This paper was presented at the 13th Wind Integration Workshop and published in the workshop's proceedings

Synergies between Wind and Solar Generation and Demand Response

An IEA Task 25 Collaboration

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***Abstract*—Recent years have seen the interest in demand response increase, in academia and in industry, for both large scale demands and aggregated domestic demands. A number of power systems have established demand response programs in energy, ancillary services and capacity markets, while many are currently undertaking system specific customizations. One of the key reasons for the burgeoning interest in demand response lies in its ability to enhance variable renewable penetration levels, through the provision of flexibility, wind/solar curtailment reduction and other system ancillary services. This paper will review and evaluate various demand response studies, projects and programs from different countries, examining the synergies with renewables integration, also identify some of the main barriers which exist to the deployment of such demand response at greater scale.**

Keywords- Wind, solar, demand response

I. INTRODUCTION

Recent years have seen the interest in demand response (DR) increase. The Federal Electric Regulatory Commission definition of demand response is the change in electrical energy usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time or to incentive payments [1]. DR is thus now much broader than traditional emergency load shedding resources as it is in a position to provide a range of system services over varying time frames, and it is also possible to elicit an increase in consumption as well as a reduction. While there is experience with DR programs targeted at large industrial energy users [2], there is also now more of an interest in extending DR to all sectors, including the residential sector [3]. Rapid advances and cost reductions in the area of telecommunications and control systems have facilitated greater controllability of demand-side resources. As a result of these advances, DR is being developed and deployed on a more continuous basis, across multiple time frames and multiple energy/ancillary-service markets. Many power systems have established DR integration programs, while others are in the process of designing programs appropriate to their system. The interest in DR is evident from the vast amount of work that has been published in recent years [4-8].

One of the reasons for the burgeoning interest in DR lies in its scope for interaction with wind and solar. The inclusion of wind and solar in the generation portfolio can present a number of issues for system operators. Variable generation can increase price volatility and increased penetrations of renewables can lead to a greater requirement for ancillary services [9]. DR is in a position to facilitate the integration of renewable generation [6], [10] by reducing the impacts related to variability and uncertainty. DR has the potential to shift system demand to more favourable periods and thus can assist with renewables curtailment reduction and provision of many of the ancillary services which are required.

This paper reviews and evaluates various studies, projects, and existing demand response programs, though of course it is by no means an exhaustive list. We begin with a discussion of the interaction between wind and solar generation and demand response. Part III summarizes DR demonstration projects in the United States and Europe and Part IV considers known barriers to demand response adoption and implementation. There is limited information in the literature regarding synergies between solar generation and DR, though where possible extensions are made in this paper from DR and wind experiences.

II. WIND/SOLAR AND DEMAND RESPONSE INTERACTION

The authors in [6], [11] discuss how price responsive load could significantly aid in the integration of variable generation sources like wind and solar if suitable institutional frameworks can be developed. The authors in [12] state that despite wind being emission free, its overall impact on power system emissions is dependent upon how the variability and uncertainty associated with wind is accommodated. Using DR in conjunction with wind, on the other hand, has a positive net emission benefit, greater than implementing wind alone [12]. Similarly, it is demonstrated that wind generation and demand response through real-time pricing together result in '*superadditive (social) surplus gains*' in [13].

While curtailment reduction is a frequently mentioned benefit of DR, in reality there are many other possible interactions between variable renewable generation and DR. It is well-poised to assist some of the issues created by renewable generation by providing benefits in key areas:

1. Energy arbitrage
2. Provision of ancillary services
3. Contribution to generation adequacy and deferral of investment in networks
4. Overall system cost reduction

A. Energy Arbitrage

Energy arbitrage can be simply defined as the act of shifting energy consumption from periods with high electricity prices to hours when the price is lower, analogous to storage [14]. The authors in [15] demonstrate that price-based DR can prompt energy arbitrage and thus can be effective in filling demand valleys. It can be seen that energy arbitrage, with and without high renewable penetration, can have considerable benefits for the power system [16],[17].

DR can also be used to reduce solar and wind curtailments by selectively increasing load at times when the marginal price is zero or negative. In the United States, future scenarios of high distributed PV penetration will result in over-generation situations. The authors in [15] show that incorporating price-based DR can reduce wind curtailment to zero, when demand has an own price elasticity of -0.1. In [18] it is demonstrated that DR can not only increase the fraction of load which is met by wind generation, but can also increase the percentage of wind that is used in real-time. Effectively, DR allows the integration of greater amounts of wind.

