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Review

A Comparative Review on Energy Storage Systems and Their Application in Deregulated Systems

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Abstract: Electrical energy is critical to the advancement of both social and economic growth. Because of its importance, the electricity industry has historically been controlled and operated by governmental entities. The power market is being deregulated, and it has been modified throughout time. Both regulated and deregulated electricity markets have benefits and pitfalls in terms of energy costs, efficiency, and environmental repercussions. In regulated markets, policy-based strategies are often used to deal with the costs of fossil fuel resources and increase the feasibility of renewable energy sources. Renewables may be incorporated into deregulated markets by a mix of regulatory and market-based approaches, as described in this paper, to increase the systems economic stability. As the demand for energy has increased substantially in recent decades, particularly in developing nations, the quantity of greenhouse gas emissions has increased fast, as have fuel prices, which are the primary motivators for programmers to use renewable energy sources more effectively. Despite its obvious benefits, renewable energy has considerable drawbacks, such as irregularity in generation, because most renewable energy supplies are climate-dependent, demanding complex design, planning, and control optimization approaches. Several optimization solutions have been used in the renewable-integrated deregulated power system. Energy storage technology has risen in relevance as the usage of renewable energy has expanded, since these devices may absorb electricity generated by renewables during off-peak demand hours and feed it back into the grid during peak demand hours. Using renewable energy and storing it for future use instead of expanding fossil fuel power can assist in reducing greenhouse gas emissions. There is a desire to maximize the societal benefit of a deregulated system by better using existing power system capacity through the implementation of an energy storage system (ESS). As a result, good ESS device placement offers innovative control capabilities in steady-state power flow regulation as well as dynamic stability management. This paper examines numerous elements of renewable integrated deregulated power systems and gives a comprehensive overview of the most current research breakthroughs in this field. The main objectives of the reviews are the maximization of system profit, maximization of social welfare and minimization of system generation cost and loss by optimal placement of energy storage devices and renewable energy systems. This study will be very helpful for the power production companies who want to build new renewable-based power plant by sighted the present status of renewable energy sources along with the details of several EES systems. The incorporation of storage devices in the renewable-incorporated deregulated system will provide maximum social benefit by supplying additional power to the thermal power plant with minimum cost.

Keywords: regulated system; deregulated system; energy storage devices; modern power system; profit; compressed air energy storage

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1. Introduction

Electrical energy storage (EES) systems have demonstrated unique skills in coping with several important aspects of electricity, for instance, hourly changes in demand and pricing [1]. Firstly, EES saves power costs by storing electricity obtained during off-peak hours when its price goes down, for use at peak hours, rather than electricity purchased then at higher costs [2]. Second, in order to increase power supply stability, EES systems assist users when electricity network disruptions occur as a result of natural catastrophes, for example. Thirdly, it preserves and enhances power quality, frequency, and voltage [2]. Electric vehicles with batteries are the most potential off-grid method for replacing the conventional sources with renewable energy [3]. Smart grid relates to power grid updates. Smart grid technology integration makes the grid more adaptable and responsive, with the potential to provide real-time feedback by sharing data among electricity producers and consumers to provide a more sustainable and efficient power supply. EES is one of the key elements in developing a smart grid [4].

1.1. Role of EES

Two properties of electricity cause challenges with its usage while also creating market demand for EES. To begin with, power is consumed at the same moment it is created. To fulfill the shifting demand, the appropriate amount of power must constantly be given. The second trait is that power plants are often positioned distant from where electricity is utilized [5].

1. Because power lines are constantly required, if a line fails (due to congestion or any other reason), the provision of energy is halted; also, because lines are always required, delivering power to mobile applications is problematic.
2. Depending on the locations and amounts of power supply and demand, a large amount of power flow may be focused onto a single transmission line, causing congestion.

1.1.1. Optimization: High Generation Cost during Peak Hours

Generation costs vary across periods. Power suppliers should supplement base-load power plants with less cost-effective but more adaptable kinds of production, such as oil- and gas-fired generators, during peak hours. Costly methods of generating can be shut down during off-peak hours. This surplus can be held in EES and used to lower generating costs. In contrast, EES can reduce energy cost for customers because it can store energy purchased at cheap off-peak prices and use it during prime times in place of costly power. During off-peak time, users can recharge batteries and may also sell to utilities or to other users during peak time [5–7].

1. From the standpoint of utilities, there is a significant opportunity to lower total generating costs by storing electricity during the off-peak hours and reintroducing it into the power system during hours of maximum demand.
2. During peak periods of higher-than-average energy use, power suppliers must supplement the conventional base-load power facilities with less costly but more flexible sources of production, such as oil- and gas-turbine generators.
3. Conversely, from the perspective of customers, EES can cut down the financial burden since it can store electricity purchased at cheap rates during off-peak and use it during peak hours, which would have been costlier if purchased during peak hours.

1.1.2. Continuous and Flexible Supply: Need of the Hour

The main issue for utilities is delivering a consistent and adaptable power supply for consumers, which is a critical quality of energy. If the proper amount of electricity is not accessible when consumers need it, power quality will suffer and service will be disrupted in the worst-case situation. To meet fluctuating power consumption, sufficient amounts of energy should be produced on a regular basis, based on an accurate assessment of demand variations [1,2]. Power generators require two extra functions in addition to the basic generating function. Firstly, producing facilities must have a “kilowatt function” that permits them to generate enough power (kW) as per requirement. Secondly, generating facilities must feature a frequency control mechanism that adjusts the output to fit minute-by-minute variations. To take care of the fluctuating power consumption, adequate amounts of energy should be generated and be available, based on an accurate estimate of demand fluctuations. Such issues are intended to be addressed by EES. When produced electricity is in low supply, pumped hydro has been routinely employed to deliver a huge amount of power [7].

1.1.3. Distance between Generation and Consumer: A Deciding Factor

Consumers’ premises are usually located far from power-producing facilities, increasing the likelihood of a power failure [8]. Natural calamities and causes due to human factors trigger system failures that interrupt power supply and have the potential to affect broad areas [9]. When power failures occur, EES will support consumers by continuing to provide electricity. Semiconductor and LCD manufacturing are two industries where voltage sag for just a few milliseconds has an impact on product quality, employ EES [10].

1.1.4. Power Grid Congestion: A Point of Concern

The power flow in transmission networks is determined by the demand and supply. Power congestion can occur during the process of balancing supply and demand [11]. Utility companies strive to avoid future bottlenecks by moving generating output or establishing additional transmission connections. EES, when installed at appropriate places such as substations at the extremities of heavily loaded lines, can help to reduce congestion [12]. This method also helps utilities delay or cease power network reinforcement.

1.1.5. Transmission by Cable: Point of Difficulty

Because power transmission usually entails the use of cables, supplying power to mobile applications and isolated areas is difficult. EES technology, with its mobility and charging functionality, can be beneficial to address this issue. It may be difficult to charge an EV in remote places without access to a power grid, but EES can aid in the creation of a green transportation system that does not rely on traditional IC engines [13].

1.2. Emerging Needs for EES

Two key market needs for EES as a critical and evolving technology are: (i) the use of more renewable energy and lower consumption of conventional fuel and (ii) a future smart grid [1] (shown in Figure 1).

1.2.1. A Step towards Greener Earth: More Renewable Energy, Less Fossil Fuel

On Grid Areas

The variability in the output of renewable sources makes it challenging to regulate the frequency of the system, and if the frequency deviation is too great, system performance may suffer [14].

Thermal generators are not operated at full capacity but rather with a positive and negative output margin (i.e., output increases and decreases) that is utilized to change frequency. If EES can reduce output variation, thermal generator margins can be decreased, and they can run more efficiently [6].

