean welfare losses(gains).

Interestingly, contract 12 which curtails the tumble dryer three times per month and includes both advance notice and an opt out is predicted to provide a mean welfare gain of €9.49 on average. 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 mean or median welfare loss until at least at nine events per month or six events per month, respectively. This could generally signal a large potential for demand flexibility from such appliances. In contrast to the tumble dryer and dishwasher, the results show that in certain cases, mean welfare losses from the curtailment of the washing machine could become statistically significant at just three 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.

4.3.2. Utilities — a back of the envelope analysis of potential savings

While the previous section focused on the consumer welfare losses (or gains) induced by curtailable load tariffs indicating the required levels of compensation payments, this section focuses on the potential savings from the perspective of the system or a utility. Note that the rough calculations presented in this section should be interpreted as a back of the envelope analysis, acknowledging that the assumptions made – while being based on realistic values from the literature – may simplify the heterogeneity of values occurring in reality. For the purpose of this analysis, the number of appliances in the country are calculated on the basis of the appliance ownership shares as elicited in the survey and the number of private households in the country (1.7 Million households according to the 2016 census CSO, 2017). Multiplying the number of appliances in the country by the average appliance use during the evening peak period as taken from Brazil et al. (2019) and assuming an average peak demand of 3kW per appliance (Stamminger et al., 2008; Hayn et al., 2018), the maximum curtailable power demand during the peak period is obtained. This ranges from 183 MW for the tumble dryer to 2,243 MW for the electric oven (see 5th column of Table 7). These values, however, do not yet account for the probabilities that consumers choose a curtailable contract for one or the other appliance in the first place. The contract choice probabilities vary strongly depending on the levels of the different contract attributes. This analysis focuses on the attributes: curtailment frequency (3, 6, or 9 times per month); and, availability of an advance notice (yes, no). The 6th column of Table 7 shows the corresponding ranges, within which the contract choice probabilities, as obtained from the choice experiment (see Eq. (4)), vary depending on the levels of these two attributes. In general the choice probabilities increase as the curtailment frequency decreases. Moreover, the choice probabilities are higher when an advance warning is offered.

On this basis, the maximum curtailable power demand is calculated accounting for contract choice probabilities (7th column of Table 7), i.e. the potential reduction in required peak supply capacity in the system, which varies between 73–106 MW in case of the tumble dryer and 298–543 MW in case of the electric oven. From these values, potential savings in CO_2 emissions are estimated (columns 8 and 9) as well as the potential financial savings from the utilities’ perspective resulting from reduced requirements to invest in and maintain peak load capacity (column 10 of Table 7). The emissions are calculated assuming that the peak demand would be supplied exclusively by open cycle gas turbines (OCGTs) in the absence of any curtailable load contracts (assuming a specific CO_2 content of natural gas of 0.2 t CO_2/MWh_{th} and an efficiency of 40% resulting in specific CO_2 emissions of 0.5 t CO_2/MWh_{el}; note, however, that this value is very similar to the average CO_2 intensity of the Irish power system according to SEAI, 2018). The financial savings from the perspective of a utility are estimated assuming that less peak generation (OCGT) capacity is needed in the presence of curtailable load contracts according to the values in column 7 of Table 7. For specific investment-related costs of 500€/kW, fixed operation and maintenance costs of 15€/kW a,[9] a lifetime of 20 years and weighted average costs of capital of 10%, annualised investment-related and fixed costs are obtained totalling 73.73€/kW a. The analysis only accounts for this part of an OCGT’s full costs as this corresponds to the “missing money” when investing in peak generation capacity. Note here that the potential financial savings are estimated on the basis of the potential reduction in required peak supply capacity (in MW) only, whereas the potential savings in CO_2 emissions are estimated on the basis of potentially curtailed energy (MWh) during the peak period. The potential emissions savings should therefore be interpreted as an upper boundary since the appliances considered do not constantly run at their maximum power demand and they may not run during the entire peak period.