According to [19] a large fraction of solar PV occurs when the system electricity demand is low. At such times, large baseload units are operating close to their technical minimum output which results in curtailment of solar PV and increased system costs [19]. In [20] it is demonstrated that while there is better coincidence between solar insolation and system demand in the summer, there is much less coincidence between the two at other times of the year.

B. Provision of Ancillary Services

DR can supply ancillary services including regulation, ramping/following, and contingency reserves. [6],[4]. This helps in two ways. First, it is a direct supply for the additional flexibility which wind and solar impose on the power system. Second, it is replacement for the flexibility that can be lost when wind and solar displace conventional generation that is also supplying reserves. The authors in [21] examine whether DR can provide a potential solution to the volatility and uncertainty of wind resources. They show, using a stochastic unit commitment program that the combination of wind generation and DR can result in less frequent commitment of the most expensive generating units. When wind generation is combined with DR there is a reduction in reliability costs compared to the wind-only case and a decrease in overall system costs compared to the case without wind or DR [21].

Variable generation also will increase the needs and use of primary/secondary and regulation reserves. Some forms of DR can be a cost effective source of such reserves - DR can be extremely fast and in principle help the system to maintain frequency stability during events with little synchronous generation online [22], [23]. According to [24], DR can be used to mitigate generation intermittency provided that the consumer/end-user is not discomforted. Integrated grid/demand-side optimisation models may be key in this respect [25], [26].

In [27] it is suggested that DR may be able to assist with the evening ramp-down in solar production in California. They highlight that, in California, when the system demand is high, the availability of the DR resource (A/C loads) is also high. It is also shown that the peak in the DR resource availability occurs very close to the time when solar output is falling rapidly. The authors in [28] demonstrate the effects of the response by millions of household refrigerators and freezers to frequency signals. These are able to keep the system frequency stable with the effect especially pronounced with higher shares of wind generation.

C. Contribution to Generation/Network Adequacy

A significant benefit of DR lies in its ability to provide capacity to the power system and to thereby avoid expansion planning costs [29], [10]. The work in [8] [Huang] demonstrates that DR can contribute to system adequacy. In addition, system reliability performance becomes less variable from year to year with the inclusion of load-shifting programs. Furthermore, given the long lead times associated with new generating plants [21], DR may prove to be a better option for dealing with diminishing generation margins as a result of load growth and decommissioning of old units.

The authors in [31] assess the impact of DR on distribution system reliability and show that, in general, responsive demand can have a positive impact. They do so by distinguishing between DR base load reduction and emergency load interruptions and by noting that in many cases, DR load reduction is preceded by a warning or notification. The improvement in reliability from DR is the result of two aspects; one, the ability to shed/shift a portion of the load and two, DR can be used post-fault to '*increase the restoration capacity and reduce the load interruption duration'*.

Distributed generation (DG) can be connected to medium voltage (MW) or low voltage (LV) networks and can create a number of challenges. DR may also be in a position to alleviate some of the associated issues and thus defer necessary upgrades. Distributed generation can significantly alter the demand patterns by locally supplying the load. This becomes particularly important in the case of uncontrolled LV DG, of which the TSO has little visibility. Generally a large penetration of uncontrolled DG on the system will increase the variability and uncertainty in demand forecasts at transmission systems [32].

D. Overall System Cost and Price Volatility Reduction

The authors in [7] show that DR could potentially reduce system costs by shifting demand away from peak periods. As a result, expensive peaking plants could be displaced, lowering system costs. Their results show that on days with exceptionally high wind energy production during low demand periods, demand-side measures achieved up to 30% cost savings and added enough flexibility to the system to avoid the spillage of wind energy. They also conclude that on high wind days, the demand behaves more flexibly.

Similarly, it has also been suggested that DR has the potential to increase system operation efficiency in [33], which also shows that utilizing DR potential in conjunction with improved wind power predictions reduces the additional balancing costs imposed by wind. The costs of balancing wind variability can be reduced by 20% if consumers engage in load management according to [33]. In [34] the balancing costs for wind power in a system with or without electric vehicles are calculated. The balancing costs of wind power without electric vehicles were 2.3 €/MWh. The balancing costs of wind power increased by 0.4 €/MWh when half of the vehicle fleet was passively charging electric vehicles. Smart charging electric vehicles decreased wind power balancing costs by 0.7 €/MWh. The analysis included both generation planning models and a unit-commitment/dispatch model.