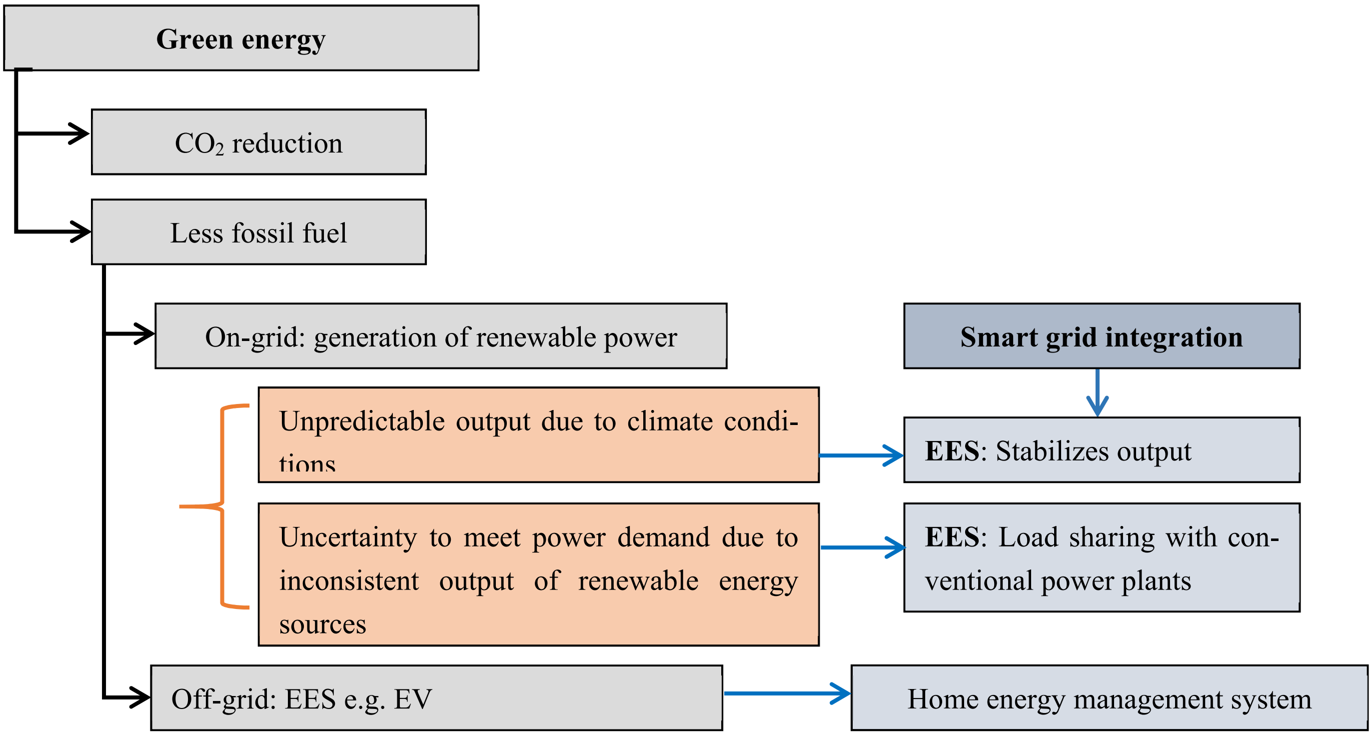

Figure 1. EES: Sustainable option towards greener earth.

Off-Grid Areas

Fossil energy should be replaced with non-fossil energy. This not only eliminates the prohibitive initial costs but also provides a good clean alternative. In particular, low-carbon power produced primarily from renewables ought to take the place of fossil fuels.

1.2.2. Smart Grid

Existing equipment may be energized with EES and be included into the smart grid. By employing a home energy management system to track their actual usage in real time, residential consumers will take an active role in changing their energy consumption patterns [15]. EVs are projected to be a new source of electricity as well as a potential storage medium in a smart grid that uses a portable, distributed energy resource as a load-shifting function, allowing utilities to continue delivering power even as electricity costs rise.

2. Types of Electrical Energy Storage System (EES)

EES systems classified on the basis of the kind of energy consumed are: (i) mechanical, (ii) electrochemical, (iii) chemical, (iv) electrical, (v) thermal and (vi) superconducting magnetic categories [8,12,16]. The classification of EES based on type of energy consumed is shown in Figure 2.

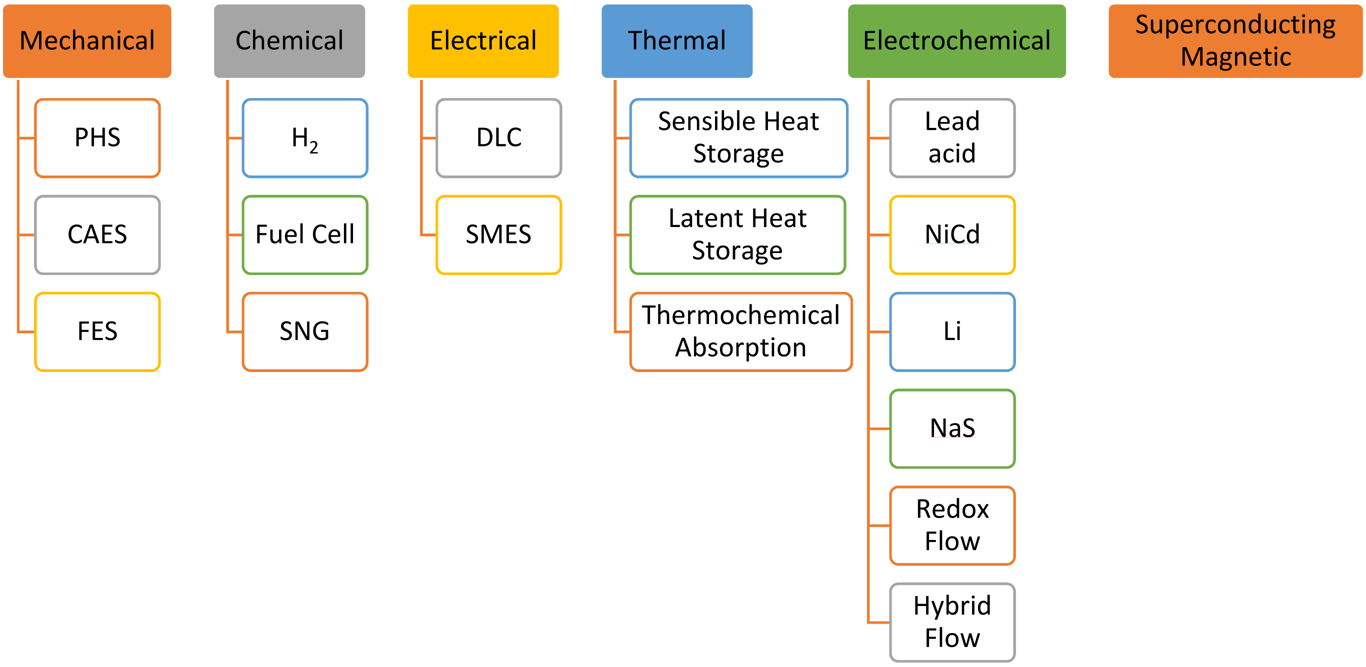

Figure 2. Classification of EES based on type of energy consumed.

3. Working of Electrical Energy Storage System (EES)

3.1. Mechanical Storage Systems

Mechanical energy storage devices store received energy by utilizing kinetic or gravitational forces. These systems are useful in real-world applications due to quality materials, advanced computer control systems, and imaginative design [17]. Mechanical energy storage operates in complicated systems that employ heat, water, or air in conjunction with compressors, turbines, and other machinery.

3.1.1. Pumped Hydro Storage (PHS)

Pumped hydro storage power plants provide for more than 95% of the world's current electrical storage capacity [18]. In pumped hydro storage systems, two water reservoirs at different heights are utilized to pump water during off-peak hours (charging), and as needed, water flows downstream from the top pool to the lower reservoir, driving a turbine that produces electricity (discharging). The efficiency of the PHS plant ranges from 70% to 85% [19]. The main benefits of this system are long life and almost unlimited cycle stability, while its drawbacks are its topography and heavy land use. The world's largest PHS plants have installed capacity of 3003 MW and 2400 MW (as of December, 2021), respectively.

3.1.2. Compressed Air Energy Storage (CAES)

CAES has been used in a range of industrial applications since the eighteenth century. Electricity is used to compress air and store it in a subsurface construction or an above-ground system of containers or lines. Subsurface storage options include tunnels, aquifers, and abandoned mines. Diabatic technology is well proven; the plants are highly reliable and can operate without external power [20] (shown in Figure 3). CAES has a large capacity, but it has drawbacks such as low round-trip performance (less than 50%) and geographical constraints.

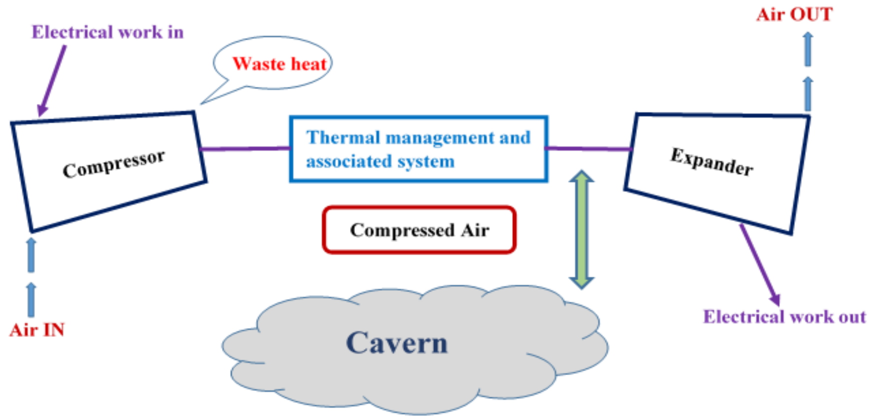

Figure 3. Compressed air energy storage system schematic.

3.1.3. Flywheel Energy Storage (FES)

In flywheel energy storage, kinetic energy is stored in an accelerated rotor which is a massive rotating cylinder. Electricity is supplied to the flywheel using a transmission mechanism and with rise in the speed, amount of stored energy increases [17]. Flywheels are commonly utilized for power quality in industrial and other applications. Flywheels have advantages of exceptional cycle stability and long life, low maintenance, greater power density and the use of environmentally friendly materials. However, it has demerits such as high self-discharge and poor current efficiency [21]. Efforts are focused on improving the management of flywheels as power storage devices for usage in cars and industries for long operation hours (shown in Figure 4).

