Applied Energy 152 (2015) 1–10

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Review

Challenges and barriers to demand response deployment and evaluation

Sheila Nolan, Mark O'Malley *

Electricity Research Centre, School of Electrical, Electronic and Communications Engineering, University College Dublin, Ireland

HIGHLIGHTS

- A review of the challenges related to DR deployment and evaluation is presented.
- There is a pressing need to evaluate DR as it could be a key resource in the future.
- Uncertainty in the value of DR compromises understanding of the resource.
- Poor understanding leads to poor representation of DR in valuation methodologies.

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 20 April 2015
Accepted 21 April 2015

Keywords:
Demand response
Challenges
Deployment
Evaluation

ABSTRACT

Demand response is increasing in popularity and many utilities are developing demand response programs. However, there exists many challenges to the deployment of demand response. One of the main barriers to widespread rollout is the uncertainty surrounding the value of demand response. In this regard, there is a real and pressing need to evaluate demand response if its full potential is to be realized. This paper presents a comprehensive review of the literature and identifies some of the key barriers to the deployment and the challenges to the evaluation of demand response and provides some recommendations on evaluation methodologies.

Contents

* Corresponding author.
E-mail address: mark.omalley@ucd.ie (M. O'Malley).

http://dx.doi.org/10.1016/j.apenergy.2015.04.083
0306-2619/© 2015 Published by Elsevier Ltd.

1. Introduction

Demand response (DR) is often described as the changes in electrical energy usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, to incentive payments or to signals from the system operator [1]. It is widely acknowledged that this is not a new concept. Historically, demand shedding was used for emergency contingency response and, in more recent times, DR programs have been targeted at large industrial energy users [2]. However, there has been much interest recently in more continuous DR, that is, DR on a continuous time-frame, and DR across all sectors. The reason for this burgeoning interest relates to the potential for DR to assist in integrating variable generation [3], the fact that it could be a more cost-effective means to meet occasional peaks in electricity than peaking plants [4] and could thus, potentially, reduce system costs [5] and harmful power plant emissions at times of peak demand [6]. Furthermore, in parallel to developments in variable renewable generation penetration, there have been rapid advances and cost reductions in the area of telecommunications, control systems and computation, which has resulted in greater controllability and flexibility of demand-side resources. Additionally, regulatory changes and electricity market reform have played a major part in allowing DR to become a more viable resource [6].

There has been significant and beneficial work in the area of DR in recent years, highlighting the potential benefits of DR [1,7]. Studies have shown that using DR to facilitate the integration of variable renewable generation is technically feasible [3,7], but there are barriers that limit the use of demand side strategies for integrating wind and solar, some of which are identified in [8]. The work in [9] develops models of DR on the Irish power system and demonstrates that DR can contribute to overall system adequacy and can displace some conventional generation.

There has also been much work reported in the literature focusing heavily on detailed modeling of individual buildings and demand control systems, as well as in the telecommunications and equipment required to implement DR [10–13]. There has, however, been less work in the evaluation of DR from a power system perspective.

Despite significant advances in power system analysis in recent times, many traditional power system models have neglected to incorporate DR. There is now a need for these models to be enhanced in order to better account for the unique characteristics of the demand side [14]. Additionally, there is a requirement to develop tools which are appropriate for quantifying the impacts of DR resources on market performance, generator dispatch and other system effects [15].

Despite the many barriers associated with DR deployment, some of which are documented and explored in this paper, it is apparent from the literature that there is considerable interest in DR because of its potential to provide significant value to the power system. There is evidence that DR could deliver some system services more reliably than conventional generation [16]. Thus, if DR proves to be the neat and sophisticated solution it is claimed to be, failure to exploit the resource is clearly suboptimal. On the other hand, if the potential value of DR is over estimated, considerable resources could be invested in order to exploit a service which ultimately cannot be realized effectively. There is evidently a pressing need to quantify the potential system and market value of DR. Indeed, it has been suggested that the limited DR capability at present in the US [1] is set to rise if it is shown that the "*flexibility it offers is valuable and properly valued*" [17]. Evaluation of the DR resource is clearly a vital step in its large scale deployment and could increase understanding of the impacts of DR on the system and markets.

DR can potentially enter into the energy, capacity and ancillary services markets and avail of multiple revenue streams. DR is capable of participating in the energy market by providing services such as peak shaving and load shifting. Such services could help to reduce system demand at times of typically high prices, potentially reducing output from expensive peaking plants and thereby lowering system costs. A study reported in [18] found that the benefits of DR also lie in the realm of avoided capacity costs, thus DR could be a prominent player in the capacity market. The literature has also shown that one of the benefits of DR lies in its ability to assist with facilitation of variable renewables through reserve provision [7]. It has been illustrated that in some cases demand can provide some responses which are greater than the responses garnered from generators [16,19]. This illustrates the potential for DR to operate in ancillary services markets. Indeed, it is indicated in [20] that an understanding of the value of DR gives an indication of the potential or opportunities that exist within particular ancillary services markets.

An understanding of the value of DR should also inform which sectors DR is most suited to operating in. The authors in [21] advocate focusing DR activities on specific large consumers, consumers who are capable of responding appropriately to real-time prices. This is, in effect, exploiting the easiest resources first. Similarly, the work in [22] demonstrates that most of the total benefit of exposing all sectors to real-time pricing (RTP) can be achieved by implementing DR through RTP in the industrial and commercial sectors only. The work in [22] is based on one specific power system and consequently, it is important to be aware that the results are likely to be quite system specific. Nevertheless, further research may show that there is no major benefit or value in extending DR to the residential sector.

To-date there has been minimal work on evaluating DR from a system level. As a result, considerable uncertainty exists regarding how DR is going to be deployed and the potential revenue for those engaging in DR programs. This consequently impedes the evaluation process of the resource. Similarly, the lack of understanding and knowledge relating to the value of DR imposes a barrier on widespread deployment. This results in a 'Chicken and Egg' type dilemma; DR will be deployed if it is valuable to do so, but an understanding of the methods of deployment and operation of DR is necessary before evaluation studies can produce meaningful results.

This paper aims to identify the barriers and uncertainty that exist for widespread DR deployment and to then show how these barriers could impact upon the analysis of the value of the DR resource. Section 2 explores opportunities that exist for DR to participate in electricity markets and some associated barriers. Section 3 then discusses the barriers to deployment associated with the demand-side of the power system as a result of the uncertainty surrounding consumer behavior and due to the requirement for a greater flow of data and information. Section 4 examines potential methodologies for determining the value of DR resources to the power system and discusses how the uncertainty and barriers in DR deployment can impact upon the methodologies. Section 5 ties together many of the elements discussed in the paper and also identifies issues for synthesis and dissemination of evaluation analysis results. Section 6 concludes the paper.

2. Demand response opportunities and barriers

DR represents a paradigm shift in how we view electricity markets since electrical load can now appear on both sides of the supply–demand equation. As previously mentioned, an appreciation of the impact of DR implementation on electricity markets would be vital for determination of its value and could indicate which markets would benefit most from DR participation. The following subsections explore the different services DR can provide and look at some of the barriers associated with deploying DR programs.