The work of [11] show that some DR resources can limit the number of price spikes even at modest levels of 2%-6% of total system load. The authors of [18] similarly show that even at low elasticities of demand, RTP can increase the percentage of load served by wind generation and can reduce the level of wind curtailment. It should be noted that in some systems large-scale variable generation is not typically available during those hours. However, DR and renewables synergy is still important since DR reduces the need for peaking generation and variable generation often makes the system more 'peakier'. DR can also increase the load during times of excess generation, reducing curtailment, improving renewable generation economics and improving power system operability. The authors in [15] conclude by modelling wind stochastically that when consumers are in a position to adjust their demand, different wind forecast error scenarios can be better dealt with. Often, small amounts of DR are sufficient to see a benefit [15].

The authors in [35] compare different forms of power system flexibility from the perspective of wind power integration with a unit commitment and dispatch model. DR with 80-150 €/MWh cost provides only small system savings and is not comparable to many other forms of flexibility analysed in the article. However, the work did not take into account the generation adequacy contribution that DR can enable. The authors in [34] demonstrate how the availability of shiftable demand in the form of plug-in electric vehicles can increase the penetration of generation sources that are not normally controlled with dispatch (e.g. wind power and nuclear). The authors in [36] present a case using the IEEE standard 30-bus test system. Two wind farms are connected to the system and the effects of multi-tariff rates and DR are investigated. DR is assumed to respond to variations in wind power output. DR appears to offer significant savings in the system operation and increase the value of wind. In [37] the DR potential and cost in several European countries, both for residential and industrial sectors, are reported. It was found that the importance of different sectors varies between countries.

There are many potential loads that can engage in DR. Indeed, the authors in [34] demonstrate the possibilities of DR from electric boilers connected to district heating network. While in [27] the use of A/C loads is advocated, the authors in [19] suggest that electric hot water heaters in commercial and residential buildings may be well suited for responding to real-time pricing and solar generation variations. Water pumping is also identified as a potential demand-side resource for load-shifting that can be applied to solar generation.

The authors in [38] analyse the technical and economic potential of DR from energy-intensive industries in Germany. Variable costs from these resources are high, which means that they cannot be used very often for energy balancing. However, they can supplant a considerable amount of investment in peak generation capacity, which will reduce the integration costs of variable generation. In [39] it is noted that despite the significant and numerous benefits of DR (see previous section), European DR is limited to large energy users, e.g. industrial users. The author in [39] shows that presently small variations between peak and off peak prices implies the potential for widespread/broad implementation of a DR or load-shifting mechanism may be restricted to significant loads. It is also mentioned that load shifting in households can result in relatively low energy cost savings, which could limit the widespread deployment of residential DR in Europe.

The author in [33] has evaluated that the DR potential in Germany could be more than 30 GW, although a major portion (20 GW) would not be available outside the heating season. German peak load is approximately 80 GW. When analysing 48 GW of wind power in 2020 with a simple model, the wind power balancing costs were estimated to be about 1 €/MWh lower with DR, which was translated to allow 10–20 €/kW/year activation cost for DR. The authors in [40] have analysed how domestic hot water heating cylinders could offer DR for price changes anticipated in the electricity market. This was inspected in relation to the anticipated significant wind power penetration in Ireland. The synergies between heat-pump related DR and wind power integration in Germany were considered [41]. In [42] the use of hydrogen electrolysers to create flexible demand is suggested. They use an example of an isolated system for which the aim is to smooth the output from wind so that a thermal power plant can operate almost continually.

DR possibilities in the household sector were analysed in [43]. It is argued that thermal storage offers more cost effective potential for wind power integration than electrical storage. The analysis concentrates on ventilation systems, refrigeration and water heating. Olsen *et al.* [44] quantified the potential for commercial buildings, residential buildings, municipal processes, and several industrial processes to provide multiple grid DR services, including capacity, energy, and ancillary services. Hummon et al. [45] implemented the DR potential profiles from [44] in a unit commitment and economic dispatch model in order to quantify the value of offering DR as a resource to the system operator. The DR capacity for energy and ancillary services was co-optimized in the day-ahead model and 100% of the energy from DR was returned to the system as shifted load. The results demonstrate that significant variations in the availabilities of different types of DR resources affect both the operational savings as well as the revenue for each DR resource.

