Review

A Critical Review on the Impacts of Energy Storage Systems and Demand-Side Management Strategies in the Economic Operation of Renewable-Based Distribution Network

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Abstract: Energy storage systems (ESSs) and demand-side management (DSM) strategies have significant potential in providing flexibility for renewable-based distribution networks. Therefore, combining ESSs and DSM strategies with renewable energy sources (RESs) to solve economic, operational, environmental, and power-related political issues has received special attention from power system planners around the world. In this regard, developed countries, which are pioneers in renewable technologies, have proposed various supportive policies and practices for the widespread use of ESSs and DSM strategies in the context of distribution networks. Hence, this paper performs a comprehensive review of the most recent actions taken to build the infrastructure necessary to achieve 100% renewable energy. On this basis, this paper firstly surveys the necessity of using ESSs and DSM strategies in renewable-based distribution networks. Then, the existing policies and incentive programs implemented in different countries for the development of RESs in optimal coordination with ESSs and DSM strategies are presented. The impacts of utilizing ESSs and DSM strategies in improving the economic performance of the renewable-based distribution networks are also investigated. Finally, prevalent energy management strategies, which are proposed to optimize utilization of ESSs and DSM strategies in renewable-based distribution networks, are investigated from the perspective of optimization approaches.

Keywords: economic assessment; energy storage systems (ESSs); demand-side management (DSM); renewable energy sources (RESs); supportive policies

1. Introduction

Environmental change is a global crisis that goes beyond national economic policies. In this regard, the Paris Agreement, which was ratified with the participation of 196 parties at the annual conference of parties (COP21) in Paris, is the largest global action to overcome the environmental issues [1]. In line with the strategic objectives set out under the Paris agreement, the committed parties annually unveil several projects to increase the penetration rate of renewable energy sources (RESs) in power systems [2]. To this end, significant incentive schemes and policies have been considered by governments to develop RESs and support investors. In the meantime, a major part of RESs development projects, especially photovoltaic (PV) systems and wind farms, has been implemented

in distribution networks [3]. Despite the sustainability and environmental benefits of RESs, power system operators face two major challenges when integrating the high-power RESs into the grid [4]. Firstly, the power output from RESs strongly depends on climate conditions and is not controllable [4]. The stochastic and intermittent characteristics of RESs affect the reliability of power grids and may cause instability of grids. Hence, the stability and reliability problems can be exacerbated by means of the high penetration of variable RESs. Secondly, the existing infrastructure of power grids is not compatible with increasing the penetration of RESs, which obliges the power grid operators to curtail a significant percentage of renewable power. For example, the curtailment ratio of wind and solar power in Germany's power grid from 2009 to 2018 is shown in Figure 1 [5]. As can be seen in this figure, the rate of wind and solar power curtailment in Germany's power grid hit a record of 5.37 TWh in 2018.
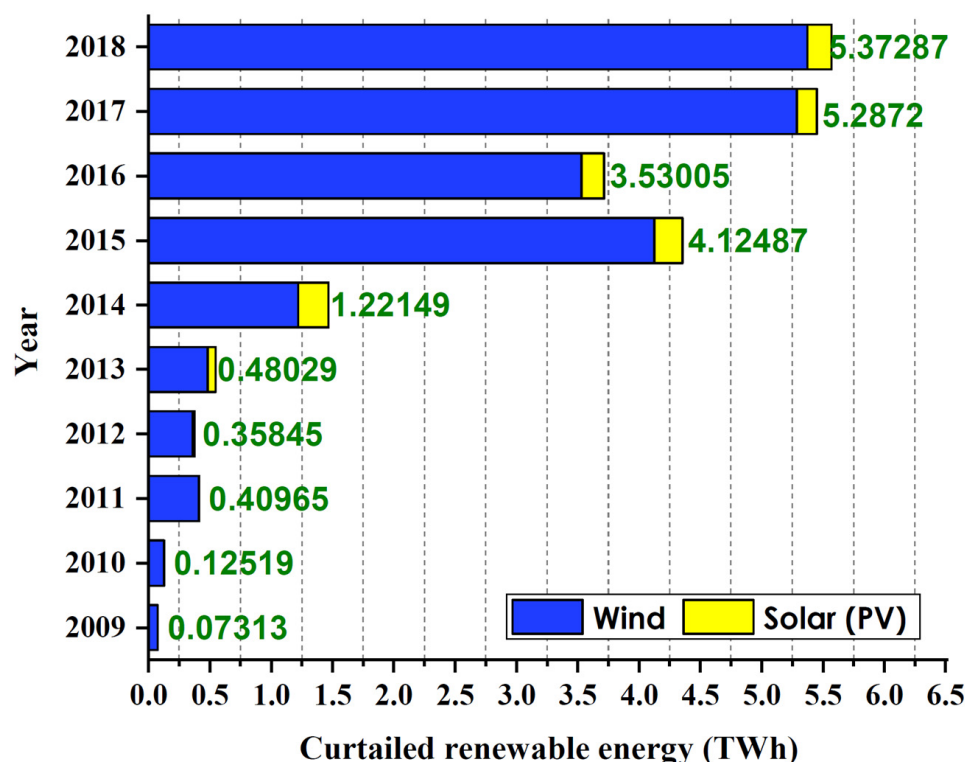

Figure 1. Curtailed wind and solar energy from 2009 to 2018 in Germany [5].

By examining the conducted studies can be found that an effective solution to deal with the above-mentioned challenges is to use flexibility options, such as energy storage systems (ESSs) and demand-side management (DSM) strategies [6]. According to some strong evidence, DSM strategies and ESSs have an undeniable role in increasing the penetration rate of renewable power production by decreasing short-duration variability due to the uncertain and intermittent nature of RESs [7]. Hence, these options should be prioritized by power grid operators to determine efficient policies to cope with social, technical, environmental, and economic constraints from a practical standpoint [6]. On this basis, the impacts of ESSs and DSM strategies on optimal use of RESs were widely addressed in the literature, and participation of these options was investigated in terms of technologies, mathematical modeling, and energy markets. For instance, in [8,9], the uncertainty and technical challenges for high-power RESs utilization were reported, while the advantages of DSM strategies and ESSs were evaluated as the flexibility options to meet the existing challenges. In [10,11], the three principal branches of the DSM strategy, namely, energy efficiency, orderly power utilization (OPU), and demand response programs (DRPs) were investigated with the aim of incentivizing the subscribers to take part in the DSM

programs and increasing the penetration rate of RESs. In the same works, various optimization models for optimal execution of DSM strategies, especially DRPs, were developed according to the optimization objectives, social and economic welfare indices, and technical constraints. The authors of [12] investigated the importance of the various types of ESSs for future renewable power systems to absorb and release renewable power in different scheduling periods. As stated in [12], ESSs can offer unique opportunities to distribution companies to mitigate the disadvantages of using RESs by smoothing power fluctuations of RESs, matching supply and demand, and balancing the power flow in the grid. For this purpose, various ESSs were categorized in terms of technical characteristics, energy policies, innovative technologies, and regulatory regimes in [13] so that the distribution network operators can use the most appropriate type of ESS depending on different geographical locations. To do so, in [14], the optimal allocation of ESSs in radial distribution networks was evaluated in the presence of high-power RESs to specify the optimal ESSs locations and power rating of ESSs. All existing studies have unanimously emphasized the importance of using ESSs along with DSM strategies for the efficient use of high-power RESs.

Another set of studies was devoted to investigating the techno-economic barriers resulting from the development of ESSs and DSM strategies in the presence of high-power RESs [15]. In this category of studies, incentive policies and economic roadmaps prepared by system planners and policymakers were analyzed to maximize the utilization of RESs in power grids. For example, in [16], the governing policies in China were evaluated to integrate DRPs and RESs, and the urgent and necessary reforms to align energy markets with existing policies were proposed. However, supportive policies for the use of ESSs in coordination with RESs were recently adopted and promoted in many industrialized countries. The authors of [17] reached the point that, by using supportive policies to develop DSM strategies and ESSs, it is possible to eliminate the obstacles that prevent the sustainable growth of high-power RES in power grids. The obtained technical results in numerous studies indicate that the incentive policies allocated to the investors, end-users, and on-site units' owners to participate in the DSM strategies and/or to install ESSs play an important role in the green infrastructure implementation that is suitable for low carbon emissions.

Given the existing literature, many surveys have examined only technical barriers to the integrated use of RES, ESSs, and DSM strategies in distribution networks. Nevertheless, the economic contexts and incentive policies of pioneering governments to improve the performance of the renewable-based distribution networks with special emphasis on the use of ESSs and DSM strategies were not well indexed. Given the new policies in many industrialized countries regarding ESSs and DSM schemes alongside RESs, there is still a need to investigate the necessity of using the technical and economic potentials arising from these ancillary services. To this end, this paper reviews the previous literature from three aspects: (i) the necessity of using ESSs and DSM strategies in renewable-based distribution networks in terms of technical issues, (ii) the role of supportive policies developed by different countries to use DSM and ESSs options to increase the penetration rate of RESs in creating economic opportunities, and (iii) existing economic optimization models for distribution networks to maximize the utilization of RESs by relying on the ESSs and DSM strategies.

This paper is organized into six sections. In Section 2, the need to use the DSM strategies and ESSs in the presence of RESs in distribution networks is presented to address the key technical issues. Section 3 highlights the supportive policies for deploying ESSs and DSM strategies in renewable-based distribution networks in some of the countries that have adopted them. Section 4 evaluates the impact of utilizing the ESSs and DSM schemes in improving the economic performance of the renewable-based distribution networks. In Section 5, the architectures of the DSM strategies and ESSs are explained, and the related literature on the optimal operation of renewable-based distribution networks by relying on the DSM strategies and ESSs is reviewed. Finally, Section 6 concludes the paper.

2. Urgency of Using ESSs and DSM in Renewable-Based Distribution Networks

The electricity grid has been developed according to the need of recent technological trends. Conventional grid solutions fail to meet growing demand, consumer's expectations, data security, reliability, etc. These issues emerged a transformation to the smart grid concept with increasing penetration of distributed generation, replacing the conventional load with demand response from consumers, development and integration of ESSs for an overall and better solution to conventional grid issues. Shortage of conventional energy sources and environmental concerns speed up the development of clean and sustainable energy. As RESs, such as wind and solar, have increasingly integrated into the grid, new challenges for operation and planning have emerged. Intermittent and variable renewable generation creates a number of issues like power quality, reliability, generation dispatch, and protection [18–20]. ESSs have been conceived as a tool for mitigating the impacts of renewable energy uncertainty [21]. Along with this, with high penetration levels of renewables, the distribution network needs greater flexibility to adjust supply and demand to maintain system stability in a cost-effective way [22]. Network operators also want to use existing energy efficiently to meet the increasing demand with avoiding extra expenditure; therefore, they implemented DSM programs [23]. With different strategies like DRPs, DSM aims to reduce the cost of electricity by managing the energy consumption of end-use customers.

