Winner Paper
ERRA Regulatory Research Award 2023

Improving Grid Efficiency: Review of Price-Based Demand Side Management

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September 2023

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***Summary*:**

The paper reviews different approaches and strategies of demand-side management. Specifically, it focuses on different price-based programs that help to balance the system by providing the consumers with price signals to incentivize them to adjust consumption according to actual time-varying market conditions. Moreover, the paper examines the advantages of these programs while also addressing the challenges they encounter, which can impede the successful implementation and overall efficiency of the programs.

***Keywords*:**

Demand-side management, variable renewable energy, IBDR, PBDR

I. INTRODUCTION

Increasing the share of variable renewable energy (VRE) raises the importance of balancing mechanisms in the energy sector. The intermittent nature of variable energy sources complicates the managing process of the electricity grid.

Besides supply-side management, promoting balanced energy consumption with demand response programs can also help maintain grid stability and reliability. Demand response programs can be categorized as incentive and price-based programs [1], which aim to encourage consumers to participate and adjust their electricity usage during peak or critical periods using different tools and approaches.

Incentive-based demand response programs (IBDR) offer some financial incentives or other benefits to participating consumers to encourage their load shifting or load curtailment. However, price-based demand response programs (PBDR) use time-varying electricity pricing structures to incentivize consumers to change their energy usage habits considering the costs they impose on the grid, smoothen electricity consumption and relieve stress from the grid.

Most residential consumers pay the same rate for each unit of electricity irrespective of the time of the day or season. Such flat rates fail to reflect the actual costs of the system varying depending on time, "thereby undermining efficient utilization of bulk generation, transmission, and distributed energy resources (DER)" [2]. Implementing dynamic prices that reflect actual market conditions can create various environmental and economic gains, such as increased grid stability and reliability, avoided or deferred capacity investments in transmission, distribution, and generation, reduced electricity costs, improved assessment of DERs, and reduced carbon emissions [2].

Several studies, including [1,7,8,], examine characteristics of different system flexibility measures on the demand side and their contribution to balancing the electricity grid. The study by Badtke-Berkow et al [2] assesses the benefits and critical considerations of implementing PBDR. Other studies [10,13] assess the impact of time-varying rates in empirical frameworks.

This paper aims to review different approaches and tools of DSM, with a specific focus on price-based DSM. Moreover, the paper examines the barriers encountered by these programs and explores potential solutions to address them.

II. Body

Importance of Demand-side management

The intermittent character of variable renewable energy is challenging for the system operators. Weather conditions are not predictable with 100% certainty, resulting in disruptions in the power systems. Because of the balancing and transmission system limitations, operators may use less variable energy than is available to maintain stability. The loss in potential energy generation is called curtailment, and the systems with a more significant VRE share tend to have bigger curtailments.

In the United States, California is the second with the share of renewables in the system. In 2022 solar energy accounted 29% of California's total electricity generation and wind 7% [3] . As the share of the VRE increased so did the energy curtailment. Figure 1 depicts the amount of unused energy due to system vulnerability.

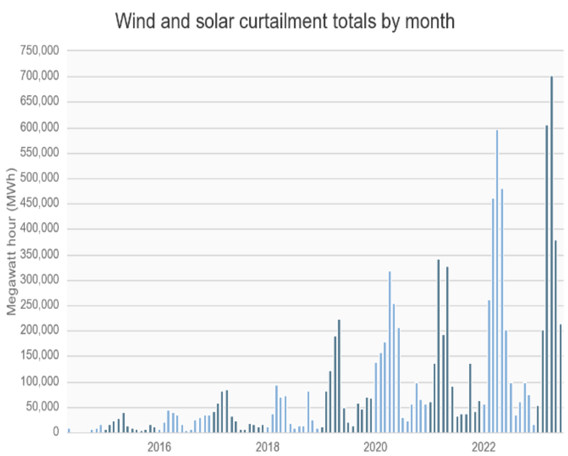

Figure 1 Wind and Solar Curtailments by Month in California. Source: caiso.com

Power systems must be more flexible to address these challenges and accommodate the increased share of VRE generation. However, some power plants need help to adjust their generation level to demand fluctuations. The cause of this problem is the economic and technical constraints related to the characteristics of conventional power plants, such as minimum load requirement for the generator, ramp rates, and start-up times.