[9] The unit €/kW a denotes costs per kW per annum.

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					
				3 per month		6 per month		9 per month	
				Mean	Median	Mean	Median	Mean	Median
1	Washing machine	✗	✗	−6.37***	−1.51	−9.74***	−5.52***	−13.12***	−7.97***
2	Electric oven	✗	✗	−24.92***	−21.10***	−28.29***	−23.72***	−31.66***	−25.03***
3	Tumble dryer	✗	✗	2.11	6.26***	−1.26	3.84	−4.63***	−0.16
4	Dishwasher	✗	✗	−2.93**	1.25	−6.30***	−2.51	−9.67***	−5.59***
5	Washing machine	✓	✗	−2.41**	2.19	−5.78***	−0.70	−9.15***	−3.83**
6	Washing machine	✓	✓	1.01	6.05***	−2.37**	2.37	−5.74***	−0.77
7	Washing machine	✗	✓	−2.96**	1.98	−6.33***	−2.46	−9.70***	−4.67**
8	Electric oven	✓	✗	−20.96***	−16.40***	−24.33***	−18.17***	−27.70***	−20.69***
9	Electric oven	✓	✓	−17.54***	−12.18***	−20.91***	−14.67***	−24.28***	−17.12***
10	Electric oven	✗	✓	−21.50***	−17.49***	−24.88***	−20.27***	−28.25***	−21.45***
11	Tumble dryer	✓	✗	6.07***	10.35***	2.70**	7.27***	−0.67	3.84*
12	Tumble dryer	✓	✓	9.49***	13.94***	6.12***	10.64***	2.74**	6.70***
13	Tumble dryer	✗	✓	5.52***	9.53***	2.15	6.99***	−1.22	3.19
14	Dishwasher	✓	✗	1.03	4.86***	−2.34*	1.27	−5.71***	−1.36
15	Dishwasher	✓	✓	4.45***	7.66***	1.08	4.77***	−2.30*	1.94
16	Dishwasher	✗	✓	0.48	4.20**	−2.89**	1.14	−6.26***	−2.41

Note: These estimates are based on the posterior conditional parameters from the RPL-C model and in the context of ownership of all four appliances.
*p<0.10, **p<0.05, ***p<0.01.

Table 7
Assessment of potential curtailable load, saved emissions and potential savings.

Appliance	Appliance ownership	Appliances in the country	Appliance use peak period (mean/day)	Max power demand incl. appliance use (MW)	Contract choice probabilities	Max power demand incl. choice probs (MW)	Saved CO_2 emissions (kt CO_2/a)	Saved CO_2 emissions (%)	Potential savings (M€)
Electric oven	89.51%	1,521,670	49.1%	2,243	[0.133–0.242]	[298–543]	[26–80]	[0.24–0.73%]	[22–40]
Tumble dryer	66.26%	1,126,420	5.4%	183	[0.398–0.578]	[73–106]	[5–14]	[0.05–0.13%]	[5–8]
Dishwasher	64.81%	1,101,770	17.4%	576	[0.349–0.664]	[201–383]	[11–44]	[0.10–0.40%]	[15–28]
Washing machine	98.87%	1,680,790	12.0%	605	[0.212–0.453]	[128–274]	[7–35]	[0.06–0.32%]	[9–20]

Note: These savings are based on the results from the RPL-Correlated model.