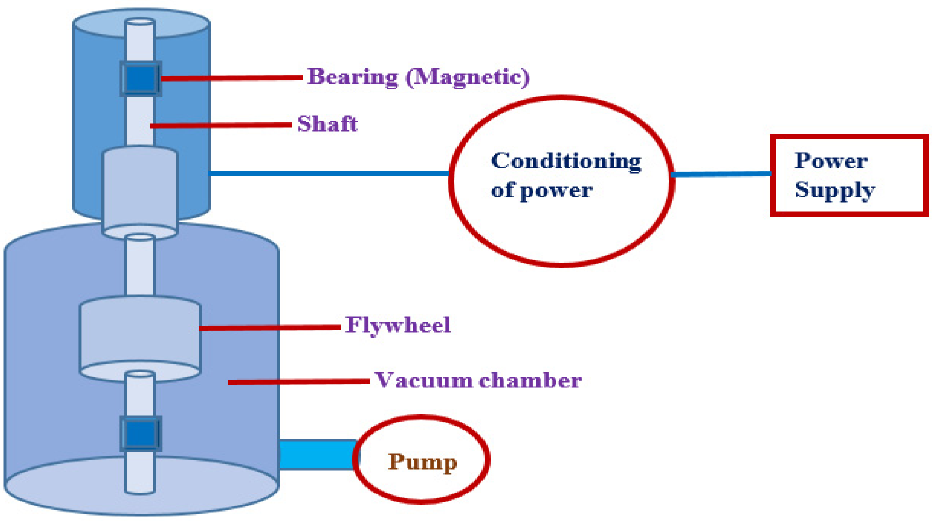

Figure 4. Flywheel energy storage system schematic.

3.2. Electrochemical Storage Systems

Electrochemical energy storage devices have the ability to make a major contribution to the deployment of sustainable energy. Electrochemical energy storage is based on systems with high energy density (batteries) or power density (electrochemical capacitors). High energy and high power densities in the same material are increasingly required in current and near-future applications [17,22]. These are categorized in two types: secondary batteries and flow batteries. The secondary batteries have again classified into following types: lead–acid, NiCd/NiMH, Li-ion, metal–air, sodium–sulfur and sodium–nickel chloride [22].

3.2.1. Secondary Batteries

A secondary battery, or charge accumulator, is a cell or set of cells with reversible cell processes. This implies that the original chemical conditions inside the cell can be restored by allowing current to flow into it, i.e., charging from outside [22].

Lead–Acid Battery (LA)

Lead–acid batteries are the most widely used form of battery in the world, dating back to roughly 1890. Service life is typically 6–15 years, with a service life of 1500 cycles at a % depth of discharge and a cycle efficiency of 80–90% [22–24]. The downsides are lower energy density and the use of lead, a dangerous element that is prohibited or restricted in some locations. Advantages include a good cost/performance ratio, simple recyclability, and a simple charging method. The current focus of lead–acid battery development is to improve their efficiency for micro-hybrid electric vehicles.

Nickel–Cadmium and Nickel–Metal Hydride Battery (NiCd, NiMH)

Before the commercial launch of nickel–metal hydride (NiMH) batteries in 1995, nickel–cadmium (NiCd) batteries had been in use since around 1915. NiMH batteries contain all of the advantages of NiCd batteries, such as greater power density, marginally better energy density, and a larger number of cycles, with the exception of a 10-fold lower maximum nominal capacity. They are far more robust and secure than lithium-ion batteries. However, due to the toxicity of cadmium, they have been limited for consumer use since 2006. NiMH batteries are currently about the same cost as Li-ion battery packs [22].

Lithium-Ion Battery (Li-Ion)

Lithium-ion batteries have been the most important form of storage in portable and mobile applications since about the year 2000. With a cell voltage of only 1.2 Volts, one lithium-ion cell may substitute three NiCd or NiMH batteries [22]. The most significant impediment is the high cost of the unique packaging and incorporated overload protection circuits. Safety is a serious problem in lithium-ion battery technology. Most metal oxide electrodes are thermally unstable and can melt at high temperatures. Lithium-ion batteries feature a monitoring device that prevents overcharging and discharging to lessen this risk [22]. A voltage regulation circuit is often provided to monitor and avoid voltage changes in each individual cell. Lithium-ion battery technology is constantly improving, with plenty of possibilities for advancement. The evolution of cathode materials is being studied [22–26]. The construction of typical Li-ion battery module is depicted in Figure 5.

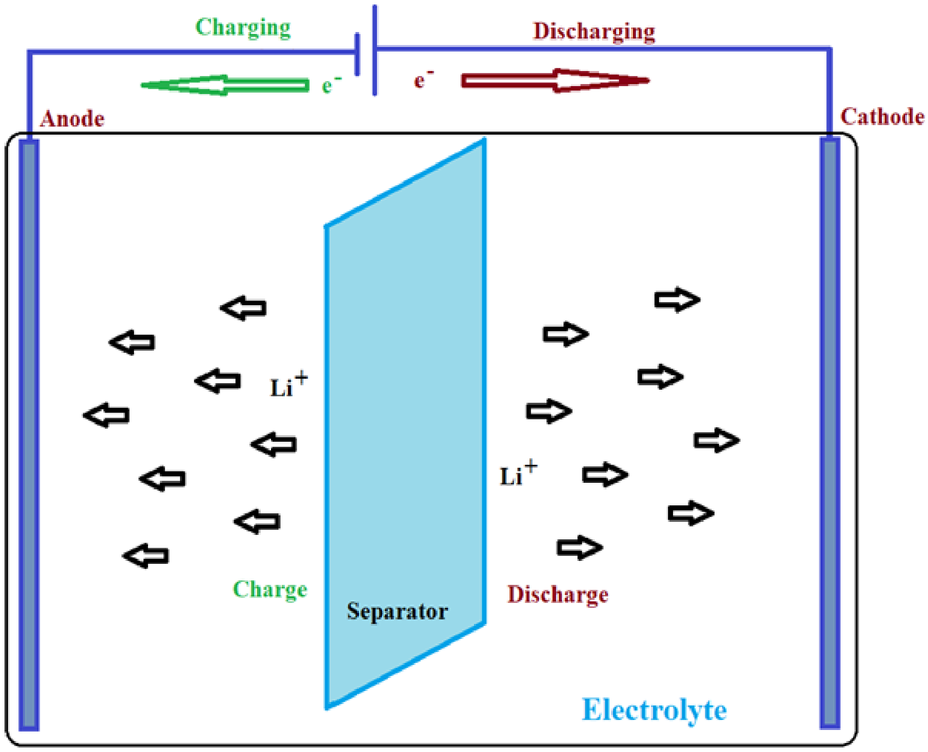

Figure 5. Typical Li-ion battery module.

Metal–Air Battery

A metal–air electrochemical cell's anode is made of pure metal, while the cathode is connected to an infinite supply of air. In the electrochemical process, only oxygen from the air is used. Because of its greater specific energy excluding oxygen (theoretically 11.14 kWh/kg), the lithium air battery is the most enticing of the several metal–air battery chemical couples [22]. Due to lithium's high reactivity to air and humidity, it can catch fire, creating a serious safety risk. Only a zinc–air battery with a theoretical specific energy of 1.35 kWh/kg (without oxygen) is theoretically practical at the moment. It is difficult to design rechargeable zinc–air cells since zinc precipitation from the water-based electrolyte must be properly handled. Although a viable, electrically rechargeable metal–air system could offer low material costs and high specific energy, none has yet attained marketability [22–26].

Sodium–Sulphur Battery (NaS)

In sodium–sulfur batteries, a solid beta-alumina ceramic electrolyte isolates the active constituents (molten sulfur at the anode and molten sodium at the cathode). NaS batteries have a discharge time of 6.0 to 7.2 h and a standard life cycle of around 4500. They are both effective and quick to respond (round-trip efficiency based on AC is around 75%) [23]. Over 200 places in Japan have tested the NaS battery technology, largely for peak shaving. Many countries employ NaS batteries as well. Although the lack of a heat source is a significant drawback, with correctly sized insulation, the heat developed in the battery may be managed in frequent use by its own reaction heat. These batteries are suited for high-frequency cycling applications [27,28]. The construction of typical NaS battery module is depicts in Figure 6.

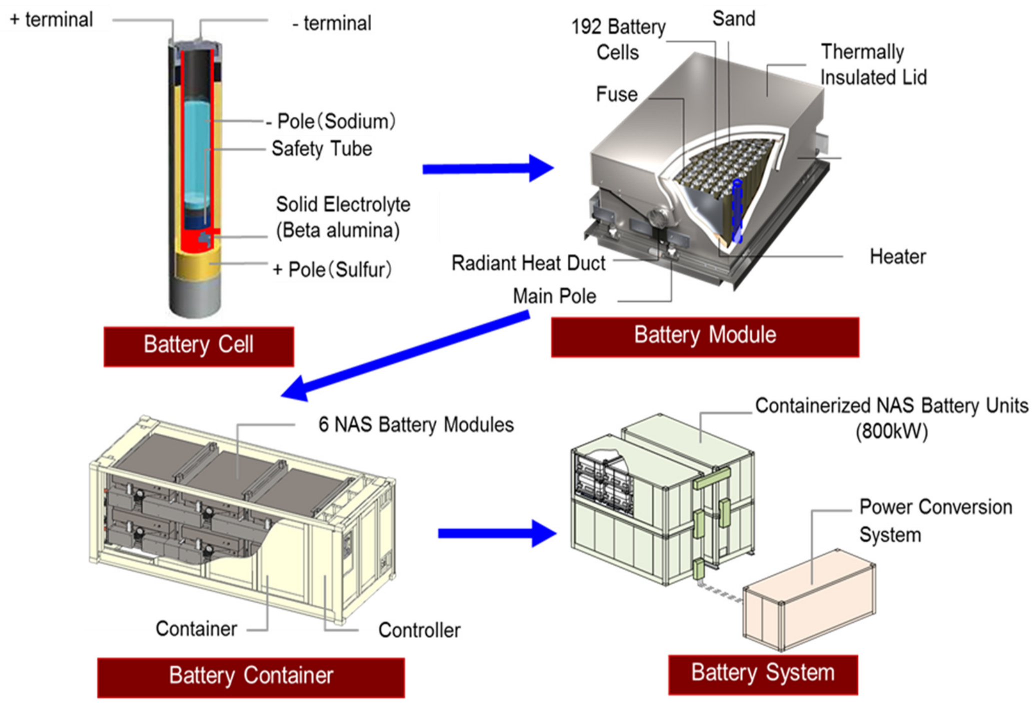

Figure 6. NaS battery system.

