Demand response literature review

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Disclaimer:
The authors do not represent the views of the Independent Electricity System Operator.
2 Executive Summary

Demand response is an efficient form of electricity conservation as it encourages load reduction only at times when the reduction would help achieve goals such as infrastructure deferral and lowering electricity prices. This paper surveys and summarizes literature to illustrate our current state of knowledge in demand response.

Firstly, the basics of demand response are defined and explained. Various models and mechanisms are highlighted with their key features.

Secondly, the various applications of demand response are explored. Demand response can be deployed to serve a wide range of interests, including: the integration of renewables; voltage and frequency control; participating in carbon emissions trading; tempering ramping costs; improving dynamic performance; providing spinning reserve; and contributing to long-term capacity planning.

Thirdly, demand response markets and models are explored more in depth. Day-ahead scheduling, price impacts, and uncertainty are addressed, while alternative models are mentioned.

Lastly, the application of demand response is discussed. The implementation of demand response through FERC Order 745 is described, as are the potential opportunities for demand response through the Environmental Protection Agency’s Clean Power Plan.

3 Introduction

In the first paper of this series, we surveyed the academic literature and existing programs for electricity conservation. Demand response was identified as one of the most promising areas for future research as it could efficiently achieve conservation goals by targeting efforts at particular times. Realizing infrastructure deferral and lowering electricity costs through conservation need to happen only during certain time periods: during peak consumption periods and during high cost times respectively. The impacts of broad-based conservation programs are diffused across all time periods, whether or not benefits are realized. However, demand response is deployed only during the relatively short periods when it is needed, therefore making it an economically efficient form of conservation.

This paper, the second in the series, is a summary of academic literature and research on demand response in electricity markets. Demand response is defined and explained, and key applications are highlighted. Its markets and models are explored more in depth, and its implementation and future opportunities through the Environmental Protection Agency’s Clean Power Plan are discussed.
4 Background

Demand response (DR) “can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. Further, DR can be also defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. [33]

Consumers can respond in three ways [33]:
1. Reduce consumption at targeted times but maintain same consumption patterns at other times;
2. Shift consumption from targeted times to other time periods so that overall consumption is the same; or
3. Use on-site generation.

Demand response increases the elasticity of demand as consumers are more sensitive and responsive to price signals, as shown in Figure 1.

5 How Demand Response Works

Demand response can be fixed (obtained through contracts) or flexible (market based).

Su and Kirchen [5] quantify the effect of demand response on electricity markets and propose a day-ahead market-clearing tool. As more demand shifts, market-clearing prices lower. They find
that the system is more efficient, and social welfare is maximized, as more loads participate in
demand response (i.e. as the load participation factor is increased). However, the law of
diminishing returns applies because as more loads participate, system operating cost savings will
saturate due to the “non-decreasing nature of the marginal production cost of the generators.”

Sezgen, Goldman and Krishnarao [1] treated demand response as options, which ISOs have the
ability to exercise in the future if they need it. Option-pricing methodologies were used to valuate
investments for load curtailment, load shifting/displacement, and fuel substitution from the
consumers’ perspectives. These help both predict and guide consumer behaviour.

Demand response has been shown to improve the efficiency of the electricity market. Kirschen
[6] finds that “increasing the short-run price elasticity of the demand for electrical energy would
improve the operation of these markets.” However, Kirschen also acknowledges the costs and
complexities associated with greater demand participation in markets. Oh and Thomas [4]
modelled the two types of demand: price-based and must-serve demand. The latter highly values
reliability, while the former is more flexible depending on price. This method was tested on an
IEEE 30 bus system to show enhanced efficiency.

Khodaei et al [38] used several case studies to demonstrate demand response’s benefits. They
found that demand response could “shave the peak load, reduce the system operating cost, reduce
fuel consumption and carbon footprints, and reduce the transmission load congestion by
reshaping the hourly load profile.”

