energies

Review

A Review and Analysis of Trends Related to Demand Response

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Abstract: This paper provides a review and analysis of trends related to demand response (DR). The authors have considered six different topics for the analysis of DR trends: Users, Network Services, Markets, Complementary Programs and Distributed Energy Resources (DER). A brief summary of the consulted articles is included and the behavior of the different DR trend-related topics is shown up to the year 2017 and their projections for 2020. As a result, the characterization of the main DR topics is obtained as well as its current and future trends. Based on the results of the study, it is concluded that the topic of complementary programs is a trendsetter for current trends and it is expected that there is a future change of focus towards the users and new services.

Keywords: aggregator; demand response; distributed energy resources; energy markets and services

1. Introduction

The development of the electric energy's chain of supply has evolved, moving from a differentiated analysis to an integral one of the generation, transmission and distribution phases and the final use. Future development trends of the electric network regarding planning and operation must consider the synergy existing between each phase of the energy chain [1,2]. In this sense, it has played an important role in the analysis of management consumption and energy self-supply and it has had an impact on the possibilities of the user of participating in the entire supply chain.

Figure 1 shows the worldwide energy consumption trend between 1965 and 2035. It is evidenced that for diverse energy sources there is a high consumption of limited and non-renewable energy resources (oil, carbon and gas), which determine the production of capital goods (competitiveness).

In the Kyoto protocol in 1985, the conference of Copenhagen in 2009 and the Paris Conference on Climate Change [3], it has been proposed to save energy from the rationalization of the consumption. This can be achieved through alternatives that combine new distributed generation technologies with demand response programs, where the management of resources is the main component encompassed within the framework of development perspectives.

Demand response (DR) can be defined as the changes that users make in their electric energy use compared to their usual consumption pattern, as a response to the electricity prices or the payment of incentives that induce low consumption on highly-priced timeslots set by the market or even to maintain a certain stability in the network [4]. DR encompasses a set of strategies that influence the energy consumption of the users participating in an electricity market through both pricing and incentives [5].

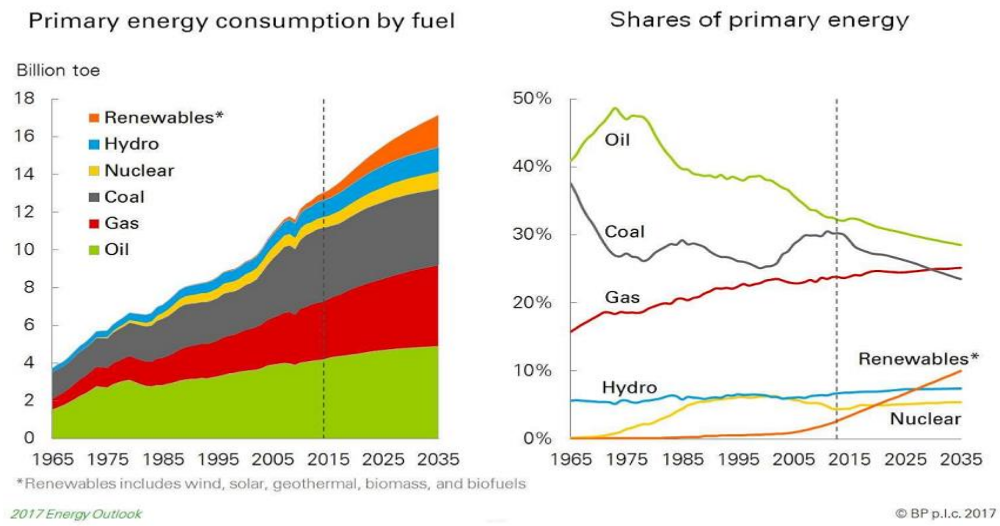

Figure 1. Trends in worldwide energy consumption from 1965 to 2035. Source: https://www.ogj.com/articles/2017/01/bp-energy-outlook-global-energy-demand-to-grow-30-to-2035.html.

The expansion of DR programs is a developing trend for the future of electric networks according to the International Energy Agency (IEA). The response to the user's energy demand is a key factor in the global reduction of the consumption. It is stated that in rational and efficient consumption scenarios the world's primary energy demand in 2035 could be reduced to half of the budgeted share [6]. The possibility for users to control their consumption in real time and make decisions referring to energy management, i.e., acquire energy from different companies or participate in DR mechanisms based on supply per fee where users acquire energy from the distributors by paying integral fees that included a fixed quota determined by the contracted power and a variable amount related to the consumption which is published in official bulletins of the State and periodically updated. Users can also adopt other DR mechanisms, based on incentives that use time as a basis. Some variables related to this strategy are Time of Use, Price in real time and Critical Price in Peak Hours. Some incentive-based mechanisms include direct control of the load, Interruptible load services, Programs of voluntary disconnection of the load, DR economic programs, emergency programs and auxiliary service programs [7].

This decision-making process on behalf of the users is typically allowed in liberalized energy markets of Europe and USA [8]; However, some regulated markets also allow it [9]. In the research field, some authors tackle DR from the remuneration, complementary programs and inclusion of Distributed Energy Resources (DER) [10]. In [11] the analysis focuses on the economic trends of DR programs while [12–14], focus on the planning of networks based on the DR resources. Finally, authors such as [12,15,16] work on DR programs in smart grids.

The demand response can be framed within a wider development line in networks called Demand-side Management (DSM). DSM can be interpreted as a series of measures to improve the overall energy on the consumer side. Some of these measures include improving energy efficiency through the use of better materials and technologies for the energy's end-use, designing smart energy fees with incentives for certain consumption habits, and the implementation of complex real-time control systems that involve distributed energy resources [17].

