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A review on price-driven residential demand response

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ABSTRACT

Smart grid enables the two-way communication between the suppliers and consumers. Price-driven demand response (PDDR) is one of the important demand response categories that uses price of the energy as control signals to affect consumers' electricity consumption. The current PDDR programs include critical peak pricing (CPP), time-of-use (TOU) pricing, and real-time pricing. In this paper, we provide a review of the PDDR studies. Detailed evaluations on advantages and disadvantages of each PDDR are provided. Concerns and future research challenges on PDDR are also addressed. It is believed that with the installation of smart meter infrastructures at residential households, price signal can be an efficient market tool for peak demand shaving, risk and reliability management, carbon emission reduction, and energy cost reduction.

1. Introduction

Electricity is a very unique commodity which cannot be economically stored in large quantity. Nowadays, nearby electricity markets are interconnected with each other to improve system reliability, reduce energy cost, increase penetration of renewable resources, and reduce carbon emission. With a much larger interconnected grid, surplus electricity energy can be stored into different forms such as hydro power by pumping the water back to the dam for later use. According to the U.S. Department of Energy, smart grid generally refers to a class of technology used to bring utility electricity delivery systems into the 21st century, using computer-based remote control and automation [1]. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries [1]. Smart grid enables the electricity energy exchange between electricity markets. It also enables integration of renewable energy resources to the energy exchange grid. Researchers are continuously working on new mechanism that can better serve the demand by either increasing supply or keeping demand bounded to the supply. While the proactive management of demand plays an important role, at times of high demand tapping into renewable energy resources or tapping into backup resources are critical components of smart grid solutions. All of these actions can also be referred as demand response.

According to the current understanding of the impact of demand response, it is still increasingly seen as a way of meeting emerging needs for better system management and concerns about energy security and environmental impact [2]. Demand response as a proactive measure can be implemented in both manual and automated ways. The manual demand response usually refers controlling use of certain appliances in different time periods of the same day. Semi-automated demand response involves a pre-programmed demand response strategy that is initiated by a person through a centralized control system. Fully automated demand response does not involve any human intervention but is initiated at a home, building, or facility through receipt of an external communications signal [3].

Although demand response is a very cost-effective way for peak demand shaving, risk and reliability management, carbon emission reduction, and energy cost reduction, industrial and residential sectors have different aspects on this topic. For industrial sector, the primary target is maximizing the profit. As electricity consumption is part of the production cost (in some industries such as chemical production companies electricity consumption is a huge part of the production cost) and demand response can reduce the electricity cost, industrial sector is able to adopt demand response very quickly. The residential sector, however, is not able to adopt demand response as quickly as the industrial sector because the primary focus of the residential sector is on increasing the comfort level. Different opinions of demand response are also rising important issues in applying such technology at the

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residential sector. According to a study proposed by Bartusch et al. [4] with 500 interviewed consumers under Swedish power system, only 50 are participated in the proposed study. People neither want their lives to be governed by tariff rates nor their demand to be remotely controlled, and they do most certainly not want to waste their time keep tracking on their electricity usage [4]. Although everyone wants to save money on their electricity bills, sacrificing the comfort level in exchange for financial incentives is not accepted by the majority of the residential sector, especially when the savings are very small. Another important reason is that most consumers are only charged by a fixed electricity rate based on the average electricity cost even though the real time electricity prices vary from time to time. In some cases, electricity costs may vary hourly or seasonally according to the seasonal and daily variations [5]. The U.S. Energy Policy Act of 2005 mentions that each electric power company should provide customers with time-based rates [5]. Currently, most utility companies offer consumers tiered residential electricity prices based on the climate zone, seasonal information, and time of use. When a consumer's total electricity usage exceeds a certain predetermined threshold, the consumer will be subjected to different electricity rates based on the tiered price structure. We believe that research on real time energy pricing and consumer behavior modification through pricing energy will gain acceleration as utility companies roll out pricing systems that charges consumers based on time of use and amount of energy consumed.

In this paper, we reviewed the PDDR studies. Advantages and disadvantages of each PDDR program are evaluated in detail with experimental results. Based on the results, a discussion section is provided including our concerns and opinions on the current PDDR programs. The rest of the paper is organized as follows: Section 2 provides a general introduction on demand response. Detailed evaluation on recent PDDR programs are explained in Section 3. Section 4 discusses the issues with recent PDDR and conclusions are provided in Section 5.

