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Review

Overview of Demand-Response Services: A Review

Daiva Stanelyte *, Neringa Radziukyniene and Virginijus Radziukynas

Smart Grids and Renewable Energy Laboratory, Lithuanian Energy Institute (LEI),
LT-44403 Kaunas, Lithuania; neringa.radziukyniene@lei.lt (N.R.); virginijus.radziukynas@lei.lt (V.R.)
* Correspondence: daiva.stanelyte@lei.lt; Tel.: +370-6053-5435

Abstract: It is essential for the electricity sector to analyze and determine the distribution capacity throughput and apply new methods aimed at increasing the capacity of the transmission system. Consequently, the transition to modern electricity networks is two-sided, i.e., involving technological and social modifications. The demand response (DR) redistributes consumption away from peak times when grid load and costs are the highest. It incentivizes customers to use electricity when supply is high and inexpensive due to various market mechanisms. The present DR policy proposals stress the importance of fostering behavioral change through competitive pricing and customer participation in reducing carbon emissions and implementing smart energy solutions (including monitoring tools, such as smart meters and applications). The internet of things (IoT) has been applied to ensure adaptive monitoring of energy consumption and cost-effective and adequate demand-side management (DSM). The article is based on the research of the most recent sources of DR implementation methods applied at the power distribution level. It explains the main concepts, classifications, and entities implementing DSM programs, and suggests new visions and prospects for DSM and DR. Moreover, it discusses the application of blockchain technology potential for the internet of energy.

Keywords: demand response; demand-side management; internet of things; internet of energy; blockchain technology

Citation: Stanelytė, D.; Radziukyniene, N.; Radziukynas, V. Overview of Demand-Response Services: A Review. *Energies* **2022**, *15*, 1659. https://doi.org/10.3390/en15051659

Academic Editors: Chun-Cheng Lin and Sergio Saponara

Received: 31 December 2021
Accepted: 4 February 2022
Published: 23 February 2022

1. Introduction

It is estimated that by 2040 market demand for electricity will rise by up to 30% compared to 2017. The rise will result from further urbanization, population growth, and increasing numbers of used devices, all of which tend to overload the existing electric power infrastructure [1]. A power grid overload results from a constant increase in the peak power load, an inadequate real-time monitoring and failure identification, automation, and rapidly developing renewable energy sources (RES) integration [1,2]. This adds to the system's operational complexity, making it more difficult to maintain generation-demand balance and grid stability [3]. In linked grids, load variations will also have an impact on electricity distribution between surrounding districts [4]. Traditional generators must be prepared to compensate for the stochasticity of renewable generators through supplementary services [5]. In order to maintain system stability, a robust control strategy must regulate and safeguard the system against unanticipated or emergency events, rapid load fluctuations, and outages in short durations [4,6–8]. As the use of photovoltaic (PV) systems grows in the power system, it's critical for PV systems to offer grid support tasks such as reactive power, transient voltage ride through, and frequency regulation, which are usually done by conventional rotating machines [9].

No universal solution exists to creating a sustainable energy system. The transition should be regarded systematically, considering all possible technologies and methods. This can be achieved through demand management, electricity conservation, investment in infrastructure, market mechanisms, and ancillary services (i.e., phase-voltage balancing, load-generation balancing by changing the generating schedule to suit demand, and volt-ampere reactive (VAR) support for voltage control), which are essential measures for improving the energy system's flexibility.

Renewable-based distributed energy resources (DERs) have grown rapidly owing to incentive schemes and widespread involvement [10]. DERs is a larger word that refers to technologies like distributed generation (DG), backup generation, energy storage, and demand-side management (DSM) [11].

DSM is a concept that provides a tool to the utilities to influence the load profile [3]. It allows customers to participate actively in power networks and can considerably enhance power system stability, efficiency, economy, and dependability [12]. The dependability of a power system is increasingly dependent on its flexibility, which is becoming more difficult to accomplish on the production side due to the widespread use of renewable energy sources [13]. DSM encompasses all demand-side initiatives aimed at lowering consumption/costs/ emissions or raising revenue from energy sales, including techniques to increase building energy efficiency [14]. DSM can accomplish this flexibility with the advancements in smart grids by requiring consumers to engage in DR programs [13].

The US Department of Energy has a formal definition of DR as follows: customer end-use electric load changes in the near term as a result of dynamic pricing and reliability data [5]. DR is a subset of DSM that solely includes non-permanent actions performed on-demand [14]. DR is a novel solution based on flexible demand/load management for balancing the network. To balance the network and receive financial incentives, consumers can increase, decrease, or adjust energy consumption (e.g., in the industry—production lines, equipment, motors; and in the case of household consumers—washing machines, boilers, heaters, air conditioners, refrigerators, heat pumps, electric vehicles (EVs), etc.) [15].

Based on the analysis of scientific articles and other literature, scientists and experts often use these terms interchangeably, making no clear distinction between them, as provided [1]. It is crucial to consider the continent or country where these terms are used, the applicable legal framework, and the distinctive features particular to electricity. Thus, an investigation is essential for these reasons alone.

Several development stages of DSM and DR have been identified. In France in 1956, the term DR was introduced for flattening the load curve. In the 1920s, Germany started using the term for direct load management. In Europe and the USA, the term DSM was introduced around 1974. The wide use of the term DSM was connected to the electricity grid changes, progressing electrification, developing industrial enterprises, growing loads, and the failure of the existing electricity system. In about 1980, a classification of DSM services was developed. The electricity market emerged in approx. 1990. Around the globe, different DR programs started to develop in 1990–2010, including air conditioning, heating, etc. Starting with 2010, intense development focused on projects with real-time markets, real-time trading, thermal energy storage, real-time balancing, and load balancing [16,17]. End-user loads are becoming more adjustable through smart devices, allowing them to respond to changes in electricity prices or other tailored incentives from a third party [18]. Consequently, the implementation of DR programs in power systems faces the key challenge of maintaining a dedicated infrastructure for information and communication technologies [19].

New technologies—smart and autonomous controllers, advanced data management software, and bidirectional communication between power suppliers and consumers—help develop automated and distributed SGs [20,21]. Among the technologies are energy storage solutions, such as batteries, that meet peak demands or accumulate excess energy [22]. These smart technologies are incorporated into various parts of the new generation power systems, starting with production and ending with power consumption monitoring, aiming to improve the system's efficiency and stability [20]. Such features for SGs as DR and load control can prevent unnecessary installations, e.g., transformers, and extend their lifetime [23].

Aiming to expand and maintain the transition to low-carbon technologies and SGs, the institutional framework must be revised for electricity generation, distribution, and consumption models. However, insufficient research is available to explain the institutional dynamics particular to socio-technical changes that must be considered to better grasp the development and implementation of DR [22]. Evidently, the need exists to better explore the role of energy companies in supporting energy efficiency and savings among end-users, considering the intricate interconnection between different policy objectives, operations of energy companies, and perspectives of energy end-users [24]. Moreover, insufficient focus has been placed on intermediaries referred to as aggregators, which are crucial in the development of DR [22].

This research is an important step in assessing interest in DSM programs and electricity tariffs. The paper closes gaps in the understanding of an aggregator and its role in the market.

The methods presented in the research are general and may apply to any country with an implemented DR program. However, factors influencing the implementation may differ primarily because each country has different renewable energy sources, legislation, policy frameworks, and electricity markets. Consequently, different requirements exist for DR programs.

The research has the following structure: Section 2 overviews the existing and relevant literature on the DSM structure, the measures to promote the use of DSM programs, and includes DSM types and the key entities implementing DSM programs.

Section 3 presents the DR structure; Section 4 gives an overview of various countries concerning demand management programs.

Section 5 overviews further research options, such as internet of energy (IoE), blockchain-based distributed trading model, and, finally, Section 6 summarizes the findings.

The main contributions of this document are as follow:

- Key differences and similarities between DSM and DR are highlighted.
- The literature was selected following a chronological review of scientific publications, programs, and projects related to the issues of demand -side management and demand response; a structured and a systematic analysis is proposed.
- Differently from many other studies, this one assesses DR experiences of different European countries.
- Based on a comprehensive assessment of DR potential in various sectors and regions, the study indicates the main challenge for the implementation of DR programs, i.e., the need for a dedicated infrastructure for information and communication technologies.
- New vision and prospects for DSM and DR are suggested

2. Analysis of DSM Structure

The deployment and development of a smart grid containing many renewable energy sources can result in hourly supply-and-demand disbalances, which can decrease the system's efficiency, exacerbate the reliability, as well as pose many other challenges. DSM is the main solution to such difficulties, moving the energy system's flexibility to the consumer side [13,15]. SGs and DSM applications should reduce technical barriers. DSM would allow users the possibility to optimize consumption, at the same time, giving network operators more system control flexibility [25]. A smart user actively monitors and automates energy consumption and perfectly integrates price signals and state-of-the-art smart technologies to ensure optimally efficient energy consumption [26]. Even though traditional DSM terms are questioned in the sense of liberalized energy markets, the concept of DSM remains an important part of the political agenda [24]. Other DSM's advantages include eliminating power outages, reducing operating costs, and lowering CO_2 emissions [20].

The main types of DSM and the major entities implementing DSM programs are given in Figure 1; however, government-designed DSM policies are usually performed using utilities (or, in the case of a smaller scope, distribution network operators (DNOs) [27]. In the hands of distribution system operators, retail demand often becomes a price-adjustment tool, helping to achieve savings. Considering more up-to-date national requirements and green programs, more operators must focus on reducing end-user energy consumption [21].

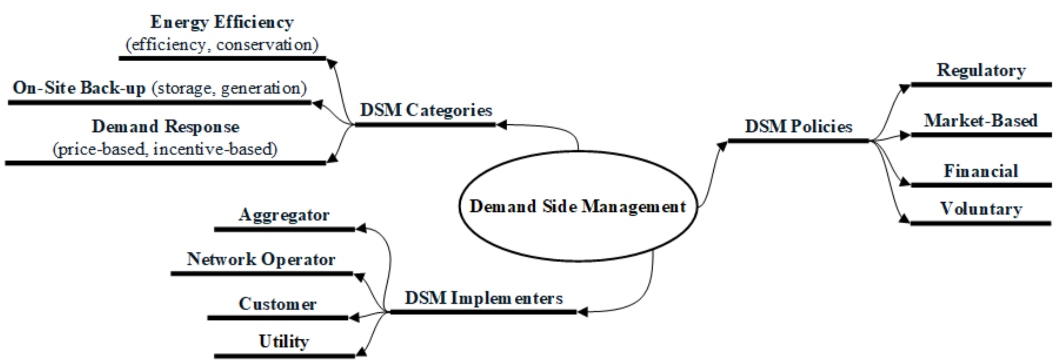

Figure 1. Defining demand side management (DSM) [27].