This article is organized as follows: in the first section, the introduction gives an overview of energy consumption from 1935 to 2035 and justifies the rise of DR and the management of energy resources in general as a development perspective for electrical networks. The second section shows the subjects taking into consideration in the analysis of DR trends such as: Remuneration, Users, Energy Markets, Complementary programs and Distributed energy resources. The third section discusses the behavior of different topics related to the analysis of DR over the last years, in terms of the developed research. A forecast on the future evolution of those topics is also detailed. In the fourth section, the topics for DR analysis are studied as well as their foreseeable trends. Finally, a set of conclusions is given on the development trends influenced by DR from a planning and an operational standpoint considering both existing and future networks.

2. DR Topics

The following topics were analyzed: Remuneration, Users, Services, Markets, Complementary programs and Distributed energy resources.

2.1. Remuneration

It represents the way in which the power disconnection on the user side is remunerated. It can be price-based, incentive-based or hybrid. DR mechanisms imply a response from the users regarding how to use an energy resources and its cost. In a price-based DR program, users reduce their consumption by reacting to the price dynamics imposed by the network operator or the formally established energy market. Incentive-based DR programs suppose that users are individually or collectively committed to reduce their consumption during a certain period of time in terms of the requirements that an operator may have or the economic transactions settled in the market. In hybrid DR variants, price-based and incentive-based mechanisms are partially combined. Table 1 gathers the most representative work on the types of remuneration highlighting their differentiating elements.

Table 1. DR programs in terms of the remuneration method.

Remuneration	References	Differentiating Factor of the Reviewed Work
Price-based	[18]	It uses multi-agent modeling and optimization algorithms under DR programs for real time prices.
	[19]	A coordination strategy is proposed between a micro-network and a price-based demand response program to adjust loads
	[20]	Bidirectional smart measuring devices are used.
	[21]	A dynamic price scheme is proposed for electricity in a smart network, by analyzing the behavior and the possible demand response of the consumer.
	[22]	A real time pricing model is presented that promotes the selection of electricity fees based on the risk that customers are willing to assume.
Incentive-based	[23]	A priority-based programming strategy for the loads to be disconnected is detailed.
	[24]	The dynamic adjustment of the offered prices is analyzed to reduce the demand and maximize its performance within T days.
	[25]	The uncertainty of the demand in the network planning is modeled and includes the integral control of the load disconnection in search of the minimum cost.
	[23]	A fuzzy-based dynamic incentive scheme is proposed for residential clients that effectively incorporate the program.
	[26]	The authors promote the participation of smart homes with the help of a controller capable of managing the electrical installation and restructuring the demand profile by changing the operation of the flexible loads.
	[27]	The authors estimate the incentives to motivate clients to participate in automatic DR programs with the purpose of compensating imbalances between offer and demand.
	[28]	A DR program is shown from the economic point of view based on optimal incentives.
Hybrid	[29,30]	Users change their consumption in response to a price signal and a dispatchable power that can commute during high demand periods. The uncertainty is evaluated in the participation.
	[18]	It defines the options based on prices and incentives in order to identify which is most favorable to the massive entry of electric vehicles at the moment of their recharge.

Focusing on Table 1, it is determined that price-based DR and DR mechanisms imply a user response in regards to using the energy resource and its cost. In a price-based DR program, users reduce their consumption as a response to the dynamics of prices imposed by the network operator or the energy market. In these types of pricing DR programs, two main variations are defined: One based on Time of Use (ToU) [31,32], and another one called real time price dynamics [33–35]. Comparative studies can be found on the Time of Use and real time pricing plans using a testing system that relates the generation cost of electricity with the fixation of fixed fees [36]. Price-based DR programs can be encompassed in the integral management of buildings to achieve a higher efficiency in the energy resources [37,38]. To implement price-based DR programs, the network's infrastructure must be optimized through the control of small loads such as home appliances when detecting an increase in prices supported in the communications system which are owned by the communication company [30,39].

For incentive-based DR programs, users behave individual or collectively to reduce their consumption during a certain amount of time in terms of the requirements of the operator or economic transactions that are agreed upon in a market. In these programs, users enter bidding processes by demand reduction as proposed by [40] In most cases, the government must promote the initial stages of these programs [41], the incentives and their permanent restructuration according to the types of users, their power levels and the participation times [42] which will be reflected in changes on the demand curve [43]. Therefore, the coordination of the load disconnection is carried out through an integrator agent supported on optimization algorithms set to reduce load peaks [44]. There are hybrid options that combine price-based and incentive-based programs such as the one presented by [45], where service curves lead consumers to observe control signals offering a distributed, scalable and robust DR mechanism that is always supported on the current legal framework [46].

2.2. Users

The classification of the users that participate in a DR program can be established based on criteria that go from average energy consumption levels up to socio-economic categories. In this work, the classification has been made according to the user profiles, dividing them into: residential users whose consumption obeys to the energy needs of a home, commercial users for which the use of electrical energy depends on the sale and purchase of services and industrial users where the use of energy is tied to the conversion of commodities into capital goods. The revision shows how the change in habits is promoted in the use of home appliances [47–49], while keeping comfortable conditions at home [50]. In concrete cases, some loads such as air conditioned are intervened [51,52] or refrigeration as seen in commercial scenarios [53,54]. Table 2 shows highlighted aspects of developments oriented to the mentioned types of users.

Table 2. DR programs for different types of users.

User	References	Highlighted Aspects
Residential	[55]	A modeling scheme in DR is proposed using a game theory algorithm where participating users offer their disconnection.
	[56]	Markov chains are modeled to define the probability of participation of residential users in DR
	[57]	Smart home appliances that could commute to photovoltaic systems in response to dynamic variations of the energy prices.
	[58]	Big Data techniques are used to gather and process the information from multiple residential users to include them in DR programs.
	[59]	An application of artificial neural networks is proposed in the management of domestic energy considering the events of DR.
	[60]	Smart networks are shown as a facilitator in the electricity market with major benefits for residential consumers and the environment.
	[61]	The acceptability of DR fees was assessed for residential users including the time of use that offers benefits to the networks.
	[62]	An algorithm is proposed so that the management system keeps the consumption of the client energy under the defined limit.
	[63]	DR programs were applied for rural residential users in Japan. The maximum demands of the aggregator were modeled using the log-normal and Weibull distributions to obtain the interruption probability in the maximum value of any system's capacity.
	[64]	A fuzzy subtractive grouping method is presented applied to a contingence scenario given by the characterization of the behavior to the demand response for domestic users.
	[65]	It states a maximization method of the social welfare of the clients, before and after changing the real time pricing policy.