Sodium–Nickel Chloride Battery (NaNiCl)

The sodium–nickel chloride (NaNiCl) battery, also known as the ZEBRA battery is a high-temperature (HT) battery that, like the NaS battery, has been available on the market since approximately 1995 [24]. NaNiCl batteries outperform NaS batteries in terms of safety and cell voltage, and they can withstand limited overload and discharge. These batteries have been employed effectively in a variety of electric vehicle designs, and they are a viable alternative for fleet applications. Upgraded variants of the ZEBRA battery with greater power density values for hybrid electric vehicles, as well as high-energy versions for conserving renewable power for load-leveling and industrial purposes, are presently being developed.

3.2.2. Flow Batteries

NASA invented flow batteries in the early 1970s as an EES for long-term space flights [25]. They have the potential to store energy for hours or days and have a power of many megawatts. Flow batteries are of two types: redox flow batteries and hybrid flow batteries.

Redox Flow Battery (RFB)

The electrolytes present at the negative and positive electrodes of a redox flow battery are anolyte and catholyte. During discharge, electrodes are continually provided with dissolved active masses from the tanks; once converted, the product is returned to the tank. During the charge exchange, a current flows between the electrodes, which may be used by a battery-powered device. Redox flow batteries are being studied for use in electric vehicles; however, electrolyte energy density has proved too low thus far. An RFB may potentially be “refilled” in minutes by draining out the emptied electrolyte and replacing it with recharged electrolyte. In RFBs today, many redox couples, such as a Fe-Ti system or a poly S-Br system, have been investigated and tested (shown in Figure 7) [27,28].

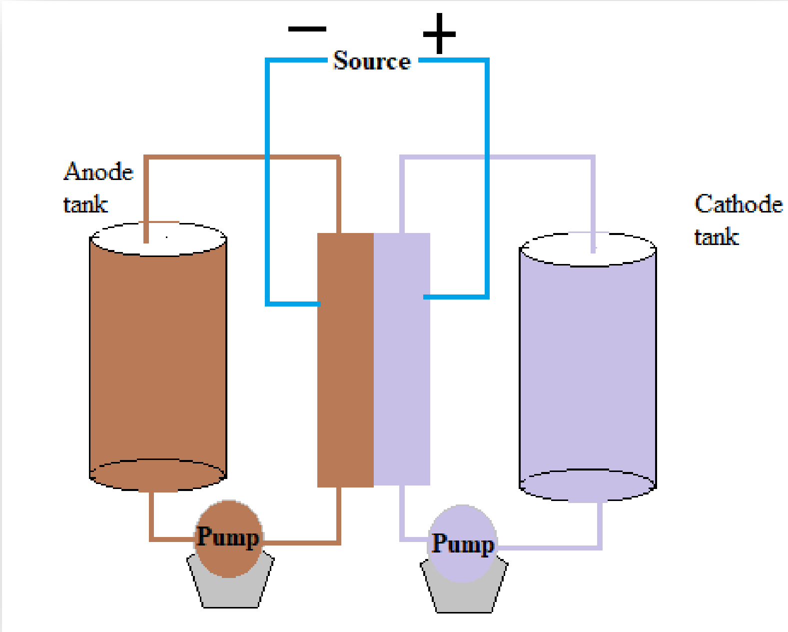

Figure 7. Schematic of redox flow battery.

Hybrid Flow Battery (HFB)

One active mass in a hybrid flow battery (HFB) is kept within the electrochemical cell, while the other is kept externally. The benefits of classic secondary batteries and RFBs are combined in HFBs. HFBs include the Zn-Ce and Zn-Br systems. The anolyte is a Zn2+ ion-acid solution, and the electrodes are primarily carbon-plastic composites. Exxon pioneered the Zn-Br hybrid flow battery in the early 1970s, and it is now being commercialized by a variety of companies. In addition, 5 kW/20 kWh community energy storage devices are also being developed [22,28].

3.3. Chemical Energy Storage

A chemical energy storage system is the only idea that allows for the long-term storage of significant amounts of energy, up to TWh, even as periodic accumulation. SNG and hydrogen may be used in a range of industries, including commuting, movement, heating, and the chemical industry. They have lesser overall efficiency than PHS and Li-ion storage technologies, but are more cost efficient and effective than ordinary batteries [26].

3.3.1. Hydrogen (H_2)

An electrolyzer is a type of electrochemical converter that splits water into hydrogen and oxygen using electricity. It is an endothermic reaction, which indicates that heat is required throughout the process. Hydrogen may be stored under pressure in gas bottles or tanks for nearly indefinite periods of time. Electrolysis releases oxygen into the environment rather than retaining it, and oxygen from the air is utilized to create electricity [26].

3.3.2. Synthetic Natural Gas (SNG)

Methane (synthetic natural gas or SNG) may be synthesized to store energy. SNG can be stored in pressure tanks, underground, or fed directly into the gas infrastructure. To prevent energy losses, CO_2 and H_2 transport to the methanation plant should be avoided. The fundamental drawback of SNG is its low efficiency as a result of conversion losses in electrolysis, methanation, storage, transport, and power production [27]. The overall AC-AC efficiency of 35% is significantly lower than that of hydrogen [13].

3.4. Electrical Storage Systems

The classifications of EES are as follows:

3.4.1. Double-Layer Capacitors (DLC)

DLCs, also known as super-capacitors, are a 60-year-old electrochemical double-layer capacitor (DLC) technology. The extremely high capacitance values, on the order of thousands of farads, and the capability to charge and discharge very fast due to extremely low inner resistance are the two important properties. This technology offers a lot of space for advancement because it might result in substantially greater capacitance and energy density than standard capacitors, permitting for more compact designs. Durability, dependability, no maintenance, prolonged lifetime, and functioning across a wide temperature range are further benefits. With the exception of the chemical used in capacitors, which deteriorate in 5–6 years regardless of the number of cycles, the lifetime surpasses one million cycles without degradation. The efficiency is often more than 90%, with discharge times varying from seconds to hours. DLCs are not suitable for long-term energy storage due to their high self-discharge rate, low energy density, and hefty investment needs [28]. As a UPS, a DLC is excellent for bridging small power disruptions. The electric automobile might be used in a unique way, as a buffer system for acceleration and regenerative braking [4].

3.4.2. Superconducting Magnetic Energy Storage (SMES)

SMES devices store magnetic energy in a magnetic field that is generated by a superconducting coil held less than its critical temperature. A temperature of around 4°K was required at the early age but now materials with higher critical temperatures (about 100°K) have been developed and are now accessible. Particle detectors for high-energy scientific experiments and nuclear fusion use large SMES systems with more than 10 MW of power [29]. The main benefits of SMES are high overall round-trip efficiency (85–90%), the extremely high power output and the extremely fast reaction time: the required power is practically instantly accessible [30]. The energy can be stored basically as long as the cooling system is running, but longer storage times are restricted by the refrigeration system's energy demand.

3.5. Thermal Storage Systems

Thermal storage systems capture heat from a wide range of sources and preserve it in an insulated storage for later use in industrial and residential applications. Thermal storage systems are used to act as an intermediary between thermal energy demand and supply, making them crucial for the integration of renewable energy sources [31].

There are three forms of thermal storage: sensible heat storage, latent heat storage and thermochemical adsorption and absorption storage [17]. A storage medium can be a liquid or a solid. Thermal energy can only be stored by varying the temperature of the storage medium. A storage system's capacity is determined by the specific heat capacity and mass of the medium used. For latent heat storage, phase change materials (PCMs) are utilized as storage media. Organic (paraffins) and inorganic PCMs (salt hydrates) are also viable options for such storage systems. Latent heat is the energy transmitted during a phase transition, e.g., ice melting [17]. It is also referred to as "hidden" heat since there is no temperature difference during energy transmission. The most well-known latent heat—or cold—storage method is the ice cooler, which uses ice in an insulated container or chamber to keep food cool on hot days. The solid–liquid phase shift is used in the majority of PCMs currently in operation, such as molten salts as a thermal storage device for concentrated solar power (CSP) plants [32–41].

3.6. Superconducting Magnetic Energy Storage

A superconducting magnetic energy storage system (SMES) is a tools that stores electricity from the electrical grid within the magnetic field of a coil contained of superconducting wire with very little energy loss. The SMES systems are categorized into three groups: power supply, control systems and contingency systems [16].

4. Review: A Journey towards the Future with Guidance from the Past

A detailed literature review was conducted on deregulated power systems with the integration of renewable energy sources and energy storage devices. The main objectives of the reviews are the maximization of system profit, maximization of social welfare, and minimization of system generation cost and loss by optimal placement of energy storage devices.

