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Concept of Hybrid Energy Storage Systems in Microgrid

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ABSTRACT

Public awareness of the need to reduce global warming and the significant increase in the prices of conventional energy sources have encouraged many countries to provide new energy policies that promote the renewable energy applications. Such renewable energy sources like wind, solar, hydro based energies, etc. are environment friendly and have potential to be more widely used. Combining these renewable energy sources with back-up units to form a hybrid system can provide a more economic, environment friendly and reliable supply of electricity in all load demand conditions compared to single-use of such systems. Energy storages Systems (ESS) present many benefits such as balancing generation and demand, power quality improvement, smoothing the renewable resource's intermittency, and enabling ancillary services like frequency and voltage regulation in microgrid (MG) operation. Hybrid energy storage systems (HESSs) characterized by coupling of two or more energy storage technologies are emerged as a solution to achieve the desired performance by combining the appropriate features of different technologies. A single ESS technology cannot fulfill the desired operation due to its limited capability and potency in terms of lifespan, cost, energy and power density, and dynamic response. Hence, different configurations of HESSs considering storage type, interface, control method, and the provided service have been proposed in the literature. This paper comprehensively reviews the state of the art of HESSs system for MG applications and presents a general outlook of developing HESS industry. Important aspects of HESS utilization in MGs including capacity sizing methods, power converter topologies for HESS interface, architecture, controlling, and energy management of HESS in MGs are reviewed and classified. An economic analysis along with design methodology is also included to point out the HESS from investor and distribution systems engineers view. Regarding literature review and available shortcomings, future trends of HESS in MGs are proposed.

KEYWORDS: *Hybrid system, Optimization, Renewable energy, Sizing*

1. INTRODUCTION

Today, the world faces a great challenge for saving their future in terms of providing one of the most necessary requirements of humankind: Energy. Nowadays, a great portion of the energy requirements all around the world is supplied from conventional energy sources like coal, natural gas, crude oil, etc. [1], [2]. Besides, the energy demands are increasing exponentially resulting into a rapid grow in need of conventional fossil fuels [3]. If there is no change in energy policy, the international energy agency predicts a 130% increase in CO_2 emissions and a 70% increase in oil consumption by 2050, increasing the global average temperature by 6 °C [1]. Renewable energy sources (RESs) are the best solution to deal with these problems. Solar and wind energies are widely used for electric power generation. The world's cumulative wind and photovoltaic (PV) installed capacity are shown in Fig. 1. The global cumulative wind and PV installed capacity in 2017 were 539 GW and 401 GW respectively [2].

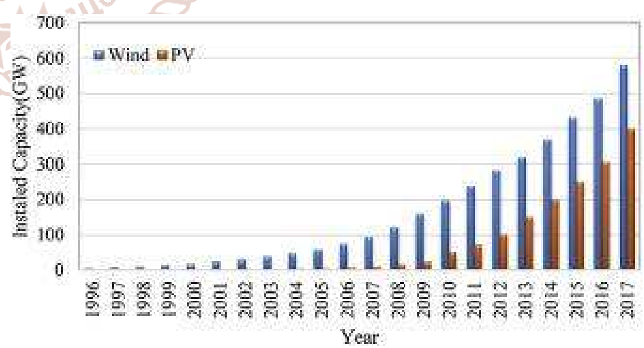

Fig. 1. PV and wind installed capacities.

RESs have been extensively used to supply the electrical energy demands and reduce greenhouse gas emission with an increasing trend. The intermittency nature of the clean energy sources influences the power generation adversely, becoming a challenge for the uninterrupted and regular supply of power to the consumer and endangering grids operation in terms of different operational and technical aspects. Microgrid (MG) as a cluster of loads and distributed generations (DGs) is proposed to take maximum benefits of RES which can be operated in both islanded and grid-connected modes. An ESS could contribute to integration of

RESs into the MG by flattening the RESs fluctuations, power quality improvement, contributing in frequency and other ancillary services [3].