Table 2. *Cont.*

User	References	Highlighted Aspects
Commercial	[66]	Commercial buildings are good candidates to offer a flexible demand due to their volume and stability in loads. They are used to study the correlation of factors that affect the DR prediction.
	[67]	The prediction of the energy consumption is achieved through the integration of building modeling approaches in an estimation scheme of Demand Response.
	[68]	The authors analyze the implementation of demand response measures using a simulation model called EnergyPlus in a building.
	[69]	The authors analyze the combined strategy of self-generation and reduction of the real demand using demand response techniques for buildings in the commercial sector in Thailand.
	[70]	A cooperative scheme of DR is proposed for buildings with an anticipated pricing policy
Industrial	[71]	The authors implement a DR program to generate a load reduction in smelting companies. They also promote the use of electricity outside the peak residential timeslots with fees that double per kWh.

2.3. Services

DR derives services that improve the demand curve [69,72], applying the scheme in high consumption hours. Tension stability is also sought [73]. With the entry of new actors in the network such as DG and electric vehicles, DR offers services to the network steered to stability [74,75]. DR seeks to offer services by flattening the demand curve which translates into partially reducing the electric energy consumption during peak or valley timeslots; the peak reduction strategy intends to apply DR only during high consumption hours and the peak transfer method forces the user to shift his consumption to timeslots where it is normally not so high. Table 3 shows the most representative services of the network based on DR programs.

Table 3. Services offered by DR programs.

Service	References	Relevant Aspects
Voltage profile	[76]	A unified control algorithm is described to offer auxiliary services to the network through a control of the energy resources. The control mechanism can conduct voltage within acceptable limits achieving an improvement in the voltage profiles.
Electric vehicle recharge	[75]	Electric vehicles are charged by controlling loads that can be interrupted in the high-priced energy moments.
	[77]	A management scheme of home energy is developed to control the charge and discharge of electric vehicles.
	[18]	The authors propose a model to charge electric vehicles and various control algorithms incorporated into a multi-agent system to assess the impact of the penetration of electric vehicles in the power system.
System reliability	[78]	Manageable loads are used as a reserve to guarantee the supply to non-unpluggable loads of the network.
Distributed generation support	[79]	DR is a back-up to the stochasticity of the energy from renewable sources and the system's reliability is thus improved.
	[13]	The research focuses in the design of a demand model that can be adapted to access a variety of energy from the generation equipment, based on the analysis and recollection of DR mechanisms.
Photovoltaic energy quality	[80]	An approach is proposed to implement the optimal demand response in the residential sector to eliminate voltage peaks, especially during the high photovoltaic generation.
Stability in the network	[14]	The smart network recurs to the demand management which includes all the activities directed towards the modification of the voltage profile.
Peak reduction	[16]	The demand response method is optimized through the differential evolution algorithm to apply it in peak hours.
Voltage stability	[81]	DR is used to analyze the voltage security for emergency situations. To perform the assessment, artificial neural networks offer a quick analysis of sensitivity and voltage.

2.4. Markets

In some markets, the loads offer operative reserves in order to reduce the consumption on a short-term basis. This capacity to reduce consumption is often called manageable power. Manageable power corresponds to a certain number of watts that each user can reduce through the direct disconnection, unlatching or gradual pacing of power [82,83]. This manageable power is clearly valuable for the efficient operation of an energy system and it is used in energy markets such as PJM, Ontario, Singapore, Alberta and ERCOT, where DR competes with the generation of reserves when facing contingencies [84,85].

Generally, DR participates in the capacity market [86,87]. Different methodologies were proposed in the dispatch market associated to the energy market [88] focusing on voltage stability, frequency and the compensation of reactive agents to participate as a complement in the auxiliary service market [89]. Table 4 shows the energy markets where DR participates.

Table 4. Energy markets for DR.

References	Markets	Relevant Aspects
[90]	Dispatch	Various contracts are handled for reduction of loads and flexible loads that can be executed for the time change.
[91]	Energy	The aggregator assigns fixed contracts based on three load reduction strategies. The tackled problem considers the uncertainty in the market price and the risk of participation of the aggregator is managed as an optimization stochastic problem.
[92]	Energy and reserve	The DR model is integrated into the energy and reserve market with a two-level focus. However, the upper level presents a stochastic behavior in the reserve market and the lower level is replaced by optimization conditions of Karush-Kuhn-Tucker.
[13]	Energy and capacity	The authors propose a centralized energy market, the direct commercialization of energy with large consumers, the local two-way commercialization and the commercialization of the generation capacities that could work for different load programming methods in real time scale.
[53,93]	Reserve y auxiliary services	Two participation methods of DR are presented: the first one helps to maintain balance and mitigate the deviation of the ideal curve of a predefined calendar and the second one participates in the control of the reserve market.
[42,43,94,95]	Energy, reserve and capacity	The DR programs are systematically organized as they apply to some markets. Afterwards, their effectiveness is considered. In some occasions, the users participate individually and on other occasions, they are grouped intro micro-networks and an integrator agent.

2.5. Complementary Programs

This includes the technologies (Smart networks, Optimization, Automation) that allow the integration of DR both technically and economically.

2.5.1. Smart Networks

It is a solid automated control structure supported by a communication network that manages conventional and distributed energy resources [12,95,96]. It enables a bidirectional relationship between users and the operator [97], which is basic for the application of DR at a large scale. The remodeling of the user's load profiles increases the sustainability of the system [98].

A smart grid is a general term that encompasses the modernization of transmission and distribution networks. Smart grids optimize network operations, reduce losses and pave the way for new markets for alternative energies based on DG, by incorporating energy storage systems. Additionally, smart grids can reduce energy consumption during peak hours through the use of DR [99].