2. Demand response

According to the Federal Energy Regulatory Commission, demand response is defined as changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price electricity over time, or to incentive payments designed to induce lower electricity usage at times of high wholesale market prices or when system reliability is jeopardized [6]. The studies on demand response started on early 1980s under the demand-side management programs. It is believed that utility companies, transmission and distribution system operators, and end-use consumers can all benefit from demand response.

The benefits of demand response for utility companies presents themselves as reduced capital cost, operation cost, and reduced carbon emission. Compared to the huge capital cost and long construction time of period building new generation plants to match electricity consumption at peak hours, demand response is an economical, and environmental friendly program that can be used to balance the supply and demand within the jurisdiction of electricity grid. Demand response can also help the utility companies operate their power generation plants at optimized speeds. This in turn will result in reduced fuel consumption, increased productivity and increased profit margins. Carbon emission can also be reduced as the fuel consumption efficiency is increased. Moreover, utility companies can benefit from the demand response by avoid use of diesel powered backup/emergency power plants and in turn reduce carbon emission. Because of such advantages, demand response is among the top priorities of energy utility companies.

For transmission and distribution system operators, demand response is also an essential asset. The transmission and distribution system operators are in charge of balancing the demand and supply within the jurisdiction of electricity grid at all time. Electricity is a special commodity which cannot, currently, be economically stored in large quantities. Demand response can provide ancillary services to enhance the voltage stability in power systems operating under increased uncertainty, and replace some or even all of the spinning reserves typically supplied by conventional generators [7]. This will avoid using rolling blackouts when there is not enough energy supply and in turn increase the electricity grid reliability and reduce congestion.

Consumers can also benefit from demand response. Under the current regulated energy transmission and distribution systems, electricity prices are generally averaged over the entire year and cost-of-service pricing is the norm. On the other hand, the real-time electricity price varies from time to time. Utility companies have to purchase high-priced wholesale energy whenever they cannot meet the demand. An extreme example occurred on November 28, 2005, eastern Denmark. The wholesale price reached DKK 13,469/MWh (equals to $2189.17/MWh USD), which is 60 times more than the normal price level [8]. These high wholesale energy prices are eventually included in the calculation of the averaged energy price and are paid by the consumers. Demand response programs can lower the energy consumption during peak hours. This will reduce the wholesale energy prices and in turn reduce the energy price paid by the consumers.

Renewable resources, such as solar, wind, biomass, and hydro, are continuously growing and playing a very important role in supplying electricity. According to the U.S. Energy Administration Renewable Electricity Standard (RES), by 2020, every state in the United States must generate one third of their electricity from renewable resources. German Advisory Council on the Environment states that Germany is aiming to transform its electricity supply to 100% renewable energy by 2050. Demand response programs can increase the penetration of renewable resources and benefit the environment in reducing carbon emission. It can contribute to the better integration of renewable energy resources such as wind power, solar, small hydro, biomass and combined heat and power (CHP) [9,10]. Excess energy from the renewable resources can be either stored into different form for later use or supply to the grid to reduce the electricity generated by the ordinary thermal generation plants. Surplus energy from the renewable resources can be stored in a different form of energy for later use in order to minimize the overall operating and environmental costs [11]. With renewable energy accessible only at certain times, the research on energy storage is also gaining momentum. We believe demand response programs will benefit from the developments in storage technologies as well as drive the developments in the storage technologies.

Currently, demand response can be divided into main categories which are further subdivided into many forms. A complete list of demand response varieties is shown in Fig. 1. In this paper we will focused on residential PDDR programs. A detailed presentation of residential PDDR programs is given in Section 3.

In the incentive or event-based demand programs, direct load control and emergency response programs are voluntary programs. Consumers will not get penalized if they did not adjust their energy consumption according to the suggestion by the local utility companies or the independent system/market operator. In the direct load program, utility companies or system operators can remotely control customers' specific appliances (large energy consumption devices) in order to respond to the demand and reliability issues. Incentives are available for involved customers. Emergency response program provides incentives in exchange for voluntary load reduction during special events. Capacity market programs and interruptible/curtailable service are mandatory programs and enrolled consumers will get penalized based on the agreement if they did not adjust their energy consumption accordingly when needed. In the capacity market program, load reduction is pre-specified and mandatory as directed by the utility companies and system operators. Interruptible/curtailable program is very similar to the emergency response program except it is mandatory. Finally, demand bidding/buyback and ancillary service market programs are market mechanisms to balance energy supply and demand based on the