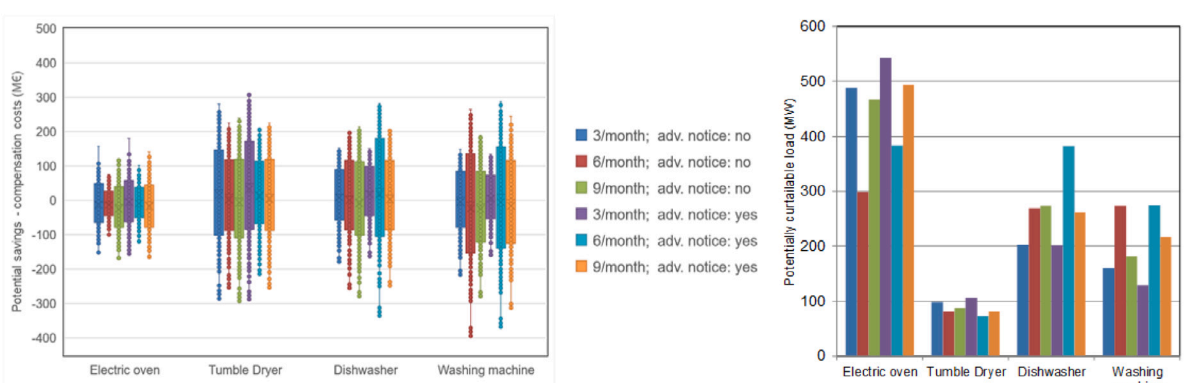

Fig. 4. Net benefits from offering curtailable contracts from utilities' perspective (left) and potential curtailable load (right).

Finally, Fig. 4 shows the range of results, when subtracting the required compensation payments obtained according to the description in Section 4.3.1 from the potential savings as illustrated in Table 7. Fig. 4 (left) shows that, on average (illustrated by the crosses in the diagram), the net benefits (potential savings less compensation payments) from a utility's perspective are negative for the electric oven regardless of the attribute levels of the attributes advance notice and curtailment frequency. The same finding largely holds for the washing machine with the exception of 3 curtailments per month when advance notice is offered. For the tumble dryer and dishwasher, however, net benefits are positive on average with the exception of the highest curtailment frequency (9 times per month) in the scenarios where no advance notice is offered. For these two appliances, the results show that the average net benefits are higher in scenarios where an advance notice is offered and the average net benefits increase as the curtailment frequency decreases. In the scenarios where advance notice is offered, the average net benefits range between 4–32 M€/a for the tumble dryer and between 2–18 M€/a for the dishwasher. Fig. 4 (right) shows that the potential net benefits and the potential curtailable load do not necessarily correlate. Comparing the findings for the different appliances, the electric oven, for instance, provides the highest potentially curtailable load but, at the same time, the lowest/second-lowest benefits. This can be explained by rather high compensation expectations, which outweigh the potential savings.

Note that not all compensating variation estimates (see Table 6) used for the analysis in this section are statistically significant. In particular, the values for contracts curtailing the tumble dryer and mostly so for the dishwasher are not found to be statistically different to zero. The results therefore need to be interpreted with some degree of caution. In general, however, Fig. 4 (left) shows that there is a large amount of heterogeneity in the RPL-C model estimates as demonstrated by the large variations of net benefits for the different contract types. This suggests that some consumers, who would generally accept curtailable contracts, accept such contracts at below-average or no compensation payments. In turn, this implies that a utility's potential savings may be higher than the average values reported before. It is also interesting to observe that the variability of net benefits is much smaller for the electric oven compared to the other appliances and this heterogeneity needs to be analysed in greater detail in future research. Moreover, note that some of the estimates used for the analysis in this section are upper boundaries. For example, since respondents might form an expectation that there are fewer curtailment events than the maximum frequency reported, the choice probabilities associated with frequencies of 3, 6, or 9 times per month are to be considered upper limits for the back of the envelope analysis and will need to be refined as part of future research. Overall, the findings demonstrate the relevance of the attributes chosen within the choice experiment as well as the importance of understanding consumers' differentiated compensation expectations for the different attribute levels when utilities want to design and offer contracts that are accepted by consumers and that are also beneficial from their own perspective.