The development of electric networks has led to the uprising of smart grids where microgrids interact while being in charge of the management of DR. It is noteworthy that electric network users can be organized through microgrids. Current microgrids are made by energy storage units, renewable and non-renewable distributed generation sources, which can be managed with demand response programs. The structure of microgrids enables the establishment bidirectional-type transactions to purchase energy from the distribution company, when the energy coming from microgrids is insufficient and to sell energy to the distribution company when the microgrid is receiving enough energy from DG sources [100].

The management of users through microgrids implies facing abnormal situations during the current operation such as grounding-related failures from storage and DG elements. However, there are developments that can adjust the topology of the microgrid to an isolated mode or every time there is a grounding failure while connected to the network [101].

Furthermore, the connection of new devices such as DG units, battery systems and load interruption controllers force a dynamic reconfiguration of the microgrid. This is often carried out by multi-agent systems, while the management system is in charge of the purchase and sale processes within the microgrid [102].

Most of the failures in microgrid systems are asymmetric such as asymmetric short-circuits, simple failures from line to ground, line to line, double failures from line to ground or open conductor failures [103]. To solve these inconveniences, asymmetric failure analysis techniques have been stated for sections with three unbalanced lines and a supply unit such as: length of the line, type of line and derivation capacitor. Additionally, some data buses have also been considered: type of load and load model, type asymmetric failure and its locations. With these data two matrices are established: one matrix for the currents injected into the buses and another matrix that describes the voltage unbalances of and bifurcated currents [104].

It is common in microgrid management to keep in mind the use of incentive-based DR programs so that users can reduce their load during peak times in order to achieve optimal results related to the offered energy costs [105]. Table 5 shows the tight relation of DR programs and smart networks.

Table 5. DR and its relation with smart networks.

References	Relevance Factor
[106]	The authors establish unified communication protocols for the integral and combined control of users with different management technologies.
[107]	Robust communication networks must exist in order to guarantee an effective control of the DR programs with ever-changing user profiles.
[108]	A neural network model is used to handle intelligent loads.
[21]	Prices are measured and communicated in real time. Energy demand is assessed.
[14]	Data management systems are used for the stability of the network and cut prices.
[60]	Smart networks are seen as a facilitator in the electricity market with more benefits for the consumers and the environment.
[109]	DR events will be necessary not only in fixed time intervals and weekdays set by static policies, but also during the change in the decision periods. This is controlled by a smart network.
[110]	Consumers are capable of giving flexibility so that consumption can be reprogrammed through energy price while being a part of a smart network.
[111]	The infrastructure of a smart network is defined to propose an algorithm that controls the consumption in illumination loads within a smart home based on price signals.
[112]	A two-phase DR algorithm is proposed for small and medium-sized clients in order to solve the energy deficit in the smart network. A disuse rate was designed to assess the clients' claims and generate the network's bills.

2.5.2. Automation

Automated solutions allow having more control on the users' disconnection so DR can be managed. Real time pricing programs are automated in charging stations for electric vehicles considering the affectation of voltage profiles [113]. Referring to the communications between the DR actors, protocols have been proposed for information exchange and balancing the demand of users by optimizing the network [106,107].

The randomness of consumption forces the inclusion of direct digital controllers for heating services in buildings, ventilation and cooling systems and dimmable ballasts for continuous attenuation in applications combined with natural lighting. This type of controllers allows good levels of energetic efficiency which effectively integrate DR. Additionally, they enable dynamic operation on loads complying with technical and economic criteria and restraints [93]. One solution to overcome the challenges regarding automated control in new electric networks consists on combining DR with hierarchy-based structures that control consumption. Such structures can reduce the need of redundant circuits, deal better with flexible loads and satisfy the power and confort requirements for users through a dynamic operation over the network which leads to an improvement on the minimum system voltage and better distribution of loads [114].

Most of the automated load management programs encourage users to manage their energy consumption within the allowed consumption allocation according to the DR price fixation schemes proposed to lower bills in the case of the price-based programs [115].

In retail markets, there are unfavorable alterations in the management of energy and prices when consumers participate in the demand response to maintain the balance of electricity in real time. Therefore, dynamic energy management algorithms have been considered against additive perturbations, whose main goal is to achieve optimal energy consumption and retail price. In this type of dynamic algorithms, energy distribution companies send information to the consumers regarding the elasticity of energy prices, based on pre-established pacts with the suppliers. Then, the consumers are in charge of managing their energy consumption, by using automated control systems based on the previously announced prices [116]. Table 6 shows the main strategies of DR automation.

Table 6. DR from the automation approach.

References	Highlighted Aspects
[117]	The predictive control model is analyzed in buildings with DR including DG.
[68]	EnergyPlus software is used to develop control routines in order to emulate the demand response in systems with high DG penetration.
[118]	A predictive control model is described that determines optimal control profiles of the HVAC (High Voltage Altern Current) system as DR with a self-regressive nonlinear neural network.
[61]	The direct control of the load is acceptable when the limits are clearly defined.
[119]	When the frequency of the system drops below 48.891 Hz, DR programs start to operate in order to restore the nominal values of the energy system.
[120]	It is proposed to control air conditioning to reduce the peak demand through load displacement with a stochastic differential equation. It is used to study the effects of the parameters and control actions of direct loads.
[121]	A domestic energy management algorithm is presented with the capacity to control home appliances and keep the energy consumption under a certain limit.
[40]	An algorithm was presented for direct control of loads and it is based on the dynamic programming technique. A framework for DR is also included where consumers can actively participate in an energy reduction program.
[48]	A disconnection and connection platform is developed for appliances.
[122]	A new DR architecture is presented for the indirect control of smart devices which offers communication data and scalability and is easy to use.
[52,111]	Air conditioning controls are designed to exchange information concerning the offer and demand of electricity so that consumption can be optimized. The cooling quality's influence is assessed as well as the impact of reducing loads with DR.