2.1. Effects of Renewable Penetration on Distribution Networks

In the distribution networks with distributed generation, different issues have been reconsidered, such as power quality, active power reserves, load following capacity, frequency control, voltage profile, reactive power, voltage control, network losses, protection aspects, and system safety. Many of those may be improved by properly distributed generation integration as well as its contribution to system restoration, black start, and solving network bottlenecks [8]. Due to environmental concerns increasing penetration levels of distributed generation based on renewable sources, some other issues need to be considered caused by the variable and almost unpredictable behaviours of them. RESs cannot be dispatched due to the generation availability at different time scales [24]. Many studies offer programs for frequency regulation problems and RESs [25,26]. Control of microgrids also includes many issues that are discussed in [27] like bi-directional power flow, stability problems, the uncertainty of load profile, and weather forecast. The authors of [28] investigated the impact of penetration level of wind power systems (5–35%) and their location. They found out that the system operated better at low penetration levels considering voltage stability, and it is better to connect wind power systems at several points instead of a single point. On the contrary, it is stated in a study [28] on long-term voltage stability that as the penetration level of wind power systems increases, the turbines can provide more reactive power support to the system. Penetration of PV systems has high effects on voltage magnitudes, and according to a study [29], high PV penetration has both positive and negative effects on system transient stability due to penetration level, network topology, and fault location. In PV penetration studies on frequency stability, simulations show that as penetration level increased from 5% to 20%, frequency stability is negatively affected [30].

With increasing interest in renewables and emerging challenges caused by them, the necessity of other solutions arises. For the effects of variation in both generation and demand, flexibility solutions such as DSM and ESSs can help to keep the network in balance besides other factors such as network design, size, and quality [22]. Flexibility needs are categorized in [31] as follows to understand the needs, identify, and select the most convenient flexibility solution.

- Flexibility for power: To maintain the frequency stability that is affected by intermittent, weather-dependent power source, it is required to keep a short term (second to an hour) balance between power supply and demand.

- Flexibility for energy: This is a requirement for keeping a medium to long term (hours to years) balance between energy supply and demand considering variable demand scenarios.
- Flexibility for transfer capacity: Due to increased peak demand and supply, short to medium period (minutes to hours) capability to transfer power between supply and demand.
- Flexibility for voltage: It is to keep the voltage between limits that may be violated by the bi-directional power flow caused by distributed generation.

2.2. Role of ESSs in Distribution Networks

Power grids with increasing integration of RESs require more flexibility to adjust supply and demand to keep the system stable [22]. In power systems with high renewable penetration, the role of ESSs includes improving power quality, supplying peak loads, and working as a backup power source at the distribution side, DSM, and demand response at the consumption side [32].

The role of ESSs in power quality problems is discussed in [33]. Power quality issues can be listed as voltage sag or swell, flicker, over or under voltage, interruptions, voltage unbalance, harmonic distortion, etc. Remote system faults, heavy load switching, or badly designed power sources may cause voltage sag or swell that occurs for 0.5 cycles to 1 min. Decrease or increase in demand, motor starting, and variation of loads may create interruption for a few milliseconds to 2 s duration, or over or under voltage issues which are nominal voltage rise or drop by 10% for more than 1 min [34,35]. Intermittent behavior of RESs and fluctuating load demands may cause repetitive fluctuations in voltage between 90% to 110% of its nominal value, which is called flickers [36,37]. Overvoltage and undervoltage problems are considered in [38], and the voltage profile is improved using rooftop PV with ESS. ESS is also used at the customer side to solve the voltage fluctuations that occur with several PV integrations to the distribution network [39]. Low voltage distribution networks with high penetration of rooftop PVs creates voltage rise/drop issues. In that case, ESS is used to mitigate voltages by charging during the peak PV generation period and using it during the peak load period [40]. For high-quality power, controlling reactive power flow is mandatory, and it can also improve voltage profile. Reactive compensation from PV inverters coordinated with ESS can maintain voltage profiles in an acceptable range for both urban and rural areas of the distribution network [41]. For network stability, frequency should be controlled to keep within the allowed limits. ESS can play an important role during the transients by adjusting the grid frequency dynamically.

As well as power quality solutions, ESSs can help to control the challenges such as reducing power supply imbalance from integrating intermittent RESs, promoting the distributed generation, and maintaining grid congestion by providing voltage support to smooth output fluctuations, mitigating supply and demand, and helping distribution network operators to operate the system reliably with meeting demand [33]. ESS may also become a useful aid in dealing with sudden power shutdowns. It can provide short-term energy supply with its fast response time and can be used as energy supply to reduce the impact of failure and maintain service reliability [42].

In literature, various applications of ESSs are investigated and summed up [21] by function as renewable capacity firming [43], smoothing micro-meso-macro scale wind variations [44], removing effects of intermittent clouds on PV, distributed generation peak voltage and frequency control, time-of-use (TOU) energy cost management [45], peak shaving [46], distribution upgrade delay [43,45,46], and end-user electricity service reliability [45,46]. ESS technologies and characteristics vary due to the purpose of applications, considering required capacity, charge and discharge time. The power system operators can select the appropriate ESS for different applications based on the advantages and disadvantages as well as the technical characteristics of each system [47–49].

2.3. Importance of DSM in Distribution Networks

With the introduction of various RESs in power systems, the system operators have led to the inclusion of many flexibility options into their operational decisions. In this regard, DSM techniques have emerged as the efficient flexibility options for matching the electricity supply with demand via different strategies such as financial and social incentives [50]. To address some of the barriers to effective service provision through cost-effective manners, the Electric Power Research Institute (EPRI) announced the DSM term for the first time in 1980. The presented concept by EPRI for the strategies included in the DSM programs is as follows: *"a series of measures intended to encourage specific groups of customers to modify their energy usage patterns in a manner consistent with the utility's DSM objectives while maintaining or enhancing customer satisfaction"* [51]. The power system operators try to use the DSM techniques in the framework of the short-term and long-term plans to enhance the reliability of supply and demand sides [52], assure system efficiency [53], decrease the rate of carbon emission [54], and reduce consumer electricity costs [55]. In order to achieve the desired targets, the successful implementation of DSM strategies depends on three main phases, namely, DSM policy development, proper strategy selection, and execution, as shown in Figure 2 [56]. Each of these phases is realized by different strategies, e.g., regulatory and market-oriented policies; methods, e.g., OPU and DRPs; and players, e.g., aggregators and consumers.
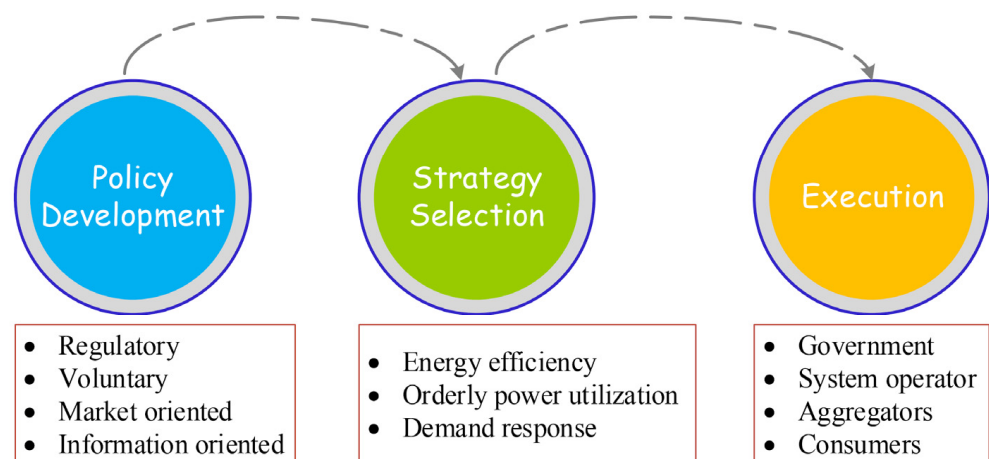

Figure 2. DSM strategies implementation process [56].

The development of the business strategies in the second phase, i.e., strategy selection, to implement DSM techniques in various sectors of the power system has been widely considered by researchers and system planners [57–59]. According to the conducted studies, the role of prevalent programs in the framework of OPU and DRPs in increasing the penetration of RESs in power systems is undeniable [60,61]. Hence, these programs have become very popular in smart power systems. The classification of OPU and DRPs is presented in Figure 3 [62]. OPU programs are divided into three categories based on the targets of the power system's operators. In the first category of OPU programs, which are called "strategic saving programs", the power consumption is decreased during peak intervals or all over the scheduling period by means of peak-clipping and strategic conservation programs. These programs are crucial for developing countries to reduce the investment costs associated with new facilities and generation capacities. In the second category of OPU programs, referred to as "strategic productivity programs", a part of the electricity consumption of flexible consumers is transferred from peak to off-peak intervals by means of load-shifting and flexible load shape programs. Moreover, the third category of OPU programs, i.e., "strategic transfusion programs", is one of the most widely used group of strategies for achieving higher load factors in a pre-defined time margin, which

encourages consumers to increase their demand at off-peak and valley intervals through valley-filling and strategic growth programs.
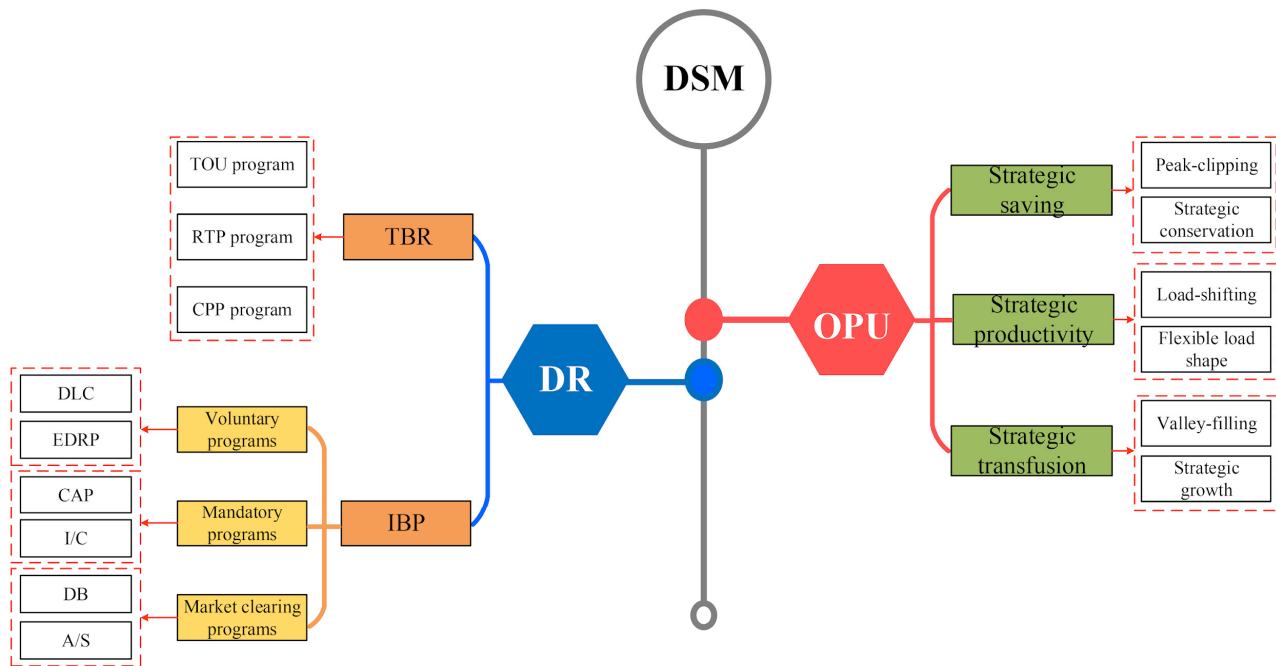

Figure 3. DSM business strategies to participate in the electricity market [62].