K.C. Divya's study [42] focuses on the incorporation of non-conventional energy sources into the power grid and the usage of energy storage devices for profit maximization. The role of electric hybrid car battery storage systems has been considered. This article proposed that energy storage using battery will play an important role in the sustainable and cost-effective functioning of smart electric grids integrated with renewable energy. There is no single storage system that can fulfill all of the criteria for an ideal EES. Various storage systems are compared by Chen in terms of technological specifications and characteristics, applications, and implementation status [43]. Among the developed technologies, CAES is beneficial in terms of the lowest capital cost. R. Banos looked at some of the major difficulties of renewable energy sources in this research [44], such as generation discontinuity, which is an environment-dependent and continuous development in optimization techniques utilizing computing resources. The current state of the art computational optimization methods is reviewed in this paper, providing a comprehensive picture of the most recent research developments in this subject. Heuristic techniques, Pareto-based multi-objective optimization, and parallel processing have all been discovered to be interesting study areas in the realm of renewable and sustainable energy. In the article [45], Aqeel Ahmed Bazmi discusses the importance of modeling and optimization in the power and supply sectors, as well as the future prospects of optimization modeling as a tool for sustainable energy systems. Modeling and optimization have been found to be effective and valuable methods for solution development in the power and supply sector, particularly for policymakers establishing policies based on extensive assessments of competing technologies and large quantities of scenario studies.

Zhimin Wang [46] developed a unique methodology for energy management in home area using EESs to facilitate energy storage, with the goal of providing wholesale energy at reduced cost and supporting LV distribution networks for network investment reduction. The aim is to create the optimum possible DRs-to-energy-price and network-congestion balance feasible, hence improving customer and network operator advantages. The authors of this work [46] suggest a novel dispatch approach for consumers and DNOs to share ownership of residential energy storage batteries. Ref. [47] discusses various applications of EES technologies in power systems, with a focus on their collaboration with renewable energy sources. The function of ESSs in intelligent micro power grids is also highlighted, as the stochastic nature of renewable energy sources might have an impact on power quality. Each type's applicability in power systems is examined and compared to others. An energy storage system's technological and physical features are also examined in depth. Yanine and Sauma's [48] research focuses on supervisory management of micro-generation systems when connected to the grid and when energy storage is not involved. The goal is to increase energy efficiency, thriftiness, and sustainability. Suggestions have been made that future advancements in smart micro-grid operation should be increasingly focused on recognizing that SHES can be intelligent. Mwasilu [49] conducted a complete evaluation and appraisal of the most recent research and advancements in electric vehicles (EVs) interaction with smart grid, depicting the future electric power system model. The smart V2G system's viability is also addressed. The interactions of electric vehicles with the smart grid as a future energy system model are thoroughly examined in this work.

Zhang [50] presented a two-stage EES-based optimum wind power dispatch system with risk analysis to increase financial advantages through day-ahead operations. Through simulations, the suggested strategy demonstrated promising outcomes in terms of improving financial benefits and risk-reduction capability. Muruganantham, Gnanadass, and Padhy's research [51] demonstrates the several obstacles that DN suffers while adopting RES. This research investigates the significance of energy storage in distributed networks and how to manage the demand. This research provides a high-level overview of the DN's evolution and issues. This provides a quick overview of distribution power flow algorithms, electricity pricing systems and the simultaneous working of DGs and DN. Huang, Xu and Courcoubetis [52] conducted an investigation on three joint market mechanisms to analyze EES investment and operation for locational marginal pricing. The numerical analysis brings out the significance of building integrated storage investment and working mechanisms, while market regulation/schemes focusing simply on EES are unable to produce socially optimal solutions. Das and Bass [53] presented an overview of optimal ESS deployment, size, and operation in power networks in their study. Flywheel energy storage (FES) should also be considered in several distribution network situations. There are many different types of ESSs, each with its own set of benefits and drawbacks. The best ESS for you will be determined by the projected performance improvements, features, and application types. Researchers have already devised various meta-heuristic methodologies for optimization, but there is always room for improvement. Thopil, Bansal, Zhang, and Sharma observed in their research [54] that the abundance of coal-powered generation is not practical, mostly because renewable energy is not yet ready to be the dominant source of energy. Adopting a hybrid and bidirectional energy paradigm, in which customers remain connected to the grid while being fueled by renewable energy sources via small- and medium-scale distributed generators that may be put within the consumer's premises, is suggested as a realistic alternative.

Hirsch (a) defines a microgrid and (b) gives a multidisciplinary portrayal of today's microgrid drivers, practical applications, problems, and future possibilities in the review paper [55]. Proper planning and understanding is needed well in advance to find the most suitable architecture to integrate various distributed energy resources. Various factors including regulations, legal issues, quality of power and financial benefits, etc. will play major roles in deciding the sustainability of microgrids in the long run. Howlader's work [56] on independent ESS to minimize profit uncertainty for retailers in the ISO Market highlighted the problem of financial burden of hour ahead considering load mismatch. This has also concentrated on lowering the cost of IESS installation. This study demonstrates a novel energy market model where IESS is used to compensate for power adjustments. Furthermore, these IESS may be utilized to compensate for predicting errors and solve a variety of other problems. Kong and Jung's research [57] study presents a way for estimating the amount of ESS when there is inadequate data for future PV and WT providers. The predicted ESS size differs from the optimal size with the least amount of error. For future RES suppliers to enhance their profitability, the suggested approach employing polynomial regression is utilized to predict the ESS magnitude. Akbari-Dibavar [58] explored the suitable energy managing techniques of a net-zero emission MPGS incorporating RERs, hydrogen energy systems, and storage units in a deregulate scenario. The robust optimization technique was used to analyze the impacts of wind power uncertainty in order to provide an acceptable level of resilience for the system. Solar and wind power are employed for clean energy generation due to the sustainability characteristic of the micro power grid system (MPGS). Ahmad, Zhang, and Yan [59] provide unique insights into a critical and systematic review of renewable energy and power projection models used as an energy planning tool. The approaches are assessed in terms of prediction applicability, spatial and temporal forecasting accuracy, and relevance to policy and planning objectives. The study's findings help in the recognition of prediction methodologies and allow users to choose the best methods for meeting their intended aims and forecasting criteria. Forecasting capabilities are improving, and some countries are coming closer to developing fully automated smart grids.

Liu, Hu, Kimber and Wang's research gives a complete categorization and assessment of ESS electric grid applications [60]. The most recent optimization and control approaches for each application category were examined. In addition, a cost–benefit analysis for three categories of investors as well as a detailed comparison of market policies regarding ESS involvement in various wholesale markets has been performed. Given the vast variety of improvements in energy storage technologies, the energy storage technologies were critically analyzed in depth and then classified, and comparative studies were conducted to understand the features, limits, and benefits of each energy storage system. Tan, Ramachandaramurthy, Solanki, and Raveendran proposed alternative energy storage system frameworks based on their application [61]. This evaluation included several HESS combinations in which multiple ESS types were blended to provide a better form of energy storage. Mcllwaine, Morrow, Al Kez, and Best [62] undertook a rigorous study of EES and quality of power at the distribution level. The research combined with a Pugh analysis emphasized worldwide trends in power markets with increased renewable energy penetration. The investigation's findings suggest that further study is needed to classify, quantify, and evaluate the installing of bulk energy storage, during distribution.

When RE penetration is low, the electrical market functions efficiently; however, when RE penetration is high, the market is frequently disrupted. Divya Asija threw light on the advancement of renewable energy generation, the inclusion of renewables into the current unregulated power sector, the composition of present power market, main obstacles with RE integration in deregulated power markets, and driving factors [63]. A research study investigated the involvement of a composite energy system comprising wind energy and CAES in the electricity market from the standpoint of a private owner [64]. Due to the high level of unpredictability linked with market values, wind power levels, and regulatory inputs, the problem was modelled using distributionally robust optimization (DRO). The ideal outputs indicate DRO's performance in terms of higher realized earnings and less conservative results. Another study looks at the prospects, problems, and technologies of EVs in a V2G linking system in depth [65]. M.A. Hannan's study demonstrates the benefits of both the EV owners and the power system, as well as relevant suggestions for the future research areas to address existing research gaps and challenges. Dhillon, Kumar, and Singal [66] conducted a detailed analysis of the fundamentals of wind energy, PSP, Wind–PSP System and their present state, applications, and issues with operation in a deregulated market, as well as optimization strategies employed in the advance planning of Wind–PSP System. The researchers proposed optimization strategies such as EA-based, GA with LVQ, HIDSS, and NSGA-II to identify the best feasible solution of complicated computational problems with instabilities for Wind–PSP operation. Global market participants may create a new electricity market architecture in order to reap the benefits of long-term agreements with stakeholders.