2.1. Energy services

DR is capable of participating in the energy market, by offering services such as peak shaving, load shifting and energy arbitrage.[1] Peak shaving and load shifting programs can assist in reducing the need for expensive peaking units and in flattening the load profile, by reducing demand at times of high prices and, in the case of load shifting, by increasing load at times of lower electricity market prices. Such DR programs are usually triggered in response to a price signal from the energy market. Many of the price-based DR programs, such as RTP programs, time of use programs and critical peak price programs are predicated on the exposure of customers to time-varying energy market prices.

RTP allows demand to respond to fluctuations in the price of electricity [25] and exposing customers to real-time energy market prices can mitigate high price spikes. It is shown that RTP is more economically efficient in the short-run than offering customers a flat tariff [26,27]. RTP is just one of many proposed means for deploying DR programs.[2] Interestingly, many "*energy market meltdowns*" in recent years can be attributed to a lack of price-responsive load [31] and could have been alleviated by DR programs. Additionally, the work in [32] shows that the more price-responsive demand that is available the more competitive the long-term electricity market and the more reliable the system becomes.

There is clearly a benefit in deploying DR programs such as RTP. However, such programs will only be implemented if they are proven to be worthwhile, but in order to assess whether or not it is valuable to society and to the power system requires data and experience from real-life DR programs. Without certainty that it is valuable, the required investment will not be available to implement such programs.

2.2. Capacity

As well as providing energy services, the demand-side is also in a position to provide capacity. The purpose of capacity markets is to ensure that there is an incentive for investors to "*build adequate capacity in line with consumer preferences for reliability*" [33] and to ensure that there is enough generating capacity in the long-term. As already alluded to, DR can provide capacity and thus receive capacity payments or operate in capacity markets and ultimately contribute to generation adequacy. This could help to alleviate the need for considerable investment in conventional generation. In [34] it is indicated that DR is ideally suited to participation in capacity markets, because the DR resource would be paid for simply being available to reduce load or provide capacity but may not actually be required to provide a response. Indeed, according to [35], in PJM, over 90% of the revenue earned by DR is from the capacity market, highlighting the importance of the capacity market for attracting DR investors. However, it is important to note that the magnitudes of potential capacity payments are largely dependent on the requirements for capacity.

One of the difficulties with trying to generalize a discussion on capacity services is that there is a large difference in capacity procurement mechanisms. Some systems simply do not have capacity markets (or payments) and in these situations the method of procuring capacity is entirely through the energy market. In such cases, regulators need to ensure that average electricity prices are sufficiently high in order for generators to recover their costs [36]. In systems where there are capacity procurement mechanisms, there is considerable on-going debate as to their effectiveness and there is significant uncertainty regarding the future of capacity markets. This presents a challenge for DR investors as they cannot rely upon sure and certain revenue from capacity mechanisms in the coming years.

Considerable differences also exist in ancillary service markets and definitions, presenting further problems for DR deployment.

2.3. Ancillary services

Ancillary services (AS) are services which the system operator employs over various time frames to maintain the supply–demand balance on a continuous basis [37]. The increasing penetration of variable and uncertain renewable generation has led to a greater need for AS and flexibility products [38] and certain types of DR are well-placed to provide some of these services [39,40]. Coupled with this is the fact that AS are, in general, difficult to provide and thus the prices paid for AS provision can be considerable. In particular, it has been illustrated that a number of DR resources can offer spinning reserve and regulation services and thus they could earn considerable revenue.

Some systems, the New York Independent System Operator (NYISO) and PJM for example, permit participation of DR resources in their AS markets [8], however, it is noted in [41] that, in the US, DR resources are minor players in AS markets in most jurisdictions. One of the barriers is that there are many market rules for AS provision and the varying AS rules and requirements can limit the '*possible scale of DR deployment*' [19]. In [41] it is suggested that the barriers associated with 'bulk power system service definitions' should be the first barriers to be dealt with in order for DR to even be in a position to provide bulk system services.

The problem is that definitions of AS have typically been built up heuristically and, traditionally, conventional generating plants were the sole providers of these services. Such definitions, when 'hard-wired' into the market design, could be considered to be discriminatory [42] and may preclude DR programs from participating. For example, in the California ISO (CAISO), a resource that is providing an AS must be capable of maintaining its capacity for a specified period of time, otherwise it will not be certified, and thus cannot bid into the AS markets [20], potentially excluding DR. A similar rule exists in MISO. Other market rules such as those governing minimum resource size [41] and those pertaining to control and telemetry [20] can hinder DR resources from participating. Additionally, rules requiring resources providing regulation to have the same capacity to move in both directions impedes many DR resources from participating, as DR resources typically favor movement in one direction over the other [41].

There may be scope for adaptation or relaxation of AS rules in certain cases. Indeed, according to [41], some systems have recently amended rules governing minimum size of resource. A revision of AS definitions and market rules to accommodate the physical capabilities of resources, generating and demand-side alike, is highly recommended. This could allow for greater participation in DR programs and also permit better exploitation of the available DR resources. It is recommended that focus is placed on the physical characteristics and capabilities of DR when designing DR programs. This recommendation concurs with [16], which stresses that the physical power system reliability requirements

[1] For more detail regarding such DR services see [23,24].

[2] For a more in-depth discussion of other DR programs, the reader is directed to [28,29] to a workshop report drafted by the US Department of Energy [24]. For a more detailed discussion and comparison on the welfare impacts of flat tariffs and different off-peak and peak prices, the reader is directed to [26] and to the highly influential work by Fred C. Schweppe in 1988 [30].

are of greater importance than the market rules. Ultimately the physical requirements should inform market design to best exploit the capabilities of the available resources [16].

The stringent requirements for AS resources, may preclude DR from participating in a potentially lucrative market and may therefore act as a disincentive for investment in DR technology. This would impede the deployment and growth of DR in general. A related issue is the fact that increasing the penetration of DR resources can suppress AS market prices [19]. This effect is observed for many resources, however, it is more pronounced in the case of DR since it is a resource that has very low or no opportunity costs. This suppression of prices may cause prices to fall to a level that is no longer attractive to investors. This price suppression, coupled with the stringent AS requirements discussed previously, would limit the amount of DR available for providing AS, which in turn would restrict the amount of DR available to participate in capacity and energy markets.

Additionally, as alluded to earlier, a similar effect is noticeable in capacity markets —the magnitudes of potential capacity payments are largely dependent on the requirements for capacity. While capacity payments may be enticing for DR participants, it is inevitable that the higher the penetration of DR, the less capacity required. Thus, the capacity payments will fall to a level that may no longer be attractive for all DR resources, depriving other markets of valuable resources. Furthermore, DR can provide services other than those discussed here, such as congestion management or network investment deferral [7]. Therefore, lack of deployment of DR in one market has a knock-on effect to other markets and to other DR services. It is recommended that all revenue streams are considered holistically as a result of this intrinsic interrelationship between multiple DR services.

While AS definitions can pose considerable barriers to the deployment of DR, the greater interaction of the demand-side with the power system also presents its own issues. This is as a result of the need for greater data collection and an increase in information flow between the supply-side and the demand-side of the power system, as well as the limitations on the DR resource as a result of consumer behavior and preferences. These issues are explored in the next section.

3. Behavioral and informational barriers

Underpinning the entire DR paradigm lies the consumer. The authors in [2] express the view that the greater involvement of consumers in ensuring maintenance of system reliability and uninterrupted electricity flows, a realm that was once solely occupied by conventional generators, is one of the main advantages of DR. If customers can understand the impact of their electricity consumption has on their expenditure, they may be able to adapt their behavior, helping to smooth load profiles and to reduce system costs. However, it is contended here that this greater level of consumer involvement also represents not only one of the greatest barriers to deploying DR but also creates challenges for evaluating DR.