The flexibility need of a distribution grid with integrated high shares of intermittent RESs are growing, and ESSs and DSM play a vital role together by providing flexibility services. A load management illustration for smoothing the demand with ESSs and OPU in the presence of RESs is shown in Figure 4 [63].
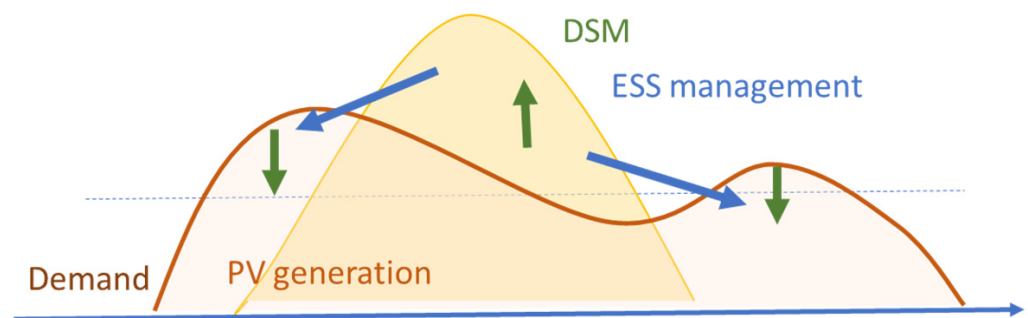

Figure 4. Illustration of load management [63].

The applications of DSM on networks vary along with the technology of RES and ESS. A summary of the impacts of DSM implementation is given in Table 1. In a residential microgrid with PV and wind turbine, energy storage is used to overcome the fluctuations caused by the intermittent nature of renewables, and a DSM scheme is implemented by shifting peak loads to an hour where demand is low. With one renewable unit per household (83% PV, 17% wind turbines), fluctuation is reduced by 12% with optimizing renewables mix; moreover, a further 4.6% reduction is reached by including storage batteries and 3.5% reduction through DSM schemes [64]. Besides such individual case studies, demonstration of DSM with field testing has been the subject of many projects in Europe, the US, China, and Japan [63]. In The Netherlands, a project with 300 households included used storage and peak shaving to balance the wind turbines, reduce the distribution network congestion, and maintain user comfort. 94% imbalance reduction is achieved by meeting user comfort

bounds [65]. In Japan, to be able to stabilize PV and wind integration by means of reverse power flow and voltage rise, a multi-energy (heat, gas, and fuel cells) network with 200 residents and 50 companies is used for field testing. Load reduction is applied as a DSM strategy, and 20% peak load reduction is achieved with TOU. The other aim of the project is to reach 50% CO_2 reduction, 20% energy saving, and 15% load shifting using power-electric vehicle charging, PV units, and storage battery [66,67].

Table 1. Impacts of DSM implementation on RES and ESS integrated networks [68].

Reference	System	DSM Method	Outcome
[69]	PV-battery hybrid system	TOU with power selling over peak period	Customer side electricity bill reduced, solar energy and battery storage usage are maximized
[67]	Industrial microgrid with wind turbine and ESS	DRPs	The overall cost of electricity was reduced by 73%, while the wind turbine reduced carbon emissions by 88% and DSM by 30%.
[63]	Residential microgrid with PV panel, wind turbine, and ESS	DSM scheme	Energy demand decreased by 16%, while CO_2 emissions decreased by 10%. Fluctuation by renewables is reduced by 12%, including storage it is reduced by 4.6% and by 3.5% through demand reduction.
[70]	Microgrid system with PV panels, wind turbine, diesel generator, battery bank, and water supply system	A new DSM mechanism	When consumers shift their loads, the operation cost is reduced by 3.06%
[71]	Household with PV systems	Load scheduling	Reduced the electricity bill and provided user comfort.
[72]	Microgrid system with microturbines, wind turbine, fuel cells, PV panels, storage devices	DRPs	Peak load was shaved from the grid tie-line. Optimal scheduling of batteries and diesel generators is provided.

3. Governments' Policies for the Development of RESs, ESSs, and DSM Strategies

In this section, renewable targets of nine selected countries that consist of pioneering and developing countries in renewable energy utilization were researched. Table 2 contains the renewable energy targets of these countries. Renewable energy policies and incentive programs implemented in line with these targets are investigated. Additionally, programs implemented within the scope of DSM and ESSs promotion in these selected countries are presented in this part of the study. This section aims to review the incentive policy to increase the renewable energy share in these countries. Additionally, the implemented programs in these countries were compiled to reveal the role of DSM and ESSs in the development of renewable energy.

Table 2. Renewable energy targets of selected countries.

Country	Target Year	Renewable Energy Target (GW or Total Share)
Brazil	2030	191.35 GW installed renewable energy capacity in the electricity grid
China	2030	35% renewable share in electricity production
Denmark	2030	55% renewable share in total energy consumption mix
Germany	2030	50% renewable share in electricity production
Japan	2030	22–24% renewable share in total energy consumption mix
The UK	2030	50% renewable share in electricity production
The US	2030	50% renewable share in electricity production
Turkey	2023	At least 38.8% renewable share in electricity production
Iran	2025	10% renewable share in electricity production

3.1. Brazil

Brazil is one of the countries that take advantage of RESs, particularly with hydropower and bioenergy. After the start of the millennium, Brazil, whose hydroelectricity

share made up 64.4% of the total electricity generation in 2017, has tried to afford to increase the share of RESs and diversity by changing and forming on energy policy and putting targets [73]. According to the 2030 energy plan, it is aimed to increase the installed RES capacity to 191.35 GW [74]. In line with this target, the alternative energy resources incentive program (PROINFA) was put into use in two phases [75]. In the first phase, feed-in-tariffs (FIT) were applied and, thus, 3000 MW renewable energy capacity was established. In the second phase, renewable energy generation projects started with a tender procedure to offer more fair prices to electricity consumers. In these auctions, a long-term fixed price power purchase agreement (PPA) is signed with the bidders who make the lowest bid per unit price. The wind power plant was the first subject to these tenders in 2009 and since this year, the installed power of wind energy has increased significantly.

The first tender on the PV system side was realized in 2014. The rate of increase in installed power compared to wind energy is rather slow. The auction-based second phase of PROINFA is still available for setting up new RES installations and for these projects, the financing system is applicable that is provided through the National Development Bank (BNDES). In 2012, The National Regulatory Agency for Electricity (ANEEL) commissioned a net metering mechanism to increase the penetration of small RESs [76]. With the net metering mechanism, electricity consumers with power up to 1 MW can meet their own consumption with the production units they have set up. ANEEL has amended the maximum capacity on net meters from 1 MW for all renewable sources to 3 MW for small hydropower and 5 MW for other RESs [77]. They can supply the electrical energy that they generate more than they use to the electricity network and have energy credits for future use as much as excess electricity they provide to the grid. In Brazil, there is also a special discounted tariff, at least 50%, electricity produced from renewable energy for supply to the electricity grid to promote the integration of renewables [78]. ANEEL took a step on the demand response side in 2015, the flag tariff mechanism was implemented under DRPs to take advantage of the flexibility of electricity consumers. The flag tariff mechanism encourages consumers to use electricity on time when usage is low. In this tariff mechanism, the electricity use of the consumers is divided into three categories as green, yellow, and red flags. The electricity tariff for the consumer on the green flag keeps unchanged and for the consumers on yellow and red flags raises in certain amounts per MWh [79]. In Brazil, there is also an effort to increase the ESSs integration to the grid. In 2016, ANEEL developed a framework that obligated the electricity utilities to invest 0.4% of their annual revenue on the research and development (R&D) of ESSs and pre-approved the proposals for ESS pilot projects [80].

3.2. China

China is the country with the highest energy consumption and emission values in the world [81]. The emissions value in the country has reached 28.5% of total emissions produced in the world in 2018, and the electricity consumption has reached 28% of the total of the world electricity consumption in 2019 [82,83]. Targets on the transition to renewable energy and reduction in emissions in China are important on a global level because of the huge amount of electricity consumption and emissions in China. The Chinese government set the target to catch up 35% share from the renewable sources in total electricity consumption and 20% share from renewables in the total energy mix [84,85]. In addition, the target related to emission reduction is 60–65% in 2030 compared to 2005. In line with these targets, the renewable energy law that set a plan for the development and deployment of RESs was put in effect by the Chinese government in 2005 and modified in 2009. One of the important support schemes that increase the share of renewable energy in China is the FIT scheme. Electricity from wind energy in 2009, biomass in 2010, and solar PV in 2011 were included in the FIT schemes [86–88]. The FIT rates vary according to the RESs. Especially for PV solar electricity, the China government has been updating FIT rates over the years due to a reduction in solar cell production costs. The tariffs are, in fact, compensated by the industrial and commercial electricity users by putting renewable

surcharge into the electricity bills as levy [89]. Another important policy applied in China is the renewable portfolio standard (RPS) that obligates grid companies to purchase a certain amount of electricity which was indicated in RPSs from renewable energy producers to supply electricity demand [90]. The Chinese government has also been producing policies on DSM. One of these DSM policies China has been implementing is the TOU electricity tariff which is mandatory for industrial and commercial users to equilibrate electricity usage throughout the day and encourage users to consume electricity on off-peak hours. Additionally, pilot projects on DSM, which were interruptible load and direct load controls programs, have been implemented in pilot cities in China [90]. The first national policy in the field of ESSs was established in 2017 which was entitled "Guiding Opinions on Promoting Energy Storage Technology and Industry Development". The second policy was on a national level that was named "2019–2020 Action Plan for the Guiding Opinions on Promoting Energy Storage Technology and Industry Development". This policy mainly focused on producing R&D activities on energy, applying policies to bolster ESSs technologies and industries, promoting demonstration projects, speeding up the standardization of energy storage, and supporting the applications of the ESSs for electric vehicle batteries.

