

An Overview of Demand Response: Key-Elements and International Experience

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Abstract

The increasing penetration of renewable energy sources (RES) in power systems intensifies the need of enhancing the flexibility in grid operations in order to accommodate the uncertain power output of the leading RES such as wind and solar generation. Utilities have been recently showing increasing interest in developing Demand Response (DR) programs in order to match generation and demand in a more efficient way. Incentive- and price-based DR programs aim at enabling the demand side in order to achieve a range of operational and economic advantages, towards developing a more sustainable power system structure. The contribution of the presented study is twofold. First, a complete and up-to-date overview of DR enabling technologies, programs and consumer response types is presented. Furthermore, the benefits and the drivers that have motivated the adoption of DR programs, as well as the barriers that may hinder their further development, are thoroughly discussed. Second, the international DR *status quo* is identified by extensively reviewing existing programs in different regions. Finally, conclusions are drawn.

Keywords: Demand response, renewable energy sources, benefits and barriers, enabling technologies, practical evidence.

1. INTRODUCTION

One of the main concerns of the Independent System Operators (ISOs) has been the fact that electric power demand may significantly vary during the day, season and year and the production facilities should be suitably dispatched in all time periods in order to satisfy it. The demand side has been traditionally considered relatively inelastic and therefore, the generation side should be adapted in order to fully supply it. However, a series of drivers such as the Climate Change, the increasing penetration of renewable energy sources (RES) and the consequent increased need for enhancing the flexibility in system operations, the target of improving energy efficiency and the need to defer costly investments have motivated efforts aiming to enable the active participation of the demand side in power system operational procedures.

The activities through which the activation of the demand side is attempted are commonly referred to as demand side management (DSM). The Electric Power Research Institute (EPRI) has defined DSM as follows [1]: “DSM is the planning,

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implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load. Utility programs falling under the umbrella of DSM include load management, new uses, strategic conservation, electrification, customer generation and adjustments in market share". The concept of DSM can be considered mature (especially for industrial consumers) with many efforts to reduce or shift the consumption of end-users in order to reduce the stress on power system assets, especially in critical peak demand periods. Demand side management comprises four actions: energy efficiency, savings, self-production and load management [2].

Among the DSM solutions, load management techniques and especially demand response (DR) strategies are gaining more attention in power system operations recently, driven by the increasing interest in implementing the smart grid concept. DR is defined as "*changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" by the U.S. Department of Energy (DoE) and comprises incentive-based and price-based programs [3]. Facilitated by the advancement in smart grid enabling technologies such as the implementation of Information and Communications Technology (ICT) in the power system, the growing numbers of intelligent energy management systems (EMSs) in end-user premises, smart grid compatible advanced metering infrastructure (AMI), etc., DR strategies have been adopted by ISOs in leading countries around the world.

Apart from technical studies, there is a broad literature of DSM and DR reviews considering different aspects, which can be classified in three main categories: i) a general DSM/DR overview followed by recommendations for future developments, ii) an overview of DSM/DR status focusing on a particular part of the world (i.e., a specific country or region), iii) an overview of DSM/DR for a specific implementation (e.g., specific consumer type response).

In the first category, Albadi and El-Saadany presented a concise review of the DR benefits from the participant, market and reliability perspectives and analysed a DR scheme based on market simulations [4]. Babar et al. [5] provided an overview of the applicability of the agility concept in DR programs, aiming to increase customer satisfaction and promote market responsiveness. O'Connell et al. analysed the benefits (from the operation, planning and economic points of view) and challenges (from the perspective of market regulation, end-user acceptability and business schemes) related to DR, including a broad literature review on DR modelling assumptions without emphasizing on real world examples [6]. Li et al. [7] provided a review study on the potential of different demand side resources, such as controllable loads and electric vehicles, to be engaged in DR activities. Bossmann and Eser [8] focused on the review of studies concerning model-based assessment of DR measures. Siano performed a general survey on smart grids and DR; however, without giving specific importance to neither benefits/barriers nor real-world examples of DR programs [9]. Another general review on DSM considering DR, intelligent

energy systems and smart loads was performed by Palensky and Dietrich [10]. Kotskova et al. performed a review on load management including DR strategies, providing also a small number of real examples [11]. Aghaei and Alizadeh conducted a general analysis of DR strategies, emphasizing on the application of DR in accommodating the varying nature of RES, presenting also a limited number of DR implementation examples [12]. Gelazanskas and Gamage briefly analysed the benefits and the drivers of DSM and proposed a demand control strategy without a further overview of other DSM and DR relevant topics [13]. Wang et al. presented an overview of real-time markets around the world (especially in North America, Australia and Europe), focusing on the technical analysis of DR integration [14]. Hu et al. analysed the existing dynamic pricing programs in the U.S. and Europe, presenting also real examples, program targets, enabling technologies and policy issues; however, incentive-based programs and the analysis of the benefits and challenges were not considered [15]. Shen et al. reviewed the role of regulatory reforms, market structure changes and technological developments to render DR more viable in the electric power system [16]. In a detailed DR review study, Varkadas et al. examined DR types, requirements and enabling technologies, presenting also some real examples around the world, as well as the optimization methods for DR applications with a broad review of relevant literature studies [17]. However, [17] did not provide a discussion on the drivers that promote DR, available DR programs in different regions, as well as the reasons for which DR is not currently evenly developed around the world.

In the second category, Strbac reviewed the benefits and challenges of DSM, specifically for the UK electric power system [18]. Similar to [18], Bradley et al. performed a review-based analysis for the UK in order to evaluate the possible benefits and required costs for wider penetration of DR [19]. Warren considered the UK case from the policy point of view for DSM applications [20]. Ming et al. [21] and Harish and Kumar [22] examined the cases of China and India, respectively, in terms of historical evolution of DSM applications together with future expectations. Dong et al. [23] focused also on the potential of DR in China, analysing regulatory issues and providing information about relevant pilot projects.

In the third category, Gyamfi et al. examined a specific DR application area concerning residential end-users by reviewing the impacts of behavioural changes of different residential end-user profiles on the success of DR strategies [24]. Soares et al. also analysed the residential end-user behaviour focusing particularly on DR using domestic appliances [25]. Muratori et al. considered residential DR from the electricity market point of view [26]. Khan et al. analysed the correlation between the success of DR and the technological advancement in Home EMSs (HEMSs) [27]. Esther and Kumar [28] surveyed architectures, approaches and optimization models for residential DR. Haider et al. [29] also discussed the current status of residential DR and the relevant strategies, as well as the ICT requirements. Merkert et al. examined the challenges and opportunities of applying DSM solutions in industrial end-users supported by a set of real industrial case studies [30]. Finally, Zehir et al. [31] analysed the impacts of volatility related to distributed generation and considered different DR approaches to accommodate it.

The objectives of this study, which also define its main contributions with respect to existing studies, are as follows:

- To constitute a reference point regarding a) the DR enabling control, metering and communication technology, b) different DR and consumer response types, c) the potential benefits of DR, d) the current status of DR development globally, and e) the barriers to the development of DR, by reviewing these aspects in a comprehensive manner,
- To present a remarkable number of real-life application examples covering several countries and regions in order to thoroughly evaluate the global DR *status quo* and to examine in-depth the key-elements that affect the integration of different kinds of DR solutions in regions with different economic, environmental and political conditions.

The remainder of this study is organized as follows: Section 2 provides an overview of DR enabling technologies and DR strategies related to end-user types. Section 3 discusses the benefits and drivers of adopting DR strategies in electric power systems. Section 4 presents a broad analysis of practical evidence related to DR across the world with numerous real examples. Section 5 performs a detailed analysis of the barriers to DR development from different perspectives. The study is concluded with final remarks in Section 6.

2. GENERAL OVERVIEW OF DR

2.1. Overview of enabling technologies

DSM and DR programmes have been practically enabled because of the evolution of the technology required to physically implement them. In this section a discussion on the required metering, control and communication infrastructure is provided.

2.1.1. Metering and control infrastructure

Among the different components of the enabling infrastructure, smart meters and AMI are the vital for implementing DR strategies. Smart meters are new generation electronic meters that have the capability of bi-directional communication between the end-user and the load serving entity (LSE). For DR activities, smart meters can receive signals from the LSE, such as the maximum allowed level of power procurement in a certain period (e.g., to reduce the loading of a local transformer) or price signals determined in a dynamic way. Besides, AMI is a network of millions of smart meters [32]. Smart meter and AMI penetration across the world is increasing rapidly and many pilot projects were implemented in the last decade. A mapping of Smart Metering Projects across the world can be found in [33].

In order to provide automated control for a more effective participation in a DR program, whether it is price- or incentive-based, EMS structures in end-user areas (residential, commercial or industrial buildings, etc.) are also critical components. A common EMS structure receives information signals from the controllable/non-controllable loads of the end-user, including the

state of the appliance, its power consumption, etc. Also, the EMS may receive information regarding the available production from RES or conventional self-production units. Besides, all the signals of the LSE including instructions during DR events, pricing data, etc., are transferred to the EMS through the AMI. By considering all the input information, the EMS decides the optimal operating strategy for the end-user, aiming at satisfying both the requirements of the LSE that calls for DR and the end-user, in terms of not compromising the fulfilment of the service the electricity is used for.

As regards the current state of EMS adoption around the world, major regional differences can be noticed. The U.S. is a leader in the adoption of EMS, and especially in the HEMS market. European utilities are also supporting relevant pilot projects [34]. Nevertheless, one may argue that since benefits for both the consumers and the utilities have been broadly recognized and due to the fact that numerous major companies (including Siemens, Intel, etc.) have already rendered commercially available EMS products [35], their penetration in the short-term future is likely to increase in residential, commercial and industrial areas.

2.1.2. Communication infrastructure

A pivotal requirement for an effective DR implementation is the handling of a significant amount of data transfer. A low-latency, moderate bandwidth communication path between the parties involved (LSEs, end-user EMS, loads to be controlled, etc.) in a DR action is an essential prerequisite to achieve this. Here, latency corresponds to the delay between the time that a request is sent by the procuring party and the time at which the responding party receives the request and therefore, can act accordingly. Moreover, bandwidth corresponds to the data-transfer rate of each enabling device in the communication path [36]. The aforementioned low-latency and moderate bandwidth specifications are significantly important for the effective transfer of DR commands and the rapid implementation of relevant responses to ensure an improved performance of a DR strategy.

Three domains of data communications are considered in the implementation of a DR program: the smart meter domain, the Internet domain and the home area network (HAN). Note that the HAN domain is a general term that may also refer to residential, industrial and commercial end-user premises. The smart meter domain is the AMI structure previously discussed and it consists of a network of a large number of smart meters. The Internet domain (the cloud) that is used as the computing and information management platform by the IT industry is the general public Internet accessed through service providers. The HAN is the gateway to the Internet and smart meter domains for controllable loads, appliances and their interactions with the EMSs within the end-user premises [32], [37]. The EMS receives signals from the LSE through the smart meter domain and implements actions through the HAN. The Internet is the interface through which multiple systems having Internet Protocol (IP) can meet to communicate in order to provide a desired task, e.g., direct load control (DLC) over suitable loads in the end-user premises. There are also some other definitions for communication domains, such as Neighbourhood Area Network (NAN) and

Wide Area Network (WAN) that represent the range of the communication area for the DR enabling communication infrastructure [38].

Many communication mechanisms are suitable in terms of being able to meet the latency and bandwidth criteria in different data communication domains. In general, the aforementioned communication technologies can be categorized as wireless or wired technologies. Wireless communication technologies have the advantage of lower investment costs due to avoiding additional wiring costs. Besides, the flexibility of the end-points is increased because wireless signals can reach areas where physical connection is problematic. However, these technologies are more prone to signal losses during propagation, a fact that limits their effective range. Furthermore, significantly stronger security mechanisms are necessary for wireless technologies in order to avoid unauthorized access. ZigBee, Z-wave, Wi-Fi, Wi-MAX, cognitive radio and recent cellular technologies can be presented as major wireless communication technologies suitable for many communication areas of a DR enabling smart grid operation [39]. On the other hand, wired communication technologies can use the existing power line or an external wiring for signal transmission. Existing wired technologies include power line communication (PLC), Fiber-optics, Ethernet, etc. Whether wired or wireless technologies are employed, the scalability and replicability, availability, reliability and security of the considered solutions should be further analysed for the specific application area in order to ensure a successful DR implementation [40]. A deeper analysis of communication infrastructure technologies and relevant requirements can be found in [38] and [41-43].