3.1. Consumer behavior

There are numerous benefits associated with DR and many different ways to implement DR, but if the end user is in anyway inconvenienced they may disengage and possibly withdraw from the program or will demand higher payments or incentives [43]. The authors in [44] explore the motivations and barriers associated with individual consumer decisions on whether to install micro-generation in their home. They indicate that inconvenience can be a dissuading factor in the uptake of micro-generation. While micro-generation is a separate, but related issue, the work in [44] does highlight an important point related to end-use consumers; financial motivations are consistently more important than desires to help improve the environment. The importance of financial motivations is worth highlighting, especially considering there is considerable uncertainty surrounding the potential revenue of engaging in a DR program, as mentioned earlier.

In [26] a related financial issue is raised, namely the fact that savings on customers' electricity bills may not be sufficient enough to warrant investment in equipment and to compensate for the inconvenience of following electricity prices on a continuous basis, when they may only be required to react on rare occasions. Of course, this will be dependent upon the type of program being implemented and the degree of customer participation required. If financial issues are the key motivating factor in adoption of DR programs and it is shown that consumers are not in a position to either recoup their initial investment in DR technologies or make savings on their future electricity bills, there will be minimal engagement in DR. This is evidently a barrier to widespread adoption of DR programs.

It was found in a study in [45] that despite receiving feedback on energy consumption from in-home displays, the majority of study participants continued with their everyday routines and habits [45]. This is a perfect example of unanticipated or somewhat irrational consumer behavior – an issue that needs to be considered in the evaluation of DR deployment. This study also highlights that there is a need to foster greater DR awareness and understanding and to furnish consumers with sufficient information regarding DR programs so that they can make well-informed decisions.

In [43] it is explained that there are two objectives of demand which is involved in a DR program: satisfy customer demand and deliver a reliable resource to the power system when required. These two objectives are usually in competition. This is because the primary role of electricity is consumption by the end-user. Consequently the length of time the load can offer a response and the frequency of resource deployment is limited since ultimately any program will be disruptive to the consumer. Thus, utilities will be reluctant to dispatch the DR resource regularly [34]. This is an important point to consider when analyzing the value of the resource and is also connected to the physical characteristics and nature of electricity loads and thus is an important consideration when modeling DR resources.

The main challenge is to fully appreciate the limitations of the DR resource as a result of end-user behavior and preferences and to appropriately account for these in DR implementation. It is crucial to represent these limitations in the evaluation analysis and to understand the motivations consumers have for engaging in or rejecting a DR program. It is important to be mindful of the effect unanticipated consumer behavior can have on the DR characteristics and to deal with it appropriately in the evaluation process.

3.2. Baselines

DR performance is typically computed as the difference in the actual demand level and a baseline level so, effectively, consumers are being paid for what they do not use [46]. The North American Energy Standards Board's definition of a demand baseline is an estimate of the electricity that would have been consumed by a customer in the absence of a demand response event [47]. The key point to be taken from this definition is the use of the word 'estimate'. It is naturally challenging to measure or calculate what would have occurred and thus, fundamentally baselines are imperfect [48].

Consequently, there are concerns regarding DR baselines and suggestions that the challenge of establishing a baseline for DR may be a serious impediment to the deployment of DR and to methodologies for determining the true value of certain DR programs in the market. Indeed, the authors in [34] suggest that a DR baseline could play an important role in determining the value DR brings to the electrical system [48]. Thus inaccurate baselines lead to inaccurate DR evaluation.

In [49] it is questioned whether baseline predictions are correct and it is suggested that such calculations may not even be possible for different types of end-use customers. It is understood that it is possible to obtain a reasonable baseline for commercial and industrial loads, where the loads can be directly controlled and closely monitored. However, for smaller devices and for end-uses with irregular or unpredictable power consumptions, establishing a robust and accurate baseline can be more difficult. Ultimately, when a load is dependent upon consumer behavior and where the power consumption cannot be directly controlled, it is typically more difficult to establish a baseline.

The implications of inaccurate baselines can be far reaching — the performance of a particular program would not be accurately ascertained and, for certain programs, baselines form the basis for customer remuneration for their participation, which is evidently a serious deployment issue. Without a robust method for determining the baseline, program participants could be under compensated. This could reduce customer willingness to participate. On the otherhand, consumers could be over compensated thereby increasing system operational costs, reducing the potential impact of some of the benefits ascribed to DR programs. Indeed, the authors in [50] analyze a number of different baseline calculations methods for residential consumers. They show that, particularly for incentive-based DR programs, baselines play an crucial part because they determine the incentive prescribed to customers and thereby influence their decisions.

In [51], the relative merits and flaws of a number of baseline calculation methodologies employed in the US are discussed. The author concludes that, in many cases, an adjustment to the baseline calculation is needed to more accurately estimate customer energy usage. This highlights that baseline estimation is not a straightforward procedure. While the authors in [50] focused on residential consumers, there has been considerable work on analyzing the uncertainty in demand response baseline models used in commercial and industrial facilities [52], which also details the inherent complexities involved in calculating a baseline. According to [52], baseline models for calculating baselines for commercial and industrial load are generated by averaging electricity consumption for a particular load over a number of days and thus can be biased. The authors in [52] thereby advocate the use of regression based baseline models to overcome this.

All of the methods discussed in [50,51] require the calculation of a baseline for each individual DR unit, for each individual customer or each individual DR resource. If the residential sector is to fully participate in DR programs and if individual baselines are to be established it is clear to see that there would be a dramatic amount of data required. The quantity of data that would be required for baseline calculations, however, is but one of the data-related issues and such issues will be explored in the next section.

3.3. Data issues

There have to date been limited numbers of large scale DR deployment projects and consequently, in some circumstances, there is insufficient data available for performing DR analysis. This limitation on data and the lack of previous experience pervades most of the challenges and barriers associated with DR. Furthermore, even if sufficient data was available, there could be implications for its accuracy. According to [8], DR participants have historically overestimated their likely performance during declared curtailment events. Additionally, the problems associated with asymmetric information may need to be accounted for in the deployment and evaluation of DR. This is because individual customers will always know more about their true electricity use than the load serving entity or aggregator and can likely profit from that knowledge [53].

In order to address the lack of data issue, it is recommended that comprehensive data recording and analysis regimes are in place for the DR demonstration projects proposed in the coming years and are continued for the programs that are currently running to ensure that there is sufficient high quality data and numerous years worth of data available for long-term analysis.

The uncertainty in the deployment of DR, the associated terminology and the lack of sufficient data will inherently impact upon the evaluation methodologies, which will be discussed in Section 4, as it is necessary to model and represent, insofar as possible, the operation of the real power system and interactions with the end-user. It is important to understand the DR resource and to appreciate the uncertainty and challenges that exist and then represent DR as best as possible and to account for any uncertainty in the evaluation methodologies applied to DR.

4. Evaluation methodologies

The US Department of Energy [1] concluded that without a robust analytical method to estimate the value of DR it is almost impossible to justify the system reliability improvement attributable to it. A poor methodology leads to a poor understanding of the value of DR and the implications of this for the power system could be considerable.