3.3. Denmark

Denmark has set very strict targets on renewable energy integration and emission reduction, and these targets are supported by government policies. The target for 2030 is the reduction of emission 70% compared to 1990 and 55% renewable share in total energy consumption mix and the target for 2050 is becoming a carbon neutral and fossil-fuel-free country [91]. These targets make Denmark ambitious to reach these goals successfully and encourage the government to put forward applicable and accurate energy policies, especially on renewable energy. Today, Denmark utilizes renewable energy, especially wind energy, effectively through these energy policies. Renewable energy investments in Denmark started after the oil crisis in the 1970s. Beginning in the early 1980s, renewable energy investments were made in wind power plants, and these wind farms were established by wind turbine cooperatives. Local citizens have set up wind turbine cooperatives to build wind turbines, and the Danish state's tax incentive for the established wind turbines has significantly increased the number of wind turbine cooperatives. By 1996, 2100 wind turbine cooperatives were operating in Denmark [92]. In the early 1900s, FIT was introduced in Denmark, which was an important policy tool for the installation of new RESs, and this policy carried renewable energy share to nearly 25% in electricity generation from 1990 to 2008 [93,94]. In 2008, Denmark drew away from the use of FIT and brought feed-in premiums (FIP) instead of FIT to promote renewable energy [95]. The premium tariff for offshore wind farms is determined by a tender between prequalified bidders. A similar situation is valid for the installation of land-based solar power plants [96,97]. These support payments are covered by the public service obligation (PSO) that mandates electricity consumers to pay these support payments in addition to their electricity bills [98]. In July 2016, a cooperation agreement was signed between Denmark and Germany for PV plant auctions. With this agreement, PV projects in Denmark would benefit from support schemes by participating in auctions in Germany, and PV projects in Germany also had the same opportunity. In addition to these auctions, electricity consumers in Denmark can set up PV generation units in their private households to generate the electricity within the net metering mechanism in which electricity consumers are billed after deducting their electricity production from their consumption [96]. For the loan taken out by wind and solar energy owners associations and local initiatives for the feasibility study to be carried out before installing the power plant, the Danish Ministry of Energy, Utilities and Climate provides a loan guarantee, and if these projects are not realized, the loan amount does not have to be paid [97]. There is an effort to ensure energy efficiency as well as the transition to renewable energy use in Denmark. An important policy named as the energy efficiency obligation scheme (EEOS) was formed in 2006 to supply energy efficiency in

Denmark. In this scheme, energy companies, such as grid and distribution companies within the electricity, region heating, natural gas, and oil sector, are obliged to diminish the end-user consumption by a certain amount annually [99]. The Danish government approves the establishment of pilot projects for the dissemination of new technologies, with a large number of grid-connected battery storage systems installed recently. These grid-connected battery storage projects provide renewables capacity firming, frequency regulation for electricity grids [100]. Another project is entitled as the power hub project that monitors the grid and provides load management by disconnecting selected industrial load established in Faroe island in 2012 [92]. Power hub installations are continuing in Denmark, and electricity sales can be made in these power hubs by transferring power from electric vehicles to the grid (V2G) [101].

3.4. Germany

As one of the leading countries in terms of renewable energy production, Germany has solid targets related to emissions reduction and enhancement of electricity production from RESs. Specifically, Germany aims to lessen emissions by 55% and increase the share of renewables in electricity by 50% by 2030 [102]. In order to accomplish these, Germany has been trying hard to make and implement various types of DSM and ESS policies, which makes Germany one of the most privileged countries in the development of DSM and ESS techniques in renewable energy integration to the electricity grid. Furthermore, under the renewable energy act (EEG), announced in 2000 and amended in 2012, the German government has applied a market-above fixed price, known as FIT, for electricity from RESs. EEG is the cardinal legislative tool for the development of renewable power that has significantly accelerated the use of RES [103]. Since the introduction of EEG in 2014, an optional sliding FIP has been presented under the named "market integration model" [104]. This FIP is paid on top of the electricity market price for electricity produced from renewables and sold directly to the spot electricity market. KfW Bank takes promotional banking actions on behalf of the Federal Republic of Germany offers loans and repayment bonus programs to support renewable energy investments. One of these programs is the KfW renewable energies program (KfW-Programme Erneuerbare Energien) consisting of two parts: standard and premium. The standard program includes low-interest loans up to 20 years and amounts up to EUR 50 million for electricity from RESs. The premium program presents loans up to EUR 25 million and repayment bonuses for heat from renewable energies generated in the large capacity plants [105]. In addition to these, in Germany, offshore wind power has a special support program described as the KfW programme offshore wind energy, which provides long-term and low-interest loans and financing packages to the companies seeking investment in offshore wind farms [97,105]. KfW Bank in cooperation with the German Federal Ministry for economic affairs and energy, has started a nationwide low-interest subsidy and loan program for ESSs integrated with PV systems which are grid-tied. The ministry pays back 30% of the energy system set-up expense, and it is anticipated that the PV system will supply power to the grid as much as 60% of its installed capacity [106].

3.5. Japan

After the Fukushima nuclear disaster, Japan made many changes on energy policies—one of them related to promoting renewable energy and making it the main power source—and have set strict targets to increase the share of renewable energy in the total energy combination to 22–24% by 2030 [107]. With the target of renewable energy, Japan simultaneously has targeted to reduce the emission by 26% compared to 2013 [108]. The Japanese government introduced several types of programs to increase the renewable energy share and reach the targets in renewable energy. In Japan, RPS had been applied for nearly nine years, since 2003, that mandates Japan utility companies to generate a certain percentage of electricity from RESs. After the RPS program, firstly, the excess electricity purchasing scheme for PV power was announced in November 2009 that only mandates purchasing excess PV power. On 1 July 2012, the FIT schemes that contained a specific purchase tariff for the

entire amount of renewable energy out of PV power was introduced in Japan and it has replaced the RPS program [109]. For the industrial and commercial users who are not included in the FIT programs, there are subsidies to produce electricity from solar PVs for their self-consumption [110]. In 2017, the Japanese government announced a PV auction program for large solar projects. In the context of this program, projects are selected by bidding competition and these selected projects receive a 20-year-long power purchase agreement [111]. There is also a tax promoting system in Japan to promote renewable energy and energy saving investments, companies, and individuals to receive immediate depreciation or tax credit [112]. The DRPs (negawatt trading) were announced by the Ministry of Economy, Trade and Industry (METI) in December 2016 to diminish the peak load and encourage consumers to save electrical energy. The participants of this program take promotional payments for their electric load reduction [113]. In the fiscal year of 2018, Japan offered a 4.1-billion-yen budget for projects to configure virtual power plants (VPPs) by the agency of the intelligent use of demand-side energy sources. This budget was used to set up the demonstration projects of VPPs and made a big contribution to the initiatives of VPPs [114]. Moreover, there are two major energy storage subsidy programs which are respectively: the renewable energy in local area plan and the storage battery for renewable energy generation program. These programs offer to subsidize up to one-half of costs related to targeted energy storage projects [115].

3.6. The UK

The UK Government has been making policies and putting them in action to improve renewable energy deployment and reduce emissions since the beginning of the 1990s [116]. In 2017 the UK reached out to 27.9% renewable share in total electricity production by successful policies [117]. For the year 2030, the UK has set a target to produce half of the total electricity production from renewables and 68% of emission cut compared to 1990 [118,119]. One of the accomplished policies implemented in the UK is named as renewables obligation, which came into force on 1 April 2002 and closed to new applicants on 31 March 2017. The renewables obligation is one of the core mechanisms supporting large-scale renewable energy projects. Through this mechanism, the government obligates all licensed electricity suppliers to source a proportion of the electricity to customers from RESs or pay a penalty [120]. In addition to the program, which concentrated on large-scale projects, there is also a government program designed to support mainly small-scale renewable energy generation units, referred to as the FIT scheme which was released on 1 April 2010 and now closed for new participants from 1 April 2019. In the context of this scheme, licensed electricity suppliers must make payments on both generation and export from accredited installations which are respectively PV, wind, hydro, and anaerobic digestion power plants up to a capacity of 5 MW and 2 kW for micro combined heat and power plants [121]. Renewable heat generation is also supported through renewable heat incentives (RHI) including two government schemes named domestic and non-domestic RHI. Eligible installations at the businesses, public sector, and non-profit organizations, under the non-domestic RHI program, and at houses, under the domestic RHI program, receive payments quarterly based on the amount of heat generated from renewables [122]. The UK government has put forth the contract for difference (CfD) program which is recently the main instrument for supporting new low-carbon electricity generation projects. In this program, the low-carbon contract companies receive payment for the difference between the strike price and the reference price of the electricity they generate from renewables. In addition to incentive-based policies, the UK government also produced an important policy to reach the 2050 net-zero target which is the smart meter program. The integration of the smart meters in energy infrastructure has provided a more flexible energy system and acceptable balance between the supply and demand-side [123].

3.7. The US

The US is the second highest electricity consuming country in the world. Therefore, the targets and the policies on renewable energy made by the US are globally important for the transition to renewable energy in the world. In the current situation, 14% of the electricity consumed in the US is produced from RESs, and for 2030, the US has targeted to raise the renewable energy percentage to 50% [124]. To accomplish this objective, the US has set forth many comprehensive and successful policies and promoting programs. The advent of many of the recent renewable energy programs traces back to the 1970s. Many renewable energy programs have been reshaped repetitively to meet altering economic factors. The US Congress has passed several energy laws since 2005 which are respectively: the energy policy act of 2005; the energy independence and security act of 2007; the energy improvement and extension act, legalized as the division of the emergency economic stabilization act of 2008; and the American recovery and reinvestment act. Each of these laws established, extended, or altered the development, demonstration, and deployment of renewable energy research and energy efficiency programs. One of the important financial incentive-based renewable energy program is the business energy investment tax credit (ITC) which is also known as a federal solar tax credit and it provides an opportunity to individuals and businesses to subtract a certain percentage of their renewable energy investment, e.g., solar energy, small and large wind, and geothermal energy plants, expenses from their taxes. In addition to ITC, there is also a tax credit program named as residential renewable energy tax credit compassing only residential [125]. Another tax credit program is renewable electricity production tax credit (PTC) which is an inflation-adjusted per-kilowatt-hour (kWh) tax credit for electricity produced by qualified energy resources and sold by the taxpayer to an unconnected person throughout the reportable year [126]. The US government offers loan guarantee programs to increase renewables share and innovative technologies in energy sectors such as rooftop solar, energy storage, and smart grid technology. The tribal energy loan guarantee program (TELGP) is another support mechanism giving loan guarantee to tribes through energy development projects including solar, wind, geothermal, hydropower, electric transmission infrastructure, and energy storage projects [127]. Rural energy for America program (REAP) loan guarantees focus on agricultural producers and small businesses in rural areas in America to promote energy efficiency and renewable energy [128]. The US government has introduced various grant programs to promote renewables, ESSs, and energy efficiency, one of them is the office of Indian energy policy and programs-funding opportunities. The recent energy technology on tribal lands (ETTL) is an applicable funding opportunity under this program. This funding opportunity aims to deploy large-scale energy generating systems or energy storage on tribal lands, install integrated energy systems for the autonomous operation to supply power during emergency situations for the endurance of the tribal society [129]. Another grant program is the high energy cost grants program (HECGP) which helps power suppliers in lowering energy expenditure for families and individuals in rural areas with very high per-household energy bills (equal to 275 percent of the national energy bill average or more). This fund may be used for off-grid or on-grid renewable energy generation, installing a backup or emergency power supply or ESSs and energy-saving appliances and devices on consumer premises. Under the REAP grant program, the US government provides funding to agricultural producers and rural small-scale businesses for RESs installations or to cut down on electricity use [130].