III. DEMAND RESPONSE DEMONSTRATION PROJECTS AND EXISTING PROGRAMS

This section examines demonstration projects and existing programs, including some of the lessons learned and a comparison of programs across the different systems.

A. Demonstration Projects and Existing Programs

1) United States of America

It is argued in [39] that there is greater load shifting and DR potential in the US because of the high electric heating, cooling loads and air-conditioning loads. This is in comparison to Europe, where electrical load levels are typically lower than those in the US, and where fossil based space heating systems are common in many residential buildings. There has been a move in recent years within state legislatures of the United States to require utilities to explore DR options for meeting system demand growth as oppose to investing in the construction of new generating units [11].

The revenue streams for DR in the US are considerable. For example, in PJM in 2013 the total revenue for DR resources from the capacity market were over $90 million. According to [46], more than 90% of DR revenue in PJM is derived from the capacity market, highlighting the importance of capacity markets for DR participants. The authors in [47] note that DR is in an excellent position to earn revenue from providing capacity, since the resource would simply be paid for being available to respond, but may not actually be required to do so. An excerpt from a PJM report [48] states that "*Economic DR resources provided between 228 MW (average LMP = $68 MWh) and 305 MW (average LMP = $125 MWh) on each of the three non-emergency summer 2012 PJM peak days. This is much higher than during 2011 summer which ranged from 3 MW (average LMP = $89 MWh) to 62 MW (average LMP = $186 MWh) but comparable with 2010 summer which was between 175 MW (average LMP = $114 MWh) and 337 MW (average LMP = $131 MWh). The majority (86 percent) of all Economic DR activity in the energy market from April through October 2012 came from a small number of very large customers (>10 MW). Further 82 percent of all activity during this same period came from customers located in Eastern portion of PJM (MAAC and Dominion)*"

Empirical results from on-going DR programs in the U.S. suggest levels of 3–9% of potential reduction in peak demand [49]. This includes industrial DR as well as household DR. While these results cannot be directly applied to the residual demand variations with large-scale wind power, it is apparent that DR offers considerable potential for increased flexibility. The GridWise project in the Pacific Northwest of America is an excellent example of a DR demonstration project, where the aim was to demonstrate the coordination of multiple demand-side resources to manage a constrained feeder on the distribution system [50]. It was found that the peak loads on the feeder could be effectively reduced and there was minimal disruption to the consumers involved.

The work in [51] examines the ability of hotel space conditioning load to provide power system contingency response. This involved testing an air-conditioning/heating control technology on the Music Road Hotel in Tennessee, allowing the hotel to provide power system spinning reserve. The testing showed that the hotel load could be temporarily curtailed by 22% to 37% [51] in response to signals from TVA (the electric utility in Tennessee). The response time was reported as faster than conventional generators.

The authors in [52] discuss industrial load's provision of frequency regulation to MISO since it opened its ancillary service market. ERCOT obtains half of its spinning reserve requirement from DR and has for years [53]. VCharge is a small DR aggregator of frequency regulation services [46]. VCharge has aggregated 250 electric thermal storage heaters, both ceramic and hydronic, in 50 houses in Pennsylvania. VCharge operates this collection of devices commercially as a "Virtual Power Plant" that buys energy during cheap hours and provides ancillary services to the grid operator [46]. VCharge [54] has retrofitted existing electric thermal storage heaters with specially designed controls and installed new electric thermal storage heaters for customers on the electric thermal storage tariff or night tariff and is in a position to supply up to 600 kW of balancing services to PJM.

Steffes Corporation design and manufacture electric water heaters and electric thermal storage units. Such electric water heaters demonstrate low-cost water heating using day-ahead locational marginal pricing while responding to the PJM frequency regulation signal [55]. Grid–Interactive Electric Thermal Storage (GETS) dynamically couples consumer usage to real-time grid needs [56]. The Steffes product is also used in a Bonneville Power Association project. For this project, Ecofys and its partners identified and applied responsive thermal end-use technologies that provide DR peak reduction and load shaping, as well as novel balancing services that assist with the integration of variable renewable energy sources such as wind [57].