It was previously acknowledged in Section 3 that limited data is a issue for evaluation of DR. Consequently, it is recommended that analysis is performed using currently available data or performed based on reasonable assumptions pertaining to market size, DR penetration level, etc. This should then be followed by a series of updates and iterations on the assumed figures as more data is made available and as greater understanding of the effects of DR on the system and the markets is gained from demonstration projects.

This section of the paper explores some of the existing methods which are deemed suitable for estimating the value of DR and identifies some of the associated challenges as a result of the uncertainty in the deployment of DR.

4.1. Integration benefit concept

Power system level studies have been performed for decades in order to understand the impacts of various resources on the power system. However, the advent of variable renewable sources has spurred greater interest from policy markers, academics and system operators alike. In recent years integration studies of variable renewables has dominated the realm of system level studies and has been an area of considerable activity, as evidenced by the number of studies documented in the literature [54–56].

An integration cost is usually defined as the extra cost imposed on a system when a resource is added, compared to the situation without that resource [54]. Increasing penetrations of variable renewables have a significant impact on power system operational costs. There is no fuel cost associated with variable renewables and they can often displace some expensive fossil fuel-based generating units. Thus, there is an operational cost saving. On the other hand, integration of variable renewables necessitate the procurement of greater levels of ancillary services, thus imposing extra operational costs on the system. Consequently, significant focus is placed on the integration cost associated with the introduction of variable renewables but ultimately there is a net operational cost saving. DR, however, for the most part, has no fuel costs associated with it but is crucially also is in a position to provide ancillary services, thereby reducing system operational costs. Like variable renewables, the net result of incorporating DR is an operational cost saving, but in the case of DR however, the saving is potentially twofold; fuel savings and the provision of AS from a cheaper resource. Therefore, the integration cost in the case of DR should be a negative cost, or a benefit, and for the remainder of this paper we are referring to this cost saving as an integration benefit.

There is considerable merit in adopting an integration benefit approach since, as stated earlier, these studies are well documented in the literature and considerable experience and understanding has been gained in recent years [55]. Furthermore, integration studies represent a significant set of methodologies to quantify the impacts of resources on the power system. Applying the concept of an integration benefit to the analysis of the inclusion of DR on the power system could provide a means to ascertain its true electricity market value. Knowledge of the value could provide an indication as to which markets and sectors are most suited to demand side participation, a view which is also expressed in [20].

The advantages of using an integration study approach cannot be overlooked and, consequently, such an approach is explored in greater detail here.

4.2. Integration study

An integration study typically includes production cost simulations, which often involve unit commitment and economic dispatch (UCED), allowing for an assessment of flexibility, cost and emissions impacts [55]. One of the advantages of a production cost simulation is that it allows assessment of both energy production and provision of some ancillary services.

Additionally, an integration study would involve generation adequacy (or capacity value) calculations, analysis of the impact of new resource on power system dynamics and power flows [55]. While, all of these assessments are an integral part of an integration study, the focus in this paper is placed on the production cost simulation and generation adequacy aspects of an integration study as these are the areas where DR can contribute to the power system and participate in electricity markets.

4.2.1. Production cost simulation

The methodology employed in an integration study is determined by the ultimate aim of the study [54]. There are two common approaches for determining integration benefits. One involves simply adding the capacity of the new power source or the DR resource into the production cost simulation and comparing production costs with a base case. The second involves replacing existing capacity with the new power source or the DR resource in the portfolio used in the production cost simulation and comparing production costs with a base case [55]. The difference in costs before and after the inclusion of the technology being assessed is often viewed as being one of the key components of the integration benefit. While many approaches can achieve the same end goal – the estimation of an integration benefit – the underlying methodologies employed and the assumptions used can be significantly different.

Ascertaining power system operating costs under different scenarios and under a range of conditions, i.e. a production cost simulation, is well understood and follows well-defined methodologies [17]. However, defining the base case for any integration study is often a source of conjecture. The authors in [54,57] highlight that study results are highly dependent on the reference or base case to which the system costs with the inclusion of the new technology are compared. Determination of the characteristics of the alternative portfolio is not straightforward and consequentially has a significant impact on the calculated operational costs [57]. It is acknowledged in [58] that the definitions of the reference or base cases used in integration studies '*is an area of significant disagreement among experts in this field*'. It is recommended in [55] that the results from integration studies should be detailed with regard to the assumptions made to ensure that the weaknesses and caveats are kept in mind.

One approach (simply adding the capacity of the new power source) leads to a decreased risk of capacity shortage as the amount of generation (or load reduction in the case of DR) is increased and there is a consequential likely reduction in operating cost [54] and a potential increase in system reliability. The authors in [56] recommend that this approach be employed when dealing with small levels of wind power penetration. They also suggest that with small levels of wind, existing operating procedures and market design should be used as a first pass, with amendments as necessary in later iterations. For very low penetrations of DR, this approach may suffice, but it should be noted that even a small amount of DR can have a significant effect on system prices, as discussed in [59,60], and thus in some cases this first approach would not be appropriate.

The second approach, which involves replacing existing capacity with the new power source, requires the establishment of the 'alternative' to the new resource, which can be a contentious issue [54]. The authors in [55] advocate the use of this approach when dealing with greater penetrations of wind power. They also stipulate that flexibility requirements and network configuration should be accounted for. Adopting this approach for the inclusion of large penetrations of DR would necessitate analysis of the markets and system operations. This is due to the fact that as the penetration of DR increases the impact on the system becomes more pronounced [15], thereby providing a more comprehensive assessment of DR. This approach would be deemed more appropriate than the first for analysis of the reliability of the system with and without the DR resource. This analysis could be achieved by choosing the 'alternative' to DR for the base case such that the generation margin is broadly unchanged when DR displaces the 'alternative'. Thus, the change in system performance between the two cases would be largely due to the operation of the DR resource alone, not due to merely increasing the generation margin.

One challenge is the choice of the 'alternative' to DR. The authors in [34] discuss how DR compares and competes with combustion turbines and suggest that combustion turbines could serve as a proxy for a flexible resource, but this may be system specific and would warrant further investigation before any recommendation can be made regarding what resources could be considered alternatives to DR.

An alternative, and recommended, approach for an integration study would involve comparing and contrasting a number of different portfolios and a number of scenarios in a manner similar to that employed in [61], rather than simply comparing one scenario without DR and one scenario with DR.

It is highly recommended that, in evaluating DR, the time-varying nature of electricity markets are adequately incorporated into the power system models in order to obtain robust and realistic results from production cost simulations. For example, the volatility of electricity and AS prices over time can have serious implications for the revenue earned by DR resources. It was found in [20] that in the CAISO South region, for the years 2009–2011, the winter months had large evening peaks in regulation up prices while the early morning hours had lower prices. Similarly, in the west reserve zone of New York ISO, for all seasons, the spinning reserve prices in the early morning hours are close to zero [20].

The importance of including this daily and seasonal temporal variation in market clearing price when assessing the value of DR participation in AS markets is highlighted in [20]. This would suggest that there are limited time periods over which to earn revenue through participation in an AS market, which may reduce the overall value of DR for the participant. The work in [62] highlights the importance of correctly modeling the variation in price of electricity over time when examining DR. The authors in [62] suggest that in certain cases for certain systems this will necessitate the incorporation of price correlation into the production cost model.

