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Review

Assessing the success of electricity demand response programs: A meta-analysis☆

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A R T I C L E I N F O

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A B S T R A C T

This paper conducts a meta-analysis of 32 electricity demand response programs in the residential sector to understand whether their success is dependent on specific characteristics. The paper analyses several regression models using various combinations of variables that capture the designs of the programs and the socio-economic conditions in which the programs are implemented. The analysis reveals that demand response programs are more likely to succeed in highly urbanized areas, in areas where economic growth rates are high, and in areas where the renewable energy policy is favorable. These findings provide useful guidance in determining where and how to implement future demand response programs.

1. Introduction

The share of renewable sources in electricity generation is increasing significantly, particularly in Europe [1]. This increasing share tends to increase the variability of overall electricity supply. Non-intermittent capacity can be used to fill the valleys in such generation, but is a costly solution since backup power plants will only be used for limited periods of time. Further, although storage technologies are improving, they are still expensive and inefficient at present [2].

A more viable option is to adjust the demand for electricity, through demand response (DR) programs, which aim to modify the demand patterns for electricity by encouraging its use during peak generation and discouraging its use at times when the load on the grid is highest. One means of modifying demand is through the use of time-varying pricing, which broadly comes in three forms: time-of-use pricing (TOU) varies prices over the hours of the day with higher prices during peak periods, critical peak pricing/rebates (CPP/CPR) increases prices or provides rebates for conservation during the critical peak hours, and real time prices (RTP) allow prices to vary dynamically with the marginal cost of electricity [3]. Other means of modifying demand may involve the use of external load control techniques.

DR policies had been slow to emerge across Europe due to limited knowledge on the energy saving capacities of DR programs and the high costs for associated technologies and infrastructures [4]. However, DR is now seen as a promising option for the integration of renewable energy (RE) [5]. The European Commission (EC) estimates the potential response by 2030 at 160 gigawatts (GW), against current programs that achieve about 20GW [6]. The Commission's recent "Clean Energy for All Europeans" proposal further proposes that customers should be entitled to access dynamic pricing contracts, DR programs, smart metering systems, and better information on their consumption [7].

Consequently, DR is being promoted through enabling policy frameworks in countries such as France, Belgium, Finland, and the UK – though several countries still face significant regulatory barriers or do not yet view demand flexibility as a resource – and DR programs are being increasingly tested and implemented, including in the residential sector[1] [6].

Residential DR programs can however be challenging to implement successfully due to the limited price responsiveness of households, equity considerations, and the high costs of metering infrastructure [10]. A further consideration of households' price – and overall – responsiveness is the focus of this paper.

There have been a number of studies aimed at better understanding household responsiveness to demand side management.

Abbreviations: CPP/CPR, critical peak pricing/rebates; DR, demand response; GDP, gross domestic product; OLS, ordinary least squares; RE, renewable energy; ROC, receiver operating characteristics; RTP, real time pricing; TOU, time of use

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[1] An overview of European smart grid projects is available with the EC's Joint Research Center [8], while a list of demonstration projects supported by the US government is available at the US Department of Energy [9].

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But this existing research has been fragmentary, due to a varying focus on different aspects of DR programs. Faruqui and George [11] found that responsiveness varies with rate type, climate zone, season, and air conditioning ownership. Brent et al. [12] state that price changes lead to greater conservation effects than moral and social arguments, that knowledge of consumption can maximize the effectiveness of time-varying pricing, and that enabling technology increases the effectiveness of such pricing. The consumer behavior studies under the US government's Smart Grid Investment Grant program found that enrolment under opt-out approaches was higher than under opt-in approaches due to status-quo effects, loss aversion resulted in higher retention rates for CPR than for CPP, and higher price ratios led to greater response [13]. Kessels et al. [14] conclude that dynamic pricing schemes should be simple to understand, with timely notifications of price changes, a considerable potential effect on the energy bill, and automated control. Often the success of the pricing scheme depends on factors influencing the behavior of end users. Gyamfi et al. [10] therefore suggest greater use of economic behavior-based approaches to overcome some of the challenges to achieving effective voluntary demand reductions.

Existing research has also occasionally thrown up conflicting findings. For instance, Gyamfi et al. [10] found that a high fraction of households − particularly the richer ones – did not respond to price signals. However, the Irish Commission for Energy Regulation [15] found that ToU tariffs do reduce electricity usage, and that higher-consuming households tended to deliver greater reductions. Muratori et al. [16] found that shifting consumption may lead to steeper rebound peaks, while Cosmo and O'Hora [17] found that reductions lasted beyond the peak period and that post-peak spikes in usage were not observed.