2.1.3. Protocols and standards

There are many efforts to standardise DR related smart grid operational aspects across the world. The U.S. National Institute of Standards and Technology (NIST) is forming a regulatory framework in order to create common smart grid interoperability standards by involving stakeholders and partners from the industry, the government, and the academia. In the short-term, the smart grid standard version 1.0 is planned to be announced with the aim to be augmented in versions 2.0, 3.0, and beyond [44]. IEEE has also numerous standards relevant to the smart grid operations available, including a significant number of standards having strong relationship to the DR implementation, especially from the communications point of view [45].

Apart from the NIST and the IEEE driven standardization approaches for DR related smart grid operations, there are also different standardization studies taking place. For example, OpenADR is a DoE approved standard developed by the “DR Research Center” focusing on the communications data model for sending and receiving DR signals from a LSE or an ISO to the customers, and vice-versa [46]. Australia and New Zealand have a common AS/NZS 4755.3.2 standard bearing the title “DR capabilities supporting technologies for electrical products” [47]. There are also many other standardization studies regarding

DR, especially in North America [48] and followed by Australia and Europe, including also the evaluation of DR as a business scheme, a fact which indicates that in the near future more standards will be available.

2.2. Classification of DR

DR programs may be classified either by their type (motivation method and trigger criteria) or according to the way in which the enrolled consumers respond according to the characterization of their load.

2.2.1. Types of DR programs

Based on their type, DR programs may be categorized as incentive-based or price-based DR programs [4]. The main difference between the programs that fall under each of these categories is that in incentive-based programs the customers are offered payments in order to deliver a specific amount of load reduction over a given time period, while in price-based DR programs consumers voluntarily provide load reductions by responding to economic signals.

2.2.1.1. Incentive-based DR

2.2.1.1.1. Direct load control

The target of DLC programs is to engage a large number of small consumers (e.g. residential). Through such programs the utility may directly control a specific type of appliance in the end-user premises. Typical examples are air conditioners (ACs), lighting, water heating, pool pumps, etc. [49]. These programs typically define the number and the duration of interruptions in order not to compromise the end-user comfort level. The participation of the end-user is compensated through discounts or benefits in the electricity bill and potentially by extra payments for being called. These programs are managed by the utility and as a result the end-user is not pre-notified for an interruption. DLC events may be triggered by economic or reliability events.

2.2.1.1.2. Curtailable load

Curtailable load programs are addressed to medium and large consumers. Participants in these programs receive incentives in order to turn off specific loads or even to interrupt their energy usage, responding to calls emitted by the utility. Like in the case of DLC programs, contracts should specify the maximum number and the duration of calls. These programs are mandatory, i.e. customers may face penalties in case they fail to respond to a DR event. Utilities may call the consumer to respond to reliability events; however, load curtailments may also be traded in the market [49, 50].

2.2.1.1.3. Demand side bidding, capacity and ancillary services

“Insert Figure 1 here”

The option of demand side bidding provides the opportunity to consumers to actively participate in the electricity market by submitting load reduction offers. Large customers may participate in the market directly and usually employ sophisticated load management tools and strategies, while relatively small consumers can participate indirectly through third-party aggregators or LSEs [51]. The demand side may also participate in capacity and ancillary services markets, providing a variety of system services in different time scales (regulation, spinning reserve etc.) [52].

A demand side bid may have the form presented in Fig. 1. Similar to the bids that are submitted by generators, the bids from the demand may be single or duplex, simple or complex. A single bid pertains the participation only in one market structure, while a duplex bid refers to a bid that pertains the coupled participation in two different markets (e.g. energy and reserve) [53]. Moreover, the bid may consist of only price-quantity pairs, i.e. simple bid, or it may be a complex bid incorporating technical conditions such as minimum energy consumption (D_{min}), maximum energy consumption (D_{max}), total energy over the considered horizon (e.g. daily), load pickup and drop rates, etc. [54]. The only difference between generation side and demand side bids is that the latter are downward. In Fig. 1 the negative slope, assuming without loss of generality a linear relationship between price and consumption, indicates that the demand would accept to consume energy (D) as long as its bid is less or equal to the market clearing price (p). In case the demand side is eligible to submit a duplex bid, then quantity-price offers for upward (R_u, C_u) and downward (R_d, C_d) reserve should be also provided. It should also be noted that voluntarily providing reserves during emergency situations is also referred to as emergency DR [10].

2.2.1.2. Price-based DR

2.2.1.2.1. Time-of-use tariffs

Electricity end-users that are priced with flat prices are not aware of the varying cost of electricity. Flat rates depict average electricity supplying cost and may remain constant for years. The basic idea behind time-of-use (TOU) pricing is to better reflect the variations of the electricity provision cost with time, in different periods within a day or a season [50]. TOU pricing is a stepped rate structure which intends to reflect prices under average market conditions with respect to the time of the day during which electricity is consumed and does not capture the day-to-day volatility of supply costs. A typical TOU structure includes a peak rate, an off-peak rate and potentially a shoulder-peak rate [49], for time periods defined by the utility.

2.2.1.2.2. Critical peak pricing

Time-of-use tariffs reflect the longer term electricity supply costs associated with using electricity during a specific period of the day. In order to capture the short-term costs of periods which are considered critical for the power system, critical peak pricing (CPP) may be employed. The CPP tariff stands for the superimposition of a time-independent high rate on TOU or flat rates, triggered by system criteria (e.g. unavailability of reserves, extreme weather conditions that cause unexpected variations in demand, etc.). The relevant contracts specify the maximum number of days per year that may be considered critical and the number of periods for which the CPP rate applies. However, the utility communicates a CPP event in a very short notice, from several minutes up to several hours before the CPP rate applies. There are also two variants of CPP, namely the Extreme Day pricing (EDP) and the Extreme Day CPP. Extreme day pricing charges higher prices for electricity but, unlike CPP, once EDP rates are called they remain active for all 24 hours of the “Extreme Day”. Extreme day CPP programs use peak and off-peak rates like in CPP programs, but only on extreme days. For the other days a flat rate applies [4, 49, 55].

2.2.1.2.3. Real-time pricing

Real-time pricing (RTP) is a pricing scheme in which the energy price is updated at a very short notice, typically hourly. Through RTP customers are directly exposed to the variability of the cost in the wholesale power market or to the changes in locational or zonal marginal prices. Currently, there are two noticeable RTP programs engaging residential end-users in the U.S., one by PJM [56] and one by the Midcontinent ISO (MISO) [57]. Both communicate the day-ahead market prices one day before the actual power delivery; however, the way in which they price the consumers differ. In the first program, end-users are priced according to the real-time prices that are settled in the end of an hour in the actual dispatch day and are the averaged 5-minute prices of that hour, while in the second program consumers are directly priced according to the day-ahead prices.

2.2.2. Customer response

2.2.2.1. Industrial Customers

The energy consumption by industrial customers represents a major portion of the total electric energy produced. It has been reported that for many utilities 2-10% of the industrial consumers are responsible for at least 80% of the electricity usage [58]. Paulus and Borggreffe [59] have investigated the potential of DSM in energy-intensive industrial customers in Germany, arguing that the highest economic potential can be found in large-scale processes that rely on a single source to satisfy their energy demand. In Germany the annual electricity demand of the 250 different branches of the industrial sector is 252.6TWh, while the technical potential of the investigated industrial processes for DR (tertiary positive reserves) is 2660 MW. Similarly, the

Swedish Government has provided the energy-intensive companies the opportunity to benefit from reduced taxation on electricity use on the condition that they take energy efficiency measures [60].

The aforementioned facts demonstrate that the industrial sector is suitable for developing DR programs. However, adopting DR programs may be challenging for the industrial firms. For commercial and residential customers, DR entails potential temporary loss of comfort (e.g. by controlling ACs). On the other hand, industrial customers may reduce their demand by on-site generation, energy storage, consumption shifting, non-critical load curtailment and temporary shut-down of several processes. Temporarily interrupting one or more processes may result in significant load reductions. Nevertheless, several constraints such as the criticality of a process, the number of available production lines, the required production target, inventory restrictions, etc., may have longer term impacts on the process line, rendering DR economically inefficient [58]. Due to their technical requirements several processes such as steel production using electric arc furnaces, cement milling and aluminium electrolysis are only suitable for load shedding, while others such as chloralkali electrolysis and mechanical refining of wood pulp can be shifted [59].

To efficiently provide DR services, industrial consumers must be equipped with an automated decision system that considers the technical constraints of the processes and the alternative energy sources available. In [61] Ding et al. have proposed such a system that performs optimal scheduling of the industrial load considering constraints posed by the processes while considering the possibility of self-generation and energy storage. Furthermore, Paterakis et al. [62] have proposed a stochastic optimization model through which large industrial consumers can provide energy and reserve services in the day-ahead market in order to balance the uncertain wind production.

2.2.2.2. Commercial and Other non-Residential Customers

Commercial and other types of non-residential premises can also provide DR for load reduction or ancillary services. AC is the most significant load that can be controlled. In [63] the capability of providing spinning reserve from a hotel was demonstrated. The preliminary tests indicated that apart from the quick response, the load could be curtailed up to 37% depending on the outdoors temperature. Furthermore, large commercial heating-ventilation and air conditioning (HVAC) systems provide easier access to a single, significantly larger demand side resource than aggregating large numbers of smaller residential loads, while automation equipment that is already present in most large commercial buildings may be exploited in order to reduce the infrastructure costs associated with the implementation of DR programs [64]. Moreover, due to the large space that commercial buildings occupy, they present higher thermal inertia, allowing for longer interruptions. Also, HVAC systems employ variable frequency drives (VFD), the speed and power of which can be quickly and continuously adjusted, following the regulation signal provided by the system operator in order to provide regulation reserve [65].

Recently, the idea of energy intelligent buildings that monitor their energy consumption and manage locally available resources as well as the energy procurement from the grid has been introduced [66]. In [67] a control and scheduling architecture for offices was proposed in order to take advantage of RTP DR by controlling a range of loads (e.g. lighting).

2.2.2.3. Residential Customers

Residential customers are suitable for DLC and price-based DR programs. Apart from shifting load manually in response to price signals, residential customers may invest on an automated system, namely a HEMS, which monitors and controls the consumption of several appliances [68]. Typical appliances that can be found in most households and are suitable for being scheduled by the HEMS in response to time-varying prices or to be rendered available for direct control by the utility are: electric water heaters, ACs, refrigerators, washing machines, clothes dryers and dishwashers. The first three loads are thermostatically controllable while the other three when equipped with communication modules are called smart appliances.

There is an abundant literature suggesting models and identifying the potential of the residential sector to participate in DR programs in order to provide various system services such as regulation and spinning reserves. For example, [69] investigates the potential of a household equipped with a HEMS to provide frequency response, [70] examines the potential of load flexibility provided by smart appliances in order to participate in reserve services, [71] employs a model of ACs in order to provide reserves by DLC through an aggregator and, finally, [72] performs a similar analysis for electric water heaters.

2.2.2.4. Electric Vehicles

Currently, the market share of electric vehicles (EVs) is relatively low, limited to a few hundreds of registered cars in most industrialized countries. As a result, the impacts of the EVs on the power system, namely the increase in energy consumption, are not currently evident [73]; however, as the electrification of the transport sector is expected to be intensified in the future, significant challenges to the integration of large EV fleets may occur [74, 75]. In order to facilitate the integration of EVs in the future, two technical measures that belong to the category of DR have been proposed: 1) controlled unidirectional charging, 2) controlled bi-directional charging, more commonly known as vehicle-to-grid (V2G). The foreseen benefits of implementing such techniques are threefold. First, a fleet of EVs may be employed in order to perform peak shaving and valley filling, improving the economic efficiency of the power system [76]. Second, EVs could increase the price elasticity of residential end-users since the EV charging load would render electricity procurement an important cost for the households [73]. Third, fleets of EVs could be used in order to provide balancing services to facilitate the integration of RES [77].