In 2018, aiming to promote the integration of RES and flexible consumption (demand following supply), the Energy Union established the energy efficiency paradigm that covered energy savings and the demand response (DR) [28]. DSM requires steps taken to minimize end-use energy consumption (i.e., to encourage energy efficiency or energy savings) or to change the time of end-use energy consumption (load shifting) [24].

DSM instruments can be classified into the following categories:

1. Energy savings—a way to reduce energy costs and promote long-term stability [29,30]. Energy efficiency is one of the means that help many countries, including the EU member states, achieve objectives related to energy security, free competition, and reducing greenhouse gas emissions [25]. The economical and productive use of electricity can become a part of the answer to pressing power demand and environmental issues. According to the International Energy Agency estimations, energy end-use reduction and savings have the greatest potential to cut carbon dioxide emissions to the expected safe level by 2035, which amounts to approx. two-thirds of the emission reduction target [24]. The energy efficiency gap results from the limited amount of information currently available to consumers as well as the failure to adapt their energy demand to price changes [25,29].
2. The purpose of DR solutions is to adjust power requirement parameters at the final point of consumption depending on, i.e., existing prices (which are calculated based on used pricing methods) or another important factor, such as available incentives, agreements to control the consumer's load directly or reduce it, or the involvement of consumers in electricity trading by submitting bids [29,30]. Fixed price levels usually prevent any demand flexibility, which is considered one of the fundamental issues faced by electricity markets. The second reason is technical barriers preventing price signals from being sent to the consumer [25,29].

In the electricity market, marginal electricity consumption can vary significantly depending on the time of day, which means that the factual electricity consumption also varies by the hour. Therefore, end-user tariffs could encourage the optimal control of resources among consumers [29].

Different optimization deployment methods can be particular to DSM systems. The methods differ by the type of user interaction (individualistic or collaborative), the method for optimization (deterministic or stochastic), and time scale (a day-ahead or real-time (intraday)).

Type of user interface. DSM systems can aim to optimize the utilization of energy resources by a single user or a collaborating user group. Optimization methods intended for individual users are established on a case-by-case basis by controlling loads on the spot. Regrettably, this approach can result in certain unwelcome consequences as decisions made by the consumer do not get coordinated. For instance, using DSM methods to reduce the financial burden, loads can be shifted to cheaper price time intervals, causing high peaks and service disruptions in demand during such times of the day [31].

Key techniques and methods used to characterize DSM are given in Figure 2.

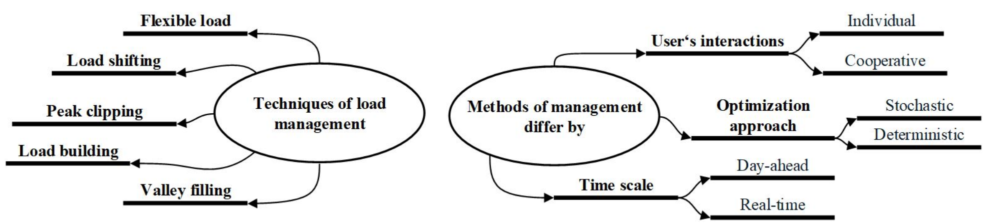

Figure 2. Most important techniques and methods used to describe DSM [31].

DSM may also involve the transfer of an energy source on the demand side, e.g., the consumer-owned distributed generation. Under such circumstances, profile characteristics of the end-user power demand may change slightly or not at all, while profile characteristics of energy supply may change significantly in respect of energy utilities [32]. The load-shifting DSM system/technique can be used to plan (forecast) controlled consumer devices at different times of the day. This ensures maximum or moderate demand control depending on a weekday or weekend. This solution reduces the operating costs for consumers. The load-shifting system/technique may be devised as follows:

$$Minimize = \sum_{t=1}^{N} \left(Load(t) - Objective(t) \right)^2 \quad (1)$$

where the objective (t) is the value of the *objective* curve at time (t), *load* (t) calculated based on the following formula: [33]

$$Load(t) = Forecast(t) - Connect(t) - Disconect(t) \quad (2)$$

Result analysis and discussion: When making daily offers to users, electricity producers must consider loads and the availability fluctuations of RES. In this context, some control strategies for traditional energy systems must be changed. A country with a high number of RES needs a well-integrated demand model.

DSM was developed to smooth energy demand fluctuations and balance the interests of different shareholders in electric power networks. Several new DSM frameworks have been created in response to the need for collaboration between various energy systems. The development of DSM technologies with automated controls allows many devices, including energy storage, to provide efficient ancillary services to grid operators. With various renewable energy supplies, price-driven demand response strategies also maximise the energy systems' flexibility.

In the future, real-life DSM applications (as customer behaviour learning, optimal device scheduling, DR, and economic dispatch and so on) will likely use optimisation methods based on nature-inspired optimisation techniques—meta-heuristics. The three fundamental challenges in selecting an appropriate intelligence to do real-time tasks are: (1) continuous data uploading in order to make real-time decisions; (2) to evaluate results in a short amount of time; (3) to be able to control several time periods rather than just a daily slot. The following may be distinguished among heuristic methods: particle swarm optimization, ant colony optimization, evolutionary algorithm, etc. However, more complex algorithms may also require higher expertise from algorithm developers, testers, and/or operators to understand the risks and anticipate actions to further control the network in a given situation considering the market and industry developments, etc. It is critical that the algorithm modeling properly evaluates full criteria and factors, is properly tested in all possible scenarios, and, most importantly, that the modeling is identical to the real-life simulation (deployed on the real network). As the complexity of algorithms is growing, it is difficult to predict their behavior without more sophisticated evaluations, simulations, or modeling. A DSM application must react quickly (preferably in real-time) and intelligently to changing conditions and adopt effective dynamic pricing strategies. The main limitations for making decisions are the complicated physical characteristics of energy transmission and conversion systems. Many studies, however, concentrate on market and trade models, but system operation and physical restrictions might significantly impact the DSM strategy's success from an engineering standpoint.

It is possible to emphasize the benefits and drawbacks of previously created tools for implementing DSM approaches. Although favorable legal conditions for DSM exist in several European countries, these factors are insufficient to build viable DSM marketplaces and entice corporations to participate. Currently, small demand units in particular are rarely included in DSM, despite the fact that their aggregate potential is considerable. Lack of (accurate) information, financial benefits, and perceived dangers have all been recognized as key impediments to additional DSM alternatives being adopted, particularly in the tertiary sector. As a result, large corporations with more defined procedures for energy efficiency and demand may be quicker to adopt DSM approaches. As a result, incorporating DSM into energy management systems may facilitate the expansion of demand-side flexibility possibilities.

Based on the overviewed studies, these strategies seem to have a high potential as they are flexible and enable using an option/program acceptable to a specific user/sector. However, the literature analysis revealed a shortage of long-term situation analysis, as the available research is predominantly based on studies and pilot projects.

3. Analysis of DR Structure

3.1. Participants and Design

DR is widely recognized as a critical element for the future of an optimized SG that incorporates a wide variety of renewable and traditional energy sources, both centralized and distributed. This is especially significant given the next generation of virtual power plants (VPPs) [34]. On a global scale, the International Energy Agency (IEA) estimates the potential for the DR to be close to 4000 TWh/year, which amounts to 15% of the total electricity demand [6]. The US Department of Energy has described DR as "a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized" [20]. As an instrument that helps to achieve the desired balance, DR can be used for energy wholesale and retail [21]. DR demand changes arise from most stakeholders, such as DNOs, politicians, and end-users [22]. Nonetheless, the end-user is the determining factor implementing DR. Traditionally, the end-user, whether a household or otherwise, used to be an isolated final node that consumed electricity as required to satisfy existing needs. However, DR anticipates an entirely different role for the user as an integrated and dynamic part in the balance of supply and demand

[26,30,33,35]. DR strives to enhance the utilisation of power plants and grids, which is a way towards more efficient use of an energy system. Therefore, DR is a critical instrument to improve energy efficiency, and these two areas should be assessed in parallel rather than in isolation [28]. The peak demand, which is the time when the grid takes the maximum amount of electricity, is the driver behind growing electricity prices. Usually, the consumer and the seller focus on financial gain. Subsequent to a review of programs for utilities, the Electric Power Research Institute estimated that in the US, DR reduced the peak demand by as much as 45 000 MW [36]. Nevertheless, DR uptake is still relatively low due to inadequate marketing strategies and low awareness-raising in the promotion of energy and cost savings [37].

The potential and practicability of DR depend on the form of electricity markets, which depends on the combination of generating capacity and usable reserve capacity, variable renewables and capacities needed to balance the interruptibility, and the maximum level of user demand, which can be considered as load shifting together with time and duration of used reserves [8].

The power market is divided into retail markets, where power retailers contract suppliers and end-users, and wholesale markets, where retailers, suppliers, generators, network operators, and aggregators interact. Within the framework of a DR program, collaboration takes place between the four major groups of participants, as demonstrated in Figure 3.

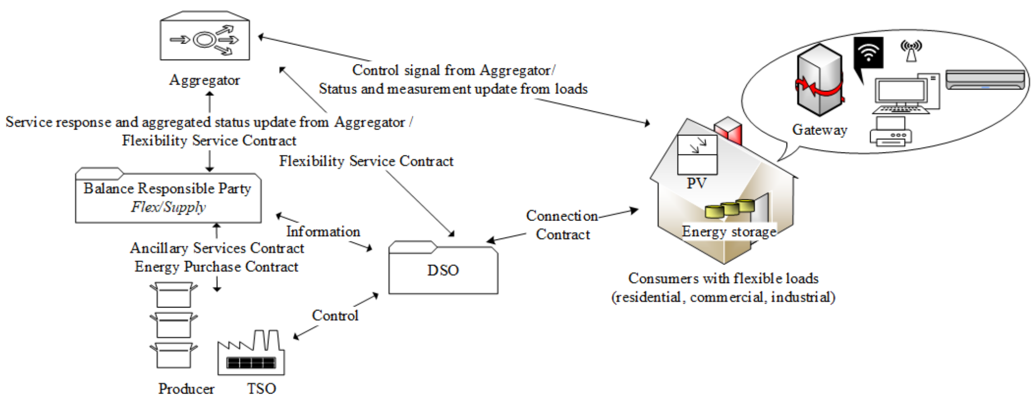

Figure 3. Major participants of a DR program.