Further, Flaim et al. [18] claim that the prevalence of dynamic pricing programs remains limited on account of too little synthesis of existing research and an over-reliance on simple yet misleading performance metrics. Most attempts to aggregate research on DR programs have taken qualitative approaches, and have mainly focused on the characteristics of the program, such as pricing structures or the existence of load controls. For instance, Kessels et al. [14] frame results from existing meta-reviews as four hypotheses on user response and test these hypotheses using a case-based approach. Stromback et al's [19] review of feedback and pricing pilots offers findings similar to Brent et al. [12], based on basic statistical analyses such as proportions and weighted averages. Hobman et al. [20] use insights from psychology and behavioral studies to draw lessons on DR design. Faruqui and Sergici [21] contain their analysis of 34 studies to the impacts of price ratios and enabling technologies. Faruqui et al. [22] further review a dozen pilot studies only for the role played by information feedback.

There is a need for more rigorous analysis of the DR experiences, collecting a range of DR aspects under one study, and taking into account other socio-economic determinants, in order to obtain more broadly valid findings. This paper attempts to address these needs, by undertaking a meta-analysis of existing literature on DR programs. It uses a logistic regression approach in aggregating results from various studies to distil common findings and trends. The paper goes beyond considering characteristics of DR programs to also look at the relationships that socio-economic environments may have with the success of these programs. This approach helps explain whether any socio-economic factors are correlated with, or contribute to, the chances of a successful DR implementation. In this way, it complements the findings of studies such as Kessels et al. [14].

2. Methods

A meta-analysis statistically combines evidence from multiple studies with an aim to identify either common effects or common causes for variation on specific research questions; it is often beneficial for overcoming the subjectivity of narrative reviews, as explained in [23] and [24]. Meta-analyses have typically been used in the field of medicine [25] [26], although their use in energy economics is not yet widespread.

In the field of energy, Sundt and Rehdanz [27] use a meta-analysis to understand consumer preferences for a greater share of RE in their electricity mix. Mattmann et al. [28] offer a meta-analysis of 32 studies on the non-market valuations of wind power externalities. Van Der Kroon et al. [29] conduct a meta-analysis to understand household fuel choice and fuel switching behavior in developing countries and aim to contribute to energy transition policies.

2.1. Data gathering and categorization

To undertake the present analysis, this paper drew upon articles from journal databases, and complemented this with studies from sources that covered analyses of DR initiatives, as well as with more general searches for other unpublished DR initiatives in an effort to address publication bias.

The focus of the search was on time-varying DR measures; studies looking at tiered pricing or at general determinants of electricity consumption behavior were excluded from the analysis. Data gathering thus used combinations of search terms such as but not limited to "residential," "demand response," and "electricity."

Studies published before 2006 were not considered, in an effort to stay relevant with the current state of play, although the underlying projects covered in these studies may have been deployed earlier.

Based on these criteria, the final sample included 32 studies, which are listed in Table A1 of Appendix A. Two of these are from emerging markets – China [30] and South Africa [31] – while the rest are from Europe and the US, reflecting the prevalence of such programs in developed countries. No results were found in low-income developing countries, since DR programs have either not been rolled out in such countries or are too recent to be able to yield concrete results.

The dependent variable is the success or failure of the DR programs, and it was coded in binary form (successful = 1, unsuccessful = 0). The 32 papers included in the meta-analysis looked at DR programs from three broad perspectives, and the dependent variable was determined based on the perspectives as follows: (i) If the study took the perspective of the electricity provider: The program was a success if the author of the study concluded that peak load was shifted and the shift was statistically significant; (ii) If the study took the perspective of the electricity consumer: The program was a success if the author of the study concluded that financial savings from load shifting were statistically significant; and (iii) If the study took the perspective of a potential rollout: The program would be a success if the author of the study concluded that the survey respondents were willing to accept the implementation of a DR program.

In this way, the definitions of the DR programs as successful/not successful were based on the conclusions of the underlying studies. The authors of this paper do not attempt to impose a standardized definition of success across the heterogeneous range of underlying studies.

A few studies included multiple DR measures or multiple offerings of a DR measure – Fell et al. [32], for instance, studied the acceptability of five types of tariffs – or disaggregated their results – such as Bartusch and Alvehag [33], who studied DR based on type of housing. In such cases, the analysis focused on aggregated results where possible, and otherwise focused on those measures/levels that had the most complete information available for each of the independent variables.

The explanatory variables are broadly grouped under two categories: those that describe the structures of the DR programs (intrinsic variables), and those that describe the socio-economic conditions under which the programs were implemented (extrinsic variables).

Data on the intrinsic features of the DR programs was obtained from the underlying studies themselves. The intrinsic variables are listed in Table 1 below.

It may be noted that the peak to off-peak ratio in variable 3 was