2.2.2.5. Data Centers

Data centers are an emerging type of consumer that in the recent years has known significant growth both in size and energy consumption. For this reason, a 2007 report from the U.S. Environmental Protection Agency has suggested that data centers should adopt DR strategies in order to reduce the strain on the power system [78]. Irwin et al. [79] have identified three main reasons for which data centers are eligible candidate customer types for DR. First, data centers are major energy consumers and therefore have a significant impact on the power system conditions. Second, their task is tolerant of delays and performance degradations, a fact that makes data centers highly price responsive. Third, servers are already equipped with power management mechanisms that are remotely programmable and therefore, the power may be accurately adjusted according to the provided signals. Masanet et al. [80] found that during 2008 the annual energy consumption of the data centers could have been reduced by 80%, while several other studies address the feasibility of DR provision from data centers [81].

Data centers are also considered capable of providing a range of ancillary services [82]. Regulation services are constantly active and data centers could adjust their consumption according to the signals sent by the grid operator every few seconds. Furthermore, by transitioning a number of active servers to the sleep state, data centers may provide short-term operating reserves or emergency DR. After the event, servers are transitioned from sleep mode back to a normal operating state. Data centers typically possess two further assets that increase the value and the flexibility of the provided reserves: backup generators and uninterruptible power sources (UPS). The former may be used in order to provide ancillary services to the grid without interrupting the workload, while the UPS could be used in order to permit longer time response.

3. DR BENEFITS AND DRIVERS

DR has the potential to offer a diverse range of benefits depending on the design and the aim of the specific DR implementation. In this section the benefits of DR are presented and discussed, especially focusing on the possible contribution of DR to the integration of high amounts of intermittent renewable generation into the power system. The benefits for the ISOs, the electricity market and its participants are also identified.

3.1. The role of DR in facilitating the integration of intermittent generation

“Insert Figure 2 here”

Large scale integration of RES in power systems plays a central role in ambitious programs initiated by leading countries around the world, such as the regional greenhouse gas emission control schemes in the U.S. and the 20/20/20 targets in the European Union (EU) [83]. Among the different RES, wind and solar capacity is expected to increase significantly in the future

[84, 85]. In the U.S. wind is expected to grow from 31 TWh in 2008 to 1160 TWh by 2030, which stands for a target of 20% of the total supply, while solar capacity is anticipated to reach 16 GW by 2020 [86]. Similar tendency is noticed in the EU as well. For example, the target for the electricity generation share of the wind in Ireland is set to 40% by 2020 [87]. Despite the potential environmental benefits that arise from the widespread adoption of wind and solar power generation, their highly uncertain nature may jeopardize the security of the power system and pose new technical and economic challenges to ISOs. These challenges primarily stem from the fact that these resources are highly varying with time, their predictability is limited and they are not controllable, i.e. they cannot be modified by instruction in order to economically match the load [87]. For example, in Fig. 2 the total hourly production of wind and solar parks in the island of Crete, Greece, for three consecutive days in April 2012 is presented [88]. As it can be noticed, the wind production ranges between 10 and 125 MW in a time span of less than 24 hours, while it presents significant fluctuations in shorter time frames. On the other hand, despite the fact that the solar production is available only during the day-time, it presents a more stable hourly pattern in this case; however, its intra-hourly behaviour may be significantly variable.

The majority of existing power systems has been designed considering the fluctuations of the demand. Nevertheless, it is questionable whether the grid can serve both varying loads and high amounts of variable generation such as wind and solar. In order to accommodate the additional uncertainty, an increased amount of reserves should be maintained. Especially regulation and load-following needs, both in terms of capacity and ramping capability, are likely to be augmented with the increasing penetration of wind and solar generation.

Generators providing regulation and load-following reserves incur significant costs such as efficiency loss because of ramping, environmental costs due to increased emissions, increased wear and tear and, therefore, increased operating and maintenance costs. Furthermore, in order to provide reserve services, a generator must operate partly-loaded, a fact that entails lost opportunity costs in the energy market [89]. As the share of RES increases, peaking and intermediate (cycling) units are likely to be displaced. In addition to that, several base load plants may need to be operated in a cycling manner, a function for which they are not designed because their operation is subject to long start-up, minimum up, down and decommissioning times. These issues can be resolved by the participation of the demand side in the load following reserves through appropriately designed DR programs. Certain types of loads such as ACs and electric space heaters have the ability to adjust their power to changes in demand instantaneously [90], while the ramp rates of conventional generators are limited. Moreover, it is argued that the ancillary services provided by the demand side may prove more reliable since the reliability of the response of an aggregation of a significant number of loads is greater than the one of a small number of large generators [91].

Another important issue that is primarily linked to the wind generation and can be tackled with the utilization of DR activities is the wind “over-generation” [92]. This problem appears when high wind generation is available during off-peak periods,

during the night or early in the day. For example, in Fig. 2 one may notice high wind generation in the night between April 10 and April 11, 2012. In such cases, due to the fact that most markets consider the wind power generators as must-run, either the output of the conventional generation must be reduced in order to accommodate the wind generation, or the excessive wind energy should be curtailed, an option that may bear high penalties, in order to maintain the balance of the system. The situation escalates when the system comprises relatively inflexible base load generators that are committed to operate near their technical minimum power outputs during such periods. In general, operating generating units at lower output or cycling base load units may compromise the environmental benefits of integrating wind power in the system. Typically, the consumption of fuel and the emissions of generators increase when they operate at a low capacity. Evidently, one solution that DR can offer is the increase in the demand in periods in which there is excessive wind power generation. Loads that can be shifted in such a way that allows the otherwise spilled wind energy to be absorbed include water pumping, irrigation, municipal treatment facilities, and thermal storage in large buildings, industrial electrolysis, aluminium smelting, etc. [93].

O' Connel et al. [6] highlight another consequence of increased RES penetration which the coordinated planning and operation of generation and DR could ease, contributing to substantial welfare gains. Power systems with increased wind penetration tend to depend on the interconnections in order to balance the grid. However, the deployment of DR may enable the economically efficient use of interconnections, since the spatial characteristics of wind may adversely affect the prices of the energy exchange depending on the scarcity of wind power generation, because nearby regions are likely to experience high or low wind power generation simultaneously.

Finally, environmental targets will intensify the electrification of the transportation sector in the future in order to displace the use of petroleum, a fact that presents a significant opportunity for DR activities in favour of a better integration of renewable energy in the power system. Fleets of EVs could act as aggregations of distributed energy storage, while their charging could be controlled. Through the V2G option they could act as an energy buffer to improve the grid regulation and other ancillary services. These issues are thoroughly discussed in [94].

3.2. Benefits for the System

DR is recognized to have potential system-wide benefits. Many utilities, especially in the U.S., are obliged by regulatory or legislative requirements to consider DR in their resource planning [95], while the Energy Efficiency Directive [96] of the EU states that the planning process should consider the peak shaving effect of DR. The traditional approach to network upgrading considers that the demand grows gradually and as a result a portion of the added grid capacity will eventually remain unexploited since the longer term forecasting of the load growth is uncertain and, therefore, network reinforcement tends to be economically inefficient in order to be on the safe-side. In general, the network expansion is planned considering a long technical life-span (several decades), e.g. more than 50 years for Norwegian Transmission System Operators (TSOs) [97].

Typically, new investments are triggered because of an anticipated increase in the load. DR can contribute to a reduced forecasted peak demand, since long-term DR programs will be implicitly taken into account in the peak demand forecasts [98]. Thus, network investments may be postponed. Furthermore, the uncertainty in the load evolution can affect the efficiency of a system reinforcement investment. More specifically, it is possible that the demand for electricity may decline, increasing the idle capacity of the system and, therefore, the operating cost of the network per unit of output [99]. On the other hand, DR programs may preventively contribute to confront an upward deviation of demand [100].

DR programs that aim to enhance the distribution system operation can also bring a series of benefits. Problems related to the voltage magnitude, distribution substation congestion and losses can be mitigated by DR activities at the distribution level. Electrical equipment is designed for optimum operation at the nominal voltage. Any deviation from this can result in decreased efficiency, damage or severely reduced life of the infrastructure [101]. Furthermore, congestion management can reduce the active power losses and improve the overall system reliability [102]. The distributed nature and the spatial diversity of demand can be exploited in order to eliminate congestions and, therefore, reduced loading of transformers and lines can defer or render redundant the need for costly upgrades and allow an increased penetration of distributed generation [6]. Also, a demonstration on the village of Hartley Bay, British Columbia, Canada, rendered evident how DR can be used in order to enhance the economic and supply efficiency of a remote community [103].

Currently, the total capacity of installed generation must be larger than the system maximum demand in order to guarantee the security of supply under contingencies or severe demand variations. Strbac has demonstrated that the frequency of large energy deficits is very rare [18]. DR can be a preferable choice in order to contemplate relatively small energy deficits. A striking example is the crisis in California in June 2000 in which a shortage of 300 MW (around 0.6% of the total system capacity) caused rolling blackouts [101]. As a result, DR may serve as an alternative to the investment in new power plants that would be underutilized in order to provide capacity reserves [50].

DR has another important side advantage to offer to the system, aiding the ISOs to render the power system more environmentally sustainable. Apart from facilitating a better integration of renewable generation in the system, as it was previously discussed, DR may improve the overall energy efficiency and mitigate the reliance on fossil fuels. A recent fact sheet regarding the DR implementation in the MISO [104] has demonstrated that DR programs which cycle residential appliances such as ACs can actually decrease the overall electricity consumption, promoting energy efficiency. Furthermore, the reduced utilization of peaking power plants that are less efficient in order to cover high demand may contribute to the reduction of the carbon footprint of the system. It is characteristically reported that in California the carbon intensity of the power system can be up to 33% higher in peak times in comparison with off-peak times. Finally, considering DR as an equal option when it comes to the system planning, the construction of more conventional power plants may be avoided.

3.3. Benefits for the market and its participants

“Insert Figure 3 here”

It is widely argued that the active participation of demand side resources could improve the performance of electricity markets and bring significant benefits to the consumers.

Regarding the positive effects of DR on electricity markets, three key elements may be identified:

- Lower and more stable electricity prices,
- Control of market power,
- Economic benefits for the consumers.

In order to demonstrate the two first points, without loss of generality the simplified example that is presented in Fig. 3 can be employed, which corresponds to markets in which the uniform spot price of electricity is defined by the intersection of the aggregated supply and demand curves, e.g. Nordpool [105]. The market operator collects the generation and demand side bids and sorts them with respect to their prices. The aggregated supply curve is upward while the aggregated demand curve is downward. Close to the maximum capacity of the system the bids tend to increase exponentially [4]. The fact that the supply curve becomes steeper as the energy quantity increases may be the consequence of the profit maximizing behaviour of the generators or can be attributed to the higher operating costs of peaking units. In such cases, a small reduction in the demand may induce a significant reduction in the market price [98]. The effect of price responsive demand on the market clearing prices was investigated in [106]. A similar analysis is carried out for markets that adopt Locational Marginal Prices (LMP) in [107]. Furthermore, it is interesting to notice that several crises in electricity markets have been linked to the absence of DR programs [108]. For example, it has been reported that a small decrease in the demand of the scale of 5% could have yielded a reduction of 50% in electricity price during the California electricity crisis in 2000 [4]. One of the reasons that lead to the electricity crisis of California is related to the structure of deregulated markets and the fact that generators do not behave as purely competitive firms. As a result, this market design is prone to market manipulation by large generators. Market monitoring is a way to address this issue; however, the economic and technical deficiencies of this approach have led to the enforcement of price caps, which in turn limits the potential of peaking units to recover their investment costs [109]. DR may prove beneficial in reducing both supplier and locational market power, limiting the ability of large producers to manipulate the price of electricity. The market clearing price p_1 is the value at which the marginal revenue of the supply equals the marginal benefit of the demand, thus constituting an equilibrium point (E1). If the demand curve is steep (DC1), i.e. the demand is not price-responsive, then the generation side may attempt to manipulate electricity prices by submitting more costly bids. This implies shifting the initial supply curve (SC1) upwards (SC2) and the new corresponding equilibrium point (E2) corresponds to an increased price p_2 .

However, in case the demand side is price-responsive, then the market leverage is limited, achieving a different equilibrium point (E3) that corresponds to a lower price p_3 . In addition to this, Siano [9] reports several other relevant benefits: the increase in the number of suppliers in the market through the improvement in the market competition, reduced concentration and restriction of collusion. Appropriate price-based DR programs and a sufficient amount of responsive demand may alleviate the need for price caps and stringent market monitoring.