2) Europe

The Danish system has a high penetration of wind generation. It relies on combined heat and power thermal generators to meet heating requirements [13]. Consequently, many thermal plants are kept online, on very cold windy nights, in order to serve heating needs, even when wind generation could meet a large portion of the demand. As a result, in such situations, wind curtailment is essential. The EcoGrid project [58] is currently running field tests in the island of Bornholm in Denmark. The project includes 1200 households on two different automated response groups, 500 household in manual response group and 200 households in the control group. The project will test a real-time market where balancing market is replaced with a calculated price updated every 5-minutes. Generators and consumers are then let to react to the price.

A collaboration between Glen Dimplex, Scottish and Southern Energy, Intel, Eirgrid, ESB Networks and University College Dublin is presently investigating the potential for DR of smart electric thermal storage loads (space and water heating applications) to provide wind integration related flexibility in Ireland/Northern-Ireland [59] and on the Shetland Islands [60].

'Demand for Wind' is a UK-based research and development project. The concept is to create a demand for wind power by turning on loads when there is a surplus of wind generation [61]. The aim is to assess the ability of DSM to tackle the issue of variability in wind power generation, on both the large scale and the small scale. The project aims, among others, to develop DR/DSM control, monitoring and communication technologies, to replace fossil fuel based water and space heating with electricity from renewables and to develop simulations to assess the market uptake of DSM technology.

IV. DEMAND RESPONSE BARRIERS AND CHALLENGES

The barriers and challenges to widespread DR have been well-documented, for example in [1-4]. The vast majority of independent system operators in the US now facilitate DR/DSM in energy markets, ancillary service markets and capacity markets. In Europe, however, progress has been slower.

Selection of appropriate measurement baselines and verification of the chosen baseline using historical data can be a challenge. Coupled with this are the challenges that DR itself can create, including potential market price suppression (particularly in the reserve/ancillary services markets) and a reduction of capacity factors for peaking plants due to their displacement by DR resources. It is not always possible for DR to simultaneously participate in all markets and exploit all revenue sources. DR is often deployed on a small scale and many revenue sources have minimum size limits. Aggregation would help, but it has been difficult to get actual aggregators to operate in many markets, although there are some examples, mainly in US (e.g. EnerNOC and Comverge).

Anticipating average reduction in loads during peak demand periods can be a challenge. The authors in [5] surveyed 15 DR experiments in which household electricity customers received some form of compensation for reducing demand (including time-of-use pricing and critical-peak pricing). It was found that time-of-use pricing resulted in modest reductions of 3–6% while critical-peak pricing had a much higher reduction effect of 13–20%. Enabling technologies, such as programmable, communicating thermostats and always-on gateway systems that controlled multiple end-uses remotely, increased the reductions considerably for both compensation schemes. Such technologies succeeded in raising the reduction to 21–36% and 27–44%, for time-of-use pricing and critical-peak pricing, respectively.

One particular challenge with household level DR is how to evaluate the actual response. In [6] it is pointed out that aggregating DR from households will include significant uncertainties in terms of actual delivery. These have to be understood and addressed. The measurement sampling rate should match or surpass the market resolution, but most smart meters installed in households so far have a coarse resolution. These meters could access hourly or 10-15 minute markets, but participation in faster timeframe reserves (i.e. timeframes of seconds) would require estimation of response. This is not easy for TSO's to accept, since reliability is critical for power system reserves. If all markets are not accessible, it gets more difficult for DR to overcome the initial investment required.

DR activation at transmission level for overall power system balancing requirements must be co-ordinated with HV/MV and LV network power quality concerns – a severe reduction in load demand could cause temporary voltage fluctuations on a weak network [23].

DR is sometimes banned from providing services it is technically capable of supplying. In Europe a few examples of potentially unnecessary rules hindering the participation of DR resources include:

- A 24/7 resource availability requirement for peak consumption programs (Austria)
- A 16 hour load reduction duration requirement (Slovenia)
- Lack of regulation or applicability of load reduction measurements (Most markets)
- Minimal single bid requirements ranging from 4 MW in Ireland to 25 MW or even 50 MW (France)
- Lack of appropriate base load measurement requirements (Great Britain and others)
- Lack of clear payment and contract structures for demand reductions (Most markets)
- Demand side resources barred from existing capacity markets (Poland, Greece)
- The aggregation of Commercial/Industrial loads is not allowed (Italy)

ACKNOWLEDGEMENT

The authors acknowledge the input of Dr. B. Hasche from 50Hz Transmission System Operator for insights on the German DR and renewables context.