Major participants of a DR program:

- Energy consumers participating in the DR program, including residential, commercial, or industrial users [20]. Devices that support DR act depending on a price-related indicator or model used by an operator of a distribution system. DR services can be used to sustain a stable network. They can manifest in the form of power companies remunerated for emergency power supply. They can act as virtual generators in the next-day market, which is the most encouraged approach [21]. Two factors determine the end-user load, namely, the size of the market expressed as the number of consumers with DR capabilities and the flexibility available in the case for each consumer [8].
- A DR aggregator that is linked to customers and manages the DR program [20]. As a market participant, the aggregator undertakes the following functions: registers users and communicates with them, makes real-time measurements, transfers measured data, implements the standard on measurement and user consumption verification, implements the standard on the safety of information regarding end-user, estimates the baseline power usage and financial reserves, calculates user engagement based on measurement data, compensation, and baseline power usage. The assumption regarding the aggregator model is based on many highly depend-

ent users that can access reliable DR services. Moreover, the aggregator must fully correspond to the requirements and specifications of the electricity market, to which it provides services [21].

- The distribution system operator (DSO), which controls the distribution network [20]. The DSO is responsible for the prevention of network imbalances by issuing regulatory signals and using various pricing systems that motivate consumers to follow the signals [34]. Considering national regulations and green initiatives, a growing number of distribution system operators must reduce end-user energy consumption. With no additional effort, price signals trigger a reaction by devices adapted to DR. Distribution system operators can also set the devices to respond to pricing patterns. There are different approaches to utilization of DR services, namely, either for ensuring the stability of the network or in the form of units that possess the necessary capacities and collect payment for emergency power supply [21].
- The independent system operator (ISO) or the regional transmission organization (RTO). ISO/RTO comprises a set of mechanisms intended (in the ideal case, at least) to compensate for resource services fully and correctly over different periods of time [20]. However, these markets and processes have always preferred the traditional power generation based on fossil fuels, not always allowing DR to be able to compete on the same terms. Rules governing the day-to-day operation of an ISO/RTO are complicated and can sometimes unintentionally prevent demand participation and aggregation [38].

3.2. Balancing Markets

Balancing markets are regarded as wholesale and mainly comprise different enterprises that offer available balancing capacity [21]. In the balancing market, the time when the offers become final is the critical variable [8]. Generally speaking, the DR program begins with an ISO/RTO, which determines the desired volume of demand and the offered duration of supply. As the market is wholesale, it is unavailable to individual households. Service providers are the only avenue for households to take part in the market. The named operators are enterprises capable of combining individual household capacities to undertake a bulk sale [21]. It is possible to pool loads using an agent referred to as a DR aggregator [39,40]. DR aggregators are supplied with data required to choose available customers to participate [39,40]. An aggregator is an agent for direct negotiations of the electricity market with the market operator and transmission companies. The physical energy flow is transferred from the generator to transmission and distribution companies and then to the consumer. The aim to provide quality services to the consumer within the structure of a competitive electricity market necessitates an aggregator to coordinate with the retailer and the distribution company. These services comprise the provision of information regarding the market price and demand. This allows small consumers to compete in the wholesale market [36,40]. Many economists agree that aggregators' involvement in DR services will provide useful options for small consumers to efficiently control their demand and become active participants in the electricity market [36]. Aggregators offer solutions for effective DR with DNOs based on a reliable asset control approach. They also present commercial offers that provide DR with a valid energy control initiative that corresponds to the business priorities of an organization [22]. However, balancing markets open to demand aggregators still encounter barriers that prevent practical participation [40]. Aggregators are commercial undertakings operating in electricity markets. Aggregators undertake the role of intermediaries in the capacity of a third party. They collaborate with industrial and other similar consumers to offer DR solutions to service providers, such as utility companies or firms licensed to distribute electricity [22].

Although most existing aggregators are related to large consumers, such as industries, the literature also focuses on residential buildings that consume about 40% of the total electricity. Such buildings have several systems that consume energy, such as heating, ventilation, and air conditioning (HVAC), which can be controlled to provide demand-side flexibility services. The aggregator can either directly manage the consumer portfolio through contracts or indirectly via price incentives [40]. Relationships and challenges in the order of hierarchy and significance for aggregators in balancing markets are demonstrated in Figure 4.

To allow demand aggregator participation at first, regulatory barriers should be avoided. Then, technical requirements need to ensure participation in the largest flexible loads pool to maximize their availability. Finally, a good market design is needed to ensure that an aggregator receives adequate compensation and minimizes its financial losses [40].

The aggregator estimates to determine the overall demand and settle accounts with RTO or ISO based on the number of consumers who consent to the DR offer. To avoid problems arising from the uncertainty particular to the distribution, aggregators can primarily address the DSO, which subsequently notifies substations regarding the overall power demand. In such cases, DR estimations originate from DR aggregators. Later, they are employed by DSOs to optimize procedures or identify distribution network issues [20]. The ENTSO-E recognizes one of the key difficulties related to DR in Europe: the inefficiency of price signals that facilitate informed judgments at a level of aggregators. The situation gave rise to two approaches. The first treats the aggregator as a conventional player that has to react to price signals. Meanwhile, the second allows aggregators to offer extra services in the balancing market. This particular approach is related to services ensuring the stability of the system and has been recognized as the most adaptable due to the least number of required regulatory amendments [21].

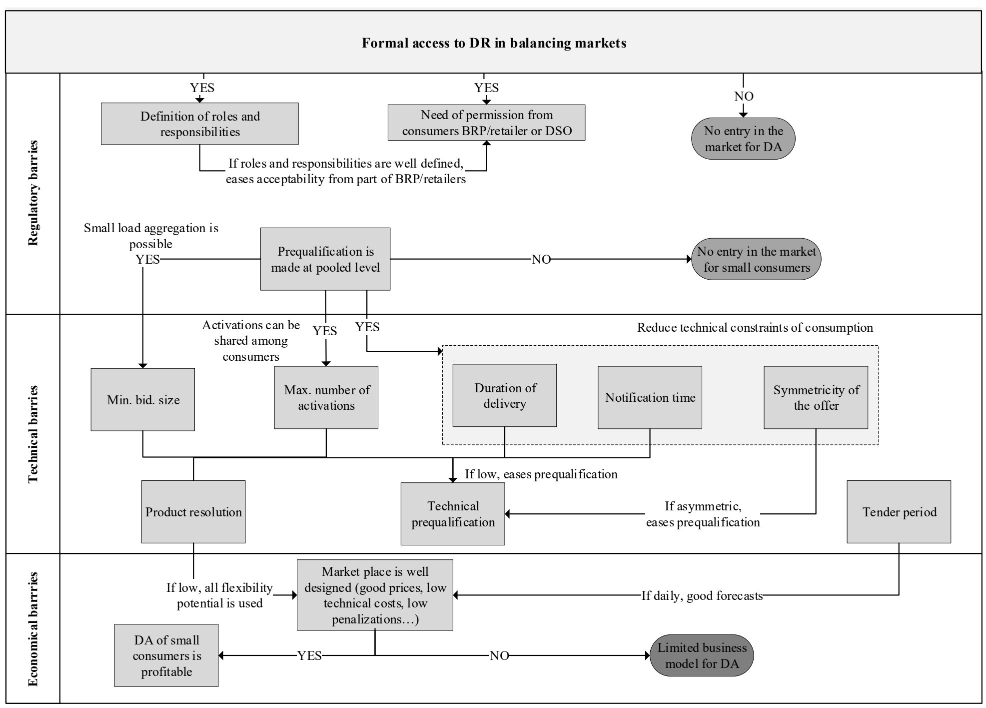

Figure 4. Relationships and challenges in the order of hierarchy and significance for aggregators in balancing markets [40].

The above-mentioned model with four participants is common, and it can involve many interacting agents who either compete or cooperate. These multi-agent systems implement distributed decision-making locally or within the entire system. The decision-making process results from negotiations and trading in the electronic market and includes processes such as DR and DG [20].

3.3. Classification of Demand Response Programs

DR programs may be grouped into three main categories, as given in Figure 5.

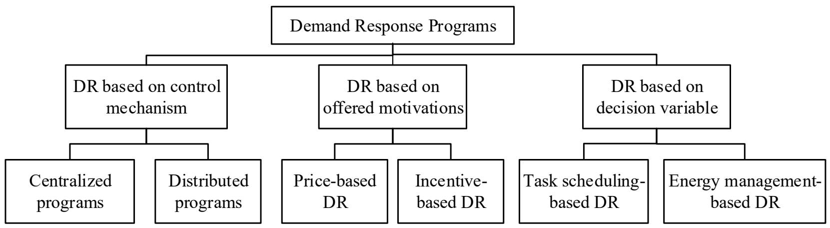

Figure 5. Classification of DR programs [20].

The first category comprises DR systems divided into centralized and distributed by their control mechanism. In the case of a centralized program, users directly contact the energy company without communicating between themselves; meanwhile, in the case of a distributed program, users interact between themselves and provide information on total consumption [20].

The second category comprises DR systems classified by incentives into two types of instruments, so-called "reward programs", namely, price-based DR (PBDR) and incentive-based DR (IBDR) [7,30,39,41–46]. The interrelation is demonstrated in Figure 6.

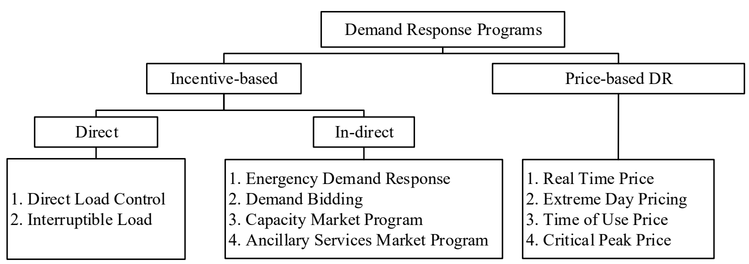

Figure 6. DR classification [42].

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions.

1. Price-based DR (PBDR) provides customers with a time-varying (dynamic) electricity rate [41,42,45,46]. Price-based programs comprise:

- Real-time pricing (RTP) provides consumers with wholesale price changes within an hour [7,25,41].
- Extreme day pricing (EDP) [7,25,41].
- Time-of-use pricing (ToU) splits a day into specific periods with a specific, predetermined price. This form of dynamic pricing is the simplest and most widespread. However, it grants only limited flexibility, often with minor price differences of the initial vs peak periods [7,25,41].

  In China, a key measure of DR service is the cost for the time of use (ToU). This solution answers several problems, including the dramatic contrast between the use of installations during peak loads and between them [47]. SG price comprises several values, including the maximum rate per hour, the regular rate, the peak, and valley rates depending on typical conditions or fluctuating based on the regular rate; it is calculated based on the following formula:

$$p_f = p_p(1+\alpha) \qquad (0 < \alpha < 1) \tag{3}$$

$$p_g = p_p(1-\beta) \qquad (0 < \beta < 1) \tag{4}$$

where p_f is the peak (maximum) hourly price, p_p is the regular price, p_g is the peak (maximum) and valley price, α is the proportion of parameters, β is the proportion of lower parameters [47].