4.2.2. Capacity value calculations

Capacity value (CV) calculations are an important component of integration studies and CV is a key measure of the contribution a resource can make to generation system adequacy [63]. The CV of a generator can be defined as '*the amount of additional demand that can be served due to the addition of the generator, while maintaining the existing levels of reliability*' [63].

One of the challenges associated with CV calculations is the fact that the methodology was developed with conventional generators in mind and then adapted and applied to variable renewables [63]. While this methodology has also been adapted to provide a high level estimate the CV of DR [64], the traditional CV methodology does not inherently capture all of the impacts on generation adequacy associated with the operation of DR.

A feature of DR that is inherently different to the characteristics of a conventional unit pertains to availability rates and probability of availability. In traditional CV calculations, individual generator availabilities are assumed to be independent of each other. This is not the case for the wind and solar resource and, indeed, the same cannot be said of DR resources. This is clearly understood with a simple example; suppose there is an industrial facility with a number of different units offering DR with one control system for all the units. Failure of that control system affects all of the DR units and in this case their availabilities would not be independent of each other. For CV calculations, another one of the required assumptions is that the failure performance of a unit is independent of the operating level, the system load and the outage pattern of other units [65]. This is not true of DR resources because they will inherently be dependent on system load. For example, a refrigeration unit will not be available to response to a signal to reduce load, if the unit was not on and operating in the first instance. If shoe-horning DR analysis into preexisting methodologies for CV calculation, the breakdown of these assumptions represents a major challenge to modeling and evaluating the DR resource and indicates the potential requirement for a novel alternative approach.

It can be appreciated that the availability of conventional generation depends upon the mechanics of electricity generation and upon the control systems in place, while wind generation availability is contingent upon natural phenomenon and the physical resource. The wind resource, although variable and uncertain, can be represented to a certain degree of accuracy and there is significant wind data and wind time series available. DR availability, on the other hand, depends upon the mechanics of the devices and upon the control systems, but crucially, also depends upon consumer behavior and user preferences. It is this influence that introduces challenges to the representation of the DR resource availability. It is crucially important, as is recommended in [66], that the wind, load and DR data is time-synchronized in CV calculations and the limited DR data can be a considerable challenge in this regard.

There is significant work to be carried out regarding the capacity value of DR so that system operators can decide how best to incorporate DR into the daily operating strategies and into long-term planning considerations.

4.3. Modeling demand response in integration studies

It is recommended that production cost simulations and CV calculations pay close attention to the physical characteristics of the DR resources. These resources have a number of unique characteristics as well as characteristics in common with conventional generation. As is the case with conventional generating units, it is crucial that the DR constraints are modeled appropriately in order to accurately reflect the physical characteristics of the DR unit. DR has constraints equivalent to the response rates, ramp rates, rated capacities and has minimum down time and maximum up time constraints typically associated with conventional generating units. Like conventional units, DR is only possible if the unit is online and available. However, unlike conventional units, which have significant ramp rate limitations, DR units have smaller physical time constants and thus higher ramp rates. Therefore it is highly improbable that DR units would need to be constrained on. It is the unique characteristics that present challenges for modeling DR across all domains and indicates the need for high resolution models in order to capture all of the physical characteristics of DR. Unlike most conventional generators, a DR resource is energy limited. After a DR unit has provided a service to the system, the energy which the unit relinquishes may need to be recovered at a later stage. If these recovery periods are uncontrolled, a number of units' recovery periods may coincide and this may inadvertently create an additional, unintentional peak in the system demand.

A method is developed in [60] for quantifying the effect increasing penetration of DR resources providing load shifting can have on electricity markets. They show that load reduction in one period can reduce the market price, but shifting that load to another point in time, can cause a rise in the market price at that time. The energy limited nature of DR is often viewed as being similar to conventional storage units and thus in many places in the literature, load shifting units are modeled and considered as storage units, for example in [9] and in [21]. This energy limited nature constrains the duration of response the DR unit is capable of providing and there may also be a limit on the number of times a DR unit can be called upon to provide a response. The energy storage dimension of the DR resource introduces an element of time shifting, making the calculation of its availability at a specific point in time complex, since the probability of DR availability in a certain hour is contingent on whether it was available or used in previous hours. It is recommended that these constraints and unique characteristics are incorporated into the model of DR used in the production cost simulation and in the capacity value calculations to obtain realistic results.

The challenge of the time-varying price of electricity and AS, discussed in the previous section, is compounded by the time-varying availability of DR resources themselves; DR may simply not be in a position to provide a response during periods of high prices, further eroding its potential revenue stream. Some DR resources can respond within hours, minutes or even seconds of a signal or a disturbance and the duration of the response can be on the time scale of minutes or hours. Capturing these inter-temporal characteristics is paramount to adequately evaluating the DR resource and time-synchronized data is a necessity in this regard. However, as mentioned earlier, there is a dearth of sufficient data of this kind available at present.

There is also a need to represent unanticipated consumer behavior in demand side models and this represents a major paradigm shift from the traditional power system studies and could present multiple challenges. However, it has been shown that aggregation reduces the irregularity and diversity associated with loads [67]. The authors in [67] even suggest that aggregation of a few thousand households transfers DR from the residential sector into a uniform response '*enough to consider it as a system resource*'.

It is based on this that aggregation is highly recommended when modeling and analyzing the DR resource.

One of the benefits of using an integration study methodology is the ability to incorporate stochastic elements in the unit commitment algorithm. In recent times, there as been considerable work in developing stochastic unit commitment tools to account for the uncertainty associated with variable renewable generation, particularly wind [68,69]. Thus, significant expertise exists to allow the incorporation of the stochastic elements of DR in production cost simulations. The authors in [70] find that stochastic variations in household energy consumption on a daily and seasonal basis can affect the optimum capacity of demand-side energy storage required. This highlights the need for stochastic demand models in order to more fully understand the economic viability of utilizing storage devices for DR and the same can be said of other DR programs.

5. Discussion

The key message of the paper is that there is considerable uncertainty surrounding the value of DR. Consequently there can be concern regarding the potential revenue for DR program participants and a hesitancy for others to engage in a program. A greater understanding of the value is required for widespread deployment of DR programs. Evaluation of the DR resource is clearly a vital step in its large scale deployment and could increase understanding of the impacts of DR on the system and markets. One of the challenges faced when evaluating DR is the need for awareness of consumer preferences and different motivating factors. It is vitally important that the limitations of the DR resource and the effect of unanticipated consumer behavior are borne in mind. This, however, can be hampered by a lack of suitable data and information, as previously discussed.

The terminology used to describe DR programs can also be problematic for the evaluation of DR. It is noted in [46] that despite the fact that some system operators have established DR programs, while many more are developing such schemes, the many ways in which to execute a DR program and the inconsistencies associated with program definitions pose considerable barriers. There are also numerous ways in which to classify DR programs, for example, in terms of application or in terms of the signaling mechanisms. It is common to classify DR programs based on their incentive structure [71], while programs can also be classified based on whether they are activated by price or by system reliability requirements [72]. Within each of these classifications there are many different DR programs and there is often considerable overlap. This can create difficulties when making comparisons between different programs and it may not be possible to draw conclusions from one system and apply them to another.