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 analysis controls for group differences between households that have all four appliances considered (washing machine, tumble dryer, dishwasher and electric oven) and households that do not have all four appliances. An analysis in the setting of the former sub-group 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 in the setting of the latter sub-group provides an insight into consumer preferences in households that do not 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 main models 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 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 h 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. 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 estimated parameters for the group that own all four appliances suggest that consumers prefer contracts that curtail either the tumble dryer or dishwasher. Whereas, the group that do not own all appliances are found to be less likely to choose contracts that curtail the tumble dryer or dishwasher. Since this group is also much less likely to own these appliances, this provides evidence for the validity of the choice experiment with respondents observed, on average, to ignore irrelevant alternatives 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 relative to the washing machine. On the contrary, consumers are found to be much more flexible with their tumble dryers or dishwashers. Moreover, consumers are found to require a discount of between 43 cents and 72 cents per curtailment event and are willing to pay €3.97 towards their bi-monthly bill for advance notice and €3.43 for an opt-out on average.

Related to the WTA estimates, this paper also conducts a welfare analysis where the compensating variation (CV) is calculated across 48 different curtailment contract options. At an overall level, the bi-monthly 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. 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. 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. Based on the discussions from the focus groups at the design stage of the choice experiment, there was a consensus amongst participants that the tumble dryer is regarded as the appliance with the most energy consumption. Participants claimed to be less likely to use the dryer since they were more salient to its higher cost and thus, more favourable to having it curtailed compared to the other appliances. They also recognised that the tumble dryer might also be easily substituted for drying clothes outdoors in good weather. Overall, this could help explain the estimated mean welfare gain from curtailing the dryer in this analysis. Another related explanation is that given there is a societal value associated with electricity curtailment, respondents could select the tumble dryer as their minimum commitment in a so-called buy-in 'warm glow' effect similar to the result observed in Ma and Burton (2016), where most respondents are found to select green electricity products based on the minimum contribution to carbon mitigation.

In an additional analysis, this paper calculates the potential savings from the standpoint of the energy system or utility for a selection of end-use specific curtailable contract scenarios. These savings are based on the peak load savings using the predicted probabilities of choosing the separate curtailable contracts as well as accounting for the compensating variation estimates from the choice experiment. Contracts curtailing the tumble dryer and/or the dishwasher have positive net benefits for utilities, while contracts curtailing the electric oven or washing machine have negative net benefits. In general, it is important for the utilities to understand the differentiated compensation expectations when designing curtailable contracts that ultimately lead to system-wide savings.

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. It has a strong association with non-consequentiality and strategic answering in choice experiments amongst other factors. With this in mind, the choice experiment aims to adopt 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 across a sequence of eight choice tasks under the assumption that many of these contracts could be provided in reality and the respondent treats each choice set as independent from the others. This aims to satisfy the incentive compatibility requirements for truthful preference revelation and mitigate against any strategic or non-consequential answering. Furthermore, it could also be argued that the reliability of value judgements could be greater for private goods, like in this study, than for public goods (Brown et al., 2008). Nevertheless, hypothetical bias could still be a limitation of this analysis.

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 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 efficiently. On the other hand, the monetary compensations required by consumers to accept these types of end-use specific curtailable contracts at high frequencies echo the high cost of demand flexibility found in other studies that aim to elicit compensations for direct load control (Broberg and Persson, 2016) and soft load control (Broberg et al., 2021). For example, Broberg and Persson (2016) estimate that the external control of household electricity, which includes not being able to use the dishwasher, washing machine and dryer, during the evening peak in Sweden requires an annual compensation to the consumer of SEK1409(€157). In contrast to these studies, however, the compensations estimated in this paper offer greater flexibility to the energy system in terms of providing more reasonable and realistic compensations for specific appliances (tumble dryer and dishwasher) at lower frequencies of curtailment. Similar to Sundt et al. (2020), 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, this study indicates 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 or six curtailment events per month, respectively. Moreover, the net benefits to the system or utility are found to be positive for curtailable contracts on both the tumble dryer and dishwasher at low event frequencies in this analysis.