Price-sensitive demand response introduces an added element of volatility into electricity markets
and could impact the ability of the power market to converge. Zhao et al [14] explored this using
two methods: a closed-loop iterative simulation method and a non-iterative method based on the
contraction mapping theorem. Convergence was affected by the non-linear price elasticity of
demand response performance curves, the demand response penetration levels, and the capacity
limits of generating units.

Models that proposed to allow consumers to participate in the electricity spot market have not
been proven to be robust enough to withstand the uncertainty of consumer behavior in response
to real time price changes. A large number of consumers adjusting their demand (either load
shifting or curtailment) based on the same data would smooth out the variations in prices, thereby
reducing the accuracy of the forecasted demand and generation. A framework for modeling and
analyzing the dynamics of supply, demand and clearing prices when real-time electricity price
information is passed on to consumers was proposed by Roozbehani [15]. The authors’ theoretical
analysis suggests that under current market and system operation practices, new demand
response technologies and storage may lead to increased price volatility. The authors concluded
that to implement an efficient and reliable real-time pricing models in a large-scale setting, more
sophisticated models of demand, deeper understanding of consumer behavior in response to real-
time prices and a thorough understanding of the implications of different market mechanisms
and system architectures are needed.
6 Applications of Demand Response

Reducing electricity consumption can have multiple benefits. Common goals include: lowering the market price for electricity due to reduced demand; deferring major infrastructure investments, including new generation, transmission, and distribution; and reducing greenhouse gas emissions. Additional benefits include system security, reliability, frequency control, wind integration, spinning reserve, voltage control (reactive power), ramping, and more. Demand response is a targeted approach that can meet these goals efficiently because the system pays for curtailment only when it needs it to meet its goals.

6.1 Wind & Renewables Integration

Demand response has been studied extensively as a tool to enable better, more efficient integration of wind and other renewable generation resources. The dynamic intermittency, uncertainty, variability, and volatility of wind can be counterbalanced with demand response in a fast, cost-effective manner.

Dietrich et al [7] modeled a unit commitment problem for an isolated system with high wind penetration and applied the model to Gran Canaria, a small island in the Canary Islands. The model tackles two scenarios: one in which the system operator remotely controls the load (Demand Shifting), and the other in which consumers independently react to price signals (Peak Shaving). Rather than maximizing social welfare, costs are minimized instead. Dietrich et al demonstrated that demand side management resulted in cost savings for all cases. In the Gran Canaria case study, demand side management “achieved up to 30% cost savings.”

Both Zhao [33] and Zhao [8] developed robust unit commitment models for demand response and wind. Zhao [33] used a two-stage approach, while Zhao [8] had a multi-stage robust mixed-integer programming problem. Both tested their models on IEEE 118-bus systems and found that their robust unit commitment models will lower unit costs for generation.

Papavasiliou et al [16] presented a stochastic unit commitment model that uses demand response to absorb the fluctuations of wind power. Three scenarios were compared: 1) a centralized load control where the system operator co-optimizes the dispatch of deferrable loads and generation sources; 2) demand-side bidding consisting of inflexible loads that pay a fixed retail price and price responsive loads that pay real-time price; and 3) coupling of wind energy suppliers with deferrable loads. Assuming a 1-for-1 demand response to wind integration level, results of the authors’ simulation showed that: 1) demand-side bidding resulted in an increase of daily cost operations from 2.43 to 6.88% from a centralized load dispatch; 2) demand-side bidding resulted in excessive load losses due to its failure to capture the cross-elasticity of demand across time periods; 3) both coupled and bidding scenarios resulted in an increase in daily cost of operations. The authors’ results also showed that integration of deferrable demand did not impose any additional capacity requirement on the system and that there is negligible waste of available wind energy. One important finding of the study was the unpredictability of the behavior of price-
responsive demand. The authors recommended further study of price-responsive deferrable demand.

The issue of uncertainty which was discussed in [8] was also the topic of Madaeni et al’s [18]. The effect of delays in consumers responding to price signals on the benefits of demand response in mitigating wind-uncertainty costs was examined. Results in [18] showed that more than 75% of wind-uncertainty costs are mitigated if loads respond to prices immediately.