From earlier in the paper, it is clear that DR can provide multiple products and that there is a relationship between them. Thus, failure to develop DR in one market can deprive other markets. Offering multiple services to the power system is not only beneficial from the power system point of view, but also allows DR participants to avail of numerous revenue streams. As a result, it is highly recommended that DR programs are not studied and evaluated separately, but are assessed as part of the larger power system so as to appropriately account for their combined impact. In [49] it is noted, however, that there is a significant challenge in evaluating DR programs holistically. The alternative, on the other hand, to evaluate the programs separately, is unacceptable since, ultimately, any program will be integrated into the larger power system and thus there will be interactions and interdependencies and the programs will form a small part of a larger portfolio of resources.

This need for a comprehensive holistic approach indicates that an integration study is a very suitable, and recommended, approach to adopt for the evaluation of DR. The approach recommended in this paper is similar to that in [55] with some additions to account for the unique characteristics of the DR resource. The ideal approach would involve detailed modeling of the physical properties and energy limited nature of the DR resource in a stochastic production cost simulation. This model would also capture the vagaries of consumer behavior insofar as is possible. The production cost simulation would involve co-optimization of energy and ancillary service markets. This is in order to determine the operation of DR resources when in competition with other technologies and strategies [8] and to take account of the intrinsic relationship between multiple DR services. Co-optimization is also noted as being of particular importance in [19]. The simulation would also utilize time-synchronized data to ensure inter-temporal variations are accounted for. A series of different portfolios and scenarios would be examined and compared. The production cost simulation would be combined with a capacity value assessment of the resource enabling examination of the contribution the DR resource can make to power system reliability.

When an integration study is completed, however, one issue remains – the synthesis and dissemination of experience, understanding and study conclusions. Such tasks are inhibited by the appreciable differences between systems coupled with the disparity in AS terminology and DR program classifications and definitions. It should also be remembered that all power systems are different and the results of system studies are inevitably system-specific. CV results, for example, are dependent on the generation portfolio and thus the requirement for capacity in a particular system. Additionally, despite the fact that DR can provide multiple products, some systems do not operate markets for capacity, while others do not have AS markets. A related issue is the fact that interpretations of the definition of capacity can be arbitrary, while AS definitions and rules vary considerably from system to system. A revision of AS definitions and market rules to accommodate the physical characteristics of DR resources is highly recommended. This could permit greater participation in DR programs and also allow better exploitation of the available DR resources.

The differences between systems have implications for evaluating DR, preventing transfer and application of the evaluation framework from one system to another. While the methodologies may be applicable, or at least adaptable, to all systems, the results are unlikely to be directly transferable. That being said, however, it is still vital that such studies are performed in order to more fully understand the value of DR and to make informed decisions regarding the future of DR.

6. Conclusion

The main contributions of this paper lie in the identification of key DR deployment barriers, from across the range of the DR literature and from many different aspects of the DR concept, in the discussion of how the uncertainty in DR deployment can impact upon evaluation methodologies and in the introduction of the concept of integration benefit. Additionally, this paper provides numerous recommendations.

There is a 'Chicken and Egg' type scenario at present in the DR field; uncertainty regarding the value of the DR resource compromises investment interest and understanding of the ideal manner in which to deploy DR programs, which culminates in limited experience with a consequent shortage of suitable data. This leads to a lack of clarity as regards how best to represent the DR resource and incorporate it in valuation methodologies and results in a minimal understanding of the value of DR.

There is a pressing need to quantify the value of DR. DR could be crucially important to the power system given that it can provide multiple services and it is paramount to be aware of how DR compares with other resources. It is also vital to understand the price that DR could receive in the various electricity markets and to appreciate the characteristics of DR which are most desirable from a power system point of view.

Acknowledgements

This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by the Commission for Energy Regulation, Bord Gáis Energy, Bord na Móna Energy, Cylon Controls, EirGrid, Electric Ireland, EPRI, ESB International, ESB Networks, Gaelectric, Intel, SSE Renewables and Energia. S. Nolan is funded by the Irish Research Council Embark Initiative.

References

[1] US Department of Energy Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them. A Report to the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005. <http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf> [February 2006].

[2] Kim J-H, Shcherbakova A. Common failures of demand response. Energy 2011;36(2):873–80. http://dx.doi.org/10.1016/j.energy.2010.12.027.

[3] Milligan M, Kirby B. Utilizing load response for wind and solar integration and power system reliability. In: WindPower 2010, Dallas, Texas, July, 2010. p. 1–18. <http://www.nrel.gov/docs/fy10osti/48247.pdf>.

[4] Earle R, Kahn EP, Macan E. Measuring the capacity impacts of demand response. Elect J 2009;22(6):47–58. http://dx.doi.org/10.1016/j.tej.2009.05.014. <http://www.sciencedirect.com/science/article/pii/S1040619009001523>.

[5] Dietrich K, Latorre JM, Olmos L, Ramos A. Demand response in an isolated system with high wind integration. IEEE Trans Power Syst 2012;27(1):20–9. http://dx.doi.org/10.1109/TPWRS.2011.2159252.

[6] Shen B, Ghatikar G, Lei Z, Li J, Wikler G, Martin P. The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges. Appl Energy 2014;130:814–23. http://dx.doi.org/10.1016/j.apenergy.2013.12.069.

[7] Strbac G. Demand side management: benefits and challenges. Energy Policy 2008;36(12):4419–26. http://dx.doi.org/10.1016/j.enpol.2008.09.030.

[8] Cappers P, Goldman CA, Kathan D. Demand response in U.S. electricity markets: empirical evidence. Energy 2010;35(4). http://dx.doi.org/10.1016/j.energy.2009.06.029.

[9] Keane A, Tuohy A, Meibom P, Denny E, Flynn D, Mullane A, et al. Demand side resource operation on the Irish power system with high wind power penetration. Energy Policy 2011;39(5):2925–34. http://dx.doi.org/10.1016/j.enpol.2011.02.071.

[10] Berardino J, Nwankpa C. Dynamic load modeling of an HVAC chiller for demand response applications. In: 2010 first IEEE international conference on smart grid communications, 2010. p. 108–113. (doi:http://dx.doi.org/10.1109/SMARTGRID.2010.5622028).

[11] Douglass PJ, Garcia-Valle R, Nyeng P, Østergaard J, Togeby M. Demand as frequency controlled reserve: implementation and practical demonstration. In: 2nd IEEE PES international conference and exhibition on innovative smart grid technologies (ISGT Europe), 2011. p. 1–7. (doi:http://dx.doi.org/10.1109/ISGTEurope.2011.6162711).

[12] Hammerstrom D, et al. Pacific northwest gridwise testbed demonstration projects part 1 olympic peninsula project. PNNL-17167. <https://www.smartgrid.gov/sites/default/files/doc/files/PNNL_GridWise_Testbed_Demo_Projects_Part_I_Olympic_Peninsula_200711.pdf>.

[13] Richardson I, Thomson M, Infield D, Clifford C. Domestic electricity use: a high-resolution energy demand model. Energy Build 2010;42(10):1878–87. http://dx.doi.org/10.1016/j.enbuild.2010.05.023.

[14] De Jonghe C, Hobbs BF, Belmans R. Optimal generation mix with short-term demand response and wind penetration. IEEE Trans Power Syst 2012;27(2):830–9. http://dx.doi.org/10.1109/TPWRS.2011.2174257.

[15] Kowli A, Gross G. Quantifying the variable effects of systems with demand response resources. In: 2010 IREP symposium bulk power system dynamics and control – VIII (IREP), 2010. p. 1–10. [doi:http://dx.doi.org/10.1109/IREP.2010.5563260].

