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Probabilistic characterization of electricity consumer responsiveness to economic incentives

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HIGHLIGHTS

- Empirical quantification of electricity demand responsiveness to incentives.
- Quantile regression for a probabilistic characterization of demand flexibility.
- Case study based on a real demand response pilot program in Spain.
- Definition of original risk measures for uncertainty of responsiveness.
- Consumers are classified on the basis of the full distribution of flexibility.

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ABSTRACT

Within a framework of assessment of demand response as an efficient flexibility resource for electric power systems, the main objective of this paper is to present an empirical methodology to obtain a full characterization of residential consumers' flexibility in response to economic incentives. The aim of the proposed methodology is to assist a hypothetical demand response provider in the task of quantifying flexibility of a real population of consumers during a supposed trial that would precede a large-scale implementation of a demand response program. For this purpose, mere average values of predictable responsiveness do not provide meaningful information about the uncertainties associated to human behavior so a probabilistic characterization of this flexibility based on Quantile Regression (QR) is suggested. The proposed usage of QR to model individual observed flexibility provides a concise parametric representation of consumers that allows a straightforward application of classification methods to partition the sample of consumers into categories of similar flexibility. The modelling approach presented here also depicts a full picture of uncertainty and variability of the expected flexibility and enables the definition of two specific risk measures for the context of demand response that have been denominated flexibility at risk (FaR) and conditional flexibility at risk (CFaR). The application of the methodology to a case study based on a real demand response experience in Spain illustrates the potential of the method to capture the complexity and variability of consumer responsiveness. The particular case study presented here shows non-intuitive shapes in the individual conditional distribution functions of flexibility and a potential high variability between different individual flexibility profiles. It also demonstrates the possible decisive influence that interaction effects between socio-economic factors, such as the number of occupants, the business as usual electricity consumption and the education level of consumers, may have on demand responsiveness.

1. Introduction

Flexibility is crucial to ensure a safe and reliable operation of electric power systems, and has become especially relevant in an environment characterized by a growing electrification of energy consumption and a generation mix that is becoming more decentralized, less predictable and less flexible due to the massive penetration of renewable and distributed energy sources [1]. Policy makers and regulatory authorities worldwide are increasingly valuing load flexibility, also known as demand response (DR) [2–4], to contribute to enhance flexibility and increase overall system efficiency. In this sense, while only energy-intensive industrial users were traditionally allowed to provide DR due to their more significant impact at system level on energy balancing and network congestion management, small active

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consumers are increasingly being included as valuable flexibility resources in DR programs [5].

In this framework, the quantification of consumer responsiveness to upcoming or recently introduced procedures and technical solutions that enable DR is essential to explore its business model and its economic impact on the energy system at any implementation level. In fact, anticipating the number of consumers willing to participate and their sensitivity to demand response signals is a basic requirement for the feasible implementation of any DR mechanism, as recently discussed in [6]. An adequate characterization of available consumers' responsiveness to changing electricity prices or explicit incentive payments is also indispensable to build decision-support systems for retailers and aggregators procuring demand response services in their daily forecasting and decision-making processes, as well as the reliability performance of power systems [7]. This is even more important since very little is known about the exact impact and the value of DR in quantitative terms [8,9].

Characterizing the responsiveness of loads to demand response signals requires a detailed understanding of how electricity is used at individual consumer level. While quantifying responsiveness is crucial for any type of consumer participating in demand response, from large industrial facilities to households, it is a particularly complex task when it comes to small residential consumers. On the one hand, traditionally domestic consumers have been largely ignored as potential effective flexibility providers [5]. On the other hand, it is widely acknowledged that for this type of consumers behavioural aspects play a more significant role than economic rationale and that their decisions many times present gaps between knowledge, value, attitude or intention and final actions [10]. Electricity load responsiveness is greatly conditioned by technical aspects [11], such as the type of electrical equipment, its controllability, its capacity of energy storage and its level of automation, but also by behavioural features, such as the perceived value of electricity, and by the nature of the DR signal received by the consumer. Understanding the influences of all these factors is vital to get the picture of demand responsiveness and estimate the potential effect of time-varying prices or explicit demand response requests on electricity consumption [8].