2.5.3. Optimization

In response to the growing energy demand, the new features of microgrid technology combined with DR have provided enormous potential, especially regarding the capacity to have an interactive coordination between energy providers and consumers. Achieving an optimal demand response programming strategy involves solving a multi-target optimization problem. As a solution to these types of problems, swarm-based algorithms, integer-mixed problems and quasi-static techniques have been proposed, often focused on minimizing the total cost of energy consumption and improving the technical parameters of the microgrid, subjected to operational restrictions and energy balance [123,124]. Within the microgrid, usually the load control is optimized by combining manageable loads with DG elements [125,126].

Its application in DR programs can maximize the economic benefits for participants and minimize the risks of instability in the system through mathematical mechanisms [96,127]. Table 7 assembles the research on DR and its optimization.

Table 7. DR from the optimization approach.

References	Relevant Aspects
[21]	The consumer demand is analyzed with the optimization and real time prices are considered more beneficial for consumers and the energy supplier.
[128]	Solutions and variations of the Nash model are characterized. A distributed algorithm is proposed for its calculation, maximizing the network's utility.
[129]	An optimization model is designed to adjust the level of charge per hour of a specific consumer in response to the electricity prices per hour.
[23]	The resulting incentive price of the fuzzy logic scheme reflects the changes in prices according to the changes on the input values.
[66]	DR predictions were carried out using an artificial neural network that is shown as an approximation which is universal, robust, tolerant to failure and immune to noise.
[80]	A sensitivity method is proposed for the load flow in order to optimize the location of DR.
[130]	The Nash balance can be ineffective to reduce the maximum peak demand and the user cost. A game theory approach was used in the implementation of DR programs to motivate the cooperation between users.
[28]	The use of software agents is proposed to automatically monitor prices and optimize the process without problems from the consumer perspective.
[62]	An algorithm is proposed for the management of domestic energy and the analysis of the demand response for a demand limit. The algorithm supervises the priority of the load and also confirms the possibilities of the disconnection according to the priority order.
[126]	Optimization algorithms are used to integrate DG with DR to improve the economy and the reliability of the system's planning. The target planning function is consolidated taking into consideration the investment, the operation costs of the Distributed Generation, the costs of transmission loss and the compensation costs of interruptible loads.
[16]	Optimization is based on minimizing the differences between the real load curve (after the control) and the target load curve through the minimum square method.
[27]	An algorithm is designed for the optimal selection of DR clients accompanied by policies that restrict the discomfort of the consumer.
[109]	Dynamic DR requires the short-term prediction of the consumption to make adaptive decisions in real time over the energy reduction. The prediction models must be used to balance the requirements in order to assure the accuracy in the prediction.
[91]	To simulate the optimization problem with SOLVER COMPLEX, the price data of the market were defined as well as the load reduction contracts for the clients.
[65]	The problem is formulated as a linear optimization to minimize the cost function of each user's welfare and achieve a reduction in the use of load.
[70]	It is formulated as a socially-restricted optimization problem where the cooperative strategy is developed to reduce the electricity costs and the consumption in peak hours.
[35]	A nonlinear programming methodology of mixed integers for the design of fees with an annual framework whose temporary variation reflects the market costs.
[92]	Using the form of a financial market, the programming task is presented without considering the technical and physical limitations of the power system.
[131]	Mathematical software R is used to generate random values used in a simulation such as initial conditions or the programming of an agent. The adjustment of the variables was analyzed with the peak load and the shape of the power curve.
[50]	An architecture is proposed for the domestic management system with an algorithm to solve the optimization problem. It is combined with the real time price methodology that can reduce the average-peak ratio.
[132]	The optimization problem is considered for the electricity prices for dynamic loads and it is modeled as a Stackelberg game.
[133]	An advanced dynamic programming method is proposed to solve the operational problem while considering the minimization of the combustible costs.
[134]	A DR program is designed that considers various prosumers (consumer and producer of energy) in an energy network connected through an aggregator which is in charge of minimizing the reverse energy of the substation and reduces the energy costs.
[51]	A combined algorithm is proposed for the DR residential program considering the comfort of homes and the dual restrictions of the transfer coefficient. The strategy reduces the energy consumption and offers quality of life to the user.
[135]	An optimal demand response problem is formulated. The algorithm is introduced to control peaks and the convex optimization problem is discussed.
[136,137]	Based on Lyapunov's optimization technique, two effective management systems were developed: the load control and DR programs.

2.6. Distributed Energy Resources

Currently, electric energy distribution networks include different components: Distributed Generation Systems, Storage methods, Compensation elements, Electric vehicles, Users with Demand Response programs, entangled with the concept of DER [138–140].

The massification of distributed energy resources (DER), especially the renewable intermittent resources, lead distribution systems to become progressively more dynamic and forces them to face new challenges in power flow management, reconfiguration of the protection scope, voltage regulation and reconfiguration of the network's topology. Additionally, the inclusion of DR programs requires that distribution management systems (DMS) use more advanced automation functions in the distribution networks. This enables tackling resource management problems with an integral focus under conditions of network topology reconfiguration and dynamic operation, while considering the active production of power [141].

Regarding the integration of DER in distribution networks, some proposals are defined such as algorithms, models and strategies, which respond to target functions that vary over time and evaluate criteria related to technical, economic and even social, legal and environmental aspects [142–144]. The management of electric networks with the inclusion of DER elements poses important challenges for its adequate management and control from the technical standpoint. When DG units are introduced, there is an initial shift from traditional one-directional power flows (for which networks were originally designed) to bidirectional flows. The latter occur when "active consumers" are capable of delivering energy to the network during timeslots, which adds a certain level of uncertainty to the direction and magnitude of the total flows in the distribution network and can turn into a significant risk for the security and reliability of the network in general [145,146]. The support of DR becomes hence relevant to compensate such effects [147].

The term encompasses the different ways to produce energy without the need to transport it to the users which includes DR, DG and energy storage. The referenced articles combine DR with another DER to maximize the benefits and minimize the system's affectation.