Wind energy system modeling is a goal oriented problem that can be solved utilizing advanced computer methodologies. Many algorithms only engage with a sub-model and do not capture the entire picture. The research by Chinmoy, Iniyan, and Goic [67] has focused on essential cost modeling for wind energy projects as well as market associated risk and its mitigation issues. A thorough research on the use of approaches in power balancing in microgrids with renewable generators by Komala, Kumar, and Cherukuri categorized the methods into distinct categories depending on their principle of operation, infrastructure required, and component of the microgrid [68]. The different methodologies, as well as their mathematical models and virtues and drawbacks in application to power balancing in microgrids, have been evaluated. During a literature review, it was discovered that optimal usage of all forms of sustainable energy resources is critical to achieving sustainable energy development (SED). The key problem for SEH modelling is determining the best design/sizing and operating strategy for system components depending on the unpredictability of renewable sources, demand, energy market spot prices, and so on. Lasemi, Arabkoohsar, Hajizadeh, and Mohammadi-ivatloo discovered that uncertainty modelling based on RO and scenario-based stochastic optimization are the most common for SEH modelling [69]. Due to worst-case scenario analysis, a robust method would provide the greatest answer for risk-averse decision makers, whereas a probabilistic approach would provide the optimal answer for risk-neutral decision makers.

Singh and Parida [70] conducted an extensive study on the betterment of the integration of flexible demand as demand response, demand-side management (DSM), and grid proficiency. The evaluation of important data revealed that effective DG allocation will be good for the environment as well as economically favorable for utilities and customers. When DGs are incorporated into the system, the passive distribution or sub-transmission network becomes active, resulting in various technical and economic challenges. Khare, Nema, and Baredar [71] conducted a detailed evaluation of many facets of HRES, focusing on pre-feasibility analysis, optimal size, modeling, control features, and reliability issues. The use of evolutionary techniques and game theory in hybrid renewable energy systems has also been emphasized. Another study looked at current global PHES capacity, technological progress, and hybrid systems (wind-hydro, solar pv-hydro, and wind-pv-hydro) and offered the best options. According to Rehman and Al Hadhrami's research, PHES is the ideal technology for tiny autonomous island grids and huge energy storage, with PHES's efficiency fluctuating in practice between 70% and 80%, with some estimating up to 87% [72]. PHES sizes vary from 1000–1500 MW to 2000–3000 MW across the world. Photovoltaic-based pumped storage systems have only been used on a small scale (few homes only).

The purpose of this study is to provide a complete analysis of current improvements in the ADS's (Active Distribution Systems) operation from the perspective of operational time-hierarchy. In contrast to earlier review publications, prospective applications of ADS devices are evaluated in terms of operating time periods. This study by Ghadi and Ghavidel covers real-world system operations in which network components are initially planned for the stated period ahead, and then their operational status deviations from reference points are updated throughout three time intervals encompassing static, dynamic, and transient periods [73]. There is always a need for DN organizations to investigate current facilities and management systems and then provide some unique practical solutions in the related areas. A critical analysis conducted by Banshwar and Sharma [74] examined the prospects of RES in energy and Ancillary Services (AS) markets and concluded that changes in market designs and norms are still needed in the existing electrical market to integrate energy, AS, and variable energy sources. In another work by Kim and Suharto, storage methods and additional assessments of similar technologies conducted by other scholars were examined [75]. The work has explained the solution techniques to address different difficulties using a case study and also reviewed the assessment parameters.

Tables 1–3 display the summary of reports for considered objective functions, applied system details, and used optimization techniques for the considered pieces of literature. Ghadi and Rajabi's [76] insightful work on the transformation of traditional passive DNs into ADSs, as well as the study based on grid operational features engaged in deregulated electricity market at the distribution level, has provided a new perspective. This study underlines the need to optimize current facility capacity through creative management strategies and practical solutions. Saboori and Hemmati [77] evaluated the challenges of optimal bus position, power rating and energy capacity estimation in distribution networks to improve the functioning of the optimal planning process. While analyzing, energy storage systems and models, as well as their applications and related objective functions, network modelling, solution methodologies and problem uncertainty management, were all taken into account. Zhou and Li's work provides an insight of the design and functional modules of smart HEMS [78], which is critical for a more secure and environmentally friendly energy supply for smart grids. For the purposes of analysis, various non-traditional sources have been considered.

Carreiro and Jorge underline the importance of energy management system aggregators in the Smart Grid framework, particularly in conjunction with demand response programs and technologies that include end-user participation in the provision of ancillary services [79]. They suggest that establishing algorithms, technological benchmarks, and low-cost systems requires deliberate collaboration among academics, industry, and regulators. Modern power management evaluates the performance of various green energy sources against several criteria rather than focusing on a single factor—consumption [80]. This study by Bhowmik and Ray examines the diverse work on separate techniques, integrated approaches, multi-criteria decision-making methodologies, and so on for the green energy planning and scheduling challenge. This study not only confirms that energy management tactics are superior to previous ways, but it also assists scholars and policymakers in implementing the processes. Sundararagavan, Sandhya's research [81] examines the prices of several energy storage systems and identifies the critical aspects that influence their economic feasibility. Rong-Gang Cong [82] identifies several important factors affecting the expansion of renewable energy generation in this article based on a review of current research. Following extensive research, a novel optimization model is developed to optimize future renewable energy generation through the best capacity planning, while taking into account various constraints such as economic, technological, and others. In paper [83], Helder Lopes extensively analyzed several energy storage devices with varying attributes and degrees of maturity. Power rating, discharge duration, energy density in terms of weight and volume, power density, effectiveness, time and cycle durability, and availability have all been compared. Aggarwal, Sanjeev Kumar [84] provides an overview of several price-forecasting approaches used in deregulated systems, as well as an analysis of important difficulties. Lixin Tang [85] presented a policy for a deregulated method to decrease CO_2 emissions in generator scheduling for thermal power stations in his study. The proposal called for a new penalty component depending on emissions. The scheduling maximizes generation profitability based on income gained from sales, cost of generating, and the emissions penalty. Enrique B. CEDEO [86] examines the numerous relationships between the various sections of the deregulated power industry, proposing an integrated model for increasing generation and transmission capacity. The purpose of this methodology is to evaluate and find the best macroeconomic indicative investment ideas.

Table 1. Summary of reports for considered objective function in the literature.

Paper ID	Type		Objective Function			
	Regulated	**Deregulated**	**Profit Max.**	**Loss Min.**	**Gen. Cost Min**	**Social welfare Max.**
[42]	√		√			
[43]						√
[44]	√		√			
[45]	√	√				
[46]	√	√	√			√
[47]	√	√				
[48]	√	√				
[49]	√	√		√		

[50]		√	√	√	
[51]		√	√		
[52]	√	√	√		√
[53]	√	√	√		
[54]		√	√	√	
[56]		√	√	√	
[57]		√	√		
[58]		√	√		
[59]		√			
[60]		√			
[63]		√			
[65]		√	√		
[66]		√			
[67]		√	√		
[68]		√			√
[69]		√			
[70]		√			
[72]	√	√			
[73]		√			
[74]	√	√			
[75]		√			
[76]		√			
[78]		√			
[80]	√				
[81]		√	√		

Table 2. Summary of reports for considered system details along with energy storage and renewable energy sources.

Paper ID	Renewable Energy Sources					Energy Storage				
	Wind	**Solar**	**Hydro**	**Others**	**Generalized**	**PSH**	**Battery**	**CAES**	**Others**	**Generalized**
[42]				EDV			√			
[43]						√	√	√		
[44]	√	√	√	Bio, Geo, Hybrid		√	√			
[45]	√	√	√	Bio, Geo				√		
[46]						√				
[47]						√		√	flywheel storage, electrochemical storage	
[48]	√	√								
[49]	√	√	√						EV	
[50]	√						√			
[51]	√	√	√				√		EV	
[52]	√	√	√			√	√	√		
[53]						√	√	√		
[54]	√									
[56]	√	√	√				√			
[57]	√	√					√			
[58]					√				Fuel cell, Hydrogen energy storage	
[59]	√	√		Geothermal						
[60]						√	√	√	√	
[63]					√	√	√	√	Flywheel, thermal	
[65]	√							√		
[66]							√			
[67]	√					√				
[68]	√									
[69]					√	√	√	√	√	√
[70]					√			√		
[72]	√	√								√
[73]						√				
[74]					√					√
[75]					√					√
[76]						√	√			
[78]						√		√		
[80]					√		√			√
[81]					√					√

Table 3. Summary of reports for used optimization techniques in the literature.

Paper ID	Optimization Techniques					
	PSO	ABC	BAT	GA	Heuristic	Others
[44]	√	√		√		Lagrangian relaxation, quadratic programming and Nelder–Mead Simplex search; heuristic optimization methods, especially genetic algorithms and particle swarm optimization; Pareto-based multi-objective optimization
[45]				√	√	simplex method, dynamic programming, Lagrangian relaxation, sequential quadratic programming, Newton's method and reduced gradient method
[50]					√	LMP
[51]				√		
[53]		√		√		
[57]			√			
[58]						adjustable robust optimization
[65]						robust optimization
[67]				√		
[70]						Monte Carlo
[72]	√			√		Game theory
[81]	√			√		MOCPSO

In paper [87], Pavlos S. Georgilakis proposes a genetic algorithm (GA) solution to the price-based unit commitment problem, which is used by each producing business to maximize its profit in a deregulated market by optimizing its generation schedule. Luo Xing's [88] provides a comprehensive comparison of the most cutting-edge energy storage methods. The study helps to alleviate the problem of selecting acceptable EES technology for a given application and deciding where they would be best integrated into a power generation and distribution system. In his work, Moein Parastegari [89] develops an optimization model for the energy market that includes auxiliary services. The model is used to jointly operate wind farms (WF), pump-storage units (PSU), photovoltaic (PV), and energy storage devices (ESD). The model takes into account WPG, energy and reserve prices, and PV generation unpredictability. A. Zahedi [90] investigated the potential benefits of grid-connected renewable energy-distributed generating in this review paper (RE-DG). It also looked at the factors that are driving the rising use of RE-DG, the technical challenges that come with high RE-DG penetration, and the effect of RE-DG connection points on system voltage. Piyasak Poonpun provided a study on the life-cycle cost of several grid-connected electric energy storage systems in the paper [91]. The results are given as a cost per kilowatt hour of stored and released power. Das [92] how energy storage can curtail risk factors in a competitive power system. In this study, Stephen Frank [93] examines numerous optimization algorithms that have been utilized to achieve optimal power flow (OPF), with an emphasis on their benefits, downsides, and computational aspects. It begins with an overview and then delves into the deterministic optimization methodologies utilized on OPF.