With this aim, a variety of approaches to quantify residential consumer demand responsiveness exist in the literature [12]. Overall, methods can be divided into two major groups: technological engineering models and econometric empirical studies. Engineering demand models characterize the fundamental components of electricity consumption and model their technical characteristics to build up realistic load profiles with different aggregation levels, e.g. [13–16] or [17]. They are valuable to understand the implications of individual uses and let us assess the impact of technological choices, such as renewed equipment or appliances that will not be available until the near future. On the other hand, econometric models for load responsiveness do not require information regarding the actual consumption processes but rather rely on statistical analysis and economic theory to regress functional forms of power demand in relation to a set of variables (e.g., seasonal indicators, prices, income, weather conditions, household size, type of dwelling, social aspects, and even available equipment).

While engineering models are best suited for the analysis of the technical aspects of flexibility at preliminary stages of evaluation, when real data is not always available, an experimental approach with econometric techniques is especially attractive to characterize demand flexibility in situations of real implementation. Having overcome the technological barrier of smart meter data collection and processing, empirical research presents the clear advantage of capturing the subjectivity and the decisive influence of behavioural factors of residential demand choices from tangible observations.

The literature on econometric estimations of load responsiveness based on empirical research in the residential sector is abundant, essentially concerning experiences from the United States, e.g. see [18–25] but also more recently from other countries as well, e.g. a Time of Use (TOU) and Critical Peak Pricing (CPP) pilot study in British Columbia, Canada is presented in [26,27]. Numerous empirical studies of pilot or real demand response experiences taking place across Europe can be found as well, e.g. the application of TOU tariffs to residential electricity users in Italy since 2010 is studied by [28], a TOU trial carried out in Ireland is analysed in [29], a dynamic pricing pilot with automated smart appliances in Belgium (*Linear* pilot) is examined in [30], the results of a large-scale TOU tariff trial for households in the London area (*Low Carbon London*) are investigated in [31] and the effectiveness of implemented demand-based TOU distribution tariffs in Sweden is evaluated in [32,33]. In addition to the well-known 2010 survey of 15 pricing experiments carried out by [34], two additional examples of up to date reviews of demand response experience results, most of them carried out over the past decade are [35,36]. Furthermore, an interesting compendium of bibliographical references is given in [37].

Among empirical studies, it is very rare to find in the literature evidence of purely incentive-based demand response programs addressed to residential consumers, as most real experiences for this consumer sector are based on TOU and dynamic prices [11]. Furthermore, it is remarkable that only average values of observed flexibility are commonly obtained with the proposed models, through measures such as relative peak load reductions, or price elasticities of demand, among others [38]. However, mere average expected responsiveness levels disregard the risks of consumer behavioural variability and heterogeneity.

Given that responsiveness to temporary and explicit requests may differ significantly from permanent and implicit time-varying prices, as the former do not necessarily interfere with normal consumption patterns during periods of no demand response intervention, a specific methodology for this type of signals is required for an accurate characterization of flexibility. Furthermore, in a realistic scenario of implementation of demand response, such a methodology should be able to provide a quantified picture of the uncertainty of different consumers' responsiveness with information of the entire distribution function. For that purpose, a probabilistic approach is required. Probabilistic modelling is commonly applied to other fields, such as electric load [39] and price [40] forecasting, and a few examples of individual electricity load probabilistic modelling are found, e.g. [41,42]. In addition, probabilistic demand response schemes have received special attention recently, e.g. [6] provides an in-depth analysis where deterministic signals are assumed to induce a probabilistic load curtailment as response following some predefined distribution functions that are part of the design elements of the system. However, in the field of empirical modelling of individual consumer flexibility to explicit economic incentives for DR, no references have been found that model electricity demand responsiveness in a probabilistic way.

The aim of this paper is to look into end consumers' flexibility and present an empirical methodology to obtain a probabilistic characterization of the responsiveness of a population of residential electricity consumers to explicit incentives. The purpose of this characterization is to serve as a tool to forecast in advance the amount of flexibility that could be activated from different sectors of this population in relation to a set of controllable and other surrounding variables. With that aim, Quantile Regression (QR) models are suggested as a flexible methodology to provide a parametric representation of the full distribution function of flexibility in terms of exogenous drivers without assuming a specific distribution. A probabilistic characterization of flexibility represents a valuable instrument to handle the risk of consumers not always reacting to these DR signals as desired, as well as to successfully design probabilistic demand response schemes for increasing consumer acceptance and program participation. The proposed methodology is based on smart meter data collected during a trial period of a demand response program so it could be used in practice by demand response providers in real scenarios of implementation at distribution network level. QR modelling provides a full and at the same time concise