Therefore, power plant categories are inflexible, flexible, or highly flexible based on their operational restrictions. Conventional power plants that cannot adapt to flexibility requirements and environmental objectives, except through affordable non-emitting alternatives, may need to offer their generation at a cost below the marginal value to avoid the expenses of enhancing flexibility or facing early decommissioning. [4]

Swings in solar energy generation are more predictable and manageable than wind output. In northwest Europe, wind energy generation poses huge trouble for system operators as they push the system's technical limitations. Western Europe may face 200GW fluctuations throughout the day by 2030. The cause of most of the deviation will be unpredictable characteristics of WPP.

As a result, wind curtailment plays a huge part in driving up balancing costs. There is a noticeable positive correlation between system balancing costs and high wind output (Figure 2). [5]

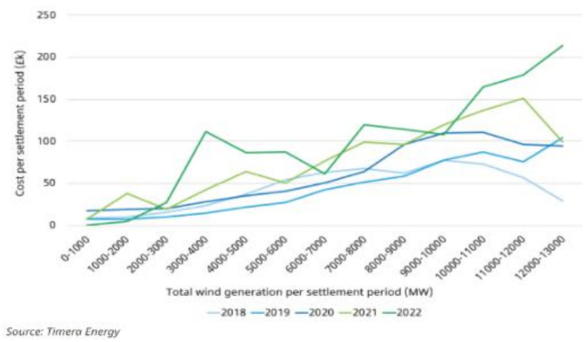

Figure 2 Average constraint balancing cost per settlement period. Source: Timera Energy

Policymakers believe that properly designed incentive and reliability programs are crucial for increasing demand side flexibility. Particularly, the advocates of Time-of-use rates claim that incentivizing consumers to adjust their electricity consumption to the market conditions, will be beneficial not only for the TOU program participants but also the system in general, since expensive an inflexible power plants will not be needed. [6]

Reliability/Incentive-based programs:

Incentive-based programs offer financial or non-financial benefits to consumers to encourage them to voluntarily participate in demand response activities to manage peak demand, grid instability, and other critical grid conditions.

Interruptible load control is a demand response program that grid operators or utilities offer to electricity consumers. Typically, the participants of this program are large industrial and commercial consumers who can adjust electricity consumption without significantly affecting the core of their operations. Under this program, the participants accept service interruptions in exchange for lower electricity rates or other financial incentives under specific conditions, such as peak electricity demand, electricity supply shortage, and grid emergency.

Unlike the interruptible load control program, in which consumers are required to curtail load at an announced DR event, by participating in a Direct load control program (DLC), consumers allow utilities or grid operators to control their load to the system. In the case of DLC, grid operators or utilities can remotely adjust, or interrupt energy usage of specific appliances or equipment used by the participating consumers for which they get compensation. Compared to price-based programs for 'slow energy trading,' DLC may be favored for rapid, predictable, and reliable demand response [7]."DLC programs can address the minute-scale VRE variability that is too fast for price-based programs. However, DLC programs have the risk of reducing the inherent diversity of loads, leading even to oscillatory load population behavior" [7].

Direct participation program in the energy market allows consumers or distributed energy resources to offer services to the grid in exchange for compensation. For instance, consumers with distributed energy resources, such as energy storage systems, solar panels, electric vehicles, or backup generators, can offer their excess electricity supply to the grid or adjust their demand accordingly.

Price-based programs

Price-based demand response programs (PBDR), which are alternatives to flat tariffs, where consumers pay the same electricity rates irrespective of the period of a month, try to restructure the energy demand profile by replacing static electricity rates with more dynamic pricing methods [1]. Based on market conditions, consumers in these programs pay different electricity rates for different periods. The goal of the price-based programs is to encourage consumers to use electricity when its production costs or demand is relatively low, to reduce consumption when the production costs or demand is relatively high, and, therefore, to align electricity usage with the costs they impose on the grid. These programs include time-of-use tariffs, critical peak pricing, variable peak pricing, and real-time pricing.

Benefits of PBDR

PBDR programs provide financial incentives to consumers for energy conservation or shifting load from on-peak to off-peak hours, where electricity rates are relatively cheaper. By adjusting their electricity usage habits, consumers can help balance the system, which results in a more reliable and stable grid and minimizes the risk of grid disruptions and blackouts. [8]

Shifting demand away from peak hours to off-peak hours leads to more smooth distribution of electricity consumption throughout the day. Therefore, it potentially decreases the need for additional generation of fossil fuel-based energy sources often used to meet peak-hour demand. It also leads to lower emissions and pollution and a more sustainable energy system.