[16] Kirby BJ. Load response fundamentally matches system reliability requirements. In: IEEE power engineering society general meeting, 2007. [http://dx.doi.org/10.1109/PES.2007.386227].

[17] Milligan M, Ela E, Hodge B-M, Kirby B, Lew D, Clark C, Decesaro J, et al. Cost-causation and integration cost analysis for variable generation. NREL/TP-5500-51860; June 2011. <http://www.nrel.gov/docs/fy11osti/51860.pdf>.

[18] Woolf T, Malone E, Schwartz L, Shenot J, A framework for evaluating the cost-effectiveness of demand response. Technical report, Prepared for the National Forum on the National Action Plan on Demand Response; February 2013. <http://emp.lbl.gov/sites/all/files/napdr-cost-effectiveness.pdf>.

[19] Ma O, Alkadi N, Cappers P, Denholm P, Dudley J, Goli S, et al. Demand response for ancillary services. IEEE Trans Smart Grid 2013;4(4):1988–95. http://dx.doi.org/10.1109/TSG.2013.2258049.

[20] Macdonald J, Cappers P, Callaway D, Kiliccote S. Demand response providing ancillary services a comparison of opportunities and challenges in the US wholesale markets. Grid-Interop 2012, November 2012. <http://drrc.lbl.gov/publications/dr-providing-as-comparison-opportunities-challenges>.

[21] Andersen FM, Jensen SG, Larsen HV, Meibom P, Ravn H, Skytte K, et al. Analyses of demand response in Denmark. Technical report, Ris-R-1565(EN); October 2006. <http://orbit.dtu.dk/fedora/objects/orbit:88362/datastreams/file_7703292/content>.

[22] Sioshansi R, Short W. Evaluating the impacts of real-time pricing on the usage of wind generation. IEEE Trans Power Syst 2009;24(2):516–24. http://dx.doi.org/10.1109/TPWRS.2008.2012184.

[23] Kirby B. Demand response for power system reliability:FAQ. ORNL/TM-2006/565; December 2006. <http://wp.ornl.gov/sci/ees/etsd/pes/pubs/TM_2006_565_Demand_Response_For_Power_System_Reliability_FAQ.pdf>.

[24] Kirby B, O'Malley M, Ma O, Cappers P, Corbus D, Kiliccote S, et al. Load participation in ancillary services. Workshop report., December 2011. <https://www1.eere.energy.gov/analysis/pdfs/load_participation_in_ancillary_services_workshop_report.pdf>.

[25] Sioshansi R. Evaluating the impacts of real-time pricing on the cost and value of wind generation. IEEE Trans Power Syst 2010;25(2):741–8. http://dx.doi.org/10.1109/TPWRS.2009.2032552.

[26] Boisvert RN, Neenan BF. Social welfare implications of demand response programs in competitive electricity markets. Technical report, Ernest Orlando Lawrence Berkely National Laboratory, LBNL-52530; August 2003. <http://emp.lbl.gov/sites/all/files/REPORTlbnl-52530.pdf>.

[27] Allcott H. Real-time pricing and electricity market design; 2012. <https://files.nyu.edu/ha32/public/research/Allcott%20-%20Real-Time%20Pricing%20and%20Electricity%20Market%20Design.pdf>.

[28] Albadi MH, El-Saadany E. Demand response in electricity markets: an overview. In: IEEE PES general meeting 2007; 2007. p. 1–5. [doi:http://dx.doi.org/10.1109/PES.2007.385728].

[29] Moghaddam MP, Abdollahi A, Rashidinejad M. Flexible demand response programs modeling in competitive electricity markets. Appl Energy 2011;88(9):3257–69. http://dx.doi.org/10.1016/j.apenergy.2011.02.039.

[30] Schweppe FC, Caramanis MC, Tabors RD, Bohn RE. Spot Pricing of Electricity. Boston, MA, USA: Kluwer Academic Publishers; 1988.

[31] Rahimi F, Ipakchi A. Overview of demand response under the smart grid and market paradigms. In: 2010 Innovative smart grid technologies (ISGT); 2010. p. 1–7. [http://dx.doi.org/10.1109/ISGT.2010.5434754].

[32] Joung M, Kim J. Assessing demand response and smart metering impacts on long-term electricity market prices and system reliability. Appl Energy 2013;101:447–8. http://dx.doi.org/10.1016/j.apenergy.2012.05.009.

[33] Cramton P, Ockenfels A, Stoft S. Capacity market fundamentals. Econom Energy Environ Policy 2013;2(2):1–21. http://dx.doi.org/10.5547/2160-5890.2.2.2.

[34] Cutter E, Taylor A, Kahrl F, Woo CK. Beyond DR maximizing the value of responsive load limits of the current DR paradigm. In: 2012 ACEEE summer study on energy efficiency in buildings, 2012. p. 77–88.

[35] Hurley D, Peterson P, Whited M. Demand response as a power system resource. Technical report., May 2013. <http://www.synapse-energy.com/Downloads/SynapseReport.2013-03.RAP.US-Demand-Response.12-080.pdf>.

[36] Miller M, Bird L, Cochran J, Milligan M, Bazilian M, Denny E, et al. RES-E-NEXT: next generation of RES-E policy instruments. IEA_RETD; July 2013. <http://iea-retd.org/wp-content/uploads/2013/07/RES-E-NEXT_IEA-RETD_2013.pdf>.

[37] Kirby B. Ancillary services: technical and commerical insights. Wärtsilä; July 2007. <http://www.consultkirby.com/files/Ancillary_Services_-_Technical_And_Commercial_Insights_EXT_.pdf>.

[38] Ryan J, Ela E, Flynn D, OMalley M. Variable generation, reserves, flexibility and policy interactions. In: Hawaii international conference on system sciences (HICSS). In: 2014 47th n, 2014. p. 2426–34. [http://dx.doi.org/10.1109/HICSS.2014.304].

[39] Kirby B, Kueck J, Laughner T, Morris K. Spinning reserve from hotel load response. Elect J 2008;21(10):59–66. http://dx.doi.org/10.1016/j.tej.2008.11.004.

[40] Callaway DS. Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy. Energy Convers Manage 2009;50(5):1389–400. http://dx.doi.org/10.1016/j.enconman.2008.12.012.

[41] Cappers P, McDonald J, Goldman C, Ma O. An assessment of market and policy barriers for demand response providing ancillary services in U.S. electricity markets. Energy Policy 2013;62:1031–9. http://dx.doi.org/10.1016/j.enpol.2013.08.003.

[42] Heffner G, Goldman C, Kirby B, Kintner-Meyer M. Loads providing ancillary services: review of international experience. LBNL 62701, ORNL/TM-2007/060, PNNL-16618; May 2007. <http://certs.lbl.gov/pdf/62701.pdf>.

[43] Callaway DS, Hiskens Ia. Achieving controllability of electric loads. Proc IEEE 2011;99(1):184–99. http://dx.doi.org/10.1109/JPROC.2010.2081652.

[44] Balcombe P, Rigby D, Azapagic A. Investigating the importance of motivations and barriers related to microgeneration uptake in the UK. Appl Energy 2014;130:403–18. http://dx.doi.org/10.1016/j.apenergy.2014.05.047.