2.6.1. Distributed Generation

Through renewable sources, this technology pretends to decentralize the energy generation and let uses participate in the production of their community's electric energy and their own. Given the growth of the production of renewable energy, the opportunity has arisen to reduce energy costs through policies and programs such as the DR. This solidifies these types of sources regardless of their inherent stochasticity [148].

The growing penetration of DG sources based on renewable energies such as photovoltaic source as well as the occurrence of loads in the system such as electric vehicles have caused unbalancing problems in voltage for several nodes of the network [149]. For a balanced distribution network, the flow control in the neutral line is always null. When the network is unbalanced, the neutral current is not zero. Some authors propose to use the neutral line current flow as a warning signal to control energy storage units that inject energy into the network and hence minimize the unbalancing effect in voltage [150].

To tackle the need to mitigate unbalancing problems in voltage some solutions are proposed that use the DR along with dynamic load controllers such as transformers called On Load Tap Changers (OLTCs). To implement DR, optimization problems related to the selection of users are solved, considering the minimum disturbance of such users' comfort [151].

It is important to pinpoint that fluctuations in the demand can occasionally lead to unbalancing problems in voltage and power over all of the commutation processes of inductive loads which involves conventional measures such as capacitor banks [152]. Particularly, some authors propose that the DG elements take charge of mitigating unbalancing problems [153]. Therefore, hybrid microgrids with photovoltaic and wind energy sources have been considered which use Maximum Power Point Tracking (MPPT) controllers to maximize the capture of energy in changing load scenarios [154]. This solution maintains the balance in both voltage and power with response times lower than 0.1 s which guarantees a dynamic operation of the system. Table 8 shows the established connection between DG and DR programs.

Table 8. DR programs and their connection to DG.

References	Type of DG	Differentiating Factors
[148]	Photovoltaic and wind energy	Energy generation from renewable sources is foreseen with Markov chains.
[19]	Various types	A microgrid is used in tandem with DR programs for the management of DG.
[155]	Wind energy with ice-based energy storage	An energy model in buildings is presented which incorporates a three-phase electric string with a modified system of ice thermal storage. This model can be adapted to the system and respond dynamically to changes in energy generation.
[12,19]	Various types	A microgrid is proposed to group elements of the DG in tandem with price-based DR programs.
[129]	Various types	DR facilitates the integration of renewable energies and is beneficial for electricity users offering financial incentives to restructure their electricity consumption pattern.
[80]	Photovoltaic energy	The generation of photovoltaic solar energy is promoted in residential areas through algorithms that can optimally locate DR under overvoltage peaks.
[156]	Various types	Clients can easily adapt to the energy prices through DR programs in the logistic production so that DG can enter on a massive scale.
[126]	Various types	An intelligent optimization algorithm is proposed which consists on vector machines to solve the integration of DG and DR in the network.
[157]	Wind energy	The integration of wind energy storage allows the displacement of the demand.
[158]	Wind energy	The growing participation of renewable energies highlights the importance of DR. Consumers have to adapt their consumption to maintain the network stability and reduce electricity costs.
[120]	Photovoltaic energy	An optimal programming mechanism is proposed for residential appliances in a smart home equipped with a photovoltaic panel and an energy storage device.
[134]	Photovoltaic and wind energy	The optimal operation of the energy network is a mandatory task of the aggregator which takes into account the load conditions such as the state of the atmosphere when working renewable sources.
[159]	Photovoltaic energy	Billing charges were calculated for the case study in which solar panels with battery storage were used. Afterwards, the result was compared with the existing billing system.
[122]	Photovoltaic and wind energy	There is a DR server that decides and distributes the intensity value based on the data aggregated to all clients. Then, each client can decide to participate and the system is adjusted in terms of penetration rates of solar and wind energy.
[160]	Wind energy	Smart load strategies are studied to help the energy system face high penetrations of renewable energy.
[32]	Various types	DR mechanisms are suggested to dampen the massive entrance of highly-random DG sources.
[161,162]	Wind energy	A mixed price of the energy is suggested to motivate users to absorb more wind energy during nighttime. The economic benefits for the user and the electric companies are assessed as well as the wind fluctuation as an equivalent load.

2.6.2. Energy Storage

In the revision, there was a notable trend headed towards the use of batteries and electric accumulators in general [145,163]. However, some articles used thermal storage [155,164] and even water storage [165,166]. The common use of storage systems is tied to the offer of the resource for the hours of higher consumption rates for the flattening of the demand curve. There is also an article that links DR, DG and energy storage in a single program. Table 9 summarizes the storage strategies associated to DR.

Table 9. DR programs and their connection with energy storage.

References	Type of Storage	Differentiating Factors
[117]	Electric energy accumulators	The generation margin is reduced through DR programs implemented with DG in homes. The transmission system is improved with electric storage systems.
[118]	Electric energy accumulators.	The supply of the HVAC system is determined as the optimal combination of the network electricity, the electricity stored and the electricity generated.
[157]	Electric energy accumulators	The DR and the energy storage are examined in systems with multiple carriers. The interruption response programs and displacement of the demand are modelled and compared in energy networks of multiple carriers to minimize the operation costs.
[54]	Thermal storage	An optimal operation of cooling storage is proposed in commercial buildings to minimize operation costs.
[133]	Energy storage	An optimal energy management is presented for micro-networks using demand response mechanisms and an energy storage system to allow the high penetration of renewable energy.
[159]	Energy storage	A DC-AC (Direct Current-Alternating Current) reversion system is used from batteries which offered operational benefits by generating a reserve energy source and saving perks for commercial and residential users.
[167]	Energy storage	A smart management system is stated to coordinate the optimal production of DG energy and its storage.
[161]	Thermal storage	Air conditioning storage is designed for DR with the purpose of promoting the storage of cold-based wind energy.
[168]	Electrochemical energy storage	The authors explore the DR techniques to manage mobile loads distributed with electrochemical energy storage with a smart network.