3.8. Turkey

Renewable energy share in Turkey is accelerating especially from the beginning of the 2000s. To sustain this acceleration, the Turkish government is adopting new policies in parallel with current developments. Turkey achieved to produce electricity 42% of the total from RESs in 2020 which was 32.5% in 2018, mainly from hydro energy [131]. The Turkish government aims to catch up at least 38.8% renewable energy share in the total electricity generation [132]. The Turkish government has performed various incentive-based

programs and produced policies to attain this target. One of them is the FIT scheme which was started in 2011 under the RES support mechanism (YEKDEM) and announced in the renewable energy law, which was published on 10 May 2005 and enacted on 8 January 2011. To benefit from this scheme, which provides 10 years fixed price for electricity, renewable energy plants must have RES certificates [133]. The appropriate renewable energy plant connected to the electricity grid before 2020 has FIT in dollars; however, renewable energy plants connected to the electricity grid between 1 July 2021 and 31 December 2025 are going to have FIT in Turkish Liras, which is being updated every three months. Renewable energy plants included in YEKDEM take extra payment over the FIT price only if they use made-in-Turkey equipment in their plants [134]. In Turkey, renewable energy plants that have a capacity below 1 MW are not obligated to obtain an energy production license, which is granted by the energy market regulatory authority. These plants can also benefit from the FIT scheme under YEKDEM [135]. A new model named renewable energy resource area (YEKA) has been put in action for large-scale renewable energy plant establishments in 2016 [136]. In this model, the FIT prices are specified by auction amongst the tenders for the specific area projects. This enables lower FIT prices than the ones of YEKDEM. In 2011, arrangements were made on DSM in Turkey. Energy efficiency label compliance (EELC) has been implemented on a voluntary basis for leading the consumers to purchase products that have EELC. The other arrangement to manage loads is that making a contract with volunteer electricity subscribers having high electricity consumption to include them in energy cut programs or encourage them to shift their loads in the required time frames. Low voltage electricity consumers (up to 10 kW power) may establish RESs in the areas where they use electricity to meet their consumptions and sell their surplus electricity to the electricity grid [135]. Furthermore, the draft of the regulation determining the activities of electrical storage units has been published in 2019 to adapt the electricity storage units to the electricity grid in Turkey [137].

3.9. Iran

Iran is mainly dependent on fossil fuel fuels, lower than 1% of energy being produced from renewables. The Iranian government has set a target to increase renewables share in electricity production to 10% by 2025 [138]. A number of incentive mechanisms have been implemented in recent years to increase the low level of renewable energy generation in Iran. One of these incentive mechanisms is the FIT that guarantees power purchase to non-governmental renewable energy investors for 20 years. Guarantee prices differ for renewable energy type and capacity, and are being updated every year according to the exchange rates; for instance, solar plant capacity below 20 kW have much more tariff rate than capacity between 100 kW and 1 MW. Tariffs can go up to a maximum of 30% for power plants constructed that use local know-how, design, and manufacturing. Tariffs multiply by 0.7 for the second ten-year period except for wind turbine projects. Transmission service charge is added to the tariff for the RESs connected to the distribution grid [139]. Additionally, there is an effort to control loads by replacing single-tariff meter devices with triple-rate devices in Iran. With triple-rate devices, electricity consumers are encouraged not to use electricity during peak hours due to high electricity prices on peak hours [140].

3.10. General Overview

In this section, the renewable energy targets of the nine countries that are selected according to their level of development are presented. The policies and incentive programs implemented in these countries to raise renewable energy share are examined in detail. The renewable energy promotion programs, DSM activities, and ESS incentives of selected countries are summarized in Table 3.

Table 3. Renewable energy incentive programs, DSM activity, and ESS promotions of the selected countries.

Country	Renewable Energy Incentive Program		DSM Activity and Program		ESSs Incentive
Brazil	The alternative energy resources incentive program (PROINFA) Net metering mechanism	PROINFA has two phases: FIT, PPA	DRPs	The flag tariff mechanism under DRPs	R&D activities and pilot projects of ESSs
China	FIT scheme; Renewable portfolio standard		TOU mechanism; Interruptible load and direct load controls programs in pilot cities		To produce incentive policies
Denmark	FIP scheme; Public service obligation; Net metering mechanism		Energy efficiency obligation scheme; Power hub project for load management in Faroe		Pilot ESS projects; Power hub for V2G charging
Germany	FIT scheme; FIP scheme; KfW renewable energies program; KfW programme offshore wind energy				Low interest subsidy and loan program
Japan	Renewable portfolio standard; FIT scheme; Power purchase agreement; Tax promoting system		Negawatt mechanism; R&D activities and pilot projects of VPPs		The renewable energy in local area plan and the ESS for renewable energy generation program
The UK	Renewables obligation; FIT scheme; Renewable heat incentive; Contact for difference; Net metering mechanism				
The US	Business energy investment tax credit; Residential renewable energy tax credit; Renewable electricity production tax credit; Tribal energy loan guarantee program; Rural energy for America program; High energy cost grants program; Energy technology on tribal lands		Grant under HECGP; Grant under REAP		Grant under HECGP; Grant under ETTL; Loan guarantee under TELGP
Turkey	FIT scheme; Domestic equipment use incentive payment on FIT prices		Energy efficiency label compliance; Voluntary participation agreement on energy cut program and load shifting		Publication of legal regulation draft study
Iran	FIT scheme		Transition to triple rate devices		

4. Economic Aspects of Applying ESSs and DSM Considering RESs

DSM programs and ESSs can be provided great advantages with applications such as peak shaving and energy shifting to operate energy systems economically. Increasing the peak demand can increase the cost of electricity generation. Generally, peak generators such as coal plants have higher costs, and their flexibility is lower. Peak generators are not required by operators to use low capacity and have new peaks because they have low income despite high capital costs [141]. In addition, the share of RESs in electricity generation is increasing rapidly, and it is predicted that this increase will continue rapidly in the future. The problems encountered with this increase and the contribution of ESSs to the solution of these problems are mentioned in the Section 2. The flexibility obtained by including RESs in the system is beneficial not only in terms of ecology but also economically. In [22], the effect of the increasing share of RESs on energy price was analyzed and the decline in energy prices in 2008 and 2014 was evaluated. Although the installation costs of ESSs are currently high, they have the potential to lower electricity prices in the future. An economic evaluation of ESS was offered, which provided frequency regulation and peak shaving in microgrids, and was developed an optimization model for economic operation for interconnected microgrids. In the same work, different system security applications were provided by using ESSs in the distribution network. In this way, in [142], the economic operation of the distribution networks was provided by meeting peak loads or providing peak shaving production using ESSs, which can enable economic planning of spare generation capacity. In [143], wind power plants and ESSs were examined and in the scenarios realized, compressed air energy storage (CAES) and pumped hydroelectric storage (PHS), which allow low installation cost, low maintenance and operating costs, and collective energy storage were used. In [144], classic power systems relied on conventional generators to compensate for uncertainty in renewable energy generation. However, as renewable energy penetration levels increase, traditional generators can have higher operating costs while having lower income. In contrast, bulk ESSs can be an economical option in the penetration of renewable energy by eliminating uncertainty in production and

storing clean energy for later use. In [145], a stochastic model was provided for different levels of renewable penetration. By investigating the short-term profitability of traditional generators and ESSs with their increasing renewable penetration, the authors emphasized that bulk ESSs come to the fore with renewable energy penetration.

4.1. Energy Storage Technologies

Electrical energy can be converted into mechanical, electrochemical, electromagnetic, thermodynamic, or chemical energy for storage. The losses that may occur during this transformation should be evaluated economically. Energy storage technologies are generally classified according to the storage principle. This classification may change according to technological developments. In this paper, the main storage systems are classified as in Figure 5. The following is an overview of current energy storage technologies, their investment costs, operating principles, advantages, disadvantages, and applications of different types of ESSs.
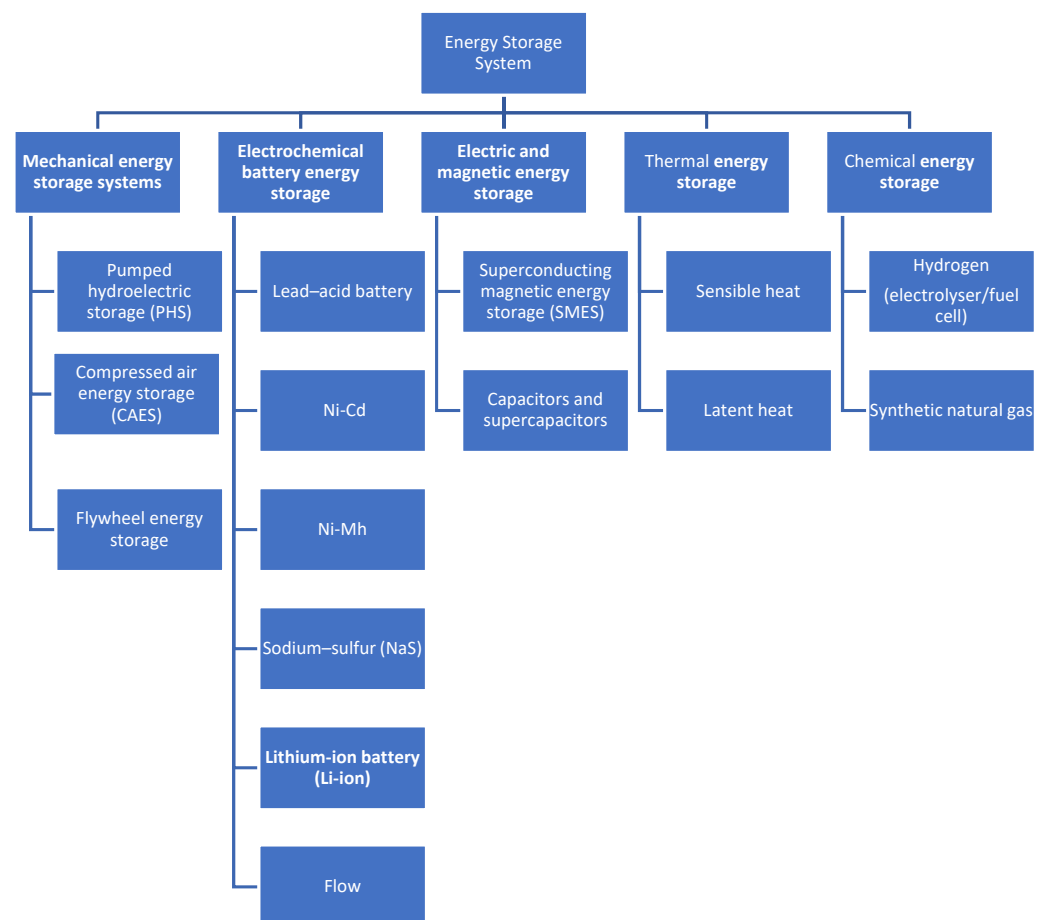

Figure 5. Energy storage technologies classification [13,144,146].