REFERENCES

[1] US Department of Energy, "Benefits of Demand Response and Recommendations for Achieving Them, A Report to United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005 (February 2006). URL 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

[2] J.-H. Kim and A. Shcherbakova, "Common failures of demand response," *Energy*, vol. 36, no. 2, pp. 873–880, Feb. 2011.

[3] J. Torriti, M. G. Hassan, and M. Leach, "Demand response experience in Europe: Policies, programmes and implementation," *Energy*, vol. 35, no. 4, pp. 1575–1583, Apr. 2010.

[4] B. J. Kirby, "Load Response Fundamentally Matches System Reliability Requirements," in *IEEE Power Engineering Society General Meeting,* 2007.

[5] C. De Jonghe, B. F. Hobbs, and R. Belmans, "Optimal Generation Mix With Short-Term Demand Response and Wind Penetration," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 830–839, May 2012.

[6] M. Milligan and B. Kirby, "Utilizing Load Response for Wind and Solar Integration and Power System Reliability," in *WindPower 2010 Dallas, Texas*, 2010, no. July, pp. 1–18.

[7] K. Dietrich, J. M. Latorre, L. Olmos, and A. Ramos, "Demand Response in an Isolated System With High

Wind Integration," *IEEE Transactions on Power Systems.*, vol. 27, no. 1, pp. 20–29, 2012.

[8] A. Keane, A. Tuohy, P. Meibom, E. Denny, D. Flynn, A. Mullane, and M. O'Malley, "Demand side resource operation on the Irish power system with high wind power penetration," *Energy Policy*, vol. 39, no. 5, pp. 2925–2934, May 2011.

[9] J. Ryan, E. Ela, D. Flynn, and M. OMalley, "Variable Generation, Reserves, Flexibility and Policy Interactions," *2014 47th Hawaii Int. Conf. Syst. Sci.*, pp. 2426–2434, Jan. 2014.

[10] G. Strbac, "Demand side management: Benefits and Challenges," *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, Dec. 2008.

[11] J. Cardell and L. Anderson, "The Influence of Demand Resource Response Time in Balancing Wind and Load," *2013 46th Hawaii Int. Conf. Syst. Sci.*, pp. 2364–2370, Jan. 2013.

[12] S. H. Madaeni and R. Sioshansi, "Using Demand Response to Improve the Emission Benefits of Wind," *IEEE Transactions on Power Systems.*, vol. 28, pp. 1385–1394, 2013.

[13] R. Sioshansi, "Evaluating the Impacts of Real-Time Pricing on the Cost and Value of Wind Generation," *IEEE Transactions on Power Systems*, vol. 25, no. 2, pp. 741–748, May 2010.

[14] R. Sioshansi, S. H. Madaeni, and P. Denholm, "A Dynamic Programming Approach to Estimate the Capacity Value of Energy Storage," *Transactions on Power Systems*, pp. 1–9, 2013.

[15] C. De Jonghe, B. F. Hobbs, and R. Belmans, "Value of Demand Response for Wind Integration in Daily Power Generation Scheduling: Unit Commitment Modeling with Price Responsive Load," in *USAEE*, 2011.

[16] H. Qazi & D. Flynn, "Power balance provision through coordinated control of modern storage heater load", in 12th Workshop, London, 2013

[17] H. Qazi & D. Flynn, "Provision of flexibility at high wind penetration levels using modern storage heater load", in IEEE PES General Meeting, Washington, 2014

[18] R. Sioshansi and W. Short, "Evaluating the Impacts of Real-Time Pricing on the Usage of Wind Generation," *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 516–524, May 2009

[19] P. Denholm and R. M. Margolis, "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies," *Energy Policy*, vol. 35, no. 9, pp. 4424–4433, Sep. 2007.

[20] P. Denholm and R. M. Margolis, "Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems," *Energy Policy*, vol. 35, no. 5, pp. 2852–2861, May 2007.

[21] A. S. Kowli and S. P. Meyn, "Supporting Wind Generation Deployment with Demand Response," in *IEEE Power and Energy Society General Meeting, 2011.*

[22] J. A. Short, D. G. Infield, S. Member, and L. L. Freris, "Stabilization of Grid Frequency Through Dynamic Demand Control," *Transactions on Power Systems*, vol. 22, no. 3, pp. 1284–1293, 2007.