3. DR Trends

The demand response articles were grouped into six topics and their classification can be seen in Tables 1–9. Figure 2 shows the DR circular diagram which is the percentage of the resulting participation of the different topics within the demand response. Complementary programs for DR (Smart networks, Optimization and Automation) represent 36% of the reviewed articles since they focus more on the execution of DR than in the design and planning phases. 19% of the articles tackle the subject of DER. The types of users with a 15% share tend to seek solutions focused on the residential sector due to their energetic potential and a consumption curve with most peaks. Remuneration with a 14% share lies more interest on pricing programs since it does not require more investment in complementary programs for their realization. Services and markets with 8% are a trend of future development.

For the analysis of future behavior in analysis topics related to DR, the use of linear regression methods allows to establish the functional relationship or mathematical equation that associates the variables as well as the strength of that relationship [169–171]. The prediction of the values corresponding to the increase in the number of research projects in the different areas of DR was carried out by analyzing the behavior of the previous relation between two datasets: the DR topics or areas and the number of research projects performed between 2010 and 2017, with a sample of close to 200 articles from which the most relevant ones have been quoted in the reference section. Table 10 shows the data used for linear regression. Figure 3 shows the trends and prognosis of DR up to the year 2020.

Table 10. Data from the analyzed DR topics used for regression and forecast.

Topics	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Remuneration	2	3	4	3	4	2	5	5	4.47	3.07	4.46
Users	1	0	4	5	5	7	6		8.15	11.18	10.29
Services	0	1	0	2	6	2	5	1	6.28	7.06	7.84
Markets	2	5	3	2	1	1	0	1	0	0.07	0
Complementary	5	11	11	10	8	15	9	3	6.01	5.86	5.71
DER	2	5	6	8	5	4	2	4	3.79	3.75	3.72

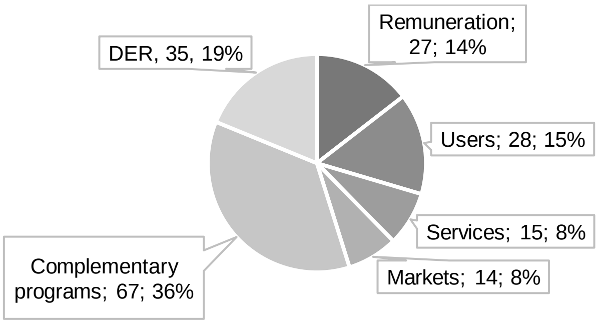

Figure 2. DR circular diagram.

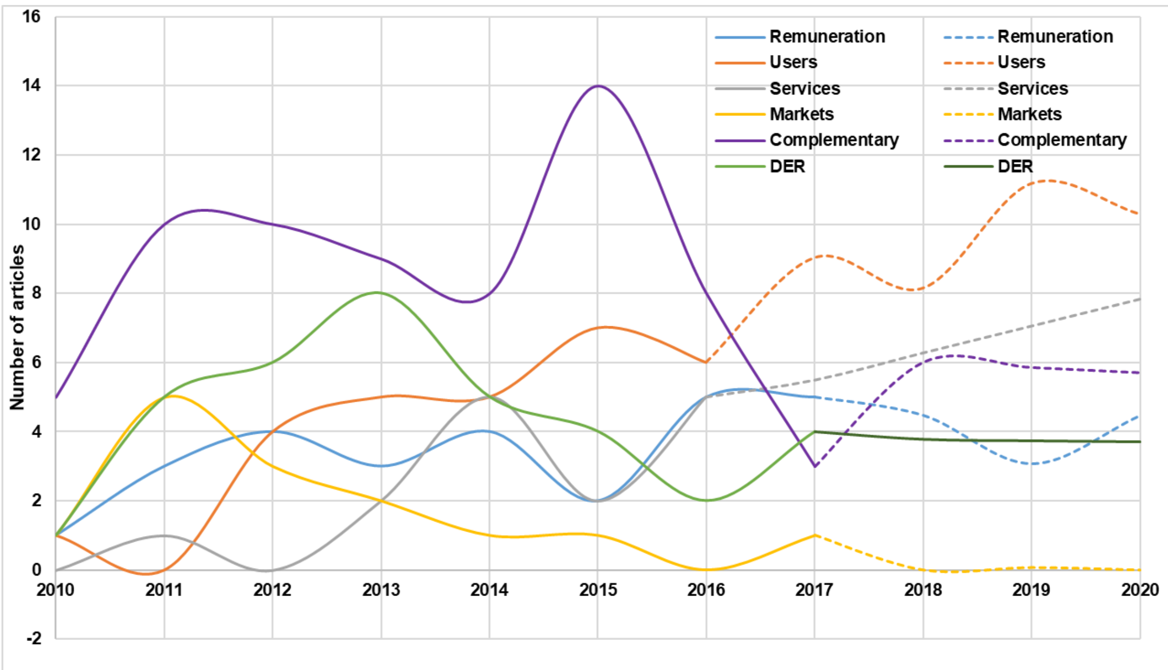

Figure 3. Trends and forecast of DR.

4. Trend Analysis

DR remuneration shows a stronger growth trend in comparison to prices versus incentives. The authors consider that this fact is due to the sensitivity of users towards the fees and the logistic advances to carry out programs of this type since it does not require direct control of loads and only an information platform is required.

By deepening on the strategies related to price-based DR programs, ToU programs are explored where an analysis is made for peak and valley stationary moments and the assessment of consumption baselines that users typically have. Real time programs (RTP) demand more flexibility from the network and an activation of measures in order to optimize the network parameters to face the displacement of sudden consumption peaks that users perform in response to the energy price per kWh.