Allowing consumers to respond to dynamic electricity prices has two anticipated effects that are also commonly referred to as “flattening” of the system load profile: peak shaving during high price periods and load shifting to relatively low price periods. In this way, the magnitude of the wholesale and the retail prices can be reduced while the price spikes and the volatility of the spot market can be mitigated [110]. As a result, in the long-run, benefits can also emerge for the consumers that do not participate in DR programs, since the lower wholesale market prices due to sustained DR programs are likely to cause a decrease in the flat retail rates as well [101]. Furthermore, the transition from flat tariffs to time varying prices is thought to increase the consumer and societal welfare [6]. Regarding small customers (e.g. residential), Allcott [111] indicates that the increase in consumer welfare is not significant since the electricity costs represent only a small portion of their overall expenses; however, it results in an increase in the overall social welfare. On the other hand, responding to time varying pricing definitely contributes to the increase in the welfare of larger commercial and industrial consumers [112]. Besides, a study concerning the DR economic welfare analysis in the PJM market has demonstrated a net benefit for the system that exceeds the total annual subsidy payments [113].

4. PRACTICAL EVIDENCE

4.1. North America

As it was reported by the Transparency Market Research, North America was the leading region in the DR capacity market in 2013, accounting for more than 80% of the global market share, followed by Europe and Asia-Pacific [114]. Thus, the analysis of DR examples in North America is significantly useful in order to observe the trends in this leading part of the global smart grid sector.

4.1.1. United States

4.1.1.1. Major States of the U.S.

4.1.1.1.1. California

California is the state with the greatest population in the U.S. reaching nearly 40 million people [115] and therefore, has a considerable potential of DR programs to be developed.

Pacific Gas&Electric Company (PG&E) offers the so-called “SmartAC” program to its commercial and residential customers, targeting at controlling ACs by cycling aggregated AC load during occasional summer peaks caused mainly due to the simultaneous operation of hundreds of thousands of ACs. For commercial customers PG&E ensures that the temperature in the working area will not exceed the nominal temperature setting by more than four degrees, while in case that the AC cycling event happens in an inconvenient time the customer can refuse to respond without facing a penalty. From a technical perspective, PG&E realizes this program by installing thermostats with communication capability that allows remotely raising the temperature setting of the enrolled ACs up to four degrees when necessary. A similar program offered to residential end-users provides 50 \$ for a 6-month participation period and the SmartAC remotely controllable device that directs the AC to run at a lower capacity during energy shortages for free. The AC settings can also be manually restored if the response to a DR event is inconvenient for the end-user. For larger customers, PG&E offers a range of DR programs such as peak day pricing, base interruptible program, demand bidding program, scheduled load reduction program, optional binding mandatory curtailment plan as business programs, aggregator managed portfolio and capacity bidding program as aggregator programs and automated DR incentive and permanent load shift as incentive-based programs. In the Peak Day Pricing Program (PDPD), a discount on regular summer electricity prices is offered in exchange for higher prices during the 9 to 15 Peak Pricing Event Days per year that normally occur during the hottest days of the summer, encouraging energy conservation during these days with higher demand. A surcharge is added to the regular time-of-use rate during the event and a pre-alert is sent to the end-user the day before in order to plan the energy conservation or shifting. A risk-free option is also proposed for the first 12 months providing a credit for the difference, if more is paid during the first year on PDPD. The Base Interruptible Program (BIP) offers an incentive to the end-user to reduce the load demand to or below a pre-selected level (firm service level – FIL). By giving an advanced notification of 30 minutes, an incentive of 8 to 9 \$/kW per month is provided while a monthly incentive payment is also given if no DR events occur. However, a charge of 6 \$/kW is imposed for the extra demand over the pre-selected level if the end-user fails to reduce its load to or below its FIL during an event. The limit of BIP is 10 events per month or 120 hours per year. The Demand Bidding Program (DBP) is a day-ahead program that allows submitting load reduction bids on an hourly basis without imposing financial penalties if the customer fails to meet its committed reduction. DBP ensures a day-ahead notice by 12:00 pm and offers an incentive payment of 0.50 \$/kWh of load reduction, having the minimum requirement of load reduction bids of 10 kW for two consecutive hours. As the PG&E is not obliged to call a DBP event, there is not an incentive given if the end-user enrolled in the DBP is not called within the monthly period and there is no penalty if the end-user fails to reduce the energy during the event periods. The Scheduled Load Reduction Program (SLRP) offers a payment for a load reduction during pre-

selected time periods for customers with a minimum average monthly demand of 100 kW by selecting one to three four-hour time periods between 8 am to 8 pm on one or more weekdays with a committed load reduction of at least 15 percent of the average monthly demand. The load reductions are measured considering a baseline that is calculated by averaging the load demand of the selected time periods in the 10 previous normal operating days. The SLRP offers a payment of 0.10 \$/kWh per month for the actual energy reductions. The Optional Binding Mandatory Curtailment (OBMC) Plan of PG&E concerns customers that can reduce their electric load within 15 minutes after a call by achieving 15 percent load reduction below their established baseline that is calculated as in the SLRP. The benefit of the customer is not a financial. PG&E requests rotating outages from all its customers in tight demand periods, while by enrolling in OBMC the customer is excluded from these rotating outages. The customers are notified via e-mail or text messaging for the load reduction ratio (5 to 15 percent) and the beginning and ending times of the event, including both holidays and weekends. If the customer fails to reduce the load to the specified level in a call, a 6 \$/kWh penalty for each kWh above the power reduction commitment is imposed, while failing to respond to a second call entails the interruption of the participation in the OBMC Plan for five years. Notably, the Automated DR Program (ADRP) provides incentives for customers investing in automatic energy management technologies coupled with DR programs (PDPD, BIP, etc.). Customers participating in the ADRP receive signals from PG&E and are granted with an incentive of 200-400 \$/kW of dispatchable load, and therefore can recover their initial investment in the required infrastructure by a pre-payment of 60 % of the total project cost initially and 40 % after the verification of customer performance in an up-to 12 months period of DR performance evaluation session [116].

San Diego Gas&Electric Company (SDGE) offers a BIP based on monthly bill credits of 12 \$/kW or 2 \$/kW during certain periods of the year for customers with a minimum reduction of 100 kW or 15% of their monthly average peak demand after a notification lead time of 30 minutes, granting also a flat credit per month even if no DR event is activated. There is a penalty of 7.8 \$/kWh or 1.2 \$/kWh (related to the period of the year) in the BIP offered by SDGE for excess energy use above the FIL of the customer. SDGE also offers Capacity Bidding, CPP, Permanent Load Shifting and Summer Saver Programs as well as Technology Incentives [117].

Southern California Edison (SCE) Company offers a more targeted program named “Agricultural and Pumping Interruptible Program” to temporarily suspend electricity from pumping equipment of the agricultural sector end-users during critical demand periods. A control device is installed to the pumping equipment or the meter of the end-user that enables SCE to interrupt the electricity supply temporarily, until the critical demand period ends. Eligible customers should have a measured demand of at least 37 kW or an agricultural load of minimum 50 horsepower. The interruption event is limited to 6 hours per event, while there is a maximum of 25 events or 150 hours of interruption per year. The customer is awarded with 0.01102 \$/kWh as a base in the monthly electricity bill in terms of credit if enrolled in the program even if no event is called. The customer is also

rewarded with additional credits up to 16.27 \$/kWh (in summer average on-peak period) during interruption events. SCE also offers ADRP, Permanent Load Shifting, TOU Base Interruptible Program, Capacity Bidding Program, DBP, Aggregator Managed Portfolio Program, CPP, OBMP, RTP, SLRP, Pumping and Agricultural RTP, as well as a Summer Discount Plan [118].

4.1.1.1.2. Texas

With a population of nearly 27 million [115], Texas is the second most populated State. The Electric Reliability Council of Texas (ERCOT) which is managing the flow of electric power for more than 90% of Texas area, enables the direct engagement of end-users to provide offers into ERCOT markets or to rationally reduce their energy usage by responding to wholesale prices [119]. Currently, Controllable Load Resources are allowed to participate in the Non-Spinning Reserve Service Market after an assessment which qualifies them to be dispatched by the Security Constrained Economic Dispatch. Moreover, a recent pilot project named “Fast-Responding Regulation Service” allows specific fast-acting demand side resources to participate in the Regulation Service Market. Moreover, the Four Coincident Peak (4CP) Load Reduction Program that targets the four 15-minute settlement intervals corresponding to the highest load in each of the four summer months (June, July, August and September) is available for Non-Opt-In Entities in the ERCOT jurisdiction area. For demand side resources, Emergency Response Service program that provides a valuable emergency service during grid stress conditions, such as rolling blackouts caused by several reasons including severe weather conditions, is also available. Transmission and Distribution Service Providers (TDSPs) in the region also provide different load management programs. Finally, Price Responsive DR Products including Block&Index, CPP/Rebates, RTP, TOU Pricing, Other Load Control and Other Voluntary DR Product are employed in the service area of ERCOT [120]. Apart from the DR schemes designed mainly for industrial and commercial end-users, ERCOT is also recommended to provide DR schemes specifically aiming at involving the residential end-users responsible for more than half of the energy usage in ERCOT area during peak summer periods due to AC load [121].

As a TDSP in State of Texas, CPS Energy operates a voluntary load curtailment program designed for commercial and industrial customers by incentivizing them to shed their loads during extreme system conditions, especially during peak summer days. The program focuses especially on weekdays between 3 and 6 pm with a two-hour advanced notification. The willing customers should demonstrate at least 50 kW of curtailable electric load in order to be qualified to enrol in the program [122]. CPS Energy has also a Smart Thermostat program for commercial and residential end-users, in which the control equipment is installed free of cost, while CPS Energy maintains the right to cycle off AC compressors for short periods of time by sending a radio signal to the smart thermostats during peak demand periods. CPS Energy does not provide the end-users with incentives but ensures a reduction in heating/cooling related costs of at least 10% because of the employment of Smart Thermostats [123].

American Electric Power (AEP) Texas offers an Irrigation Load Management Program in collaboration with EnerNOC for the agricultural end-users with electric irrigation pumps of 50 hp or greater, willing to allow their irrigation pumps to be remotely shut down during peak demand periods in return for a financial incentive. This Program covers the time span from 1pm to 7 pm on weekdays with a required duration of 1 to 4 hours per event, following an advanced notification interval of 60 minutes. A maximum of 4 events are allowed per month in this program [124]. AEP Texas also provides Load Management Standard Offer Programs (SOPs) for customers with an installed power of 500 kW or higher, supplying them with incentives for load interruptions on short notice during peak demand periods. There are 5 different options in this program regarding the maximum number and duration of interruptions [125].

Austin Energy Company introduced a “Rush Hour Rewards” pilot program in the summer of 2013, having enrolled approximately two thousand customers in Austin, Texas. The aforementioned program in collaboration with Nest Company, supplied the participating end-users with the purchase amount of smart thermostats together with additional incentives to avoid operating their ACs during “Rush Hours” of energy usage in summer periods. This was realized with remote control of the installed thermostats by increasing the temperature set point [126]. Reliant Energy Company has also a similar DR program [127]. Moreover, Austin Energy is currently running a program called the “Load Cooperative Program” in which the end-users are offered a payment of 1.25 \$/kWh for their curtailed load with a 60-minute notification interval during summer peak periods [128].

CenterPoint Energy Company offers a Commercial Load Management Program to commercial end-users for mandatory load curtailments in summer periods between June 1 and September 30 of each year from 1 pm to 7 pm on weekdays. Participating customer groups are required to provide an aggregated peak demand of 750 kW. Furthermore, each of the enrolled group members should have at least a normal peak demand of 250 kW plus the capability of curtailing at least 100 kW for a maximum of 5 curtailments per year. The enrolled customers are paid up to 35 \$/kW for the verified curtailed load. This means the supply of at least the amount of curtailment agreed in the beginning of the contract year [129].

El Paso Electric Company has a Load Management Program for non-residential customers with a minimum of 100 kW of curtailable power capability upon notice between June 1 and September 30 of each year. The curtailment can last up to 5 consecutive hours per event. Nine forced curtailments or a maximum of 50 hours of interruption per year together with scheduled curtailments are requested by the terms of participation in the program. The customers may gain up to 60 \$/kW for curtailed power during events in the mentioned program [128, 130]. Furthermore, Oncor Company has a similar program called “Commercial Load Management Program” for commercial end-users who can render 100 kW of load available for curtailment [131].