4.1.1. Mechanical Energy Storage Systems

- Pumped hydroelectric storage (PHS): PHS briefly works on the principle of pumping water from lower level to higher level and then passing this water through a turbine to generate electricity. This system is often used in grid-scale bulk ESSs [147,148]. PHS currently dominates the total installed storage power capacity, with 96% of the total 176 gigawatts (GW) installed in mid-2017. China, Japan, and the US account for almost half (48%) of global energy storage capacity [145,149]. It is home to the largest capacities of PHS, although they are emerging as important sites for new and emerging electricity storage technologies.

- Compressed air energy storage (CAES): CAES focused on the concept of energy storage in the form of compressed air. Electricity is used to compress air with the aid of a compressor, and the compressed air is stored in an existing or purpose-built enclosed space. When the energy demand is high, compressed air is released from the reservoir and passed through a turbine, thereby generating electricity. CAES can be divided into underground and aboveground areas according to the regions where the gas is stored. Regarding the underground compressed air storage unit, salt caves, natural aquifers, and depleted natural gas reservoirs are respectively the most cost-effective. Aboveground CAES, i.e., typically a pressure vessel, with higher costs but easier project implementation compared to the underground type [147–149]. Cost estimates of CAES systems are very difficult because they are site-specific and are affected by environmental constraints. The installation cost is estimated to be around 50 USD/kWh and possibly fall to 40 USD/kWh if there is an existing reservoir. The disadvantages of CAES systems are low discharge rates and low efficiency. This technology is estimated to have a 17% reduction in cost by 2030.
- Flywheel energy storage: Flywheel technology can also be defined as transferring energy on a rotating object and keeping this transferred energy above the momentum of the rotating body. The cycle life will increase as friction losses decrease and efficiency increases. Flywheels have high power potential. It is more suitable for short-term storage applications due to high energy installation costs ranging from 1500 to 6000 USD/kWh and very high self-discharges up to 15% per hour. The energy installation cost of a flywheel system is expected to decrease by 30% by 2030.

4.1.2. Electrochemical Battery Energy Storage

- Lead–acid battery: Lead-acid batteries have a wide usage area. Featuring flooded vented lead-acid (VLA) and valve-regulated lead-acid (VRLA) design types, these batteries have a power range of several MW and an energy range of up to 10 MWh. This technology is expected to be used more widely in the future, as it has high efficiency and low maintenance costs despite the low capital cost. In addition, lead-acid battery recycling is the economical manner, and today they are mostly recycled.
- Sodium–Sulphur (NaS): NaS batteries are relatively mature proven technologies with high energy density. They are operated at high temperatures to preserve the molten state of the battery. The largest installation is a 34 MW/245 MWh system located in Aomori, Japan, which has been installed for wind stabilization. NaS batteries are predicted to become much more affordable in the future. Installation costs of NaS can be reduced by 56–60% by 2030. Despite the advantages of these batteries such as relatively low installation costs, high energy density, they have high maintenance and operating costs because they are operated at high temperatures.
- Lithium-ion battery (Li-ion): Li-ion batteries are formed from lithiated metal oxide cathode and a battery based on charge and discharge reactions from graphite anode. Li-ion batteries have a wide range of uses from consumer electronics to grid support of RESs. This technology is costlier in stationary use than those used in EVs, due to the difficult charge/discharge cycles. On the other hand, it is seen that the costs of small-scale Li-ion battery systems decreased by 60% between 2014 and 2017. It is estimated that this cost will decrease by 54–60% in fixed applications until 2030.
- Flow batteries: Flow batteries consist of two electrolyte solution units, namely, cathode and anode. It stores energy by passing through the electrolytic membrane. These batteries, which are still under development, have advantages such as long lifetime and easy scalability. Flow battery costs are expected to be greatly reduced. The total installation cost of these batteries is estimated to decrease by around 65% by 2030 [145–149].

4.1.3. Electric and Magnetic Energy Storage

- Capacitors and supercapacitors: Generally, capacitors consist of two conductive carbon-based electrodes separated by an insulating dielectric material. When voltage is applied to a capacitor, opposite charges accumulate on the surface of each electrode. The charges are kept separate by the dielectric, thus creating an electric field that allows the capacitor to store energy. Supercapacitors use an electrochemical double-layer charge to store energy. Supercapacitors are low-energy and high-power devices that react very quickly. Since they do not have a chemical reaction unlike other types of batteries, they can withstand a very high number of cycles. In addition to the technical and economic advantages of this type of ESSs, since the voltage varies linearly with the charge in the system, they require power electronic devices to have a constant output.
- Superconducting magnetic energy storage (SMES): SMES devices store electricity in a magnetic field generated by current flowing through a superconducting coil. Made of a superconducting material, the coil has no resistance when current flows through it and its losses are almost zero. A cooling system is used to maintain the superconducting state and needs power electronics equipment. SMES has a high response speed and a very high cycle life. In addition, SMES systems have high productivity, and their burnout periods are long. However, due to technical factors such as cooling requirements and system complexity, they are in the development stage and have high costs. Therefore, SMES systems are used only for short-term storage [148,150–152].

4.1.4. Chemical Energy Storage

- Hydrogen energy storage: Hydrogen ESSs are based on the principle of chemically converting electricity to hydrogen. It is separated into water components by electrolysis and stored. In renewable energy production, cheap excess electricity can be used to feed electrolyzers and this excess energy can be stored by converting it to hydrogen. Hydrogen can be stored in three main ways, each with different implications for the energy capacity of the system and its layout: (1) as gas in very large underground caverns within geological formations or in high-pressure tanks; (2) as liquid in cryogenic tanks; or (3) as solid or liquid hydrides. Electrolysis is run in the opposite direction to recover electricity. These technologies have a minimal environmental impact and are highly reliable and precise. However, there are some losses in the conversion process and the installation costs are very high [148,153].

4.1.5. Thermal Energy Storage

Thermal energy storage can be defined as the storage of energy in a storage environment as heat or cold. The most common method of thermal storage is sensible and latent sense. The storage medium can be a naturally occurring structure or within structures built to prevent heat loss. The storage environment is critical to installation costs.

4.2. ESSs Technologies and Levelized Cost of Electricity (LCOE)

Although ESSs have the ability to better overcome uncertainty and interruptions in the production of RESs and to react quickly, the biggest obstacle to collective energy storage is high investment costs. LCOE is a method used to calculate the unit energy cost of power generation plants. LCOE is calculated by taking the initial investment cost, operating and maintenance costs, and fuel expenses into consideration. Thus, it can be calculated to determine the minimum price at which the energy should be sold. In [154], the net LCOE was formulated considering the losses due to the efficiency factor. In the same work, it was stated that the storage cost should also include the cost of electricity generation to be stored in the ESSs. The authors of [155] evaluated the LCOE for various types of ESSs, and found that PHS and large-scale CAES systems are still the most economical storage types. However, as they are mature technologies, future cost reductions are expected to

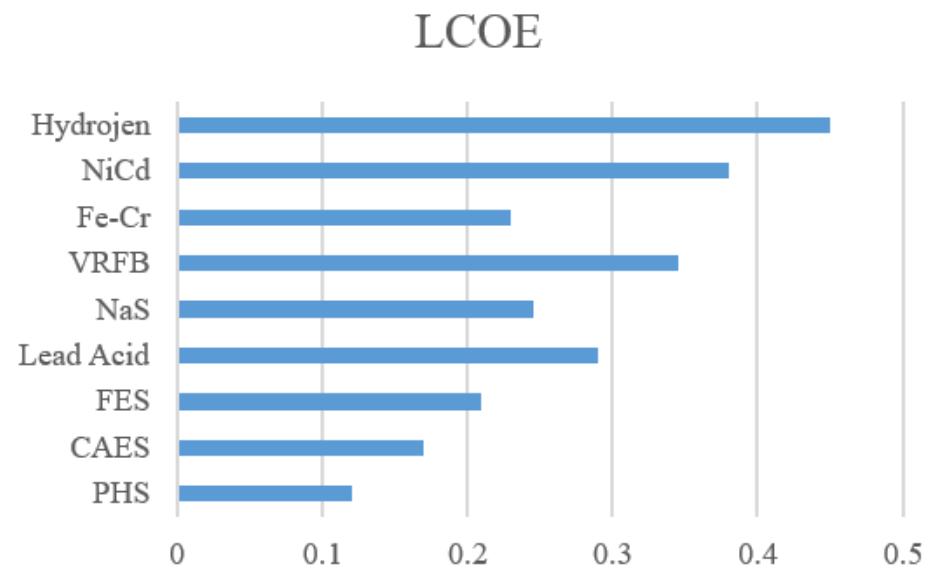be limited. Figure 6 shows the average values of LCOE calculations for the respective storage technologies.

Figure 6. LCOE (EUR/kWh) [155].