De Jonghe et al [22] proposed three different methodologies to integrate short term responsiveness into a generation technology mix optimization model considering operational constraints. Results showed that the integration of demand response dampens system peaks, decreasing the required investment in peaking generation capacity; creates valley filling effects, lessening over-generation problems during the night or high wind generation periods; and increases system flexibility, facilitating integration of variable wind power.

Another analysis for evaluating the effect of demand response on the German market was done by Klobasa [44]. The study showed that demand response potential together with improved wind power predictions can significantly limit the additional balancing costs in the German market.

### 6.2 Voltage and Frequency Control

To ensure the stability of the power system while balancing supply to changes in demand, two equilibrium points must be maintained: voltage and frequency. The traditional way of maintaining these equilibrium points was through the deployment of load-following (spinning and non-spinning) power plants. Today, demand response can be integrated into the power system to help maintain the voltage and frequency equilibrium points. The integration of uncertain renewable power sources and demand response to the power system is adding a new dimension to the problem of voltage and frequency control.

The control systems used to maintain the voltage and frequency are called corrective voltage control (CVC) and load frequency control (LFC), respectively. Rabiee et al [17] addressed the impact of wind integration and demand response to CVC. Taking into account the problem of uncertain wind power generation, demand reduction from voluntary demand-side participation, demand reduction from involuntary load curtailment, and fast re-dispatch of active and reactive generating units, a multi-objective optimization problem was proposed in [17] using the $\epsilon$-constraint method and fuzzy satisfying approach to maximize load margin while minimizing the corresponding corrective voltage control cost. The results of the authors’ simulation showed a greater corrective voltage cost in order to attain higher load margin values.

### 6.3 Carbon Emissions Trading

Carbon emissions trading is also taken into account for demand response situations. Behrangrad et al [35] included reserve supplying demand response (RSDR) in minimizing total system cost subject to a specified cap on carbon emissions. Both Ai et al [36] and Zhang et al [37] considered
carbon emissions trading in a smart grid environment, which allows greater and more sophisticated load participation in electricity markets. Ai et al [36] proposed a new approach, demand side reserve (DSR), which combines demand response with carbon emissions trading (CET) in smart grid environments. This uses “reasonable auction models” to encourage reduction in total carbon emissions as carbon emissions quotas (or credits) are circulated among loads and generators. Zhang et al [37] used an improved particle swarm optimization (IPSO) algorithm to solve its model, which includes various demand side resources and takes into account CET. Rather than a hard cap on carbon emissions, CET simulates a cap-and-trade system in which emissions credits are traded. The authors found that both the total cost and total emissions decrease with the inclusion of demand side resources.

Zeng et al [20] presented an integrated methodology that considers renewable distributed generation (RDG) and demand response (DR) as options for planning distribution systems in a transition towards low-carbon sustainability. As DR enables the electricity consumption to more closely follow the intrinsic production patterns of RDG, the joint planning has demonstrated a super additive effect in terms of environmental benefits than integrating RDG independently.

While wind generation is emissions- and cost-free, real-time output can be highly variable and uncertain. It requires additional conventional generating capacity that can increase generator emissions rates to be committed. Madaeni and Sioshansi [19] solved this through demand response and introduced a model that treats demand response with real time pricing (RTP) as a dispatchable resource that the system operator can use to serve the load.

6.4 Ramping

Wu et al [9] considered ramping costs as a penalty and show that demand response would lower costs for system operation, ramping, and congestion. Therefore, the electricity market is more efficient when both demand response and ramping costs are considered.

6.5 Dynamic Performance

Pourmousavi and Nehrir [10] proposed a demand response control loop that improves system stability and dynamic performance. They added the demand response feedback loop into a traditional load frequency control (LFC) model, and loads can respond in real-time to the market price and provide ancillary services.