There are also other load management programs for non-residential end-users offered by different service providers [128]. Another interesting example of DR applications in Texas is the “Free Nights or Weekends” program provided by TXU Energy. This program offers customers willing to participate, totally free electricity at night or during the weekends on the condition that they accept significantly higher daytime or weekday rates, which aims to shift more load to off-peak hours. The aforementioned program has engaged more than 100,000 participants [127].

4.1.1.1.3. Florida

With a population of nearly 20 million [115], Florida is also one of the major States. DR programs in Florida are similar to the ones in California and Texas. For instance, Florida Power&Light (FPL) Company has a Commercial Demand Reduction Program which aims to seize direct control of large scale end-users’ total load demand by an installed load control device that sheds the pre-determined loads under a pre-notice by the FPL. For each kW of curtailment during events, FPL provides credits to the end-user together with a flat monthly payment for being enrolled in the program [132]. FPL has also an “On Call Program” for business areas that enables FPL to temporarily turn off ACs (15 to 17.5 minutes per 30-minute period for a maximum 6-hour time period) remotely in critical periods. FPL pays a flat monthly credit even if no DR event is called [133].

Tampa Electric Company (TECO) offers a load management program to control the selected equipment (ACs or any specialized equipment) in the end-user premises. TECO installs a remotely controllable device to shut down the equipment selected by the end-user during critical peak power periods in order to operate cyclic or continuous load management programs. As far as cyclic operation is concerned, the end-user earns 3 \$/kW, while for continuous operation of the curtailment the end-user earns 3.5 \$/kW for the curtailed load during an event [134]. TECO and Progress Energy Company are also offering on-site generation option based programs under two different names: “Standby Generator Program” and “Backup Generator Program”, respectively. Both programs aim at enabling the control of an available on-site generator by a service provider in order to cover a portion of the end-user’s load demand by this generator in order to lower the demand from the grid in peak power periods. Progress Energy also offers a DLC program that enables the service provider to control selected equipment of the customer during critical periods, similar to the program offered by TECO [135].

4.1.1.1.4. New York

New York occupies a smaller geographical area compared to California, Texas and Florida. However, New York accommodates a population of 20 million and therefore is also a major State in terms of population [115].

New York Independent System Operator (NYISO) offers four different DR programs named “Emergency DR Program (EDRP)”, “Special Case Resources (SCR)”, “Day-Ahead DR Program (DADRP)” and “Demand Side Ancillary Services

Program (DSASP)". EDRP and SCR programs offer incentives to industrial and commercial end-users in order to reduce their power in critical periods. DADRP enables end-users to bid their load reductions into day-ahead market which in turn allows NYISO to determine which offers are more economical to pay at the market clearing price. Lastly, DSASP allows retail customers to bid their load curtailment in day-ahead and/or real-time market in terms of operating reserves and regulation service. The market clearing price for reserve and/or regulation is paid for the scheduled load curtailment offers [136].

ConEdison Company offers also different DR programs. Customers enrolled in a 2-hour or less pre-notification program named "Distribution Load Relief Program (DLRP)" receive 6 \$/kW or 15 \$/kW (considering their status) monthly and 1 \$/kWh for the reduced load during an event. As another DR program, the 21-hour pre-notification program "Commercial System Relief Program (CSRP)" offers 10 \$/kW per month and 1 \$/kWh for the reduced load during event. The customers enrolled in either DLRP or CSRP are required to be involved in an one-hour mandatory test every year and they should supply the load reduction for at least 4 hours during actual events from 6 am to 12 am, any day of the week [137].

4.1.1.2. Other States and Territories of the U.S.

There are also many DR programs with similar structure with the ones in California, Texas, Florida and New York, but with different rules and incentives applied in smaller States of the U.S.. For further information on these programs, readers may refer to [138, 139].

4.1.2. Canada

Apart from the U.S., Canada also demonstrates several applied DR programs and strategies. The Independent Electricity System Operator (IESO) of Ontario allows aggregators to manage demand side flexibility in order to maintain the balance of the grid together with the applied price-based grid balancing strategies. The aggregator pre-notifies its facilities to supply the required load reduction in order to ensure the request of the IESO in terms of total load reduction in critical periods [140]. ENBALA Power Networks Company is a leading aggregator that engages hospitals, wastewater treatment centers, universities, cold storage facilities, etc., to ensure the required load reduction in critical conditions. ENBALA aggregates specific loads of different end-user types such as pumps in water/wastewater treatment plants, compressors, evaporators, etc., in refrigerated warehouses, HVAC units including air handling and chiller equipment in hospitals, universities and colleges and commercial buildings through a platform named "GOFlex" [141]. There are many examples of ENBALA applied demand side solutions [142]. One of the most remarkable examples is the enrolment of the McMaster University Campus in Ontario in DR aggregation activities through GOFlex. GOFlex manipulates the temperature settings and therefore, the power usage of five chillers with a

16,000 ton cooling capacity within the HVAC system of the McMaster University Campus. Through a communication panel employed in the end-user premises, the Building Management System (BMS) of the campus receives real-time requests and signals from ENBALA GOFlex platform and accordingly adjusts the aggregated settings of the chillers in order to reduce consumption in critical periods without a noticeable deviation from the normal comfort conditions.

Many other LSEs across Canada offer classical DR programs. Toronto Hydro Corporation as a LSE and Rodan Energy Company as a DRP are such examples [143].

4.1.3. Other North America Countries

Another part of North America that demonstrates demand side participation actions is Mexico, especially with the potential smart grid investments (such as Smart Metering project [144]) in Mexico City directed by Comisión Federal de Electricidad (CFE) of Mexico. Thus, more implementations in terms of DR solutions can be expected from this North American country in the near future.

4.2. South America

4.2.1. Brazil

As the leading country in South America in terms of demand side solutions, Brazil is considered to have a good potential in this area. Brazil has demonstrated better progress in terms of energy efficiency improvement efforts; however, there is also some progress in DR applications that can serve as a basis for more advanced implementations. First of all, apart from the energy efficiency solutions, there are other pilot applications concerning the improvement of smart metering infrastructure in the service regions of different LSEs. For the implementation of DR solutions, AES Eletropaulo Company, which is the major LSE in terms of consumption and revenues in Latin America, has launched a smart grid pilot implementation plan aiming at implementing DR solutions for different end-user types, especially during critical peak periods in order to improve the loading factor of distribution system assets [145]. Furthermore, the Brazilian Electricity Regulatory Agency (ANEEL) has discussed changes in the tariff schemes to motivate price-based DR programs in Brazil [146]. Thus, Brazil could be considered as a good candidate for wider penetration of DR activities in the future within the Latin America region [147].

4.2.2. Other South America Countries

Apart from Brazil, there are some applications at an initial stage in Colombia and Chile regarding demand side applications and with additional regulations these markets also seem promising grounds for DR solutions [148].

4.3. Europe

The North American DR market is a leader in what regards the development and deployment of DR programs. Nevertheless, Europe holds the second place and the EU countries have recently demonstrated interest in occupying a wider portion of the DR market in the future.

4.3.1. United Kingdom

According to an interview published in the Reuters [149], “Longer term, UK's aggressive renewable energy goals, fairly large size, and deregulated market structure make it one of the best potential regions for DR”, which clearly indicates the potential of the UK taking a leading role across Europe in DR applications.

KiWi Power Company offers a Demand Reduction Strategy (DRS) that presents similarities to existing programs in the U.S., aiming to temporarily reduce the consumption of certain end-user systems such as HVAC, lighting, etc. through the installation of a remotely controlled equipment in peak energy demand periods. KiWi Power offers different control systems for different end-user types in order to provide reductions when necessary. For example, airport chillers and air handling units (AHUs) in areas such as baggage halls and concourse areas are offered to be turned off while generators serving runway lights or communal retail areas can be also utilized during DR events. Besides, in the case of supermarkets, temporary reductions in the lighting level of retail areas or turning off refrigeration plant compressors in freezers are candidate strategies. Different solutions are also presented for hospitals, steel manufacturing, telecommunications, logistics, etc. [150].

The UK Power Networks Company has developed programs to enable the demand side participation in the UK. In the “Low Carbon London” project, the UK Power Networks Company works with Flexitricity, EDF Energy and EnerNOC companies as aggregator partners to enrol industrial and commercial participants for a DR trial in London aiming at inducing load reductions in the MW level during estimated high demand periods. Moreover, in the “Smarter Network Storage” project, storage systems in the MW/MWh level installed in the distribution system will play an active role in residential or commercial DR. Storage units will compensate the deficiency in production during peak periods in order to cover the demand, while they will absorb excess energy when renewable power plants provide high generation (in sunny or windy days) or in times in which the demand is low. The Smarter Network Storage units are planned to be integrated in the National Grid's ancillary services market for providing Frequency Response and Short-Term Operating Reserve [151].

There are also different demonstration trials of DR solutions in the UK, which are expected to play an important role in the DR market both in Europe and globally in the future.

4.3.2. Belgium

Belgium is a country which has also practically involved DR solutions in the daily electricity market operations. ELIA, as Belgium's electricity TSO, accepts DR capacity to compensate mismatches between production and peak power demand [152], in which industrial customers are given vital importance as also supported by the Federation of Belgian Industrial Energy Consumers (FEBELIEC) [153]. DR aggregator companies, such as REstore [154] and Energy Pool [155], provide the required capacities to ELIA under stress conditions, to which hundreds of MWs have already been contracted in order to add flexibility to ELIA's operation in the Belgium's power system.

4.3.3. Other European Countries

Many other countries of the EU are also progressing towards implementing DR actions into their electric power system structures. Apart from the UK and Belgium, France, Finland and Norway, Sweden, the Netherlands, and Germany have also improved their progress in the development of DR activities. A recent report on DR in Europe discusses the status of DR in such countries thoroughly and thus readers are addressed to [156] for further information.

4.4. Oceania

4.4.1. Australia

In Australia many efforts take place in terms of developing different DR schemes. The LSEs have announced many short-term targets regarding the application of DR strategies. Following the announcement of new obligations for LSEs to publish "Demand Side Engagement Strategies", enabling the participation of demand side resources in the market by the Australian Energy Market Commission (AEMC) in 2012 [157], the number of DR strategies offered by several LSEs has significantly increased. These strategies are firstly implemented in pilot projects. Several successful strategies are already applied in a larger scale while many are still in a trial phase. The Ausgrid Company regularly announces the possible DR strategies and the relevant pilot [158]. One of these possible DR strategies under trial is "Dynamic Peak Rebate Trial" for non-residential medium to large scale customers, which is basically similar to many different existing DR programs around the world, incentivizing customers to reduce their consumption during peak periods, approximately 20-30 hours during the summer (from December to February for Australia). In the first trial in the summer of 2013, 5 demand reduction events were requested from February to March 2013 resulting in an average reduction of 2500 kVA [159]. A similar test was also conducted in the same period by AusNet Services Company for commercial and industrial customers in order to acquire insights into the effectiveness of different DR strategies, through which the company also aims to evaluate and then potentially actualize strategies such as embedded generation, mobile

generation, energy storage, tariff and incentive-based DR strategies [160, 161]. The Demand Side Engagement Strategy Report of a joint program by CitiPower Company and Powercor Company considering different DR options was also announced in [162].

Among the currently applied strategies, Endeavour Energy presented the “Energy Savers Program” for large consumers in Arndell Park and Rooty Hill areas. Even more noticeable are the “CoolSaver”, “PeakSaver” and “PoolSaver” DR programs for residential end-users. “CoolSaver” program is based on mounting the AC of the residential end-user with a remotely controllable device that will automatically adjust the power of the AC during summer periods for a maximum of 6 days, between 2 pm and 7 pm, when there is a critical grid power peak due to very high temperatures. The enrolled customer is promised not to feel discomfort but is not paid per event neither per reduction. On the contrary, the customer is paid a flat 60 \$/year and also 100 \$ worth free AC service as a Sign-Up bonus for the program. “PeakSaver” is a DR program in which Endeavour Energy pre-notifies enrolled end-users via SMS, e-mail or recorded voice messages for demand reduction events during the Australian summer period and by reducing energy consumption through actions such as turning off unnecessary lights and appliances and postponing cloth or dish washing during the event. This program rewards the end-user with 1.50 \$/kWh of saved energy with respect to the customer’s baseline. Finally, “PoolSaver” program requests from the end-users to allow the company to install a new circuit to the power supply of the customer pool pump, which allows it to work in a pre-determined mode during specific off-peak hours. There is no payment for energy curtailment but the company argues that operating the pool pump in off-peak hours will save more than 40% of the pool pump energy consumption cost. Apart from this, the enrolled customers are rewarded with a gift card [163].