LCOE calculations show that PHS and CAES are still the most attractive for collective services. However, batteries are becoming more economical for transmission and distribution supports, and costs are expected to drop significantly by 2030 [149]. Therefore, batteries should not be far from being economically attractive. Figure 7 shows the expected reduction in the installation costs of batteries until 2030. Finally, the proper selection of the ESSs at the grid-scale depends on several factors such as system capacity, required performance, cost and reliability of the ESSs, and the type of application. Some of these features are listed in Table 4 for the storage technologies reviewed [33,42,145,147,151].
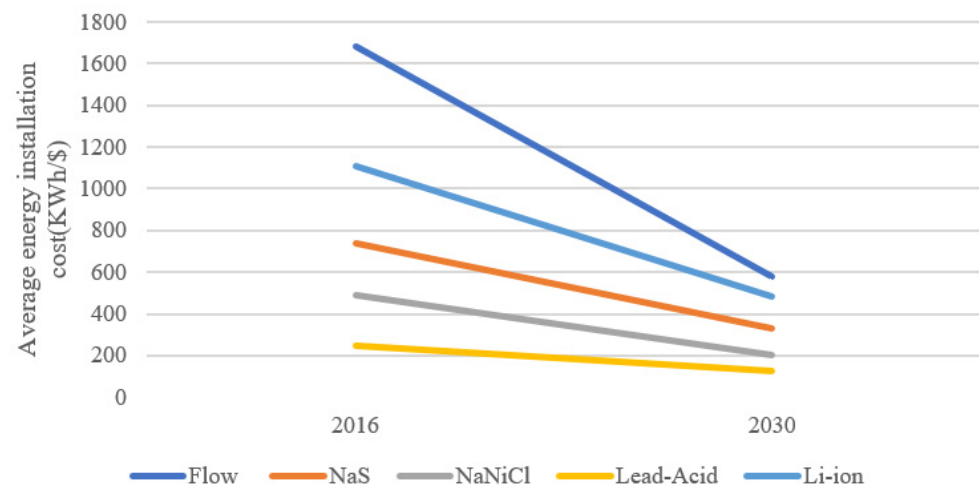

Figure 7. Estimating the reduction of installation energy costs of different ESSs [149].

Table 4. Technical and economic features of various ESSs technologies [33,42,145,147,151].

ESS Technologies	Maturity	Capacity (MW)	Lifetime (Year)	Power Capital Cost ($/KW)	Energy Capital Cost ($/kWh)	O&M Cost ($/(kW$ year))	Advantage	Disadvantages	Application
PHS	Mature	100–5000	40–60	2000–4300	5–100	0.75	Higher capacity and lower cost/unit capacity	Disturbance to local wildlife and water level	Seasonal storage, Network expansion, RESs integration, Peak shaving, Consumer services
CAES	Deployment	5–1000	20–40	400–1000	2–120	2.5–10	Higher capacity and lower cost/unit capacity	Difficult to select sites for use	Seasonal storage, Energy management, Load Shifting
Lead-acid	Deployment	0–40	3–15	300–600	200–400	10–15	Lower capital cost	Lower energy density	Seasonal storage, Network expansion, RESs integration, Power quality, Peak shaving, Consumer services
NaS	Deployment	0.05–34	10–15	350–3000	300–500	20–25	Higher energy density and efficiency, almost zero self-discharge	High production cost, need recycling for Na	Seasonal storage, Network expansion, RESs integration, Spinning reserve, Peak shaving, Consumer services
Lİ-İON	Deployment	0–100	5–15	1200–4000	600–3800	25	Higher power and energy density, and high efficiency	Require recycling of costly Lithium oxide and salt	Power quality, Consumer services, Network expansion, RESs integration, Spinning reserve
Supercapacitors	Demonstration	0–0.3	25–30	100–450	300–2000	5	Long lifetime and high efficiency	Toxic and corrosive, low energy density	Power quality, Consumer service
SMES	Demonstration	0.1–10	20–30	250–350	1000–10,000	10	High power and efficiency, long lifetime, and potential of 2000+ MW capacity	Impact to health for large-scale sites	Power quality, Consumer services, Network expansion, RESs integration, Spinning reserve

5. Optimal Operation Strategy for Integrated Evaluation of RESs, ESSs, and DSM

Numerous techno-economic strategies were considered in the literature with special emphasis on adopting coordinated procedures between DSM techniques and ESSs to create a sustainable platform for the development of RESs in the context of distribution systems. In this section, the architecture of DSM techniques and ESSs are evaluated in line with the various optimal scheduling programs from different players' perspectives.

5.1. Architecture of DSM Techniques

A number of studies investigated the impact of OPU programs in coordination with RESs to improve the socio-technical parameters of distribution networks. The authors of [156] examined and modeled the novel load control algorithm based on the flexible load shape technique to maximize the utilization of RESs. In [157], the peak-clipping and load-shifting techniques were considered to develop an energy management strategy based on the consumers' behaviors in the real-time and day-ahead scheduling stages using the Internet of Things (IoT) platform. In the same work, the presented energy management strategy was analyzed from the perspective of economic methodologies. The authors of [158] used the model predictive approach to evaluate the effect of the load-shifting technique on improving the economic performance of renewable-based microgrids. To this end, the influence of DSM strategies was evaluated in the proposed optimization program to minimize the total operation cost of the whole energy system in the day-ahead energy markets. Sarker et al. [159] presented a home energy management strategy consisting of the renewable-based microgrid framework and load-shifting technique that integrated peak load, peak to average, and energy cost factors and characteristics in the energy management process of microgrids, especially in determining the performance of RESs. Moreover, in [159], a tri-objective function was presented based on the high penetration of RESs and load-shifting technique to improve the load factor index in the residential power distribution system. The main targets of the tri-level model were to minimize the operation cost, emissions, and the deviation between the output power of RESs and the demand curve using a stochastic scheduling problem. The main features of the above-mentioned studies on the DSM optimization problem are explained briefly in Table 5.

DRPs are another type of available tool to implement DSM strategies in line with the considered goals by distribution network operators. DRPs were defined as *"customers' willingness to change their usual consumption patterns in response to the designed incentives at critical times, where the system reliability may be compromised, or in response to changes in the electricity price"* in [160]. DRPs can be classified into two categories: time-based rates (TBR) programs and incentive-based programs (IBP). The main objective of all DRPs is to control the power consumption of different consumers with regard to economic stimulators. A number of extensive benefits of DRPs for different entities, e.g., distribution network operators, retailers, utilities, and end-users, can be summarized as follows [161–163]:

- The use of DRPs that assist renewable energy system owners in mitigating the power fluctuations of RESs.
- Market-based demand response (DR) mechanisms lead to the realization of the goals of restructured systems. For example, the use of DRPs can increase the efficiency of electricity markets by decreasing the probability of market power exercise by generation companies in wholesale markets.
- The use of DRPs can lead to more efficient use of resources in power systems by increasing the dependence of electricity retail tariffs on the wholesale electricity market price.
- The use of DRPs reduces power production using fossil fuels, resulting in a significant reduction in greenhouse gas emissions.
- Consumers can reduce their energy bills by rescheduling their power consumption patterns using various DRPs.

Generally, there is a large body of studies that were evaluated the performance of power systems in the presence of the high penetration of intermittent RESs and DRPs.

For instance, Hajibandeh et al. [164] presented an economic model for the integration of renewable power and DRPs. In the same work, the TOU model and emergency DR program (EDRP) were used to create a cost-and-emission-based preventive maintenance problem with maximum utilization of RESs. The most common mathematical formulations for implementing TBR programs—i.e., TOU, real-time pricing (RTP), and critical-peak pricing (CPP)—and IBP, e.g., EDRP and direct load control (DLC), which are also used in [164], are presented in (1) and (2), respectively.

$$P_t^f = \eta_p \times P_t^i \times \left\{ 1 + \sum_{h=1}^{24} E_{t,h} \times \left[\frac{\lambda_h - \lambda_h^{fx}}{\lambda_h^{fx}} \right] \right\} \tag{1}$$

$$P_t^f = \eta_p \times P_t^i \times \left\{ 1 + \sum_{h=1}^{24} \frac{E_{t,h} \times A_h}{\lambda_h^{fx}} \right\} \tag{2}$$

where P_t^i and P_t^f are respectively power consumption profiles before and after applying DRPs, λ_h and λ_h^{fx} are electricity tariff after applying the DRPs and fixed rate electricity tariff, $E_{t,h}$ is elasticity of demand, η_p is the participation rate of consumer in DRPs, and finally A_h is rate of incentive in peak intervals during IBP.

The authors of [165] presented a bi-level pricing model to exchange the power between the interconnected microgrids, of which RESs are the main source of power generation. In addition, the step-wise DRP in the form of the demand bidding (DB) program was considered to reach the cost-effective operation. In [166,167], the structural optimization problems between the residential consumers and different energy markets were developed to increase the economic indicators considering multi-energy TOU programs and RESs. In all of these studies, unique architectures were developed based on DRPs from the perspective of the system operator or different consumers. The principle target of all these studies is to use DRPs to increase the efficiency of RESs in optimal scheduling problems by means of various control options. Table 5 summarizes these studies.

Table 5. Summary of the used DSM techniques to integrate RESs in power systems.

Ref.	Research Objectives	DSM Techniques	Consumer Type
[161]	Providing the load control model based on appliances' thermal parameters; Maximizing the use of RESs; Adjusting the response levels for each appliance.	OPU-Flexible load shape	Residential
[162]	Developing a day-ahead energy management mechanism based on the load-shifting technique; Creating the real-time energy management mechanism based on the peak-clipping technique; Utilizing IoT platform to implement the developed energy management strategies.	OPU-Peak-clipping, Load-shifting	Residential
[163]	Evaluating the influence of DSM strategies on the performance of renewable-based microgrids; Developing the model predictive approach to optimize the shifting of demands based on the renewable power production.	OPU-Load-shifting	General
[164]	Implementing the proper energy management strategy and utilizing of RESs to enhance the energy efficiency of microgrids.	OPU-Load-shifting	Residential
[166]	Developing a tri-objective function for the DSM optimization problem by relying on the high-power RESs to assess economic, environmental, and reliability indices; Improving the load factor of the residential power distribution system by optimal shifting of flexible loads.	OPU-Load-shifting	Residential

Table 5. *Cont.*

Ref.	Research Objectives	DSM Techniques	Consumer Type
[167]	Presenting a market-based optimization model for the integration of renewable power and DRPs.	DR-TOU, EDRP	General
[168]	Developing the optimal energy management problem to minimize the operation cost of renewable-based microgrids by relying on the TOU program.	DR-TOU	Commercial
[169]	Creating a pricing model to trade power between microgrids considering DRPs and high-power RESs.	DR-DB	Residential
[170]	Providing a DR platform to share power between the user's home and power market; Constructing a load management system based on IoT technology.	DR-IBP, TBR	Residential
[171]	Investigating the impacts of RESs and multi-energy TOU program presence on the energy consumption in residential buildings.	DR-TOU	Residential

5.2. Architecture of ESSs

Pursuant to the identification of the novel concepts, e.g., DSM strategies, and the rising trend of distributed generation and RESs utilization in the distribution systems, the ESSs have become a critical component of the smart power systems. ESSs serve the system operators by creating a trade-off between the optimal and economical operation of power systems. Power system operators can manage the consumers' demands in different scheduling intervals, i.e., peak, off-peak, and valley, by combining different ancillary services, especially ESSs and DSM strategies. Hence, the use of ESSs to increase the flexibility and reliability of power systems is at the forefront of many planners and policy-makers. From the point of view of power system operators, the benchmarks of an effective ESS are [168,172]:

- Dispatchability: Responsiveness to fluctuations in electricity demand that occur in daily, weekly, or seasonal scheduling cycles due to changes in the behavior of different types of consumers.
- Adaptability: Ability to respond to renewable power fluctuations in coordinated interaction with other generation units to maintain stable performance of the power grid.
- Efficiency: Ability to switch between different operating modes in the shortest possible time and with the least amount of energy losses.