Chen et al [21] proposed a distributed direct load control scheme for large-scale residential demand response (DR) built on a two-layer communication-based control architecture. Numerical results show notable improvement in the system’s ability to match a prescribed load consumption profile, with actual demand levels.
6.6 Spinning Reserve

Spinning reserve service has been one of the main applications of demand response. Partovi et al [43] discussed the idea of participation of demand response in the reserve market from economical and technical points of view. Economically, demand response participation led to less committed generating units in energy scheduling and accordingly less operation cost. Technically, within peak load hours the share of generator participation in providing reserve capacity becomes lower than the share of demand response participation, while in other hours the opposite trend is observed.

6.7 Long Term Capacity Planning

Earle et al [39] measured the load carrying capacity of demand response in California, USA using 2002 data and came to the conclusion that at a certain point, reductions in demand during the critical peak window do not provide the expected contribution to system reliability. If load shifting is considered, an increase in load occurs outside of the peak window, and this further reduces the capacity value of demand response.

The effects of changes in demand, prices and generation technology over time was analyzed by Choi et al [40] using a least cost capacity expansion model as a mixed-integer linear programming problem. Using Georgia, USA as the case study spanning a planning period of 20 years from 2010-2030, results of the simulation showed that with a carbon cap-and-trade policy and renewable electricity standard without initial free allowance, demand growth was flat due to the resulting high price of electricity. Another finding was the reduction of greenhouse gas emissions through generation mix changes and demand moderation if energy policies were introduced.

By integrating short-term demand into their long-term investment planning models, Jonghe et al [41] showed that own-price elasticity resulted in immediate response to price changes while cross-price (hourly pricing difference) elasticity resulted in load shifting. Additional results of the authors’ simulation included the findings that increasing demand elasticity also increased the optimal amount of wind power capacity and that energy efficiency expenditures reduced the effect of demand response but it still reduced the optimal amount of wind power capacity.

Satchwell et al [42] provided an analytical framework to incorporate demand response into long-term capacity planning by analysing the planning process of 19 load serving entities in the US Western Interconnection from 2011 to 2013.
7 Markets and Models

7.1 Markets

A lot of research is being done in the field of demand response markets. Wu et al [9] proposed a day-ahead scheduling model in which the hourly demand response (DR) is considered to reduce the system operation cost and incremental changes in generation dispatch when the ramping cost of thermal generating units is considered as penalty in a day-ahead scheduling problem. Numerical results show that the hourly DR would offer a flat load and Locational Marginal Price (LMP) profiles and lead to lower system operation costs, lower ramping costs, and lower congesting costs. A higher market efficiency can be achieved in the day-ahead scheduling by considering a combination of ramping costs on the generation side and DR on the demand side.

Parvania et al [24] presented a hierarchical demand response (DR) bidding framework in the day-ahead energy market that integrates customer DR preferences and characteristics in the ISO’s market clearing process. The hourly load reduction strategies include load shifting and curtailment and the use of onsite generation and energy storage systems. The results indicate that the explicit modeling of customer DR would provide ISOs with more flexible options for scheduling the available energy resources in day-ahead energy markets.

Sarkar and Khaparde [25] designed a security-constrained locational marginal pricing framework with specific emphasis on creating clear incentive for the demand side to make participation in serving the reserve option. A new format of demand side participation in the security program is designed by employing a concept of load service security where different prices are defined for different levels of service security.

Kazemi et al [26] presented a combined scheduling and bidding algorithm for constructing the bidding curve of an electric utility that participated in the day-ahead energy market. A bidding strategy was proposed for a utility that managed a retailer and generation units together. Effects of the retail side and its risk reduction in short-term planning were studied. The demand response program was included in the retailer part of the utility and its effect on bidding strategy of the utility was also discussed. The process of deriving bidding curve was presented to manage the risk of participating in the wholesale market.

Menniti et al [27] proposed a Monte Carlo-based algorithm has for the formulation of multiple purchase offers in the day-ahead energy market (DAEM) by coalitions in which consumers vary in their sensitivity to DRP, manifesting different responsiveness to hourly tariffs based on the hourly market clearing prices.