Energex Company offers a program named “PeakSmart AC” to end-users who are willing to replace their old ACs with new PeakSmart capable ACs which are remotely controllable via a signal receiver. The implementation of the new PeakSmart program enrolls ACs and determines the rewards according to their cooling capacity. Customers possessing ACs with a cooling capacity of less than 4 kW receive 150 \$, between 4-10 kW receive 250 \$, while for more than 10 kW the payment reaches 500 \$. Furthermore, households and businesses can get separate rewards for up to 5 AC unit replacements. The PeakSmart ACs are controlled by the LSE in case of critical summer demand during high temperature days (a few days per year) by slightly changing the AC setting without affecting the end-user comfort significantly. There are also two programs named “Pool Rewards” and “Hot Water Rewards”, for end-users that are willing to enrol their pool pumps and hot water systems, respectively, to a specific tariff. Furthermore, Energex offers rewards for business centers willing to install BMS or to increase the efficiency of specific systems [164].

SA Power Networks deploys pilot projects on direct AC load control for residential areas (involving around 1,000 volunteering households) by switching off AC compressors but not their fans in order to maintain comfort levels [165]. Pre-

notification based residential DR programs are also employed by the United Energy Distribution Company for 4,500 households in Melbourne for a maximum of 4 events per summer and a reward of up to 25\$ per 3-hour event [166]. Western Power Company has also performed trials on direct AC load control, named as “Air Conditioned Trial (ACT)” through the Perth Solar City Program of Australian Government, in which ACT AC compressors were cycled via wireless communication while AC fans continued running to maintain a sufficient end-user comfort level [167].

Several smaller scale implementations of different DR strategies which are not mentioned here have also taken place in Australia. Relevant information and annual reports by LSEs in Australia can be found in the official website of the Australian Energy Regulator (AER) [168].

4.4.2. Other Oceania Countries

Among other countries in the continent, only New Zealand shows a rather remarkable progress regarding DR programs. Transpower Company runs a program for commercial buildings (office buildings, hospitals, data centers, etc.) with standby generators which are requested to be operated in order to reduce the power drawn from the grid in critical peak periods. Besides, Transpower is currently launching new DR programs for the Agricultural sector [169]. EnerNOC, through the “DemandSMART” program, enrolls interruptible commercial and industrial end-user loads into the Instantaneous Reserves (IR) market. The program limits are 30 min per event for a maximum of 6 events per year in the North Island, while 2 events per year are allowed in the South Island. The targeted loads include refrigeration compressors and fans in cold storage/food facilities, pumps with storage and aerators in water treatment facilities, refiners, chippers and fans in pulp, paper, board and wood processing facilities, electric furnaces and smelters in manufacturing facilities, and finally HVAC systems in data centers and large buildings [170]. There are also different solutions presented by LSEs, DRPs and technological companies in New Zealand [171].

4.5. Asia

Asian countries do not generally have an active DR market. However, several pilot projects are in preparation or evaluation phase, especially in the Asia-Pacific region.

4.5.1. Singapore

Singapore is one of the leading countries in Asia in terms of DR applications. The Energy Market Authority (EMA) of Singapore has already introduced DR programs to enhance the competition in the National Electricity Market of Singapore (NEMS), in which consumers can participate directly or through retailers or DR aggregators. All customers that can offer at

least 0.1 MW of reduction for half an hour can participate. The consumers participating in the program share one-third of the savings obtained by the reduction in electricity prices as incentive payments, up to 4,500 \$/MWh that is the cap of wholesale electrical prices. The enrolled consumers can provide temporarily the required reduction by switching off non-critical equipment, reducing HVAC or pumping system power or even using on-site back-up generators for short periods [172].

The Diamond Energy Company has been the pioneering actor in DR applications in the Singaporean market, having applied load interruption programs to confront abnormal events such as unexpected peak demand or forced outages of power generation [173]. The CPvT Energy Company is also a retailer registered with EMA and participates in the load interruption program [174]. There are also other market participants in the DR market of Singapore, which is currently the most promising for future developments amongst the Asian countries.

4.5.2. Japan, South Korea and China

Japan, South Korea and China are also countries that are expected to develop DR programs in order to induce more active demand side participation in the future. Kyocera, IBM Japan and Tokyu Community have started an Automatic DR Management System pilot project in Japan. In the mentioned project the automatic DR system is planned to send a power-saving request (DR signal) to consumers under system stress conditions, or even to control the end-user Energy Managements Systems (EMSs) if necessary [175]. Comverge, OpenADR Alliance and Fujitsu have also initiated pilot DR projects in Japan [176, 177], which aim at providing a considerable DR sector in Japan that has suffered from intense energy requirements during high emergency conditions, especially after the Fukushima nuclear incident. OpenADR (Open Automated DR) Alliance, being a non-profit corporation created to foster the development, adoption and compliance of the OpenADR smart grid standard, has also taken significant steps towards developing DR applications in South Korea in collaboration with local authorities and associations [177].

In China, a collaborative pilot project between the Natural Resources Defence Council, Shanghai Electric Power, NARI Group and the State Grid Corporation of China and Honeywell as an international partner started in Shanghai in 2014 and is the first official DR demonstration project in China. The mentioned pilot project has contracted 33 commercial and public buildings, 31 steel, chemical and automotive industrial customers, which present an aggregated capacity of 100 MW available to be curtailed with a considerable payment per unit of curtailed load. The project is in place, demonstrating the economic and technical sides of DR strategies for different consumer types [178].

4.5.3. Other Asian Countries

Some other DR activities also take place in the wider Asian continent, being mostly in the pilot stage. CLP Power Company in Hong Kong announced an Automatic DR pilot project in which existing BMS facilities in commercial and industrial customers will be integrated with the Automatic DR concept that will also enable CLP to curtail some loads directly during emergency conditions [179].

Noticeably, a small country in the Far East Asia, Bangladesh, currently employs demand side actions mostly by advertisements rather than incentive-based programs. The Bangladesh Power Development Board (BPDB) that is the major regulatory entity in Bangladesh power system has established motivational advertisement based programs to enhance the awareness of the end-users. BDBP has started campaigns through electronic and print mass media to request end-users to be more rational and economical in electricity use during peak hours; for example, by switching off unnecessary loads at residential end-user premises or by shifting irrigation load to off-peak hours. It was estimated that with the aid of the campaign around 400 MW of irrigation load was shifted to off-peak hours in the last years. Besides, industries operating with two shifts are requested to interrupt their operation during peak hours. An interesting piece of evidence from BDBP is that it monitors the closing time of shops and obliges them to close at 8 pm, an action that contributes to load shifting from peak to off-peak hours by 350 MW and reduces the load shedding necessity [180].

There are also some early-stage studies on DR implementations in some other countries such as India, which could be developed in the future, depending on the policies of the regional governments.

At this point, it should be noted that no remarkable DR activity has been noticed in the Middle-East and thus no information exists about countries in this region.

4.6. Africa

The African continent is hosting different nations that present significant differences in life quality among the population. A very small portion of the population has relatively high income while many others do not even have access to electricity. Thus, DR programs in Africa are limited; yet, there are some remarkable examples. Eskom Company in South Africa offers different DR programs especially to its large customers. The “Standby Generator Program” requests the enrolled customers to supply all their load demand by own on-site generators (minimum 1,000 kW) up to 2 hours during any requested day and for up to 100 events per year. The control of the generator is not in the responsibility of Eskom. Eskom pre-notifies (from 3 pm of the previous day to 30 min prior to an event) for the DR event period and the end-user is not enabled to use grid power in the mentioned period. The end-user is paid a rate for the self-generated power based on the curtailed grid power. Another program offered by Eskom is “Supplemental DR Compensation Programme” for industrial and commercial customers which can reduce

their consumption by 500 kW or 10% of the average MW of their load demand (whichever is greater) during pre-specified critical periods announced by Eskom. The limits are 1 to 2 hour reductions on a scheduled day for up to 150 events per year with a pre-notification from 3 pm of the previous day to 30 min prior the event with a payment for each kWh of energy curtailed by the customer [181]. Eskom also started pilot projects for residential load management based DR programs. More than 10,000 geyser relays have been installed in residential end-user premises to shed appliances remotely during a critical peak power period with a credit based compensation for the customer [182]. There are also many consulting and technical companies in South Africa supporting DR implementations and improvements regionally (e.g. Enerweb Company [183]). The DR market is growing in Africa with new pilot studies across the continent, especially in the most developed countries. A more complete analysis of the DR status in Africa can be found in [184].

5. BARRIERS TO THE DEVELOPMENT OF DR

The potential benefits of DR and the intensive research recently have been the drivers for initiating and developing DR programs around the world. However, one may notice considerably asymmetric progress in enabling the active participation of demand in the power system procedures between different regions. This situation is related to a series of challenges and barriers that limit the active participation of demand in electricity markets. In this section the challenges towards the adoption of DR, as well as the barriers that are present in different regions are critically compiled and discussed. The challenges and barriers are classified in six distinct, yet intersecting, categories.

5.1. Barriers associated with the regulatory framework

The first obstacle towards the integration of DR resources in the electricity markets structures is the absence of rules that implicitly consider their participation in the provision of different services, or the presence of rules that limit their potential.

Power system service definitions or security of supply standards refer to the way that an ISO, a reliability organization or a balancing authority define the services that are required in order to maintain the secure operation of the power system. These technical definitions directly define which resources are eligible to provide a given service. These definitions may explicitly exclude or effectively limit the participation of demand side resources in ancillary services markets. In the U.S. the North American Electric Reliability Corporation (NERC) has provided definitions that are functionally based and technology neutral in order to include DR participation. However, several regional reliability organizations in the U.S. such as the Western Electricity Coordinating Council (WECC) do not currently allow the provision of reserves from DR resources [185]. Furthermore, ISO New England does not allow DR resources to participate in the regulation markets [186]. It is to be noted that although most regional reliability council definitions comply with NERC's standard, there are several issues that could be

viewed as important challenges yet to be overcome, such as issues of fair treatment of DR in comparison with generation when it comes to the qualification of capabilities in resource adequacy planning such as in MISO [187].

Despite the fact that in the U.S. these issues have been long recognized and are being addressed, the situation in Europe is different. The EU policies have generally been more focused on energy efficiency and DSM, rather than DR. Evidently, until recently, EU was more interested in climate change actions, promoting energy efficiency and renewable energy growth and did not perceive DR as a key solution to address its environmental objectives [188]. With the Third Energy Package and especially with the Energy Efficiency Directive (EED) the European Commission has demonstrated strong interest in DR. The main driver seems to be the fact that DR may play an effective role in supporting higher penetration levels of the intermittent renewable generation [189] and therefore has the potential of becoming a catalyst in achieving the EU's 2030 and 2050 energy policy and decarbonisation targets [190]. Article 15.4 of the EED explicitly states that DR participation in balancing and reserve markets and ancillary services procurement should be promoted, while Article 15.8 states that national energy regulatory authorities should encourage DR resources to participate alongside supply in wholesale and retail markets and guarantee that DR is treated in a non-discriminatory manner, on the basis of its technical capabilities [96]. Although the phrasing of the EED could be viewed as progressive and direct, the implementation of DR across Europe is not homogenous. This is due to two reasons: firstly, the directives of the EU have to be adjusted to national level, considering the particularities and the constraints of each system, that is a task that will definitely need time, and secondly, the EU does not have an adequate system in place to monitor the market [188]. Currently, fewer than 5 out of the EU 27 Member States have created regulatory and contractual structures that support DR. France and the UK are the only countries with developed DR programs, while Finland, Belgium, Austria, Ireland and Germany are undergoing fundamental regulatory reviews; however, they are still in the formative stage of this process. The rest of the Member States follow national regulations that prohibit consumer participation in balancing, reserve and energy markets, as opposed to the countenance of the EED. The Third Energy Package has also set common rules for the organization of the energy markets in Europe in order to facilitate the completion of the Internal Energy Market [191]. In this context, the absence of homogenous DR products in different European countries could potentially constitute a barrier for DR. For example, capacity mechanisms are considered an attractive market opportunity for DR resources and countries such as France, Italy and the UK are currently developing their own national implementations [192]. Different motivations and priorities could raise conflicts and confusion in contrast with the harmonization targets at European level [193] and as a result the development of DR could be hindered.