Based on the initial electricity price and continuously revising the value that represents the difference between prices for each period, consumer loads per period will be altered to promote the price difference. The transfer rate of a user load can be estimated as a function of segments. The coordinates are values that represent the difference in prices for relevant periods. The *Y*-axis indicates the load transfer rate and the customer response, as demonstrated in Figure 7 [47].

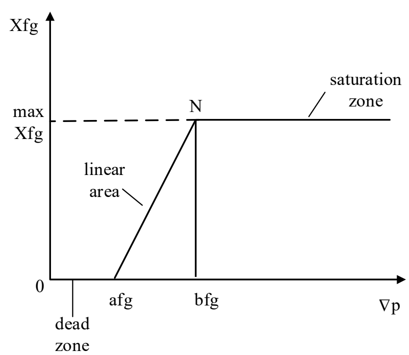

Figure 7. Curve for the peak period to valley time load transfer rate [47].

A dead zone refers to the substantial response of a customer (or the lack of it) to this power distribution range; above the limit, linearity becomes particular to the response of a customer as well as the price for the transfer of the load. A specific position of a customer expresses a reaction, which can either be minimal or saturation-dependent. X_{fg} represents the speed at which the peak interval turns into the valley.

∇p represents the difference in prices of peak and valley intervals, a_{fg} represents the threshold of a dead zone, and b_{fg} represents the threshold of saturation [47].

DR is considered the most economical and efficient solution for smoothing the demand curve under stress conditions experienced by the system [20].

Critical peak pricing (CPP) is based on the same concepts as ToU but divides segments into smaller units (baseline, time of day, and critical peak periods). A signal alerts users about a critical peak period [7,25,41].

2. Incentive-based DR (IBDR) offers participants a rate discount or incentive pay-outs over certain periods [7,39,41,42,45,46,48]. Demand sources provide system reliability services and are useful for the entire system during power peaks or emergencies. In a deterministic or real-time policy, incentive-driven demand encourages consumers to allow power cuts in cases of power shortage or short-term system reliability issues. Consumers would also receive direct compensation or a reduced rate at other times [25,49]. Such programs are predominantly aimed at large industrial users [41]. Load reduction during a critical event, such as changing the frequency of power systems, is an example of incentive-based DR [48]. There are two groups of IBDR, namely, methods of indirect and direct control. The latter permit direct changes to participant loads, including the interruptible load (IL) and direct load control (DLC), which are intended for electrical devices with functionality for remote turning off and quick switching. Meanwhile, the intermittent load is for electrical devices, which are more useful if their operation is interrupted or weakened in seconds. It is anticipated that indirect control methods would offer appealing incentives to lessen peak loads, such as programs for capacity market or ancillary ser-

vice market, emergency response, and demand offers. Emergency response tools notify participants of the situation in a 30-minute to two-hour advance to encourage the reduction of the peak load. For the nearest interval of 30 minutes to two hours, tools for emergency response may be used to minimize peak loads and ensure the reliability of the network frequency with the help of technologies that can forecast loads in short-term as well as historical data regarding demand and prices for power [42]. Table 1 presents the timing of different DR messages.

The third category comprises DR systems that use the decision variable to determine task scheduling and power control-based DR systems [20]. Typical DR notification time is given in Table 1.

Table 1. Typical DR notification time [42].

DR Type	Notification Time
DLC	1–60 s
IL	1–60 s
Emergency demand response	1800–7200 s
Capacity market program	3600–7200 s
Ancillary services market program	3600–7200 s

In addition to regulatory and policy hurdles, one of the most significant DR challenges is its dependence on end-user behaviour. Human behaviour is a relatively complex and stochastic variable, which significantly impacts the adoption and success of several DR programs, as most of them, if not all, require greater user engagement compared to the current passive role [50]. Customers can take steps to disable devices or change their settings. Actions based on equipment involve utilizing distributed generators, batteries, etc., to modify the initial customer demand [51]. The European Commission recognizes that the optimum DR potential has not been utilized, and the existing regulatory framework does not offer consumers a signal or value to participate in the market. Set and controlled prices that stop new market players from providing consumers with real price signals create a barrier to successful DR. This problem has been discussed in the proposal for a new EU directive on the internal electricity sector, which provides consumers to choose real-time retail prices and aims to provide price signals that promote demand flexibility [41]. Moreover, better insight is required in terms of how consumers perceive and interpret smart solutions [42].

In recent years, much attention has been given to a new type of DR referred to as the behavioral demand response (BRD). To promote customers to reduce electricity consumption, social and behavioral sciences must be engaged rather than economic signals [49].

3.4. Demand Response Resources

Demand response resources (DRRs) can be applied in a variety of ways in energy markets. An active distribution network (ADN) has many resources, including load and DG. DRs comprise inflexible loads, DG, flexible loads, EVs, and energy storage at the user-end and are closely related to users (Figure 8). DRs have distributional characteristics and are extremely diverse, having different properties, etc. [52].

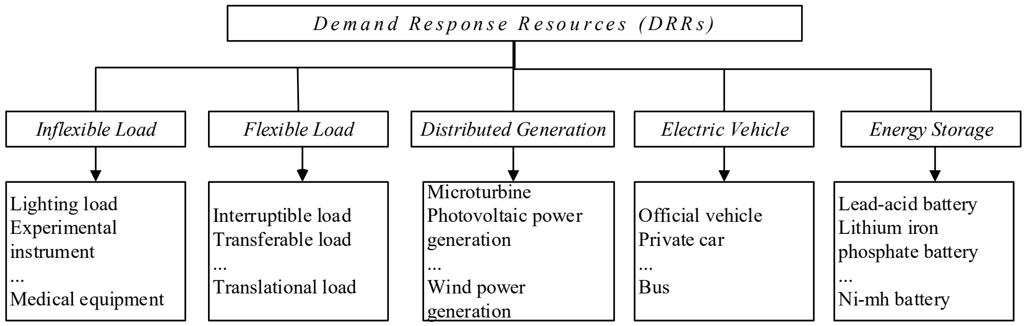

Figure 8. Detailed demand response resources structure [52].

Loads are typically classified into inflexible loads, which cannot be cut or transferred, and flexible loads. Flexible loads can be adjusted according to consumption patterns, considering changes in electricity prices or incentives. They can be divided into three different models: base load displacement, which requires constant power for a specific period, but its time of use can be modified [39].

The flexible load-response modeling framework is based on the objective feature of reducing the net energy/power charge to the consumer, and the net energy/power charge is the difference between the purchasing price of energy/power and sales revenue.

To optimize distributed photovoltaic energy consumption at the local level, the photovoltaic output is primarily supplied to energy storage components and household loads. At present, if the photovoltaic output is surplus, the network is redirected. Consequently, the target function of the model: [2]

$$\min \sum_{i=1}^{N} price_i \left(\left(\sum_{\delta \in A} P_{\delta,i} \right) - \left(P_{ESD,i}^{dch} + P_{PV,i} \right) \right) \Delta t \tag{5}$$

$$price_i = \begin{cases} price_{buy,i} & \left(\sum_{\delta \in A} P_{\delta,i} \right) \geq \left(P_{ESD,i}^{dch} + P_{PV,i} \right) \\ price_{sell,i} & \left(\sum_{\delta \in A} P_{\delta,i} \right) < \left(P_{ESD,i}^{dch} + P_{PV,i} \right) \end{cases} \tag{6}$$

Here, the total number of control steps for optimization is N, Δt is the duration of one control step, δ is the set of power-consuming devices, and $P_{\delta,i}$ is the power consumption of a certain power consumption device during time i. Parts $P_{ESD,i}^{dch}$ and $P_{PV,i}$ are the output power of the energy storage devices and the distributed photovoltaic over a period of i. $price_{buy,i}$ and $price_{sell,i}$ show the buying and selling prices during the period i for the electricity that interacts with the grid [2].

The inflexible load consisting of lamps, TV sets, and most kitchen appliances is difficult to transfer or regulate as it depends on user convenience and preferences [49].

Electric vehicles have promising prospects and will play an essential role in energy savings. The number of EVs in China will soon reach 5 million and amount to 80 million by 2030. The battery charging power will exceed 140 million kWh, while DR capacity will theoretically reach 50 million kW. By 2030, the DR capacity will reach 700 million kW. The current number of EVs in China exceeds 1 million. To achieve the optimal control of EVs charging and discharging and to regulate electric grid companies, charging or storage operators and EV owners, the selection can be made between the day-forward mode or real-time market operations [53]. Connecting multiple EVs to the grid can dramatically increase peak load; besides, they can provide power to the grid in the vehicle-to-grid (V2G) mode [39].

Distributed generation can affect power system voltage status and network losses. DG sources are installed near the center of the electrical load. Appropriate layouts can help reduce power losses [54].

The main objective function in voltage control strategies aimed at the reduction of voltage deviation is as follows:

$$\min f\left(v\right)=\sum_{k=1}^{N}\left(v_k-v_R\right)^2\geq 0, \qquad f\left(v_R\right)=0 \tag{7}$$

where v represents a voltage deviation vector at N monitoring nodes, and v_R is a reference voltage.

Based on load flow equations, the voltages in DNs with DGs is the function of the following parameters.

$$v=h\left(P_L,Q_L,n,P_{DG}Q_{DG}\right) \tag{8}$$

where P_L and Q_L—load parameters (active and reactive power), n—voltage regulator tap positions, P_{DG} and Q_{DG}—DGs active and reactive power [54].

Energy storage systems can operate at specific times or in emergencies. Devices of such systems target issues related to the quality of power, e.g., instability of frequency or voltage, and can be used in schemes aimed at prolonging battery life, etc. [54].

Many demand-response resources (DRRs), such as flexible loads and EV charging loads, are a part of DR. One response source has response parameters that vary depending on time. For instance, different power usage circumstances require different daily response capacities, response rates, and default power. Therefore, rewards and penalties vary depending on a consumer's ability to react. Rewards and penalties must be objectively differentiated depending on the circumstances under which consumers operate. Therefore, the circumstances must be categorized according to different response capacities and load response resources. DRRs mostly involve transferable load (TL) and interruptible load (IL), which have different response characteristics [52]. As a prerequisite for other factors, accurate load data is essential for DR. The development of the control system and the planning of incentives essentially depend on information about the load as it defines the possibility to alter the load schedule, i.e., it may influence the correct timing and amount of load switching and lowering [51]. However, the environmental impact of demand changes between peak and off-peak periods can depend, among other things, on a particular system's generation portfolio as well as interconnections between different systems [29].