Research has been done on the relationship between demand response programs and energy costs. Wu [45] analysed the impact of price-based demand response (DR) on market clearing and locational marginal prices (LMPs) of power systems using the network-constrained unit commitment (NCUC) model. Results indicate that with the current market clearing mechanism which maximizes the system social welfare, DR dispatch may augment LMPs by displacing less
flexible generating units and/or triggering additional transmission congestion and, in turn, increase DR loads’ payments, which will ultimately influence the financial stability of DR providers and the sustainable deployment of DR programs.

Negash et al [32] solved the problem of unbalance in markets occurring from paying for load reductions (DR) by proposing a cost allocation method based on LMP sensitivity that accounts for the effect of congestion on the distribution of benefits between nodes with different LMPs. It also defined a fairness index to evaluate the performance of the proposed method as compared to a load-based allocation.

The problem of uncertainty was also discussed in many research works. Wang et al [28] studied the stochastic unit commitment problem with uncertain demand response to enhance the reliability unit commitment process for independent system operators (ISOs).

Taylor and Mathieu [46] solved the uncertainty problem by balancing utilizing well-characterized, good loads and learning about poorly characterized but potentially good loads where demand response is formulated as a restless bandit Problem. This formulation yields index policies (which are extremely simple and scalable) in which loads are ranked by a scalar index, and those with the highest are deployed.

Amelin [29] studied how the impact of wind power forecast errors can be reduced performance can be improved by changes in the market design as a shift from day-ahead to intraday trading and increased penetration of demand response. The result showed that intraday trading and demand response can have a significant impact on the prices in the real-time balancing market.

7.2 Alternative Models

Zhong et al [30] presented a formulation and critical assessment of a novel type of demand response (DR) program (Coupon Incentive-Based Demand Response) targeting retail customers (such as small/medium size commercial, industrial, and residential customers) who are equipped with smart meters yet still face a flat rate. Results showed that CIDR can effectively induce inherent demand flexibility and reduce system-wide operational cost while maintaining a basic flat rate structure on the retail level.

As the participation of residential customers in demand response programs increases, the need for physical-based residential load models emerges. Shao et al [31] presented the development of such load models at the appliance level. These include conventional controllable loads, i.e., space cooling/space heating, water heater, clothes dryer and electric vehicle. Each load model is validated against the real electricity consumption data of the associated load type. The comparison of the aggregated load profile at the distribution circuit level also shows similarity with the actual distribution circuit load profiles.

Papadaskalopoulos et al [11][12] proposed a novel pool market clearing mechanism, combining the solution optimality of centralized mechanisms and the decentralized demand participation
structure of dynamic pricing schemes based on Lagrangian relaxation (LR) principles. The mechanism involves a two-level iterative process, consisting of a number of independent local surplus maximization sub-problems — expressing the market participants’ price response — coordinated by a global price update algorithm — expressing the market operator’s effort to reach an optimal clearing solution.

Nguyen et al [13] proposed a new demand response eXchange (DRX) in which demand response is traded among buyers and sellers. (This is separate from the regular electricity market.) The DRX is run and coordinated by a DRX operator (DRXO) maximizes market benefit after collecting bids and offers from sellers and buyers respectively. Demand response is treated as a public good so that multiple users can share a single unit.

8 Implementation of and Opportunities for Demand Response

8.1 Federal Energy Regulatory Commission Order 745


FERC ordered that demand response resources must be treated as an alternative to a generation resource when it’s cost-effective as determined by the net benefits test. In those cases, demand response would receive market rates (i.e. the Locational Marginal Price, or LMP). This applies to both day-ahead and real-time energy markets, which are run by Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs).

There was some controversy about the billing unit effect, by which dispatching demand response instead of generation could result in an increased cost-per-unit because there is less load to share the total costs. To remedy this, FERC implemented the net benefits test to ensure that benefits outweigh costs.