These programs synchronize electricity consumption with renewable energy generation patterns. Electricity demand does not always align with consumption patterns.

By incentivizing electricity consumption when it is cheaper, which indicates the abundance of renewable energy in those periods, PBDR facilitates the integration of renewable energy into the system.

Time-varying demand response programs allow consumers to respond to price discrepancies in different periods and take advantage of lower electricity rates in off-peak hours. Hence, they can reduce electricity costs by adjusting their consumption behavior.

- time-of-use

One of the most common PBDR programs involves using time-of-use tariffs, where consumers are charged for consumed electricity with rates depending on the consumption period. Consumers who opt for TOU tariffs pay predetermined prices for electricity, which are set by regular authorities or utilities, considering the historical demand patterns, supply costs, and policy objectives [9]. TOU tariffs are usually predetermined months or a year ahead. Hence, consumers have predictable incentives to decide their electricity consumption structure and are protected from unforeseen price shocks [10].

Under this program, consumers can only effectively lower their electricity bills if they change their behavior significantly and do not shift energy-intensive tasks from on-peak to off-peak hours. For example, they can charge electric vehicles, run pool pumps, charge batteries, and pre-heat or pre-cool houses during off-peak hours, where the rates are relatively lower. It is time- and energy-consuming for consumers to follow up the frequent changes in electricity rates to reduce costs; however, energy management tools, such as smart thermostats, energy monitoring devices, or home automation systems that can automatically adjust electricity consumption based on TOU rates, can help them to achieve this goal.

Fewer people using energy in peak times means less supply shortages, more grid stability, and less production and environmental costs induced by cost-ineffective energy sources. If the tariffs were higher during peak times, it would disincentivize consumption, and therefore, variable energy resources would be able to satisfy a higher share of demand, and fewer energy sources with high carbon emissions would be necessary to balance the remaining demand. Therefore, implementing TOU tariffs would result in a more efficient and sustainable use of energy resources that complies with the EU's goals.

Revenues/costs change for participants with solar energy resources under this program, considering that credits for the excess supply of electricity they send to the grid during off-peak hours are worth less than those they send during on-peak hours. Many participants pair their solar energy resources with solar batteries to consume or send an excess supply of stored electricity to the grid during high electricity rates instead of paying for expensive electricity from the grid. [9]

The general structure of TOU tariffs considers setting the rates in advance, which vary depending on the period based on expected market conditions and not the actual market conditions. Hence, although the TOU tariffs are an improvement from the flat tariffs, where consumers pay the same rate for electricity for the whole month, they still need to acquire the whole information about the changes in the market conditions in different periods.

CEEP [10] thoroughly analyzes TOU rate efficiency and discusses its potential to increase system efficiency. They use data from California and Texas's utility providers, where TOU rate programs have been implemented. Their analysis concludes that the correlation between TOU rates and spot prices is relatively low. However, if it is conditioned upon the system's technical characteristics, the correlation coefficient increases up to 0.9. Also, implementing several critical pricing periods helps TOU rates to represent the market's actual condition hence shifting demand in the right direction [10].

- critical peak pricing

Another way of time-varying electricity pricing structure to manage electricity consumption during the on-peak periods is the critical peak pricing program (CPP). In this program, participants must pay standard rates for every period except the expected peak periods, in which they will be charged significantly higher pre-specified rates. This program operates to incentivize consumers to reduce or shift their electricity consumption away from peak hours, which will allow them to reduce electricity costs and help balance the grid during peak hours, potentially avoiding grid disruptions and blackouts [8].

The system operator announces critical pricing periods a few hours before the event, and the maximum number of peak events is predefined yearly [10]. French tempo tariff is one example of CPP with a maximum of 22 peak days [8] with the highest price. Also, there are 'white' (300 days a year) and 'blue' (43 days) periods, with regular and higher prices. After implementing the program in the 1990s, France reduced the national peak load by about 4% [11], with approximately 30% of the households participating in the program and redistributing the 6GW load daily [12].

- Variable peak pricing

Like critical peak pricing, the variable peak pricing program also includes setting peak periods in advance; however, prices are not pre-determined for those periods and depend on market conditions. The prices are communicated to consumers in real time, which allows them to reflect on changes in electricity rates and adjust electricity usage accordingly. Real-time pricing information raises awareness of the value of energy consumption among consumers, encouraging them to be more conscious of their energy usage habits.