Various storages technologies are used in ESS structure to store electrical energy [[4], [5], [6]]. Fig.2 depicts the most important storage technologies in power systems and MGs. The classification of various electrical energy storages and their energy conversion process and also their efficiency have been studied in [7]. Batteries are accepted as one of the most important and efficient ways of stabilizing electricity networks [8]. They are attractive because they are economical, compact, and easy to deploy. A battery composed of multiple cells connected in parallel or in series, which uses a chemical reaction to convert the stored chemical energy into electrical energy and vice versa. Various battery technologies can be used for MG applications. Fig. 2shows power density and energy density capabilities for different battery technologies. Among the different ESSs, pumped hydro energy storages and compressed air enable to support large-scale energy storage applications [9]. However, the pumped hydro energy storage dependence on specific geographic and environmental conditions, making its development quite difficult challenging [10]. Flywheel energy storage system is electromechanical energy storage [[11], [12], [13]] that consists of a back-to-back converter, an electrical machine, a massive disk, and a dc bus capacitor. However, this type of storage system has mechanical components that can affect efficiency and stability. In order to overcome some problems with the flywheel, a superconducting thrust bearing system for flywheel energy storage with low loss and maintenance cost is proposed in [14], which has low loss and maintenance cost. In this structure two bearings are used. The one composed entirely of permanent magnets provides the levitation force and the other, which consists of a permanent magnet and a superconductor, provides the stabilization. Super capacitors (SCs) are the electrostatic storages, and the high degree of recyclability and high power density are their main advantages [15]. Superconducting magnetic energy storage (SMES) is one of the few direct electric energy storage systems. The SMES is based on a cooling system, a superconducting coil and an electrical and control system for the adaptation of currents, and the optimization of the process [16].

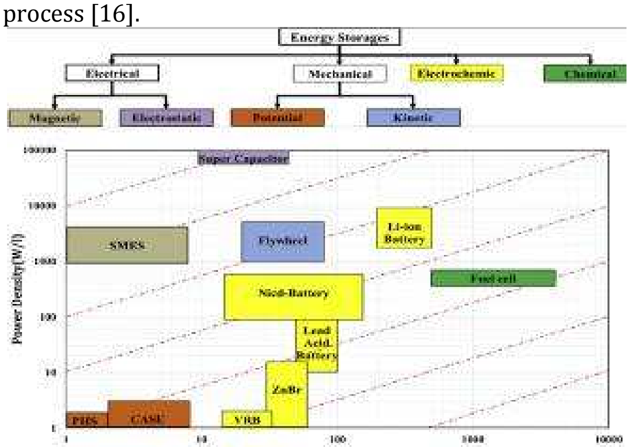

Fig. 2. Energy storages classification.

Power density and energy density are two main characteristics of energy storages technologies. The power and energy density of different energy storages are shown and compared in Fig. 2. An ESS technology featured with low power density but high energy density like batteries and fuel cells (FCs), creates power control challenges as the dynamic response of these technologies is slow. In contrast, technologies like SCs and flywheels can supply a high power demand that decreases the lifespan of the storage system [17]. None of the existing storage technologies can meet both power and energy density at the same time. Due to storage technological limitations, it is often necessary to enrich the transient and steady state performance of storage system called as hybrid energy storage system (HESS) [18,19]. Appropriate technologies with required control schemes should be combined for secure and optimum operation of MG. The overall design of a HESS in MG depends on four coupled factors: the choice of storage technology and rated capacity, power converter topology, energy management and the control strategy where should be dealt carefully.

Various review papers have been presented with the HESS. From the literature, most of the review papers focus on the HESSs in electrical vehicle [6,[19], [20], [21], [22]] and some of them focus on HESS in renewable energy [3,23,24] and MGs [17,25]. The converter topologies, control methods, and applications are investigated in most of the review papers. However, none of them addresses the comprehensive review of hybrid storages in MGs and RESs in detail. In addition, new control methods are proposed for HESS control in recent research. Classification and analysis of the HESS capacity sizing methods have not been carried out in the previous researches, which is fully addressed and categorized in this paper. The main contributions of the paper are listed below:

- Studies different operational and technical aspects of hybrid storages in MGs field and presents general outlook and complete outlook of state of art developments.
- Comprehensive study of HESS for MGs application from the different point of view including HESS sizing, HESS applications in MGs, HESS configurations and connection, and HESS control methods.
- Comparison of control methods, capacity sizing methods and power converter topologies.
- A conceptual flowchart for correlation of different sections of HESS for implementation in MGs.
- Regarding literature review and available shortcomings, future trends of HESS and the research gaps technology are proposed.

2. Benefits and applications of hybrid energy storage systems

As mentioned before, MGs and RESs suffer from problems like the intermittency nature, poor power quality, stability issues, frequency control, and unbalanced load. In a typical MGs, the ESS usually experiences irregular and frequent discharging/charging pattern which truncates the ESS lifespan, therefore the replacement cost of the ESS increase significantly [26]. HESS is an appropriate solution to overcome MGs and RESs challenges. Many studies have been done in recent years with the common goal of demonstrating the positive effects of HESS on the RESs [[27], [28], [29]]. Depending on the purpose of the hybridization, different energy storages can be used as a HESS. Generally, the HESS consists of high-power storage (HPS) and high-energy storage (HES) where the HPS absorbs or delivers the transient and peak power while the HES meets the long-term energy demand [30,31]. HESSs provide many benefits for MGs and RES including improving the total system efficiency, reducing the system cost, and prolonging the lifespan of the ESS [32]. Due to the various types of energy storages technologies with different characteristics, a wide range of energy storage hybridization can be formed. Fig. 3 shows the combination of different storage technologies which can be used for various applications [6]. It can be seen that the SC/battery, SMES/battery, FC/battery, FC/SC, battery/flywheel, battery/CAES, and FC/flywheel HESS are commonly implemented in RESs application [4,9,11,33]. Selection of appropriate HESS combinations depends on the variety of items, including storages hybridization targets, storage costs, geo-location, and storage space availability.