8.2 Environmental Protection Agency’s Clean Power Plan

8.2.1 Summary of the Clean Power Plan

In an effort to limit carbon emissions from fossil-fired electricity generating stations, the United States Environmental Protection Agency (EPA) issue the Final Rule for its Clean Power Plan (CPP) on August 3, 2015. The plan sets carbon limits for each state and requires states to submit plans on how they will meet those targets. [3]
The CPP sets limits at the State level for carbon emissions from coal and natural gas plants. The total mandated reduction is 32% of 2005 levels by 2030, and 28% of electricity generation must be from renewable sources.

8.2.2 Criticisms

Resistance is strong among states and industries that rely on coal. Some states will challenge the CPP through the courts, and it is expected that their cases will go before the Supreme Court. These states are concerned that the CPP will raise the price of coal and therefore cause job losses and economic decline in their regions. They also contend that the US’s CPP on its own – without international agreement or cooperation – will not be able to make a difference for climate change, which is a global issue.

8.2.3 Potential Paths and Outcomes

The CPP leaves it to each state to decide how to meet their emission limit. While some resistive states may decide to flout the CPP and not file their plans, amenable states have several public policy tools available to reduce carbon emissions from their generation facilities. These tools include: a carbon tax; a cap and trade system; and regulations.

The cap and trade system is a likely choice for many states because it is more economically efficient than regulations and more politically viable than a carbon tax. Also, several states are already voluntary members of the Western Climate Initiative, a “multi-sector, market-based program to reduce greenhouse gas emissions” – essentially a cap-and-trade system. This existing framework eases the implementation for new members.

8.2.4 Opportunities for Demand Response

The CPP presents an opportunity for a greater role for demand response (DR). Factors that would encourage more widespread use of demand response include:

8.2.4.1 Carbon Prices

If states opt for a cap-and-trade system or a carbon tax, the price of carbon would be transparently included in the cost of fossil fuel generation. This presents an opportunity for demand response to compete, especially if the carbon prices are high. If the cost of demand response is less than fossil fuel generation, then demand response would be dispatched in its place.

Coal-fired generation produces larger amounts of carbon than natural gas, but the production cost for coal is less than gas. The actual carbon prices will determine whether coal or gas (or another form of generation) could be displaced by demand response.
Having a price on carbon pushes up the bid offers from fossil-fired generation. Demand response offers incremental value when the DR offer price is in between the generation price with and without carbon. In those cases, DR would be dispatched when a carbon price exists, but not without it. (If the DR price were less than the generation price without carbon, it would have been dispatched anyway.)

8.2.4.2 Ramping

The ramping of coal generation emits disproportionately more carbon the normal, steady-state operations. During periods of hard ramping, demand response could be dispatched to slow ramping and displace carbon emissions.

8.2.4.3 System Reliability Issues

The North American Electric Reliability Corporation (NERC) is concerned about the CPP’s impacts on reliability. With less coal and gas production, NERC would like assurance that replacement sources (such as intermittent renewable energy) would have adequate reserve margin levels. Demand response could offer this reliability at a competitive price.

8.2.4.4 Energy Efficiency Targets

The CPP assumes that energy efficiency gains will outpace demand growth, resulting in overall declining electricity consumption. This assumption has been questioned, and should it turn out to be false, demand response could have an opportunity to help the EPA reach its targets.

9 Conclusion

Demand response has been shown to be useful in solving a myriad of power system issues, including: the integration of renewables; voltage and frequency control; participating in carbon emissions trading; tempering ramping costs; improving dynamic performance; providing spinning reserve; and contributing to long-term capacity planning.

As governments continue to take increasing action on climate change and the mitigation of carbon emissions, demand response could find growing opportunities to provide economic solutions. Future research in this area could also be used to inform sound public policies to protect the public interest.
### 10 References

#### 10.1 Non-Technical


#### 10.2 Technical – IEEE Transactions on Power Systems


10.3 Technical – Other Journals


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