Ramesh Kumar Selvaraju [94] investigated the efficacy of a deregulated electricity system combined with various energy storage technologies in this study. For determining the LFC controller gain values in a deregulated environment, the Artificial Cooperative Search technique, a new two-population-based optimization strategy, is devised. In paper [95], Patil examines the impact of wind energy system on a deregulated energy market from different perspectives. Bus sensitivity factor and locational marginal pricing have been given special attention. Different optimization algorithms have been investigated and slime mold algorithm has been implemented for the first time in this field. In another work [96], same author examines a hybrid system with energy storage and studies profit maximization in deregulated energy market with imbalance cost improvement. It also covers value at risk and cumulative value at risk factors. In paper [97], Ustun examined integration of EV storage with local solar generation to maximize renewable energy capture without overburdening local distribution network. Driving patterns and solar generation profile are studied along with local load profile to actively control EV batteries to maximize local renewable energy capture,

5. Facts and Analysis of Renewable Energy: A Glimpse

A more significant change in the generating mix is hidden by the total power generation's comparatively high resilience. In particular, generation from renewable sources (wind, solar, biofuels, and geothermal energy, etc.) saw its greatest ever growth despite the decline in overall power consumption. Strong gains in the generation of wind and solar energy were the main drivers of this expansion [98].

The proportion of renewable energy in the world's generation has increased at its quickest rate ever. Around 60% of the increase in worldwide power output over the previous five years has come from renewable sources, with wind and solar power being major among them (shown in Figure 8) [98,99].

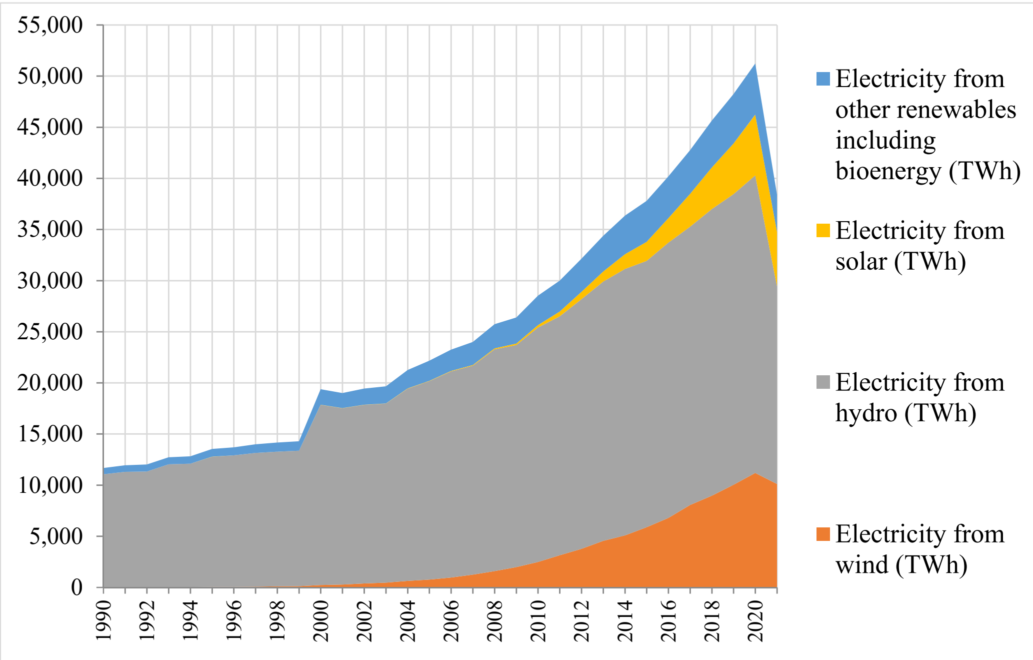

Figure 8. Transition of renewable energy generation around the world.

An emerging market economy is a developing country's economy that is getting increasingly involved in global markets as it expands. A developing economy is one with a low human development index, low growth, low per capita income, and a preference for agriculture-based activities over industrialization and entrepreneurship. In other terms, a developing economy is also known as a developing country or a less developed economy. With increased infrastructure expenditure in Europe, China, and the United States, investments in power networks are anticipated to increase by 10% in future after dropping for the fourth straight year in 2020 due to the COVID-19 epidemic. As part of the effort to attain carbon-free power generation, measures to build more robust and digital grids are being incorporated with ambitious growth and recovery plans.

However, in the Net Zero Emissions by 2050 Scenario, the level of grid investment triples by 2030, particularly for smart grids and digital investments, which should make up around 40% of all investments in this decade (shown in Table 4 and Figure 9) [98,99].

Table 4. Investment spending in electricity networks by region, 2016–2021 in USD billion.

Region	2016	2017	2018	2019	2020	2021
USA	63.1	65	66	71	75.8	77.1
China	86.9	83.7	83.2	76.6	70.7	82.6
Emerging market and developing economies	93.9	88.2	81.1	63.5	53.5	60
Europe	50	48.7	49.5	48.5	51.8	56.7
Rest of the world	17	17.5	15.9	12.6	10.8	12.6

The maximum net generating capacity of power plants and other facilities that employ renewable energy sources to create electricity is used to measure the capability of renewable power generation. The data shows the installed and connected capacity at the end of the calendar year for the majority of nations and technologies (shown in Figures 10 and 11) [99–101].

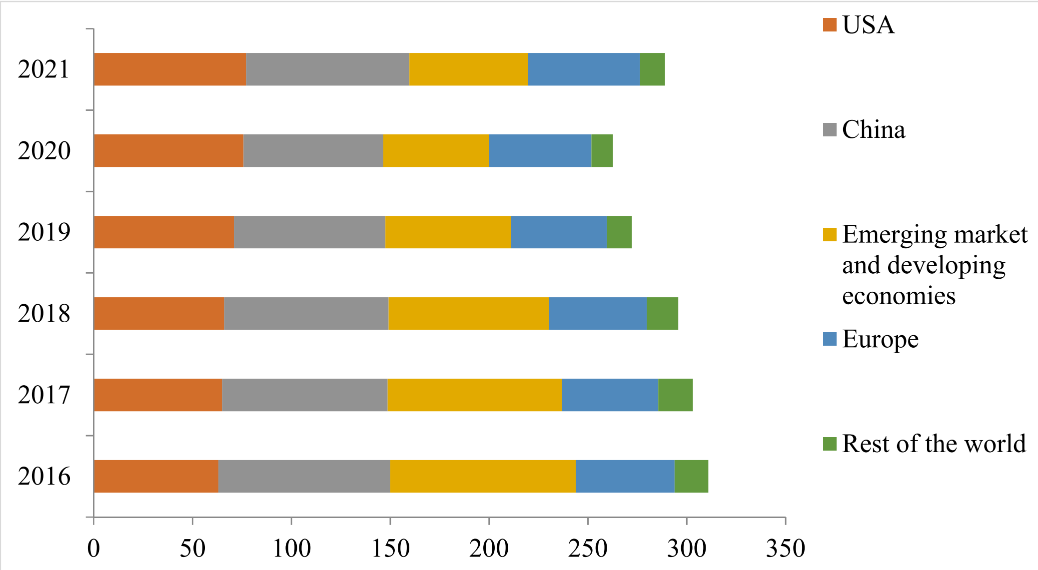

Figure 9. Investment spending in electricity networks by region.

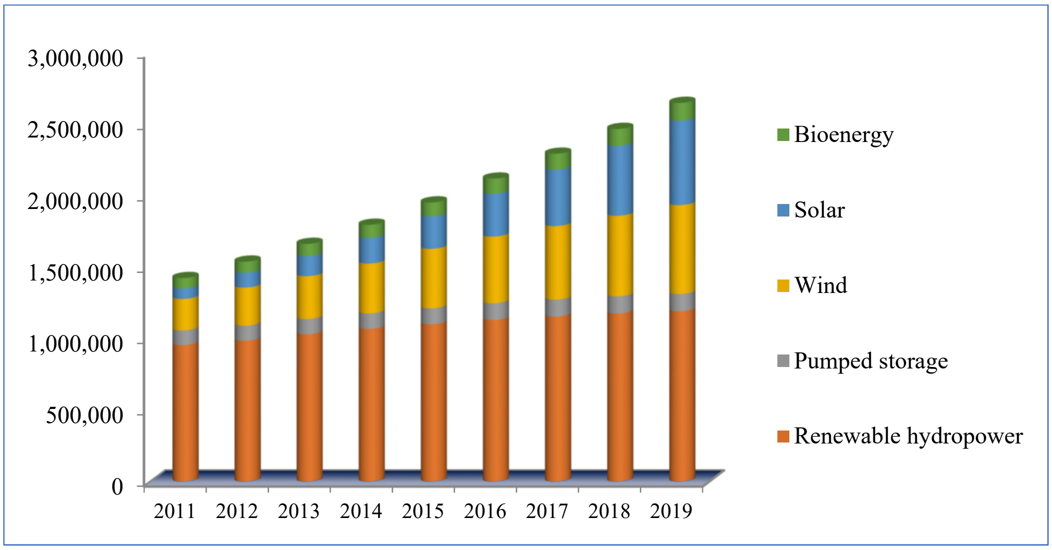

Figure 10. Worldwide renewable electricity capacity (MW) statistics.