3. APPLICATIONS OF ESSs

This section identifies the potential applications of ESSs in the existing grid-connected/off grid DG power system incorporating RERs. ESSs have inherent flexibility to cover a wide range of applications in power system and can be used in grid side, generation side, end-user/load side applications and integration of RERs. The suitability of any typical ESS depends on its capability and application requirement, however, no ESS is suitable for all applications. These applications are often grouped according to the duration of discharge; power quality (short-term), bridging power (medium term) and energy management (long-term), as summarized in Table 8 and also Figure 3, which show the applications of different ESSs according to the duration of discharge and power rating.

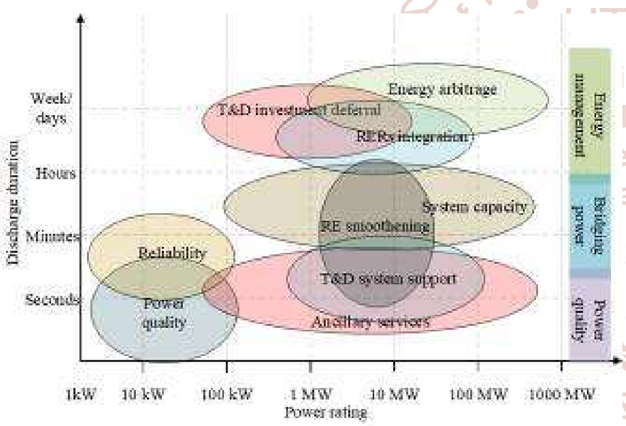

Figure 3 Applications of ESSs according to duration of discharge and storage capacity

3.1. Power quality applications

These applications require very prompt response from the ESS as the delay may cause the collapse of the whole power system, thus involve short time duration (less than a minute). Further, these are high power and low energy applications.

3.1.1. Voltage regulation

Voltage stability is one of the prominent grid stability indices and with the increasing penetration of RERs in DG power systems, there are associated challenges for voltage regulation. Reactive power support is the force which maintains the voltage stability at various levels in power system. ESSs, which are suitable for counteracting voltage variations, should exhibit fast reaction time and deliverability. An earlier example of ESSs providing voltage regulation services is the handful of batteries, but recently other ESSs, having fast response and high cycle life, like FES, SMES, FBESS, and super capacitors have emerged and become common alternatives in voltage regulation applications.

3.1.2. Reactive power support

Generally, in DG power system, incorporating wind energy, squirrel cage induction generators (SCIG) are employed because they are relatively inexpensive and have strong mechanical characteristics but they consume a large amount of reactive power. Heavy motive loads and uncompensated transmission/distribution lines also draw reactive power which causes voltage instability. For maintaining the proper voltage level in the power system, reactive power support is very crucial. Fast response of the ESSs to the variation in reactive power demand is the main requirement for such applications, therefore, short timescale ESSs like BESS, FBESS, FES, supercapacitors, and SMES are well suited because of high enough ramp rate [11,75]. Four quadrant power converters enable the ESSs to constantly supply the reactive power to the system without affecting the real power stored in the ESSs.

3.1.3. Frequency regulation

Frequency regulation acts as a stabilizing force to maintain the balance between real powers: generation and demand. In DG power system incorporating RERs, frequency regulation problem is more prominent as the generation doesn't follow the demand as it does in the conventional system because of the uncertain weather conditions. ESSs definitely can play a crucial role in frequency regulation services. By nature, frequency regulation services require the constant need of charge/discharge of ESSs at high ramp rate over the duration of huge number of full charge and discharge cycles (500000+ cycles). FES systems, due to high cycle life, deep discharge capability and fast response time are some of the most suitable candidates for frequency regulation services and self-discharge, which is a limitation of FES, is not a hindrance in this service. Generally, all types of batteries are well suited to this service besides SMES and supercapacitor that also have the desired characteristics as required in frequency regulation applications.