In incentive-based DR programs, it is common to perform direct control actions over the loads, whether on behalf of users or a centralized system. This also requires an information platform and is comparatively more expensive in price-based DR programs. In these types of programs, the coordinated participation of unpluggable loads is analyzed both indiscriminately or considering priority levels. The prioritization in the selection of loads to be disconnected in a DR program can be tied to the price per disconnected kWh or be related to the impact of the disconnection of a user load on the network behavior. In hybrid type programs, users can subscribe to interruptibility of load contracts under certain contingencies that the network experiences such as an excess in the demand and in par with regular consumption scenarios of prices per kWh in consumption peaks and valley periods.

Regarding the types of users, there is more interest in the residential sector due to the potential that the growing demand offers, and the particularities related to the stochasticity of her behavior which makes difficult forecasting long-term energy supply. Concerning the variability of the demand, there are tools such as Big Data and Markov model analysis. Furthermore, the subjective behavior of residential users is assessed, who not only react to the variability in energy prices but also to the comfort degrees and environmental motivations to participate in DR programs. For these users, a balance is sought between the improvement of the network operation, the conservation of minimum comfort levels for users and the establishment of the optimal cost of kWh for both users and the network. For commercial and industrial users, common aspects can be identified in the research carried out. Initially, some authors indicate a deterministic character in the user consumption so there is a real possibility of foreseeing changes in the demand patterns for certain timeslots (hours, days, weeks, months). Another common aspect for commercial and industrial users lies in the behavior of their analysis where global users can be seen on occasions as a whole and at other times the approach focuses on particular loads such as cooling or heating equipment or industrial production units (engines, ovens and electric machinery in general).

Services where DR can partake are focused in the management of the demand curve and its peaks and serve as a reservoir for the network operator. Nonetheless, the set of possible services that DR can offer to the network has been increasing and includes the improvement and stability of the voltage of the network, frequency regulation and the general safety of the electric network. With the advent of new actors in the electric network such as DG and electric vehicles, DR offers stability and reliability services to the network.

The participation of different energy markets through the offer of the individual interruptible load for big users and on other occasions with the joint work of DR aggregators. Most of the research analyzes the processes of receiving demands and offers that come from DR programs, emphasizing on the assessment of not only the cost of the offered services but also the impact of the network operation.

The appearance of DR programs in electric networks has been an important development factor for smart networks since it forces an establishment of the automated control protocols in many occasions and are almost always subject to the existence of a communication infrastructure that allows an adequate management of the resources of the DR. Some features of smart networks with management of DR resources are the flexibility and frequent stability of the users and the power of the networks. To manage the resources, smart networks use optimization algorithms that determine which loads are susceptible to be disconnected under contingencies or requirements of technical, economical or environmental performance. The advent of microgrids has been greatly driven by the inclusion of DR programs that, when combined with distributed generation elements, lead to higher autonomy margins for microgrids at the moment of entering isolated operation modes.

Optimization tools and control algorithms are commonly used which are ultimately in charge of the execution of DR programs. Reviewing specialized literature shows that the implementation of DR programs implies the direct or indirect solution of optimization problems from different perspectives both during the operation of the network and its planning (in some cases). Optimization criteria and the restrictions related to seeking solutions take into account the perspective of the network user in terms of the targeted minimum costs of the consumed energy, but comfort and welfare levels are also maintained within acceptable limits. Optimization criteria and restrictions from the network operator's standpoint are also established (and even from the energy provider) such as the loading capacity of the lines, the changes in the voltage profiles, the balance of the network power flows and other performance parameters tied to security, quality and reliability that the electric supply network must offer. There is research whose goal lies in finding points of the network where profiting from the DR resources is optimal attending to technical, economic and social criteria.

The control and automation of processes are immersed in the execution of DR programs. The variety of applications is wide and goes from the use of ON-OFF controllers for direct load control, devices for continuous load shedding, velocity shifters, temperature controllers up to more complex automated systems such as PID (Proportional Integrative Differential) controllers and the variations. Automation even allows to keep track of user participation and assess the state of the loads and the network in general when facing emergency events such as cuts or demand surplus that require the application of DR resources. The global focus lies on the energy consumption of a user, but it also centers on lighting, home appliances and equipment such as air conditioning, heaters and engines for the case of commercial and industrial users. It is important to highlight the support that new technologies (such as the internet of things) offer to control and automation tasks.

Concerning DER such as DG and storage systems, it is evidenced how the DR resource has made possible the integration of renewable energy sources majorly solving problems tied to the intermittence of these types of energy supplies. The relationship between DG and DR represents a mutual benefit as indicated in indexed magazines since work scenarios were seen where DR serves as a reservoir and stabilizing element for networks with high penetration of DG. In other cases, DG takes part in DR programs when prices per kWh are too high for users.

Regarding the energy storage systems, they are used not only as a support for the solidity of DG sources, but also as a backup towards the commitment to power disconnection offers that a user or group of users performs in the incentive-based DR framework. In general, it is common to observe research articles where the design and planning of the operation of new networks considering distributed energy resources in an integral manner.

5. Conclusions

The results, analysis and discussions lead to the following conclusions concerning demand response trends: (1) DR users are remunerated using price-based and incentive-based strategies but there are hybrid propositions for a better energy solution; (2) For users (residential, commercial and industrial), the demand curve shows more consumption in the residential sector; (3) The services inherent to DR offer flexibility to the network's management, contributing to the solution of different quality, safety and reliability issues of energy supply; (4) In markets that include DR (Energy, Reserve, Auxiliary Services and Capacity), the trend is oriented towards the energy market with optimization processes that maximize the benefits of both users and the operator; (5) Complementary programs, such as smart networks and optimization and automation strategies, make possible the implementation of DR programs; (6) On a general level in distributed energy resources, there is a trend towards the integration of DG and storage systems with DR programs in the adaptation or creation of new smart networks. This aims at robust energy solutions characterized by their scalability, adaptability, robustness and sustainability; (7) A current research trend is identified in which distributed energy resources (Demand response, Distributed generation and energy storage) focus on the real execution and application with the support of technologies and complementary programs (smart networks, optimization and automation); (8) In future trends, it is expected that the popularity of complementary programs and DER diminishes to give way to projects focused on user participation and new network services.

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