The principal objectives of the DR system are summarised below:

1. To reduce the total energy consumption to achieve profits both for energy suppliers and consumers. This reduction should not only arise considering customer needs but also due to the losses associated with transmission and distribution systems.
2. To reduce the total power generated as the main outcome of the above-named goal. On the condition that a DR scheme is effectively executed, it can eliminate the need to initiate the use of expensive power plants to meet the top demand and enable energy suppliers to meet their pollution obligations.
3. To modify demand considering the existing supply, aiming to enhance the entire energy system's reliability and pay particular attention to regions that stand out by intensely used solar, wind energy or other RES.
4. To reduce or even eliminate distribution system overloads. A distribution management system (DMS) can help achieve this goal as it undertakes the monitoring of distributional functions delivered by the system and takes decisions in real-time required to improve the system's sturdiness [18,20].

Three main groups of barriers interfere with the DR deployment:

1. Technology-based hurdles, such as the lack of standardization and protocols and additional criteria for investments. It is difficult to ascertain the basis for business when investing in DR, as valuing DR is not a simple issue. It is difficult to decide who should pay for the necessary investment since the DR benefits are shared between various actors.
2. Established market structures and regulatory frameworks impede the DR deployment, i.e., integrating DR resources into existing markets while maintaining system stability or market entry barriers faced by DR manifesting as unequal treatment of participants.
3. Barriers are also faced by energy end-users, even though their participation is crucial to the DR success. Barriers related to technologies and regulations affect consumers, but they are also seen as barriers. There is uncertainty regarding the number of DR resources expected, as electricity consumers represent a very diverse and distributed resource [55].

Each of these control measures necessitates the creation of incentives or contracts for customers that take into consideration their behavior and preferences. DR solutions heavily on AI-based technologies to attain this purpose. Reliable and efficient communication must be ensured within a smart network to execute a DR scheme, namely, quality of service (QoS), interoperability, scalability, flexibility, and security [20].

Result analysis and discussion: The literature suggests that DR has a favorable influence on system operation and planning, with financial benefits for both the operator and the participating customers. The number of realities considered and the precision of DR modeling, however, are required for an appropriate assessment of these various DR advantages. The majority of DR models reported in the literature are limited to either the economic, technical, or techno-economic aspects of DR, but only a few have attempted to link DR with non-technical factors of customers such as household appliance usage habits, willingness to participate in DR, or other social aspects that have a significant impact on an individual's DR performance.

DR can also be divided into industrial, commercial, and residential categories according to the power usage of the end-user. Industrial and commercial demand consumes more energy than residential consumers, therefore a variety of enterprises engage in the electrical market at reasonable pricing. As a result, industrial and commercial customers may be able to quickly implement DR programs. However, because each sector works with various processes, it's difficult to build a generic way to assess their potential to provide DR services. Furthermore, predicting whether all companies will engage in DR projects is challenging.

The ToU is an economic response to DR that incentivizes user energy efficiency. The installation of smart meters with dynamic pricing schemes and user feedback demonstrates that users respond to the information/signals provided. However, the application of the ToU tariff system may not prevent various social problems. Lower-income families with small children seeking to benefit from cheaper tariffs may encounter some discomfort in meeting their needs. However, even average users may have dilemmas choosing the plan to satisfy their needs. To address these gaps, an automated system compatible with DR operation is needed. The system needs to have the capacity to adapt to a dynamic environment, learn and respond to the needs/requests of users.

A smart grid uses smart technologies, control, monitoring, and communication systems to integrate distributed generators and energy storage devices (including EVs) into the distribution grid. As renewable energy can be integrated into energy systems centrally and in a distributed manner, the power supply flexibility may be divided into conventional power supply flexibility and demand-side flexibility. EVs may be highlighted as having high potential in terms of DR as mobile energy storage. EV technologies are under development and deployment, battery production is also incentivised, and the V2H technology using bi-directional chargers may be distinguished. For household users with EV charging stations, the technology offers a flexible load possibility. At the same time, when designing a power system, it is important to consider the number of EVs, the number of charging stations (EV charging station-EVCS), their location and size, as this affects the system's performance. Research sources on the closer interaction of DGs and EVs were found lacking by the research. During the EV charging period, renewable energy may be insufficient to cover the EV charging load, which implies importing electricity from the grid.

Innovation in the energy system is also characterized as iterative design, deployment, improvement, and testing actions. DR deals with large amounts of data and processing, often requiring real-time decision making, which means that the energy sector has already started applying such technologies as artificial intelligence (AI), including machine learning, multi-agent systems, artificial neural networks (ANNs), nature-inspired optimization techniques. AI methods and algorithms can be applied across the whole DR spectrum to solve many problems, such as user clustering and assigning them attributes, load forecasting, dynamic pricing application, appliance control, resource planning, etc. In DR systems, the number of heterogeneous devices (EVs, batteries, etc.) is increasing, and their management problem is non-linear. AI approaches provide a better solution than traditional methods, which are likely to be less used or abandoned in the future. It is predicted that the DR of smart grids will be focused on highly precise control of user loads to be achieved by accurate load and cost forecasting. However, synergies with other energy forms (heating networks, gas, etc.) should not be forgotten. Multi-agent systems can be used in DR applications to apply multiple interacting agents to achieve better planning and decision-making results. The use of neural networks in DR applications would depend on the network topology (centralized, decentralized, local, hybrid) and the assigned numerical coefficients. AANs in DR applications can be used to predict the demand of specific groups/clusters, the price of electricity, both at aggregator and user level, etc.

It is possible to emphasize the benefits and drawbacks of previously created tools for implementing DR approaches. The lack of substantial technological hurdles to DR is a crucial advantage, as much of the essential communications and monitoring technology has already been established, with the installation of sophisticated metering infrastructure already underway in certain countries. The establishment of standards and protocols so that all components of this complex system are harmonized and efficient communication can be achieved across the system remains a technological challenge. The most significant remaining challenge for DR, in general, is the development of precise control and market frameworks to ensure that this diverse and geographically distributed resource can be optimally utilized, taking into account the needs of both the power system and the individual consumer.

4. Experience of Various Countries concerning Demand Response Programs

An analysis of scientific and applied sources revealed Europe's current focus on DR (load transfer rather than energy efficiency), monitoring, and SG-enabled control solutions. SG projects have been implemented for the last 20 years; however, their implementation was not uniform across the EU, and current efforts may be challenging in terms of cross-border cooperation. Another problem is that the EU has no harmonized DR policy or EU-wide programs. Countries that develop power supply systems based on SG technologies can allow their electricity users to participate in DSM programs. Previous studies suggest that DSM is the most beneficial when applied to major user sectors rather than minor, and source [8] states that European industrial users represent 36.1% of total electricity demand, while households and services represent 30.9% and 30.4%, respectively.

European countries are encouraged to open their markets to aggregators and DR, and only a few have done it so far [56]. DR is seen as an important tool for integrating renewable energy sources and a reliable electricity supply in Europe and the US [28,30]. However, in many developing countries, similar problems, such as a rigid electricity market or a monopoly, are almost non-existent [30]. The country where such a DR program is implemented represents a factor influencing the development and application of the program. It happens primarily because each country has different energy resources, different regulatory and policy frameworks, as well as different electricity markets. This results in different requirements for DR programs on the supply side. For instance, in some countries wind energy is more relevant, while solar energy is in others: different peak time of generation requires a different shift in demand [50]. Many nations throughout the world, including Germany, Denmark, Finland, and others, have significant variable renewable energy penetration in their power systems and are grappling with different grid reliability issues [57]. As the single European electricity market is not yet existent, programs in the EU countries are highly dependent on each country's initiative and its specific regulatory framework [45]. Cross-border interconnection would mean electricity transmission over high-voltage lines between countries, but it requires appropriate infrastructure and regulatory transaction processes [27]. Any country with one or more network points assumes responsibility for these connection points. This is known as the balancing responsibility, where the balance-responsible party (BRP) (countries) must develop programs related to electricity generation and demand [8]. Currently, individual EU member states have a set of four to nine separate electricity markets (day-ahead, capacity, next day, intraday, and balancing ones), and each of these markets has its own rules for participation [45].

The United Kingdom. The US started experimenting with DR in the early 2000s, but the UK network regulator OFGEM was only allowed to launch the capacity market in 2013 after the Energy Act was adopted to promote the DR development [26]. The UK was among the first European countries to open its markets to DR [55]. The UK market for DR in the electricity sector took hold when the national grid started using aggregator services to balance supply and demand for electricity in the transmission network through such programs as short-term operating reserve (STOR) [22]. The DR analysis shows that besides Belgium and Switzerland, the UK was the leader among European countries potentially most appropriate for comparison [22]. The UK is among the few European countries where the market and the regulatory framework enable the commercial and public sectors to participate in DR, and these account for about a third of the aggregators' portfolio [55].

Germany. Germany is often considered a leader in sustainable energy control [58]. It is a member of the synchronous area of continental Europe that has liberalized its electricity sector by separating its activities. Moreover, it has a top-most reliable system, ENTSO-E [8]. In Germany, energy efficiency measures are much more common than DR [28]. The German demand reduction control is particularly significant as it is based on comprehensive and high medium-term and long-term demand targets, some of which are more ambitious and longer-term than those set out in the EU energy efficiency directive [58]. The value of the German DR highly depends on the penetration of RES into the energy system and on the system's reliability [28]. In Germany, the penetration of RES is so high that the wholesale market has become too volatile [59].

German DR technical potential is 6.4 GW/h, of which 3.5 GW/h is reached under the current regulation and market scheme. If a more appropriate market and regulatory framework are developed, DR could reach up to 10 GW [60]. The country needs a good price-setting mechanism [59].

Finland. Finland is considered a leader among the European countries that has a DR system and is also a forerunner in the implementation of smart meters [15,61,62]. The Finnish transmission operator Fingrid Ltd. (Helsinki, Finland) is responsible for the network functionality and responds to demand through the existing market mechanisms [6,40]. As the country transitions to commercial activities, active retailers usually offer price tariffs to end-users insistently, thus encouraging a change in consumption depending on the market situation [62].

Switzerland. DSM policies are usually defined and implemented on the local level. Unlike other European countries, Swiss utilities have used two DSM tools for decades: ripple control and ToU. Ripple control is a traditional tool of load control to keep the power grid stable. A higher frequency signal is set on the standard power signal (50 Hz). Loads can be switched on and off, e.g., public street lamps, electric boilers, and heaters.