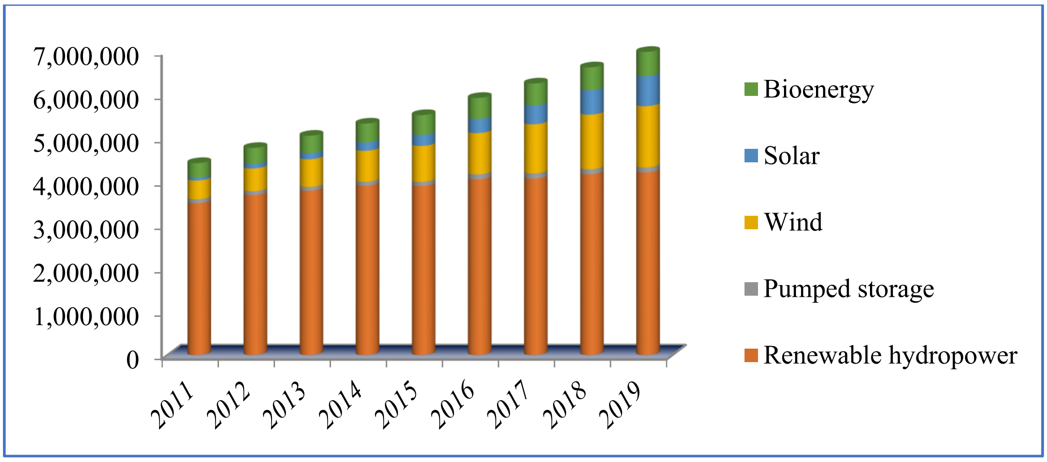

Figure 11. Worldwide renewable electricity generation (MW) statistics.

Comprehensive Energy Storage Roadmap (India)

India has set a target of 40% non-fossil power production in the energy mix by 2030 and is dedicated to lowering GHG emission intensity by 33 to 35% from the level in 2005. In order to achieve this, the percentage of renewable energy (RE) must be scaled up above and above the current goal of 175 GW by 2022. In the upcoming years, grid operators will face a challenge in ensuring grid reliability and the supply of 24 × 7 quality power due to the increased penetration of renewable energy sources and electric vehicles (EV). This will open the door for the deployment of energy storage systems for grid support [102,103]. This will enable utilities to understand the economic opportunities of such systems at various levels of RE and EV penetrations, as well as their impact on grid reliability (shown in Figure 12) [104].

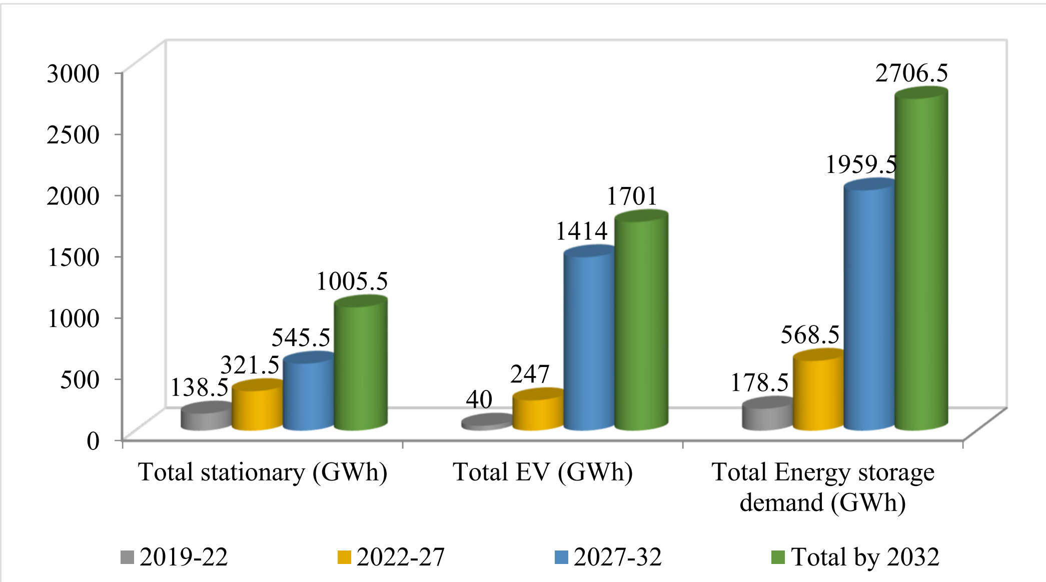

Figure 12. Comprehensive energy storage roadmap of India.

From this section, it is observed that the use of renewable energy system is not an option, it is essential [105]. Due to the discontinuous availability of renewable energy sources, energy storage system is essential for any renewable integrated power system [106,107]. This is especially true for off-grid systems that are more vulnerable to system deviations [108–118]. It may come in different forms, such as hydrogen storage [119], EV battery applications [120] or together with other novel devices such as smart inverters

[121–124] In this scenario, this paper provides the clear idea about the different types of energy storage system with the constructions and applications [125].

6. Comparative Study of EES Systems

The comparative study of different types of EEs systems are depicted in Table 5 [126–129] and Table 6 [130–132]. The efficiency, discharge time, cost, and environmental impacts of EES systems are considered for this study.

Table 5. Comparison of EES Systems in terms of efficiency, discharge time and cost [126–129].

System	Max. Power Rating (MW)	Efficiency (%)	Discharge Time	Cost/KW (USD)	Cost/KWh (USD)	Energy Density (Wh/L)
PHS	3000	70–85	4 h–16 h	600–2000	5–100	0.2–2
CAES	1000	40–70	2 h–30 h	400–800	2–50	2–6
FES	20	70–95	sec–mins	250–350	1000–5000	20–80
Lead–acid	100	80–90	1 min–8 h	300–600	200–400	50–80
NiCd/NiMH	40		sec–hours	500–1500	800–1500	60–150
Li-ion	100	85–95	1 min–8 h	1200–4000	600–2500	200–400
Metal–air	0.01	50	secs–day	100–250	10–60	500–10,000
Sodium–sulfur	0.05–8	75–90	sec–hours	1000–3000	300–500	150–250
RFB/HFB	100	60–85	hours	700–2500	150–1000	20–70
H2	100	25–45	min–week		10	600
Fuel Cell	50	60–80	secs–day	10,000		500–3000
SMES	10 MW	95	millisec–secs	200–300	1000–10,000	0.2–2.5
Thermal	150	80–90	hours	200–300	30–60	70–210

Table 6. Comparison of EES Systems in terms environmental impact [130–132].

System	Life Time/Cycles	Environmental Impact	Description of Impact
PHS	30–60 years	-ve	Cutting trees and landscapes for reservoirs
CAES	20–40 years	-ve	Remains from fossil fuel
FES	20,000–100,000	Negligible	
Lead–acid	6–40 years	-ve	Toxic residues
NiCd/NiMH	10–20 years	-ve	Toxic residues
Li-ion	1000–10,000	-ve	Toxic residues
Metal–air	100–300	Very small	Slight residues
Sodium–sulphur	10–15 years	-ve	Toxic residues
RFB/HFB	12,000–14,000	-ve	Toxic residues
H2	5–30 years	Yes	Emission of hydrogen in atmosphere can create disturb in distribution of methane and ozone; thereby causing imbalance.
Fuel Cell	5–15 years	-ve	Remains from fossil fuel
SMES	20 years	-ve	High magnetic field
Thermal	30 years	Small	Releasing charge into atmosphere

7. Conclusions

Presently, while the entire world is concerned about the future of the planet in terms of reducing the carbon footprint and making it a greener one, the electricity industry is focusing on more efficient and sustainable power supply, judicious consumption of energy and CO_2 reduction. While doing so, main areas of research are identified as anticipated growth of renewable generation, design of renewable technology for better performance, design and implementation of smart grids, integration of RNE into smart grid for better energy demand management by optimization techniques.

The followings are important in the present scenario of the electrical system:

- Energy storage systems will play a pivotal role for managing contingency situations apart from acting as integrated part of smart grid.
- The modest and scattered EES market is likely to be large when the smart grid and microgrids are implemented.
- The market for EES systems, particularly small and distributed ones, is growing and will grow in tandem with the renewable energy sector.
- Technical challenges, and also cost and compatibility/sustainability, are potentially critical topics for future initiatives.
- There is scope to work on optimization, power quality and safety issues.
- Upon comparison of different optimization techniques, it has been found that meta-heuristic algorithms outperformed heuristic and linear optimization techniques with the considered objective functions.

Considering the future and investors' interest, it is obvious that the maximization of system profit and minimization of system generation cost and loss will help in increasing societal benefit. This study examines numerous aspects of renewable integrated deregulated power systems and provides an in-depth appraisal of the most recent research advances in this sector. In this context, this study will be helpful in understanding, analyzing and applying the EES technologies for a better tomorrow.

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