5.2. Barriers associated with the market entry criteria

Historically, the qualifications regarding the entrance of new market participants into various types of markets (energy, reserve and ancillary services markets) have been developed considering that the sole resources of the system are large centralized generators, which present similar operational characteristics. As a result, the relevant rules are not in position to reflect the diverse technical and qualitative characteristics of other resources such as DR and as a result the market structures cannot integrate such resources without a revision of the existing market entrance criteria. The following issues associated with the requirements that a resource should satisfy in order to participate into several markets, if not addressed, may constitute a direct practical barrier to the development of DR:

- Minimum resource bid size,
- Possibility of aggregation of multiple small consumers and geographic boundaries of aggregation,
- Bid direction,
- Number of call events (e.g. on a weekly, yearly basis),
- Load recovery period,
- Response time,
- Duration of response,
- Fixed trading charges, membership and entrance fees.

Traditional generators have relatively large capacities (tenths of MWs) and as a result the minimum resource bids that have been set in order to participate in several market structures are high in comparison with the individual consumption of the majority of the loads, explicitly disqualifying DR to participate in these markets. This barrier has been recognized by many ISOs and efforts have been made in order to relax this prerequisite. For example, the ERCOT and PJM have set the minimum bid size to 0.1 MW, while the requirement in MISO is 1 MW [186]. In contrast with the U.S. markets, in Europe this issue is yet to be addressed. Several countries have decreased the minimum size that qualifies the participation of a resource in a variety of services. Finland provides a good example of a DR friendly country. The minimum bid size in order to participate in normal operation reserve program is 0.1 MW while in order to participate in the frequency controlled disturbance program the minimum bid size is 1 MW. Similarly, in Italy the resource must render available at least 1 MW in order to be eligible. In the Netherlands and in the UK the minimum allowed resource capacity is 4 MW (regulation, reserves) and 3 MW (short-term operating reserve-STOR), respectively. In order to evaluate whether the minimum resource capacity size constitutes a barrier, the characteristics of the system loads should be taken into account. For example, in the Canary and Baleares Islands the minimum required reduction potential is 0.8 MW; however, the fact that an insular power system structure differs from the mainland grids should be taken

into account during the evaluation. In contrast with these relatively positive developments in some countries, in Denmark and Norway, participation in tertiary reserves requires a capacity of at least 10 MW since the instructions are manual (the participants are notified by telephone). One could argue that this barrier will not be radically addressed in the near future as regards the majority of European countries since the entry criteria have been only recently revised (2014) [156].

Another important factor to consider together with the high minimum capacity requirements is whether the market rules allow the aggregation of multiple small consumers and to what geographical extent the aggregations are possible. In several markets, aggregation is not legal (e.g. ERCOT, MISO, Austria, Spain) or it is legal but not practically feasible due to other legislation issues (e.g. in Denmark). Furthermore, restricting the geographical extent of the aggregation can further bound the capability of aggregators to participate in markets because of not meeting the minimum capacity requirements. The combination of high capacity requirements and the unavailability of aggregation options exclude residential, commercial and small industrial consumers and limit the DR provision option only to large industrial consumers, such as in Denmark and the UK [194, 195].

Several market structures require that the bids are symmetric. This means that resources should provide equal capacity to change in both directions that in the case of DR would mean that the loads should be equally able to decrease and increase their consumption. This is a requirement that directly restricts the pool of eligible DR resources since only a few types of load would be equally flexible in both directions. Examples of markets that require symmetric regulation capacity offers are MISO, PJM while in Denmark, for this reason DR is not allowed to participate in secondary reserves. In Switzerland tertiary control allows asymmetric bids while secondary reserves require symmetric capacity. The German market allows asymmetric bids but consumers cannot practically participate in reserves because negative deviations (load increase) bear significant penalties.

Other service attributes such as the number of call events, time between two calls, response time and duration of response can potentially hinder the deployment of DR resources. The primary aim of demand is not to provide flexibility to the power system but to serve the specific needs of the end-user. Furthermore, the existing emergency DR programs strictly limit the number and the duration of DR calls per year since the deployment of such resources entails interruption of service for the consumers. In order not to demotivate the consumer participation, utilities have been conservative with the utilization of DR calls. For example, in 2007, California ISO (CAISO) has issued DR calls spanning less than 1% of the year, while only in less than 60% of the highest load periods DR calls were issued. Most markets require the resource to maintain its response from 4 to 12 hours (e.g. Austria and Germany, respectively) during a call. There are also examples of markets that require permanent availability of regulating resources such as the Swiss market, which is a barrier for most consumers to provide DR except for the case of a few large industrial consumers. Nevertheless, it is generally reported that reserves are not typically required for more than 1-2 hours. This is aligned with the requirement of STOR service in the UK in which a call must have duration of 2 hours. However, even in this case commercial consumers are practically excluded [193]. The majority of existing market structures allows the

participation of these resources either through direct bidding or through bilateral contracts in the day-ahead market. This fact implies that the planning of the use of such resources should be performed hours ahead of the real-time operation of the system. As a result, the use of such resources is limited to emergency situations that can be predicted by the ISO the day before the actual operation of the power system, while several calls for DR prove to be unnecessary in the real-time. Day-ahead market decisions are connected with high uncertainty and ineffective scheduling of DR calls impairs the forecast error as regards the generation and load response in comparison with dispatch decisions that are made closer to real-time. This situation reduces the competitiveness of demand side resources in comparison with flexible generation resources (such as open cycle gas turbines - OCGT plants) that have the ability of fast start-up and ramping, despite the fact that several load types are capable of adjusting their demand instantaneously, and therefore limits their value for the ISO. Furthermore, the need for advanced notification for DR calls hampers the participation of demand side resources in contingency reserve markets that require short-term response, typically between 10 and 30 minutes, an interval which is shorter than the minimum notification time for DR. ERCOT is one of the few examples of markets that allow the efficient participation of load in reserves [196], together with the recently revised market rules in Norway that require activation of reserves in 15 minutes.

Finally, the entrance fees for aggregators or DR providers are generally considered to be reasonable, and thus they do not constitute a direct barrier. For example, in Finland the aggregators have to pay €200 per month to the TSO, while they have to guarantee a bank deposit in order to reduce the risk of bankruptcy [156].

In order to effectively revise these rules, the ISOs should firstly realize a fundamental difference between the impacts of large centralized generation and highly dispersed DR resources on the reliability of the power system, in case that the resource fails to respond to an instruction. Currently, the ISOs require stringent monitoring of the response of both generation side and demand side resources. However, as it was demonstrated in [197], this last requirement may not be necessary for the case of DR since the aggregation of small-scale consumers (e.g. residential) statistically presents a more reliable response in comparison with a large generator. Furthermore, according to [198] several DR resources may have faster response than generators, be more resilient to rapid changes in consumption than generators are to changes in production (cycling) and do not suffer from increased losses such as generators when operating partially loaded. Given these favourable capabilities of DR, not revising the existing market entry criteria in order to reflect the diverse technical capabilities of loads constitutes a severe underutilization of available system resources.

5.3. Barriers associated with market roles and interaction implications

Competition in electricity markets has been promoted in the past decades. Unbundling within electricity markets refers to the separation of electricity generation, transmission, distribution and retail sales that have been vertically integrated structures. The

rationale behind unbundling is the promotion of competition by guaranteeing access to the power system for all participants on a non-discriminatory basis. Unbundling can be realized in terms of accounting, legislative framework and ownership rights [199]. The liberalized environment has enabled several entities in electricity markets that have different roles, responsibilities and objectives.

This situation may impose barriers towards the uptake of DR, especially because of the contrasting views and the absence of an aligned position as regards the use of flexibility between TSOs and DSOs. The majority of DR resources are connected in the distribution system and as a result the collaboration between TSOs and DSOs is important in order to exploit DR. However, issues regarding the purpose of DR deployment may complicate the development of DR programs. For instance, TSOs would view the flexibility provided by DR as a means of balancing the system, while DSOs would use it in order to mitigate local congestions. This implies that coordination between these entities should be developed in order to design different DR products that would transparently and legally allow the utilization of DR in the system and market operations [190].

Another important issue is that despite the unbundling process, in many regions TSOs and DSOs are still regulated entities, responsible for the technical management of the system and as such, the only entities permitted to intervene in investment decisions, excluding the participation of private initiatives. However, the investments of a TSO/DSO are limited by the allowed remuneration that in general limits the expenses on R&D, having a negative effect on the development of new technologies, especially in Europe [200].

The effective business/market scheme under which the demand side would participate in electricity markets is yet debatable and remains in the forefront of the barriers to the uptake of DR. Three main business models can be identified: direct contracts with the TSO, aggregation of small consumptions and real time response of demand to market prices. There are several challenges associated with each of these demand participation options. First, the direct contracts with the TSO allow only the participation of a few capable large industrial consumers that are able to meet the market entry qualifications as it was previously discussed. Second, aggregating demand may compromise the fundamental benefits of dynamic pricing tariff schemes, such as RTP, which is the pricing of the end-user with the market price. The reason for this is that an aggregator has to bid in the market and fulfil its obligations through its portfolio. In order to achieve its targets, this kind of entity could alter the prices in order to reflect not the market prices but the requirements of the market as regards the behaviour of the aggregator [201]. Given that aggregation is an option that would allow the participation of smaller consumers (residential, commercial) in the market, unclear definition of the role and the responsibilities of an aggregator constitutes a barrier to be addressed. Besides, aggregation of consumers is currently illegal or practically infeasible in several markets. Third, the response of demand to real-time market prices [202] raises concerns regarding the demand and price volatility. This is the result of the asymmetry of information, i.e. the time span between the communication of the price and the response of the load and as a result the ISO

should perform a prediction. Generally, flexible consumers tend not to contribute to the mitigation of volatility since they can achieve their economic targets, in contrast with relatively inflexible consumers that would have incentive to inform the ISO about their intended consumption pattern. To deal with this issue, appropriate control regulations should be developed in order to define the interaction between demand and the market in order to reduce the volatility of demand and price; however, this would deteriorate the economic efficiency [203].

Finally, it is important to highlight several implications that emerge due to the individual objectives of the different market participants as regards the integration of DR resources into the market [18]. The TSOs and the DSOs will utilize this flexibility in order to facilitate the satisfaction of operational constraints at critical moments. A competitive retailer will use DR in order to reduce the risk of being exposed to high prices in the spot market [204]. On the other hand, commercial aggregators will focus on maximizing their profits, thus expressing their preference to a specific market, a fact that is likely to prohibit the participation of DR resources in other markets such as in France. The absence of a coordinative framework could provoke competitiveness over the utilization of DR. For example, the behaviour of responsive consumers may benefit also consumers that are not flexible by inducing lower electricity rates, implying transfer of wealth from the generation side to the demand side [113]. It is evident that within the liberalized market context, each individual entity would more likely aim at utilizing the flexibility of DR for its own benefit that is not necessarily aligned with the maximization of the social benefit (improved reliability, economic efficiency, no comfort loss for consumers etc.). The diverse and conflicting views for DR are the source of a series of further challenges such as difficulties in perceiving DR as a crucial system resource, justifying and allocating the requirement investment costs and finally engaging consumers. These issues are covered in the following sub-section.

5.4. Barriers associated with DR as a system resource

There is also a category of barriers that is related to the effects of the widespread integration of DR resources in the electricity markets and power systems. These challenges may be compelling since generator shareholders would oppose to the introduction of such resources and the ISOs would perceive DR as a complicating factor for the system operation rather than a beneficial addition to the system.

The most promising application of DR is the balancing of the fluctuations that come from the high penetration levels of intermittent renewable generation. The response characteristics and the availability of several DR resources qualify them for such utilization. However, significant response of the load would probably limit the capacity factors of peaking and intermediate generators that are currently responsible for regulation, load following and ramping. This situation would be favourable for the economic efficiency of the system since the services from these units are expensive and base units operate more efficiently at constant output. However, the revenues of these generators would significantly decrease and therefore it would be harder for

their owners to recover their investments, leading to a potential decommissioning of such power plants. This outcome would not be viewed positively by the ISO since several ancillary services (e.g. voltage support, system restoration) cannot be provided by loads [196]. Furthermore, these units would be required in order to meet unsatisfied fluctuations that DR fails to mitigate. The drop in reserve market clearing prices is another potential outcome that would not be viewed positively by the existing stakeholders. Some types of DR have little or no opportunity cost to provide certain types of reserves. Thus, the entry of a large amount of low cost resources would potentially cause a decrease in the clearing price of these services that are an important source of income for flexible generators in several regions [205].