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 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. For example, an important source of this heterogeneity could be whether or not consumers use such appliances during peak times on average. In future research it would be interesting to examine if consumers that do not typically use appliances at peak times are willing to accept lower compensations compared to consumers that do.

CRediT authorship contribution statement

Jason Harold: Conceptualization, Methodology, Software, Data curation, Validation, Formal analysis, Visualization, Writing - original draft, Writing – review & editing. **Valentin Bertsch:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Harrison Fell:** Conceptualization, Methodology, Writing – review & editing.

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Appendix A. Additional information and tables

Information script

This study seeks to examine consumer preferences for residential electricity contracts.

In the future, households could save money if they adapted their electricity consumption at peak times.

One way to do this is to enter into a cheaper contract with your electricity supplier which permits them to curtail (restrict) electricity for some household appliances at peak times in certain situations. The

Table A.1
Variance covariance elements from the RPL-C model.

	Electric Oven	Electric Oven ×Own	Tumble Dryer	Tumble Dryer ×Own	Dishwasher	Dishwasher ×Own	Frequency	Advance Notice	Opt Out	ASC-SQ	ASC-SQ ×Own
Electric Oven	6.096***	−1.615*	−0.428	−0.685	−0.034	−0.113	−0.102*	−0.007	0.110	−0.044	3.477
Electric oven × Own		1.356	−0.336	0.630	−0.439	0.667	0.134***	0.129	0.126	−0.285	0.598
Tumble dryer			7.421***	−3.675***	3.636***	−2.814	−0.075	−0.432	−0.411*	−2.391***	0.314
Tumble dryer × Own				2.394*	−1.152*	1.245	0.041	−0.018	0.389*	1.169	0.081
Dishwasher					4.646***	−2.641***	−0.138***	−0.784***	0.217	−1.705	0.486
Dishwasher × Own						1.808	0.119**	0.447*	0.028	0.971	0.316
Frequency							0.041***	0.003	−0.020	−0.207**	0.139*
Advance Notice								0.661***	0.040	−0.057	0.825**
Opt Out									0.171**	0.096	0.615
ASC-SQ										17.041***	−2.332
ASC-SQ × Own											11.101**

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

Table A.2
Correlation elements from the RPL-C model.

	Electric Oven	Electric Oven ×Own	Tumble Dryer	Tumble Dryer ×Own	Dishwasher	Dishwasher ×Own	Frequency	Advance Notice	Opt Out	ASC-SQ	ASC-SQ ×Own
Electric Oven	1	−0.625***	−0.064	0.147	0.001	0.130	−0.064	0.032	0.069	0.002	−0.103
Electric oven × Own		1	−0.371*	0.107	−0.437	0.474**	0.085	0.091	0.233	0.210*	0.633**
Tumble dryer			1	−0.864***	0.641***	−0.696**	−0.171	−0.180	−0.411*	−0.318***	−0.351
Tumble dryer × Own				1	−0.380**	0.508	0.123	−0.061	0.378*	0 .312**	0.151
Dishwasher					1	−0.906***	−0.273***	−0.430***	0 .232	−0.172***	−0.095
Dishwasher × Own						1	0.226	0.446*	0.074	0.254***	0.266
Frequency							1	0.038	−0.229	−0.065	0 .044
Advance Notice								1	0.173	0 .230**	0 .023
Opt Out									1	0 .266*	0.581***
ASC-SQ										1	0.115
ASC-SQ × Own											1

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

restriction only affects the appliances defined in such a contract and you would still be able to use all other appliances as usual.

Curtailment means that occasionally you would be unable to use a specific appliance or if a specific appliance is running during a curtailment event it would be paused for the duration of the event.

The questionnaire will take you about 15 min to complete and you should find it interesting.

All answers will be kept strictly confidential.

The survey is split into four parts:

PART 1: About you, your electricity bill and appliance use

PART 2: Choice cards

PART 3: Post choice questions

PART 4: Background information

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 is 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

See Tables A.1 and A.2.

Appendix B. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105454.

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