Most Swiss utilities apply ToU pricing to their users, where prices vary depending on the time of day, with higher daytime prices (during peak hours) compared to the night-time ones (during off-peak hours). The difference between peak and off-peak prices varies from 50 to 100%. In recent years, utility companies have introduced energy efficiency measures, such as smart meter rental, information campaigns, and the financing of efficient appliances [63]. By promoting RES, decentralized power plants can generate most new electricity; thus, additional flexibility will be needed at the medium and low voltage grid levels to balance supply and demand [64].

Norway. The main DR potential in Norway stems from electric heating in the industrial, household, and services sectors [6].

Belgium. Due to the planned decommissioning of some nuclear power plants and the steady increase in RES capacities, DR programs are increasingly in focus, especially in the residential sector [40]. The national transmission operator is looking for ways to promote flexibility through lower energy bills. Such flexibility is particularly important during winter months when electricity demand reaches its peak representing approx. 12,000–14,000 MW, which is approx. by 2000 MW higher than in summer [65].

Baltic Countries. The Baltic power grid's balance management is becoming increasingly complex for two reasons. First, the power of easily regulated traditional big power plants is dropping in the Baltics, while less controllable, less predictable, and distributed output, such as wind power, is expanding, comparable to changes in Central and South-Eastern Europe [66]. Second, the Baltic countries plan to disconnect from Russia's unified power grid by 2025, necessitating the development of extra flexibility sources to provide electrical balance in both normal and exceptional conditions [67]. This will be accomplished thanks to a project approved by the Coordinating Committee of the European Union Infrastructure Network's Connecting Europe Facility, which intends to make the Baltic power systems self-sufficient on a frequency basis with Poland and other continental European nations. In the Baltics, the energy-intensive industry is not highly developed, and therefore the DR potential is trapped in smaller consumer markets [68]. Implicit DR is now offered to consumers in Latvia and Estonia through energy supply contracts where the retail price is tied to the spot price. In Estonia, a DR aggregation pilot program has been undertaken since late 2017 [69]. The absence of a legal framework specifying the tasks and obligations of aggregators, as well as the compensation mechanisms between different energy system participants, is currently the major impediment for aggregators in Latvia [66]. In 2020, the Lithuanian transmission company "Ignitis" started its cooperation with an Estonian start-up Fusebox, which aims to become Lithuania's first independent power demand aggregator. The electricity demand service is a new addition to the Lithuanian electricity market, and it is critical in terms of energy security and efficiency.

Result analysis and discussion: Based on the analysis of the specific examples of countries, DR development practices in Europe differ from country to country. Depending on the country, contracts between market stakeholders may be concluded as bilateral transactions (over the counter (OTC) or through organised markets (pool auction, exchanges). Finland applies efficient DR systems and may be named the leading European country in this respect. The status has been achieved by the well-designed market regulation framework and technological investment. The UK was among the first to integrate DR solutions and is among the few European countries to have opened DR activities to the commercial and public sectors. At the same time, Finland and the UK are the only countries where residential users are aggregated. So far, Switzerland has not had a national policy framework related to energy efficiency. When analyzing the measures applied in Germany, we see that energy efficiency measures are much more common than DR measures. In Germany, DR has not gained much popularity due to the lacking regulatory framework, shortage of information, and a clearly insufficient common policy on financial issues. The most suitable option for Germany and Belgium is acceptance in the form of a "strategic reserve". This suggests that dedicated generating capacity will be retained in these countries to be used only if an energy shortage is imminent. In Norway, the highest DR potential comes from the industry, the service sector, and individual homes. The overall DR potential is particularly high in Norway and Sweden due to the widespread electric heating used for indoor spaces and water.

The technical rules should remain the same for cross-border members of the power system. To ensure the security of the interconnected transmission system, it is essential that load facilities and distribution grids, including closed distribution ones, understand the requirements for connection to the network uniformly. The voltage ranges of the interconnected systems should be harmonized as they are critical to ensure the reliable planning and operation of the power system of the synchronous area.

The evolution of the legal framework at the national and EU levels requires special attention. The focus should be directed to creating and studying potential business models and services, which must comply with EU and national legislation. Each country must define its own goals for what it wants to accomplish. It is important to focus on DR programs, evaluate them, verify their functionality, and, if required, make new program proposals. If new DR concepts become developed, it will be important to evaluate how they should be implemented and function. Participants, both developers, and consumers, could get some assistance in the early stages.

The more detailed research and follow-up of this study will focus on applying specific DR measures in various parts of the world and assess renewable energy sources, legislation, and applicable policy frameworks.

5. Blockchain-Supported Demand Response in Smart Grids

The electricity sector must reduce electricity generation and primary energy consumption. More intense utilization of smart energy solutions (SES) is one of the measures that can help achieve these goals. However, the spread of SES should not be encouraged for its own sake but as an instrument to reach common goals [70].

However, because of the great complexity of DR activities, their use of large-scale data, and the frequent requirement for near real-time choices, artificial intelligence (AI) and machine learning (ML) (a branch of AI) have just lately emerged as crucial technologies for enabling DR [32]. Power production and supply were revolutionized by the internet of energy (IoE), which used the internet to connect sensors, RES, SGs, and various other technologies [1].

Internet of energy (IoE) with energy trading is given in Figure 9.

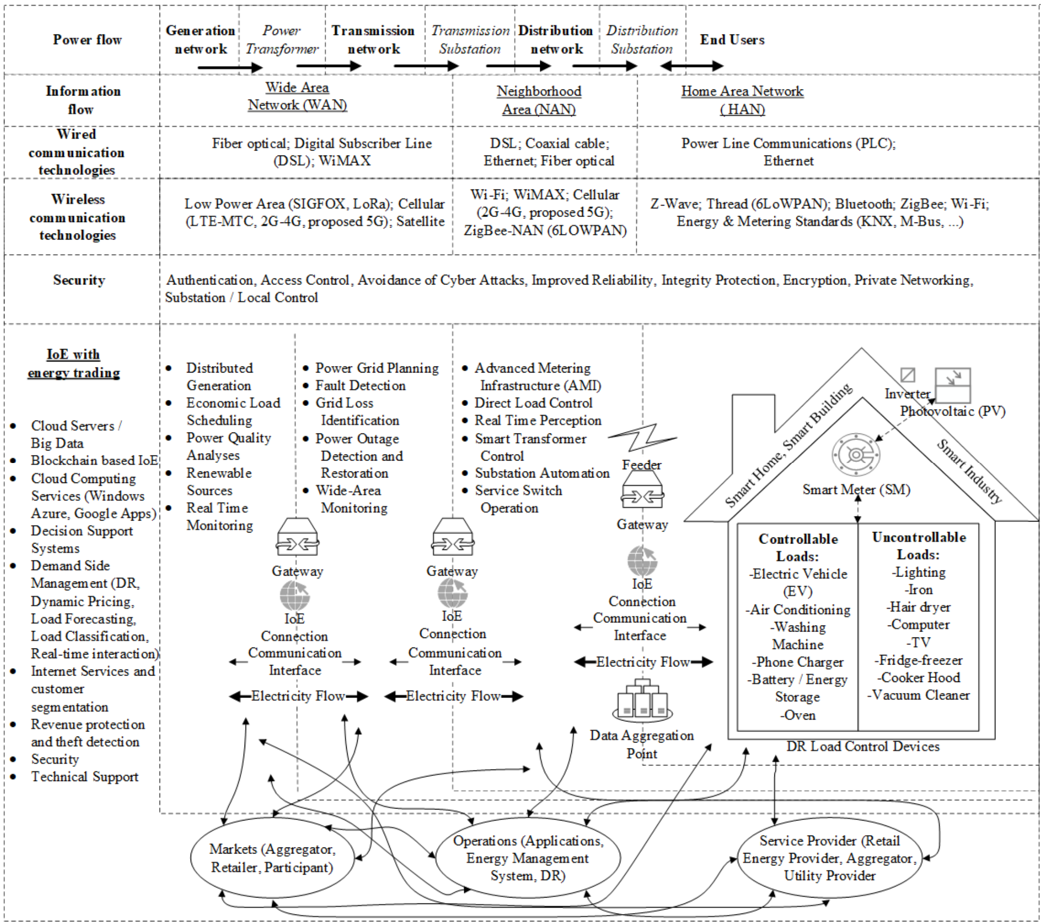

Figure 9. Big data-related sources of IoE: energy domains (generation data, transmission data, distribution data), energy sectors (residential, commercial, industrial), functional blocks (platforms, services, applications, and clouds), hierarchical networks (HAN, NAN, WAN).

Conservation and energy efficiency initiatives, DR programs, and residential or business load control programs make up DSM programs. Smart homes can increase the flexibility of the power load and give great possibilities for power DRs by altering the schedule of consumer electricity usage. However, the magnitude of the potential impacts of smart homes participating in power demand response is uncertain, and very little research has been undertaken on the field. In particular, smart homes can participate in power DR in two ways: (a) smart homes can achieve "peak shaving and valley filling" to flatten the load curve by transferring the load throughout a particular time horizon; and (b) smart homes can transfer a load to a low-priced time period to save on residential electricity fees.

The concept IoE evolved from the internet of things (IoT) to refer to industrial applications that incorporate ubiquitous computing, big data processing, and machine to machine (M2M) communication [71]. Through standardized communication protocols, the IoT expands the range of the internet to reach the devices installed on the energy system [72]. Multiple energy sources, supply and demand coordination, centralization and decentralization, and substantial public engagement are all characteristics of IoE [73]. IoE promises many important benefits, including power monitoring, energy demand management, spreading integration of renewable energy, less wasted power, reduced power outages, self-regulation, and resource control [1]. The IoE is a grid that connects a large number of distributed energy harvesting devices, distributed energy storage devices, and various types of loads to achieve efficient, clean, and safe energy consumption [73].

Objectives of the IoE technology are given in Figure 10.

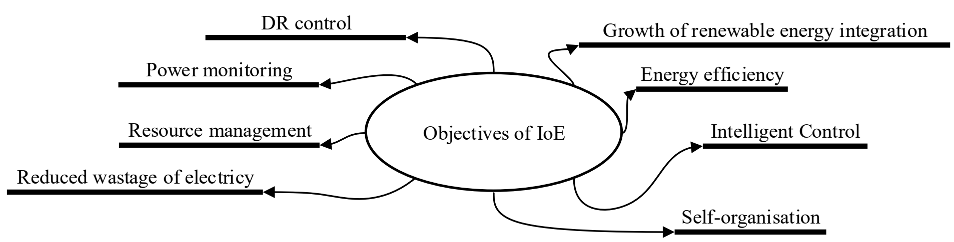

Figure 10. Objectives of IoE technology [1].

Large data gathering and the deployment of intelligent algorithms (for example, for DR and economic dispatch—evolutionary algorithm, particle swarm optimization [74], game theory [75,76]) for real-time data analysis can assist in monitoring and controlling energy usage trends of diverse users and devices throughout time scales [77]. Interoperability, security, scalability, precision, accuracy, programmability, low latency, dependability, resilience, automation, and serviceability are all examples of how the IoE may save energy in industrial processes [71].