According to the existing literature, in most studies, the authors have tried to maximize the hosting capacity of RESs using the optimal operation of various ESSs along with other flexibility tools, e.g., DRPs. For instance, in [169,170], systematic approaches were provided to address the challenges of integrating high-power RESs into the distribution networks by unequivocally considering fast response ESSs and/or DRPs. In the absence of proper energy management strategies, power fluctuations from high-power RESs can cause various technical problems in terms of power quality, power system reliability, stability, and security to system operators and consumers. In this regard, the development of appropriate charging and discharging protocols for each ESS with respect to the optimal efficiency and lifetime of ESSs was considered by researchers and network planners [171]. For this purpose, in [173–175], robust operational strategies for economic operation of ESSs were presented. In the same works, the main objectives of the developed energy management strategies were to integrate RESs in distribution networks, facilitate peak load shaving, mitigate the intermittency of RESs, minimize line congestion, and decrease degradation cost of ESSs. To obtain these objectives, the comprehensive charging and discharging rules were expressed in [176]. These rules can be stated as (3) and (4).

$$P_t^{ch} = \min\left\{ \left(F_t^l - CR^l \right), P^{e\_ini}, (E^{max} - E_{t-1})/\Delta t \right\} \tag{3}$$

$$P_t^{dis} = \min\left\{\left(CR^l - F_t^l\right), P^{e\_out}, \left(E_{t-1} - E^{\min}\right)/\Delta t\right\} \tag{4}$$

where, P_t^{ch} and P_t^{dis} are the consumed/generated power in charge/discharge modes by ESSs at interval t, CR^l is the rated power capacity of line l, F_t^l is the power flow of line l at interval t, P^{e_in} and P^{e_out} are the rated charge and discharge capacities, E^{max} and $E^{\min}$ are the maximum and minimum capacity of ESSs.

Equation (3) indicates the optimal charging strategy. Based on (3), if line congestion occurs, i.e., $F_t^l - CR^l > 0$, ESSs can be charged considering the charge rate capacity of ESSs, i.e., P^{e_in}, as well as the availability of the ESSs. On the other hand, (4) demonstrates the optimal discharging strategy. Based on (4), when different lines are in normal condition, i.e., $F_t^l - CR^l < 0$, ESSs can be discharged considering the discharge rate capacity of ESSs, i.e., P^{e_out}, as well as the availability of the ESSs.

In addition, damage to electrical equipment such as transformers, distribution and sub-transmission substations, and distribution network lines due to different electrical/natural events are among the common phenomena that threaten the stability of distribution networks. However, the optimal utilization of high-power RESs along with suitable energy storage technologies and DRPs can help to prevent outages and increase the overall reliability and stability of distribution networks [177,178]. In all accomplished research in this field, special emphasis has been placed on the significant impact of ESSs as an effective flexibility option. However, the impacts that come from the integration of ESSs have to be quantified by technical indicators. For example, in [179–181], the flexibility indices were considered as an influential criterion for analyzing the status of the renewable-based power systems with and without the presence of ESSs. One of the most important flexibility indices is to evaluate the amount of power injected into the power grid from the upstream network at the point of common coupling (PCC). Determining the optimal location and sizing of ESSs alongside RESs can reduce the amount of exchanged power between distribution network and upstream system during the scheduling period. From another standpoint, ESS can act as the backup energy production unit to cover vital consumers in the distribution networks in emergency conditions.

5.3. Mathematical Optimization for Scheduling Strategies

From the perspective of the used optimization approaches, two types of mathematical programming frameworks were mostly used in the existing studies on the optimization of low-voltage networks in the presence of RESs, ESSs, and DSM strategies. In the first category, the uniform objective functions were used with the aim of minimizing the total operation cost [182–184], or maximizing the utilization of renewable energy [185]. On the other hand, the second category includes multi-objective optimization functions to improve the technical parameters of the distribution networks [186,187] and decrease environmental pollution [188,189] along with economic analysis.

From the perspective of the used DSM strategies, IBP and TBR programs were more welcomed by researchers. Among the IBP and TBR programs, DLC [189,190] and TOU [191,192] options were used repeatedly in the context of the optimization processes to achieve the goals set. Furthermore, in [193], the combination of TOU and DLC options, and in [194], the combination of TOU, RTP, DLC, and EDRP was used. From the perspective of the consideration of uncertain sources to find the optimal performance of distribution networks in the presence of RESs and DRPs, in [195–198] different methods, including stochastic programming and robust approach were used to model the uncertainties of renewable power generation and load demand. Software such as GAMS, MATLAB, Python, Gurobi, and OpenDSS was used to model and simulate the optimization programs, although GAMS was widely accepted by researchers. The principal features of some selected studies on the optimization process in renewable-based distribution networks by relying on ESS and DSM strategies are summarized in Table 6.

Table 6. The main aspects of some studies to evaluate the effects of DSM and ESSs in renewable-based distribution grids.

Reference	Objective Function	Optimization Algorithm	Point of View	Time Horizon	Flexibility Options	Simulation Platform
[174]	Minimize the total operation cost	Robust-stochastic MINLP model	System operator	Day-ahead	ESSs-load shifting (OPU)	Modified general distribution system
[175]	Minimize the annual operation cost	Stochastic MILP model	Microgrids operator	Two-stage	ESSs-load shifting (OPU)-DLC (DRP)	Multiple interconnected microgrids
[177]	Maximum the utilization of RESs	Stochastic MINLP model	RES owners	Two-stage	-	33-bus distribution system
[179]	Maximize the distribution system operator's profit; Minimize the energy not supplied index	Multi-objective stochastic model	System operator	Day-ahead	ESSs	Multiple interconnected microgrids
[186]	Minimize operation cost and environmental pollutions	Multi-objective stochastic model	System operator	Day-ahead	DLC (DRP)	69-bus distribution system
[198]	Achieve a robust PV inverter dispatch solution	Robust MILP model	System operator	Two-stage	ESSs	33-bus distribution system; 123-bus radial network

Note that: MILP: mixed-integer linear programming; MINLP: mixed-integer nonlinear programming.

6. Conclusions and Future Directions

This paper provided a critical review on the economic operation of renewable-based distribution networks based on the impacts of ESSs and DSM strategies. It was presented the urgency of using ESSs and DSM with RESs to overcome the challenges caused by the intermittent and variable generation of them. As the flexibility need of distribution networks are growing with high renewable integration, both ESSs and DSM play a vital role in balancing supply and demand. DSM strategies change not only according to RESs and ESSs technologies but also according to the incentives provided by governments. The renewable energy promotion programs and DSM activities of different countries were examined and summarized. Among the countries studied, Germany is a model country with its successful renewable energy incentive programs. The German government has achieved a capacity increase in almost all types of renewable energy by implementing successful programs. The FIT schemes and low-interest loan programs have a significant contribution to increasing the renewable energy capacity of Germany, and FIT schemes have been implemented by other countries after Germany's success. Today, in Germany, FIT has been replaced with FIP to support renewable energy installations, similarly in Denmark. Except for the US, the FIT schemes have been applied or are being implemented at the national level in all selected countries. Unlike other countries, America has mainly provided loan guarantees, tax credits, and grants to promote renewable energy. In addition to America, there is also a tax support mechanism in Japan for renewable energy promotion. China, Japan, and the UK have created obligatory programs like RPS and renewable obligation out of incentive programs. Brazil, Denmark, and the US use net meter mechanisms to encourage electricity subscribers to install RESs to meet their electricity consumption and ensure a reasonable balance between load and generation in power grids.

In addition to the renewable energy integration effort, considerable efforts have been made in controlling loads in recent years. Brazil, Iran, and China respectively have the flag tariff mechanism, TOU, and triple rate tariff to shift loads to off-peak hours. The US electricity grants eligible electricity subscribers for the reduction in their electricity consumption. In Japan, electricity consumers receive payment for the cut in consumption per kWh under the negawatt mechanism. Unlike other countries, Denmark mandates electricity utility to diminish the end-user consumption by a certain amount annually. Additionally, pilot DSM projects have been put into operation in Japan and China. The government of Turkey has launched volunteer-based DSM programs. Within the scope of the integration of ESSs to the network, Brazil realizes R&D activities and establishes pilot projects. China and Turkey make regulatory arrangements for ESSs integration. Germany supports ESSs with low-interest loan subsidies. Additionally, in Denmark, there is a power hub project for carrying out V2G charging. With an overview, it is an inevitable fact that countries need to produce reasonable and applicable policies and incentive programs in order to reach their renewable energy targets. Besides the supply-side solution, proper DSM policies and programs need to be implemented due to unpredictable load increase in the electricity grid. Finally, with the integration of the ESSs in power grids, to use electricity from renewable energy more effectively and produce powerful solutions on load management issues is possible.

As well as country policies, the effects of ESSs technologies on economic aspects are considered in detail. Economic review of current energy storage technologies including electrochemical, battery, thermal, thermochemical, flywheel, compressed air, pumped, magnetic, chemical, and hydrogen energy storage, was provided. Storage categories, comparisons, applications, recent developments, and research directions were discussed. Using ESSs in distribution networks has the potential to reduce the system operation costs of the electricity networks. Currently, most energy storage technologies have higher costs than alternatives that have responsiveness to meet peak demands (such as gas turbines). Although capital costs have dropped somewhat due to technological advances, they have not yet become more economical. While PHS and CAES have relatively low LCOE among

ESSs, electrochemical ESSs have the potential to achieve high performance and become commercially viable.

Lastly, according to the studies reviewed on distribution networks planning/scheduling with the aim of integrating RESs, ESSs, and DSM techniques into the existing networks, the following points should be considered:

- A detailed comparison among various DSM approaches in terms of their impacts on social welfare and response fatigue index is lacking in the literature and recommended as a target for future studies.
- Formulating DSM optimization programs in optimal coordination with RESs and ESSs with special emphasis on the realistic conditions of the networks and end-users is recommended as a direction for future studies.
- Considering multi-carrier ESSs in the optimal operation of renewable-based distribution networks is highly recommended to maximize the penetration rate of RESs.
- Detailed investigation of the impacts of the integrated operation of multi-carrier ESSs, DSM techniques, and RESs on different electricity markets, e.g., day-ahead, intraday, and balancing, with imperfect competition is recommended as a direction for future studies.

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