[45] Nilsson A, Jakobsson Bergstad C, Thuvander L, Andersson D, Andersson K, Meiling P. Effects of continuous feedback on households electricity consumption: potentials and barriers. Appl Energy 2014;122:17–23. http://dx.doi.org/10.1016/j.apenergy.2014.01.060.

[46] Chuang AS. Demand-side integration for system reliability. PowerTech 2007;2007:1617–22. http://dx.doi.org/10.1109/PCT.2007.4538557.

[47] North American Energy Standards Board. Wholesale and Retail Demand Response Definition of Terms; August 2009. <http://osgug.ucaiug.org/sgsystems/OpenADR/Shared%20Documents/Reference%20Documents/naesb_dr_definitions.doc>.

[48] ENERNOC. The demand response baseline; 2011. <http://www.enernoc.com/our-resources/white-papers/the-demand-response-baseline>.

[49] Thanos G, Minou M, Ganu T, Arya V, Chakraborty D, Deventer JV, et al. Evaluating demand response programs by means of key performance indicators. In: Fifth international conference on communication systems and networks (COMSNETS); 2013. [http://dx.doi.org/10.1109/COMSNETS.2013.6465597].

[50] Wijaya TK, Vasirani M, Aberer K. When bias matters: an economic assessment of demand response baselines for residential customers. IEEE Trans Smart Grids 2014;5(4):1755–63. http://dx.doi.org/10.1109/TSG.2014.2309053.

[51] Grimm C. Evaluating baselines for demand response programs. In: AEIC load research workshop, San Antonio, Texas; 2008. <http://publications.aeic.org/lrc/12_Evaluating_Baselines_for_Demand_Response_Programs_PAPER.pdf>.

[52] Mathieu J, Callaway DS, Kiliccote S. Examining uncertainty in demand response baseline models and variability in automated responses to dynamic pricing. In: IEEE conference on decision and control and European control conference (CDC–ECC), Orlando, Florida; 2011. p. 4332–9. [http://dx.doi.org/10.1109/CDC.2011.6160628].

[53] Bushnell J, Hobbs BF, Wolak FA. When it comes to demand response, is FERC its own worst enemy? Elect J 2009;22(8):9–18. http://dx.doi.org/10.1016/j.tej.2009.08.004. <http://www.sciencedirect.com/science/article/pii/S104061900900219X>.

[54] Soder L. Modelling approach impact on estimation of integration cost of wind power. In: 7th European IAEE conference European energy markets in transition Bergen; 2005. <https://www.ieawind.org/task_24/task_24_secure/taskReports/Soder-IAEE.pdf>.

[55] Holttinen H, Soder L, Malley MO, Dillon J, Flynn D, Orths A, et al. Recommendations for wind integration studies. In: IEA task 25; 2012. <http://www.ieawind.org/task_25/PDF/WIW12_101_Task%2025_Recommendations_submitted.pdf>.

[56] Holttinen H, Meibom P, Orths A, Lange B, Malley MO, Tande JO, et al. Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration. Wind Energy 2011. http://dx.doi.org/10.1002/we.410.

[57] Meibom P, Weber C, Barth R, Brand H. Operational costs induced by fluctuating wind power production in Germany and Scandinavia. IET Renew Power Gener 2009;3(1):77–83. http://dx.doi.org/10.1049/iet-rpg:20070075.

[58] Milligan M, Hodge B-M, Kirby B, Clark C. Integration costs: are they unique to wind and solar energy? American wind energy association conference, WINDPOWER 2012, Atlanta, Georgia; 2012. [NREL/CP-5500-54905] <http://www.nrel.gov/docs/fy12osti/54905.pdf>.

[59] Caves D, Eakin K, Farugui A. Mitigating price spikes in wholesale markets through market-based pricing. Elect J 2000;6190(April):13–23. http://dx.doi.org/10.1016/S1040-6190(00)00092-0.

[60] Su C, Kirschen D. Quantifying the effect of demand response on electricity markets. IEEE Trans Power Syst 2009;24(3):1199–207. http://dx.doi.org/10.1109/TPWRS.2009.2023259.

[61] Nabe C, Malley MO, Bömer J, Broad D. The Irish all island grid study methodological approach and outcomes. In: Power systems conference and exposition, Seattle, Washington; 2009. p. 1–5. [http://dx.doi.org/10.1109/PSCE.2009.4840194].

[62] Ferreira R, Barroso L, Carvalho M. Demand response models with correlated price data: a robust optimization approach. Appl Energy 2012;96:133–49. http://dx.doi.org/10.1016/j.apenergy.2012.01.016.

[63] Keane A, Milligan M, Dent C, Hasche B, D'Annunzio C, Dragoon K, et al. Capacity value of wind power. IEEE Trans Power Syst 2011;26(2):564–72. http://dx.doi.org/10.1109/TPWRS.2010.2062543.

[64] Nolan S, O' Malley M, Hummon M, Kiliccote S, Ma O. A methodology for estimating the capacity value of demand response. PES General Meeting | Conference & Exposition, 2014 IEEE, 27–31 July 2014.

[65] Goel L. Power system reliability – concepts and techniques. In: IEEE PES distinguished lecturer program India, November/December 2011. <http://sites.ieee.org/hyderabad-pes-ias-pels/files/2011/12/PPT.pdf>.

[66] Hasche B, Keane A, O'Malley M. Capacity value of wind power, calculation, and data requirements: the Irish power system case. IEEE Trans Power Syst 2011;26(1):420–30. http://dx.doi.org/10.1109/TPWRS.2010.2051341.

[67] Pagliuca S, Lampropoulos I, Bonicolini M, Rawn B, Gibescu M, Kling WL. Capacity assessment of residential demand response mechanisms. In: Proceedings of the 46th international universities' power engineering conference (UPEC), 2011. p. 1–6. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6125500&isnumber=6125473>.

[68] Barth R, Brand H, Meibom P, Weber C. A stochastic unit-commitment model for the evaluation of the impacts of integration of large amounts of intermittent wind power. In: International conference on probabilistic methods applied to power systems, 2006. PMAPS 2006, 2006. p. 1–8. [http://dx.doi.org/10.1109/PMAPS.2006.360195].

[69] Meibom P, Barth R, Hasche B, Brand H, Weber C, O'Malley M. Stochastic optimization model to study the operational impacts of high wind penetrations in Ireland. IEEE Trans Power Syst 2011;26(3):1367–79. http://dx.doi.org/10.1109/TPWRS.2010.2070848.

[70] Zheng M, Meinrenken CJ, Lackner KS. Agent-based model for electricity consumption and storage to evaluate economic viability of tariff arbitrage for residential sector demand response. Appl Energy 2014;126:297–306. http://dx.doi.org/10.1016/j.apenergy.2014.04.022.

[71] ENERNOC. Demand response: a multi-purpose resource for utilities and grid operators – White Paper (2009). <http://www.enernoc.com/our-resources/white-papers/demand-response-a-multi-purpose-resource-for-utilities-and-grid-operators>.

[72] National Action Plan for Energy Efficiency. Coordination of energy efficiency and demand response. Prepared by Charles Goldman (Lawrence Berkeley National Laboratory), Michael Reid (E Source), Roger Levy, and Alison Silverstein; 2010. <www.epa.gov/eeactionplan>, <http://emp.lbl.gov/sites/all/files/REPORT%20lbnl-3044e.pdf>.