IoT systems rely on data collected from numerous types of sensors, each of which has limited resources. The data received from the sensors are sent to the cloud, processed, and stored [78]. The cloud analyzes data using a variety of artificial intelligence technology and presents it to the consumer as data analytics. Microsoft Azure IoT Suite, IBM Watson IoT Platform, Google Cloud IoT Platform, AWS IoT Platform, and Cisco IoT Cloud Connect are some of the most popular IoT cloud platforms in the market [78,79]. However, implementing IoT in energy systems has its own set of challenges, including security, bandwidth management, interface compatibility, connection, packet loss, and data processing [72].

The centralized classification of systems within the IoE is given in Figure 11.

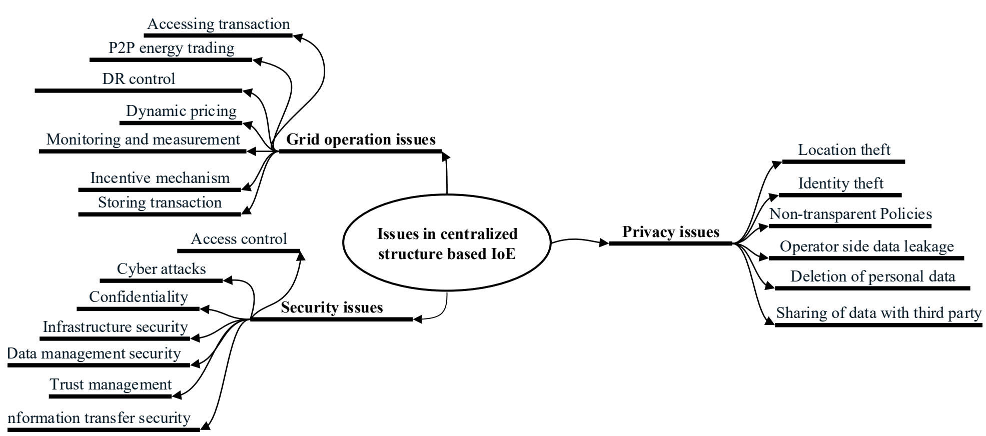

Figure 11. Centralized classification of systems within the IoE.

IoE for Smart Grids. Smart grids provide a two-way connection between consumers and operators, enabling the improvement of reliability and optimization of energy production, transmission, and distribution to: (i) reduce electricity costs, (ii) manage peak loads, and (iii) reduce electricity costs for RES generation fluctuations, which can disrupt energy systems [49]. An SG, on the other hand, enables a solution for energy production, supply, and storage, attaching data on the latest energy prices [1]. Implementing SGs in distribution networks requires innovations overcoming network constraints in cases where usual grid strengthening solutions are expensive or inapplicable [22]. Constraints of conventional centralized power systems are challenged mainly by the wide-scale deployment of smart metering devices and the possibility to integrate many distributed small-scale RES [34]. The current energy sector must transform into decentralized and distributed, and these facts indicate such a need [1]. Nevertheless, energy management in decentralized energy systems is complicated, especially in the case of the high penetration rate and speed of fluctuating RES and battery energy storage systems (BESS) [49].

However, in the context of Smart Grids, DR schemes pose significant issues, which we will describe below. First, interoperability in the power market arises from countless utility suppliers, sellers, and hardware and software stakeholders. Secondly, the mass deployment of smart meters, IoT devices, and DERs results in the growing number and complexity of agents and actions associated with power systems. Finally, the aim to encourage buyers and various energy sector players to participate in wide-scale DR schemes and facilitate market growth necessitates a decentralized infrastructure that at least provides a possibility for a financial settlement in energy transactions [80]. Consequently, B2B e-commerce platforms are utilized to benefit from the growing energy demand and numbers of involved parties. Standardized market procedures function as the foundation for such platforms, yet they can be adjusted accordingly, depending on their purpose and function. Balancing market processes can serve as an excellent example because they cover various major functions, including the supply of energy and ancillary services. Ancillary services can also be offered by service providers, and such services can be defined as special solutions for standby power generation capability or controlled energy usage. A market operator initiates the provision of balancing services following internal/external rules and generator schedules [21].

IoE and solar energy. The application of AI techniques in solar PV farms has been available for the last two decades in order to improve modeling, control optimization, and output power forecasting efficacy of the sizeable datasets [81]. The controller and the electrical appliance are the two primary components of every DR program. To put it another way, the DR program assists in the balance of power generation and consumption, and the two control loops (supplementary control and DR control) work together to govern the system [82]. IoT can assist in real-time data sharing from PV sensors, as well as remote controllability over the functioning of solar units for breakdown and defect detection, as well as predictive and preventative maintenance [83]. Recent applications of smart PV monitoring systems based on IoT are presented in [84–87]. PV modules are observed and managed like IoT nodes using smart monitoring systems [81].

As the use of solar energy grows, distribution system operators (DSOs) are increasingly likely to pay attention to the impact of PV intermittency on optimum power flow (OPF) and voltage control. One efficient strategy to address such PV integration difficulties is to fully use DR capabilities [88]. In addition, technological advancements have enabled systems to incorporate a variety of inverter control strategies. Furthermore, these inverters perform a variety of tasks, including voltage control, active and reactive power production, and power extraction from the PV module or array [89]. Frequency is regarded as a major factor of network stability [7,21]. A deviation from the normal frequency either implies a demand for more power or excess power in the system [21]. In such an instance, the system frequency drops with demand being higher than supply and vice versa, making DR an effective solution for the maintenance of network frequency [42]. The majority of the devices used in DR programs can swiftly turn on and off, balancing the needed power on the consumer side for system stability [82].

The single-phase PV inverters may inject uneven power from energy sources located at different locations in an active distribution system. When voltage control and DR are used at the same time, the three-phase symmetry of voltages and currents can be disrupted by single-phase devices such as inverters, voltage regulators (VRs), and capacitor banks (CBs), resulting in increasing imbalance levels [90]. A smart PV inverter or a standard PV inverter connects a distributed PV system to the grid [91]. Smart PV inverters are the only ones that can execute sophisticated control functions for PV systems (e.g., active power curtailment, fixed power factor control, volt-var control, volt-watt control, and frequency-watt control), whereas standard PV inverters can not. As a result, smart PV inverters can minimize the number of voltage and frequency control devices that must be installed in an electric power grid, lowering installation and maintenance costs [91].

Communication system. Modern SGs can now communicate bidirectional information and data quickly and reliably thanks to developments in communication technology [90]. The marketing and emergency signals of DR may be delivered using a two-way communication system (wireless, wire, GSM, and internet) to improve power reliability and quality as well as prevent electricity blackouts. Furthermore, this type of technology aids the utility in settling the billing system and sending incentive offers to consumers who verify DRs [92]. In this context, the IoE can match supply and demand data in real-time, integrate and distribute demand, and produce energy transactions and DR. Instead of being sent to a remote location, energy data is dispersed and kept on a specific node in the local or network [82]. The communication protocols allow the various devices to communicate with the controllers or decision-making centers and share their data. LoRa or Sigfox (acts as a backbone for the cloud-based services in future grids), ZigBee, Z-Wave, Bluetooth, Wi-Fi, and cellular technology like LTE-4G and 5G networks are just a few examples of these technologies [77,93]. 5G technology can address various current challenges related to faster transmission, shorter communication delay, better security, and higher interconnectivity of devices [7]. Because of its low latency and great dependability, 5G is a viable alternative to fixed connections. Special performance requirements, especially very low latency (less than 1ms), are common in SG communication [94]. A clearly superior DR infrastructure will emerge with further development of 5G solutions, which will raise the bar in terms of transmission, trustworthiness, safety, and interconnectivity [7]. Open automated demand response (OpenADR v2.0) is a new standard for the transmission of DR signals between system operators, power suppliers, customers, and connected installations with the help of existing IP networks, such as the internet. The increase in the number and intricacy of agents and operations related to power systems results from the mass deployment of smart meters, internet devices, and DERs [80]. For instance, new smart meters with a dedicated communication channel at home area networks have been developed by Enel Info +, Smart Demo Grid, and FLEXICIENCY projects [7]. Currently, the popularity of outsourcing platforms is growing. Many platforms hire agents to serve consumers who consider wait time an important factor [95]. DR aggregators can use available innovative technologies to meet the requirement for each DR installation to have online bidirectional communication with a national control center [7].

Cybersecurity challenges in smart grids. Improved sensing, communication, and control techniques are necessary with the introduction of smart grid technologies that accommodate DERs and EVs [96]. Cybersecurity breaches, cascade failures, blackouts, and other attacks on the electric grid can result in infrastructural breakdowns [94]. For example, information regarding the availability of residents may be gleaned from the use of heater or air-conditioning data in a residential home management system throughout the summer or winter seasons. This information leak might lead to the robbers committing a criminal conduct in the house. This is a critical issue since the central server stores all of the utility providers' information and needed data and is accessible to regulators at any time [93]. Various devices linked over wide geographical area networks pose a problem for smart grids. The most difficult task is securing small devices in the context of broader infrastructure [97]. Cybersecurity has received more attention in the frame of current DR projects and respective communications systems, for instance, OpenADR in the US and China's reform of the management system for air conditioning in public buildings [7].

Blockchain for secure smart grid. The aim to develop a decentralized energy system based on micro-grids, RES, and EVs demands a trading model that is reliable, scalable, and efficient. Besides, communication, transmission, and distribution infrastructure must be improved, ensuring the possibility to manage network processes and functions autonomously. The growing number of security and privacy challenges posed by IoE centralization accelerates the utilization of new solutions. Blockchain technology can serve as an example as smart contracts and cryptography can be employed to achieve complete decentralization and autonomy [1,98]. Consumers demand a smarter, cleaner, and more sustainable energy supply with advancing technologies and declining renewable energy costs. Blockchain technology will encourage sustainable power consumption and achieve the circular economy by offering a decentralized exchange mechanism [99]. Initially used for the digital currency Bitcoin, the blockchain technology allows entities to safely engage in transactions and ensures direct contact between buyers and sellers without any third parties. Bitcoin was followed by the second generation of blockchain technology known as the smart contract platform for the creation of smart contracts [80]. Founded on the principal initially used for Bitcoin, blockchain for smart contracts is considered a new technology that can be used in a decentralized network topology that enables the mechanisms required for distributed operations [34]. Blockchain can be used by power companies for smart contracts on DERs, e.g., to receive, finance, and trade power generation from RES [1,80]. The deployment and utilization of RES and the smart grid will make blockchain technology crucial in developing the IoE market [1]. Blockchain, IoT, and other interconnected intelligent devices help the seamless operation of intelligent grids and make energy transactions more secure and efficient. At the same time, it allows using power from micro-grids, power grids, and other sources [80]. All possible advantages for promotion should be used, and more active efforts are required to develop possible successful system protocols for blockchain-based power systems [95].