[23] Qazi, Burke, Flynn 'Challanges in Utilisation of Demand Side Response for Operating Reserve Provision' IEEE ISGT Conference Istanbul 2014.

[24] D. P. Chassin, P. Du, and J. C. Fuller, "The Potential and Limits of Residential Demand Response Control Strategies," in *IEEE Power and Energy Society General Meeting, 2011.*

[25] Brunninx et al 'Short Term Demand Response of Flexible Electric heating Systems, The Need for Integrated Simulations', KU Leuven working Paper WP EN2013-04.

[26] Bacher, Madsen 'Identifying suyitable Mopdels for the GHeat Dynamics of Buildings', Energy and Buildings 43 (2011) 1511–1522

[27] M. E. H. Dyson, S. D. Borgeson, M. D. Tabone, and D. S. Callaway, "Using smart meter data to estimate demand response potential, with application to solar energy integration," *Energy Policy*, vol. 73, pp. 607–619, Jun. 2014.

[28] J. A. Short, D. G. Infield, S. Member, and L. L. Freris, "Stabilization of Grid Frequency Through Dynamic Demand Control," *Transactions on Power Systems*, vol. 22, no. 3, pp. 1284–1293, 2007.

[29] R. Earle, E. Kahn, and E. Macan, "Measuring the Capacity Impacts of Demand Response," *Electricity Journal.*, vol. 22, no. 6, pp. 47–58, 2009.

[30] D. Huang and R. Billinton, "Impacts of Demand Side Management on Bulk System Reliability Evaluation Considering Load Forecast Uncertainty," in *IEEE Electrical Power and Energy Conference*, 2011, no. 2, pp. 272–277.

[31] S. Mohagheghi, F. Yang, B. Falahati, and S. Member, "Impact of Demand Response on Distribution System Reliability," in *IEEE Power and Energy Society General Meeting, 2011.*

[32] NERC, "Potential Bulk System Reliability Impacts of Distributed Resources." URL: http://www.nerc.com/docs/pc/ivgtf/IVGTF_TF-1-8_Reliability-Impact-Distributed-Resources_Final-Draft_2011.pdf

[33] M. Klobasa, "Analysis of demand response and wind integration in Germany's electricity market," *IET Renewable Power Generation*, vol. 4, no. 1, p. 55, 2010.

[34] J. Kiviluoma and P. Meibom, "Influence of wind power, plug-in electric vehicles, and heat storages on power system investments," *Energy*, vol. 35, no. 3, pp. 1244–1255, Mar. 2010.

[35] J. Kiviluoma, E. Rinne, and N. Helistö, "Economic comparison of technical options to increase power system flexibility," in *11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Farms*.

[36] V. Hamidi, F. Li, and F. Robinson, "Responsive Demand in Networks with High Penetration of Wind Power," in *IEEE/PESTransmission and Distribution Conference and Exposition, 2008.*

[37] J. Ikäheimo, "SGEM project Deliverable D5.1.48: Cost estimates for smart resources," 2013. VTT-R-03309-13

[38] M. Paulus and F. Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany," *Applied Energy*, vol. 88, no. 2, pp. 432–441, Feb. 2011.

[39] N. Prüggler, "Economic potential of demand response at household level—Are Central-European market conditions sufficient?," *Energy Policy*, vol. 60, pp. 487–498, Sep. 2013.

[40] P. Finn, C. Fitzpatrick, M. Leahy, and L. Relihan, "Promotion of Wind Generated Electricity Using Price Responsive Demand Side Management : Price Prediction Analysis for Imperfect Energy Storage," 2010.

[41] Papaefthymiou, Hasche, Nabe 'PotentialofHeatPumpsforDemandSide Management and Wind Power Integration in the German Electricity Market',IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, VOL. 3, NO. 4, OCTOBER 2012

[42] E. Troncoso and M. Newborough, "Electrolysers as a load management mechanism for power systems with wind power and zero-carbon thermal power plant," *Applied Energy*, vol. 87, no. 1, pp. 1–15, Jan. 2010.

[43] I. Stadler, "Power grid balancing of energy systems with high renewable energy penetration by demand response," *Utilities Policy*, vol. 16, no. 2, pp. 90–98, Jun. 2008.