According to the "Smart Study TOGETHER program" conducted in 2011, VPP encouraged OG&E's consumers to reduce their peak demand by 32% in Oklahoma. [2]

Also, the study found that it would be possible to avoid the investment of 210 MW in Peaker plants if the participants' share in the VPP program increased to 20 % of the residential population [2].

- real-time pricing

Real-time pricing (RTP) is a demand-side management in which retail prices the consumers pay for electricity vary in real-time to reflect changes in the wholesale prices. RTP provides consumers with price signals that reflect the actual costs they impose on the grid by consuming electricity, incentivizing them to shift consumption to periods with lower prices.

According to [8], a real-time pricing program in Illinois launched by Con Ed, in which participants paid prices depending on electricity load in each period, helped consumers to save 15% of their electricity costs from 2007 to 2016.

Prices in this program are usually determined by adding suppliers' margins to the wholesale prices and vary hourly or even more often. For instance, in Finland, the participants of the real-time pricing program pay wholesale prices, retailer's premiums, and a fixed fee at which they agreed to participate in the program in the contract. [8]

Comparison

Even though these non-flat pricing techniques have shown positive effects on demand smoothing, they do not incorporate participants' preferences, leading to limited participants' responsiveness to those techniques. For instance, a 2015 study in a selection of the European Union showed that the primary barriers to the efficiency of TOU tariffs are the lack of awareness of consumer benefits, the misconception of sufficient savings achievable within this program, and the lack of policy framework supporting dynamic pricing. [8]

Implementing time-of-use tariffs does not require having a complex two-way communication system. On the other hand, in the case of real-time pricing, price signals are sent from suppliers to smart meters, which then requires the transmission of peak signals and analyses of responses to those afterward. [13]

Additionally, as discussed in [10], TOU rates must be more efficient to capture actual market disruptions or needs. The introduction of CPP tariffs alongside the TOU rates shifted demand in the right direction and decreased peak load [10].

Challenges of dynamic pricing programs and possible regulatory framework used to resolve those Various challenges and concerns remain for time-varying pricing structures, impacting their successful implementation and consumer participation.

One of the critical challenges of implementing a dynamic pricing structure is that it usually requires significant investments in sophisticated and accurate metering infrastructure necessary to measure and communicate pricing information to consumers that may impose a substantial financial burden on consumers and utilities.

Consumers may not significantly change their consumption patterns as a response to a dynamic pricing structure due to a lack of awareness or behavioral barriers, which reduce the program's overall effectiveness. Different characteristics, such as habits, non-acceptance of changes, limited financial incentives, complexity, and confusion associated with the program, may encourage consumers to adjust their electricity usage based on price dynamics. According to [16], even though spot pricing is technically possible, it is still challenging for customers. They tend to be risk-averse, and reacting to the price change might be more costly than beneficial. Regulatory authorities must encourage consumer participation by raising awareness of potential benefits and costs that emerge from those programs, for which they can arrange educational training or open discussions between the stakeholders.

Furthermore, implementing those programs may require changes in regulations. These policies apply to consumers and utilities, which may require lots of time and effort to gain approval from authorities.

Additionally, price-based programs, especially those that involve real-time or dynamic pricing, may raise privacy concerns considering that these programs require collecting and using detailed electricity usage data. The role of regulatory authorities is crucial to address this issue. By implementing clear and strict guidelines, they can ensure that consumers' data is well protected, and their privacy is secured.

A well-tailored dynamic pricing structure can be achieved through clear communication and cooperation of the authorities, potential and existing consumers, and utilities.

To contain the primary message, with clear line of thought and validation of the techniques described.

III. Conclusions

As significant as increasing the share of renewables in the energy mix is, as crucial it is to have a flexible and efficient power system. This paper discussed the importance of increasing demand flexibility to ensure electricity system stability.

Demand-side flexibility plays a crucial part in building flexible power systems.

We analyzed different programs that are in practice and compared their results.

The paper concludes that price-based incentives are efficient tools to drive consumption right direction. Especially dynamic rates have more significant outcomes than static ones since they capture actual market conditions. Variable peak pricing in the United States and Critical peak pricing in France worked well in capturing market disruptions and smoothening peak demands.

Technical improvement in metering systems and billing processes,

raising awareness about the importance of demand response will help utilities and system operators to engage more consumers in the programs, resulting in more flexible demand.

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