From the point of view of the ISOs there are three major concerns regarding the introduction of DR in their operational practice. The first is the justification of DR as a valuable system addition in comparison with other technologies. Strbac [18] argues that the value of DR lies both in system operation and system development. The key towards assessing the value of DR is the operational status of the system. In a system that is stressed, i.e. the system's loading is close to its maximum capacity, the value of DR could be high. Another factor that determines the value of the addition of DR resources is the flexibility of the existing generation mix. It is more likely that DR will have greater value in systems with significant penetration of non-dispatchable renewable generation and relatively inflexible base load generation. Furthermore, even in such cases the DR based solutions are not always competitive in comparison with traditional approaches such as the OCGT units that are technically proven and significantly flexible generation side resources.

The economic compensation of DR participation in the energy market is the second issue to be addressed by the ISOs. This discussion is controversial in most markets around the world [196]. One argument is that DR providers should be compensated at the full market price, similarly to the generators, since the two services are identical, which is the case in ISO New England (ISO-NE) and NYISO. However, the decision not to purchase energy is not the same as physically supplying energy. The loads participating in wholesale markets would receive dual benefits, being paid at the market price for their service and achieving retail bill savings because of the reduced consumption. In order to promote a more efficient DR compensation from the point of view of the ISO, in MISO and PJM the DR is compensated at the full market price minus the retail rate [187]. On the other hand, DR providers argue that DR creates positive externalities such as economic and environmental benefits, and thus they should be granted payments higher than the market prices. The CAISO [206] identifies the problem of the compensation of DR as one of the main barriers as well. Insufficient compensation of DR may limit its investment recovery capability and thus demotivate its development, while excessive subsidies may jeopardize the economic stability of the market.

The third challenge for the ISOs is the lack of suitable and transparent tools in order to evaluate, measure and verify the demand reductions [15]. The European Network of TSOs for Electricity (ENTSO-E) recognizes that inefficient data handling in European electricity markets is a hindrance that may limit the growth of DR [190]. Currently, stakeholders have limited access

to data that prevents them from fulfilling their role, while rendering difficult the coordination and the verification of the realization of DR. Furthermore, the existing forecasting and planning methodologies are not adequate to investigate the capability of DR to serve as an alternative to conventional system expansion approaches [207]. The absence of standard methodologies to study the cost-effectiveness of DR hinders the decisions to perform investments. There are also two problems in identifying the size of DR resources. First, it is difficult to evaluate the number of customers that are willing to be involved in a DR program and therefore its potential capacity [208]. Second, there is not a standard way to determine the customer consumption baselines in order to accurately depict the normal consumption of a customer. A flawed methodology bears the risk of consumers gaming with their baselines in order to get paid without providing real load reductions and would render the deployment of DR resources economically unreliable [187].

5.5. Barriers associated with infrastructure and relevant investment costs

The key technologies for the implementation of DR have already been developed. However, the current levels of penetration of control, metering and communication technologies in the power systems should be increased in order to enable widespread DR activities [18].

A range of DR activities may require a small number of limited duration interruptions and could be performed manually (e.g. light dimming, equipment shut down, etc.). Nevertheless, participation of demand in ancillary services would require more frequent and much shorter interruptions. Control and automation technologies must be adopted by the consumers to provide such services, especially regulation. This implies that consumers, with the potential of being subsidized by a utility, would have to uptake such investments that bear operating and maintenance costs. Furthermore, metering equipment that allows real-time data transmission should be placed in order to comply with service verification requirements and this constitutes another significant economic burden since telemetry equipment has costs that tend to increase with the required speed of response [185].

Stakeholders in MISO [187] and CAISO [206] have raised concerns regarding the costs, especially to install equipment in order to comply with the telemetry requirements of the available DR programs that have been characterized as unreasonable. For example, Alcoa, a metal industry that participates as a DR resource in MISO region has reported a total cost for the telemetry infrastructure, the EMS, the bidding interface and the database system of \$750,000. It is evident that such costs are bearable only for large industrial consumers, explicitly excluding smaller resources from the participation in DR activities. Similarly, the commercial sector perceives the capital costs of manual and automatic DR as prohibitive in order to participate in DR programs [209]. Finally, the increased cost of residential EMSs is a barrier to the development of residential DR [35], while the limited savings from consuming energy in low price periods would not meet the investment costs. Currently, automated residential DR

is viable only for longer term home owners who have the income to support such an investment, unlike low income social groups and tenants living in rented residences [210].

5.6. Barriers associated with electricity end-users

When it comes to DR the greatest challenge is related to the successful engagement of customers in DR programs. Despite the fact that in the U.S. DR has been developing for more than a decade, only 23% of customers were enrolled in available DR programs in 2012 [211]. Evidently, lack of customer interest and support is a definite factor limiting the development of DR [212]. There is a series of reasons for which the engagement of consumers is an impediment towards the evolution of DR programs.

The first challenge is that unlike the generation side, the electricity consumers do not necessarily follow an economically rational behaviour and, therefore, their response cannot be predicted using conventional economic models. The majority of electricity consumers view energy as a good rather than a commodity and as a result minimizing their electricity bill by responding to price signals or raising revenue by participating in other types of DR programs may not be their primary concern. O'Connell et al. [6] have compiled the main results of studies regarding residential customers enrolled in TOU and RTP programs that demonstrate evidence for the lack of economic rationality and the need to develop more advanced economic models in order to predict the response of the consumers considering factors such as the effect of weather on consumption and the asymmetry between information and response. There are also several limitations as regards the non-residential customers. The basic challenge for this sector is that loss of comfort because of consumption limiting or interruption may negatively affect their primary intentions. For example, according to a field test in the U.K., hotels are likely to provide a considerable short-term response through managing the AC unit load; however, the duration of this response is limited by the thermal comfort of hotel guests. Also, shopping centers theoretically present comparable DR potential, but perceive the loss of comfort linked with DR as a negative factor for the commercial gain [193]. Another factor that renders commercial customers reluctant to enrol in DR programs is the relatively short warning period that does not allow for efficient decision making to take place [209]. Finally, in many regions, especially in Europe, the majority of end-users are accustomed with a uniform price of electricity and therefore the awareness about the volatile cost of electricity is limited. As a result, exposing them to dynamic electricity prices raises concerns about the value of postponing the usage of electricity in contrast with the immediate satisfaction of their needs as a result of consuming electricity [204].

The second challenge is related to the contract design. Different consumers should be offered appropriate contracts, tailored to their consumption profiles. Without appropriate and transparent information, consumers could be confused with too many unclear offers, complex contract handling and the multiple parties involved. The consumer acceptance could be raised in the

presence of a single billing scheme in which the retail supplier, network charges and DR payments are all included in the same bill [190]. As a result, absence of tools and mechanisms such as price comparison tools and standardization of contract design may pose difficulties to the end-users deliberately choosing the most suitable contract for them [213].

Issues regarding the deployment of smart meters and consumer protection relate further the end-users to the challenges that need to be overcome in order to facilitate the development of DR programs. Currently there exists a broad legal framework on privacy and data security at the EU and international level regarding data processing for billing purposes. However, DR is not specifically covered by this legal framework, since it would require a significant increase in processing frequency and data granularity. The EU is currently promoting the active deployment of smart meters because of the perception that it constitutes the core element towards transparency, yet fixed tariff and several varying pricing schemes such as TOU pricing do not require two-way communication [204]. Overall, the low physical security of the meters and control equipment, the prospect of using the internet for communication and services and the increased number of intervening parties should be covered by clear privacy laws. The absence of a common framework fosters an instable regulatory environment for investors and confines consumers' acceptance [191].

6. Conclusions

The current advancements in metering, communication and control infrastructure allows for the development of DR programs targeting at different types of customers through appropriate incentives. Engaging consumers in order to shift, forego energy during periods of system stress can prove beneficial in many aspects. Mostly, DR is likely to prove an important resource in order to enhance the flexibility of power systems in order to accommodate increasing amounts of intermittent renewable generation. The thorough review of existing DR programs around the world demonstrated a highly asymmetrical development between different regions. The U.S. is evidently leading in the adoption of DR, offering diverse programs in order to exploit the response from various types of consumers. Europe and Oceania are also taking important steps towards engaging demand side resources in the system practices. It is interesting to notice that despite the lack of homogeneity, efforts to develop DR programs are pursued globally, clearly indicating that utilities are starting to perceive DR as a useful rather than a complicating factor. Given that the required infrastructure to implement DR programs targeting at any customer type is nowadays available, in order to further promote the activation of the demand side a series of barriers, mainly regulatory and economic, are yet to be addressed.

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Figure Captions

- Fig. 1. Example of demand side bidding.
- Fig. 2. Photovoltaic and wind power production in the island of Crete (10/4/2012-12/04/2012) [88].
- Fig. 3. An illustration of the effect of responsive demand in electricity markets.

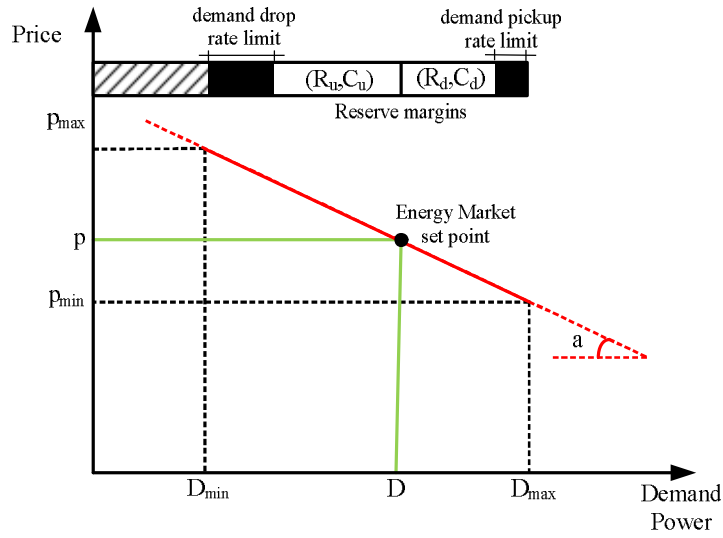


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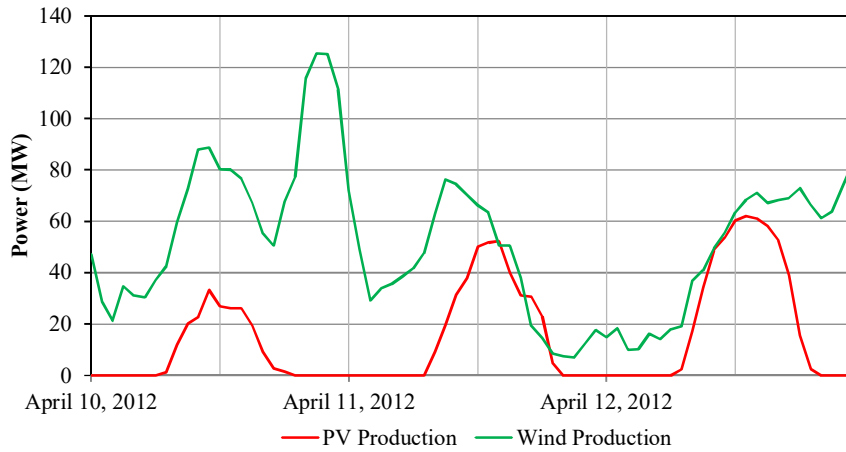


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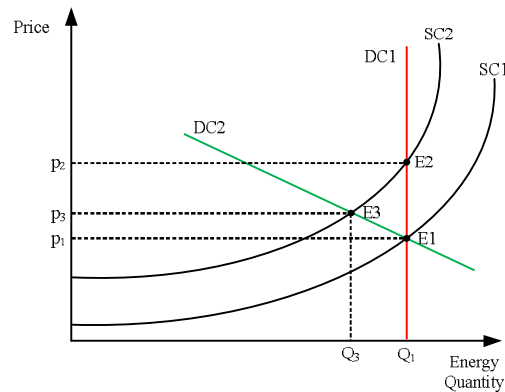


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