Several articles stand out in the study of recent research that employs differentiated indices to lessen the impact of DR technology on customers. The authors of [100] offer a new method for reducing customer discontent, system capacity, and demand rebound by constructing consumer convenience and demand rebound indices and creating objective functions based on these indices. The authors of [101] concentrated on a self-scheduling model for home energy management systems (HEMS), proposing a novel formulation of a linear discomfort index (DI) that incorporates end-user preferences into the everyday operation of home appliances.

To develop a sustainable energy system, there is no one-size-fits-all approach. Rather, the shift should be undertaken methodically, taking into account all available technologies and methods.

Result analysis and discussion: The introduction of smart meters, AI, internet technologies, and smart energy solutions (SES) to the electricity market is changing the way energy is supplied and patterns of electricity use. New technologies can contribute to more sustainable, secure, and efficient energy systems. Smart devices and numerous virtual platforms are becoming instruments that consumers use to play with and adapt a smart energy system to their behaviours. In the near future, properly coordinated and managed devices (such as smart meters, PV inverters, etc.) will play an important role in energy infrastructure. The IoE enables the use of smart devices in conjunction with the internet to contribute to a sustainable energy system. When dealing with big data and IoT, the need to process and analyze this data arises and results in machine learning. Machine learning techniques can be used to predict demand, load, electricity prices, etc.

However, another problem faced is the number of devices used in DR applications on the service provider's and the user's side. It is technically difficult for a service provider to manage all user clusters with their devices. An automated device control system is needed to solve this problem.

The reason behind the slow dissemination of IoT is an especially wide variety of communication standards, which are niche and keep growing in numbers every year. Different communication connections (e.g., KNX, ZigBee, Z-Wave) between devices stand in the way of unified operation. A solution could be suggested, e.g., for large manufacturers, such as Google, Amazon, and Apple, to cooperate in providing one standard and making it open (with smaller manufacturers possibly contributing), which could make IoT popular. Applying Wi-Fi technology, there is a disadvantage on the energy side being less efficient compared to, e.g., ZigBee, Z-Wave. Different standards consume an energy source differently; thus, it is important to evaluate and select the technology for devices to be installed in a smart home or network.

5G technology is based on marketing. It allows to transfer more data and ensures faster feedback; however, the stability can be affected, and packet delays are possible.

Because of the growing use of inverter-based resources, synchronous grids' inertia response and main frequency control capabilities are deteriorating. Differently from conventional electricity networks, distributed energy resources have no clear harmonized standards and network codes, lack the diversity in network topology modeling with network-supporting or shaping technologies, there is an increase in control points, etc.

The management of large amounts of data is the essential problem related to data acceptance in the development/teaching of load forecasting models. With large networks, tens of thousands of substations must be managed. The design of appropriate mathematical models should result in the data exchange ensuring the collection of substation data and the option to update substation management functions (e.g., load forecasting, customer segmentation, scheduling, and control consumer/aggregator).

The IoT deployment in the smart grid infrastructure is also subject to cyber-attacks. The smart grid is exposed to malware, resulting in inevitable financial losses, physical risks, or confidential data leakage. There are security standards in place, but compliance with standards does not always protect against cyber-attacks. Many different types of attacks are identified, which are grouped into insider threats caused by the ones within the network, and external threats, where a cyber-attack is launched to the system from another network. Cyber-attacks are identified as data theft from smart meters, breaches of communication infrastructure, misleading information sent to users, use of energy storage equipment, etc. When purchasing a device, the price must be considered as well, as it may conceal certain technological solutions for the collection of data about the user. Equipment from well-known brands usually has security issues resolved. Devices made by well-known manufacturers are difficult to "hack" as they aim to protect their reputation. Machine learning techniques are used to ensure cybersecurity. The application of blockchain technology to the internet of energy (IoE) can increase security against cyber-attacks. There is a growing interest in smart grid cybersecurity among the research community, which shows the relevance and promise of research in this area. Applying blockchain technology on the IoE could incite aggregator fraud schemes. Popular platforms (e.g., Discord channel) and social networks (Facebook, Instagram) with large user numbers can be employed to target audiences with advertising on how to make money quickly. This means that experts (or aggregators in this case) would advise household, industrial or business consumers when it is appropriate to trade electricity based on the offered price signals. Aggregator fraud schemes may emerge based on monthly or annual membership fees for household, industrial or business consumers to fictitiously supply good price offers for the trade electricity daily (or even in real-time). Investing in electricity trading platforms could be another suggestion for household, industrial or business consumers desiring to earn a high income quickly. For those lacking initial large investments, the electricity trading platform organizer could offer leverage to borrow money. The larger is the investment, the higher is the fee paid to the organizer who would incur no risk. However, the leverage might result in a situation where the fall in the bitcoin price leads to the loss of the entire investment for the investor. Such trade would be rapid, risky, and dependent on unreliable signals, leading to a loss of the entire investment. Moreover, registered platform members could be offered incentives for bringing new users. Such fraudulent schemes may become very popular. An injured participant-consumer may press charges, claiming they followed all recommendations and invested based on sent signals but incurred losses. However, fraudsters bear no responsibility for their actions as they only provide recommendations on the use of price signals without involving any coercion.

To facilitate the transition of ordinary users to innovative technologies and more efficient electricity use, they must be enabled to play an active role in the energy market. Many people lack information to make decisions regarding the most appropriate technology for a particular case. Consequently, it would be appropriate to apply a smart recommendation system platform. The recommendation system would inform consumers about certain alternative services, service prices, and all this could be presented in the form of advice. The application of such a service in DR control could greatly improve user energy efficiency.

6. Conclusions

DR is one of the most important instruments for market-based effects created by transmission and distribution system operators and energy suppliers for end consumers. This approach can be used successfully for handling peak loads in power systems, and DR increases competition in the balancing market. The effectiveness of DR programs has been demonstrated in mitigating most power system challenges, such as high production costs during peak hours, reliability issues, and overloading in the generation, transmission, and distribution systems. However, adopting these measures poses challenges for users, as they lack the technical expertise, money, or time to implement such measures. Consumers, DSOs, load-serving entities (LSEs), aggregators, and other stakeholders must all be considered when estimating the impact of DR prior to its adoption. Such analyses are extremely important for power system planning and operation, as well as for consumers. Due to a broad client base with a variety of appliances and usage patterns, the work is time-consuming. Due to a broad consumer base with a variety of appliances and usage patterns, the work is time-consuming. According to empirical research, the most prevalent hurdles to success originate from customer incentives, supplier incentives, or industry structural features, and in many cases, they relate to insufficient knowledge. This means that users delegate energy system issues to aggregators, contract consultants, etc. DR programs, on the other hand, have failed to secure a permanent place in many of the world's power sectors, whether regulated or liberalized.

In terms of DR, any business model is subject to constraints similar to principles that apply to DG; therefore, an open energy market is required. An effective open market requires advanced communication infrastructure and real-time response, and two-way communication can lead to novel and more efficient energy consumption and higher consumer compensation for services.

Unfortunately, in many parts of the globe, DR is still considered an experimental approach since programs typically fail to fulfil their objectives and potential. The article presented the largest European markets with demand management systems. The positive effect on technologies, infrastructure and the economy of the energy sector is confirmed by the experiences of countries that have implemented such solutions. Increased social consciousness in the control of energy use dictated by network demand has a positive impact on the production of DR. Moreover, trans-border links are an integral part of ensuring the energy stability of power systems. Based on research, high-end energy infrastructure, SG systems, the IoT, DR services, and other new technologies are likely to grow more popular in developing countries. Inadequate collaboration between TSOs, DSOs, aggregators, and users is a barrier to DR implementation. Other barriers include the lack of technical requirements for DS capabilities, the shortage of incentives to invest in transfer, and the absence of uniform conditions to access wholesale and retail markets. Aiming to ensure economically effective DR utilization for load matching, it is recommended to harmonize the methods used for price-setting. Such a solution would ensure that market players receive incentives and the right price signals.

The centralized market model allows all electricity generation and DR companies to participate logically and competitively. While the drawbacks of a centralized trading model can be compensated for by a blockchain-based distributed trading model, there are many ongoing technological challenges and restrictions associated with applying blockchain technology to the needs of trading in the energy sector.

Innovative energy services are key in the effort to solve difficulties connected with energy inefficiency and assist users in transitioning to actions directed towards energy sustainability. To achieve these goals, scientists have extensively used artificial intelligence solutions to address situations where traditional methods could not provide sufficiently efficient or reliable results. However, many of the proposed solutions are short on experimentation, modeling, and real-world application. Thus, to develop more accurate models and AI solutions, additional research initiatives, feasibility studies, and closer engagement of industry, business, and users in research are still needed.

A thorough literature review suggested that the following advanced smart grid functions need to be further developed: the retrofitting projects for industrial, service or individual buildings must install the highest possible number of smart devices and optimisation instruments to respond to smart grid and service signals and contribute to the increase in energy efficiency; the development should focus on information and communication channels and various social platforms to provide consumers with commercial offers of services based on their lifestyle, i.e., habits and social status, thus encouraging them to participate in DR programs, at the same time ensuring reliable communication, data security and privacy; loads should be predicted using artificial intelligence solutions aiming to maintain the stability of energy networks; DR applications should be further developed, searching for alternative services or selecting the most advantageous ones from the available services to design a hybrid service that would contribute to the maintenance of frequency stability and the reduction of power quality (Power quality) interferences; the communication should be maintained (and improved) for a fast response between distributed RES and inverters, which determines the quality of electricity and affects energy prices.

Future research should focus on the evaluation of the DR system by companies in specific sectors.

Author Contributions: Conceptualization, D.S. and V.R.; methodology, D.S.; validation, D.S., N.R. and V.R.; formal analysis, D.S.; investigation, D.S.; resources, D.S.; data curation, D.S.; writing—original draft preparation, D.S.; writing—review and editing, D.S.; visualization, D.S.; supervision, D.S.; funding acquisition, V.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DERs	Distributed energy resources
DG	Distributed generation
DLC	Direct load control
DNOs	Distribution network operators
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EVs	Electric vehicles
IL	Interruptible load
IoE	Internet of energy
IoT	Internet of things
ISO	Independent system operator
RES	Renewable energy sources
RTO	Regional transmission organization
SG	Smart grid
TSOs	Transmission system operators
VPPs	Virtual power plants

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