[44] D. J. Olsen, N. Matson, M. D. Sohn, C. Rose, J. Dudley, S. Goli, S. Kiliccote, M. Hummon, D. Palchak, J. Jorgeson, P. Denholm, and S. Ma, "Grid Integration of Aggregated Demand Response , Part 1 : Load Availability Profiles and Constraints for the Western Interconnection," 2013.

[45] M. Hummon, D. Palchak, P. Denholm, J. Jorgenson, D. J. Olsen, S. Kiliccote, N. Matson, M. Sohn, C. Rose, J. Dudley, S. Goli, and O. Ma, "Grid Integration of Aggregated Demand Response , Part 2 : Modeling Demand Response in a Production Cost Model." NREL/TP-6A20-58492. URL: http://www.nrel.gov/docs/fy14osti/58492.pdf

[46] D. Hurley, P. Peterson, and M. Whited, "Demand Response as a Power System Resource," Technical Report 2013.URL: http://www.synapse-energy.com/Downloads/SynapseReport.2013-03.RAP.US-Demand-Response.12-080.pdf

[47] E. Cutter, A. Taylor, F. Kahrl, and C. K. Woo, "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, pp. 77–88.

[48] P. Interconnection, "2012 Economic Demand Response Performance Report : Analysis of Economic DR participation in the PJM wholesale energy market after the Implementation of Order 745," 2013.

[49] P. Cappers, C. Goldman, and D. Kathan, "Demand Response in US Electricity Markets: Empirical Evidence," 2009. LBNL-2124E. URL: http://emp.lbl.gov/publications/demand-response-us-electricity-markets-empirical-evidence

[50] S. Katipamula, D. P. Chassin, D. D. Hatley, R. G. Pratt, and D. J. Hammerstrom, "Transactive Controls : Market-Based GridWise TM Controls for Building Systems," PNNL-15921. 2006.

[51] B. Kirby, M. O'Malley, O. Ma, P. Cappers, D. Corbus, S. Kiliccote, O. Onar, M. Starke, and D. Steinberg, "Load Participation in Ancillary Services," 2011.

[52] D. Todd, M. Caufield, B. Helms, A. P. Generating, B. Kirby, and J. Kueck, *Providing Reliability Services through Demand Response : A Preliminary Evaluation of the Demand Response Capabilities of Alcoa Inc* . 2009. ORNL/TM-2008/233. 2009.

[53] B. Kirby, J. Kueck, T. Laughner, and K. Morris, "Spinning Reserve from Hotel Load Response," *Electricity Journal*, vol. 21, no. 10, pp. 59–66, Dec. 2008.

[54] V-Charge, "Transactive Load Solutions," 2014. [Online]. Available: http://vcharge-energy.com/transactive-load-solutions/. [Accessed: 09-Sep-2014].

[55] J. Mathieu, "Demand Response Today," in *CDC Workshop: "Ancillary services from flexible loads to help the electric grid of the future"*.2013 URL: http://ccc.centers.ufl.edu/sites/default/files/files/DR%20today.pdf

[56] P. Steffes, "Dairyland Power G & T Grid-Interactive Energy Storage Case Study and Lessons Learned Cost Effective Electric Storage Grid-interactive Electric Thermal Storage (GETS) GETS Dynamically couples consumer usage to," 2012. URL: http://www.demandresponsetownmeeting.com/wp-content/uploads/2012/03/1-A-Steffes-Paul-Steffes.pdf

[57] D. Broad, K. Christensen, K. Dragoon, K. Lee, K. Spielman, and S. Parkinson, "Smart End-use Energy Storage and Integration of Renewable Energy," 2012. URL: http://www.ecofys.com/files/files/ecofys_2012_smart-end-use-energy-storage_bpa_project_overview.pdf

[58] Ecogrid - http://www.energinet.dk/EN/FORSKNING/Energinet-dks-forskning-og-udvikling/EcoGrid/Sider/default.aspx

[59] Greenway - http://www.dit.ie/media/update/11-03-2013/130307_dimplex%20quantum%20leads%20Greenway_electric.ie.pdf

[60] Nines - http://www.smartergridsolutions.com/about-us/our-experience/northern-isles-new-energy-solutions.aspx

[61] P. Taylor, H. G. Svendsen, C. Barbier, and C. Welby, "Demand for Wind, Maximising the Value of Wind Power Through Demand-Side Managment," in *CIRED Seminar 2008, SmartGrids for Distribution*, 2008, no. 2, pp. 1–4.