3.1.4. Power quality

Apart from voltage and frequency variations, the interaction between RERs and load can also lead to increased harmonics, low power factor and phase imbalance. These power quality issues can be addressed by the power converters associated with the ESSs. Technically, in power quality applications, efficiency and cycle life is not as much important as the availability of full power at a fast rate. On an average, power quality applications require to mitigate 100 events annually. Technical characteristics of Li-ion, NaS, and LA batteries make them suitable for power quality applications. FES, SMES, and supercapacitors can also provide power quality services due to their fast response and high DoD.

3.1.5. Low voltage ride-through (LVRT)

LVRT is the ability to make the generating system stay in connection with the grid in the event of a fault or large load change or a steep downfall occurring in the output power of the generating system. This not only can cause the remarkable reduction in the voltage but can also limit the power extracted from the devices. Furthermore, some grid codes also require that DG power system should supply maximum reactive current during such condition. ESS can prevent this situation by integrating itself at the location of connection with the grid and thus reduces the risk of total power system collapse. ESSs, having high power capability and fast response, like batteries, flow batteries, SMES, and supercapacitors are well suited for LVRT application.

3.1.6. Fluctuation suppression
In DG power system, RERs are the major generating sources especially in the islanding operation. Due to the intermittent nature of RERs coupled with lower system inertia as compared to conventional system, fluctuations in the generation can cause instability of the system. With an aim of mitigating the fluctuations, ESSs with fast response time and high cycle life are suitable which provide continuous operation and fast power modulation, as required. FES, SMES, supercapacitor, and BESS (excluding LA battery), individually as well as in hybrid combinations, have the potential of suppressing the fluctuations.

3.1.7. Oscillation damping
Penetration of RERs in DG power system up to some extent is manageable by the flexibility of existing sources. But, the increase in penetration level of RERs may cause the oscillations and stability issues in the system. ESSs can be used to damp out these oscillations by injecting or absorbing the real power at a frequency of 0.5 Hz-1 Hz. The duration of real power injection or absorption by ESSs is in the range of seconds to minutes. Therefore, ESSs with high ramp rate and fast response time are preferred. Thus, FES, SMES, batteries, flow batteries, and supercapacitors are preferable options for this application.

3.2. Bridging power applications
The bridging power applications require the ESSs which can provide services in the range of minutes to an hour, forming a bridge between the limited RERs generation and highly variable electricity load besides seamless switching between different RERs.

3.2.1. Transmission support
ESSs can help bring about an improvement in the performance and load carrying capacity of the transmission system by compensating the disturbances and irregularities like subsynchronous resonance, voltage sag or swell and unstable voltage. ESSs to be used for transmission support should be reliable and able to provide both active and reactive power. Large cycle life is another desirable characteristic as ESSs has to undergo frequent charge and discharge cycles. Short to medium duration ESSs such as BESSs, FBESS, SMES, and supercapacitors have applications in transmission support.

3.2.2. Transmission congestion relief
Transmission congestion is a problem that arises in transmission system when demand for transmission capacity exceeds the transmission line capability. Considerable penetration of RERs in the power system can also lead to the congestion in transmission and distribution systems. This condition adversely affects the thermal, voltage and angular stability of the system. Large-scale ESSs have great potential so far as providing congestion relief is concerned by way of injecting/absorbing a specific amount of power to/from the grid. However, the technologies to be used in these applications should be prepared in advance for such situations. PHES, CAES, and TES are suitable technologies which can effectively contribute to congestion relief as well as in avoiding heavy congestion charges.

3.2.3. Black start capability
It is the ability of the generating units to regain its operating condition after shutdown condition without any assistance from the grid in the event of a catastrophic failure. ESSs with an appropriate interface to the grid have the ability to provide system black start. ESSs, which are able to provide a significant amount of active and reactive power (more than 10 MVA) for several hours, are suitable for this application. The storage technologies have to be in fully charged state when demanded. CAES, BESS, and FBESS are the preferable technologies to be used in such services.

3.2.4. Contingency reserve
Power utilities and independent system operators (ISO) maintain a contingency reserve at various levels to avoid unstable and insecure operation due to sudden outage or failure of generating unit(s) or transmission lines(s). Contingency reserve can be divided into spinning and non-spinning reserve depending on the response time required. Spinning reserve is the first line of response and its capacity is equal to the largest unit in the area. These reserves are able to provide its service immediately should a requirement occur. Non spinning reserves are a similar type of units and used as the second line of response which is able to be in service within 10 minutes. ESSs such as CAES, PHES, HESS, BESS, and FBESS are well suited for this application.

3.2.5. Uninterrupted power supply (UPS)
UPS systems are primarily utilized for providing uninterrupted, reliable, and high-quality power for critical loads like medical facilities, emergency equipment, server database, and security systems. They, in essence, protect critical loads from power outage as well as from irregularities in voltage, oscillation, and harmonic distortion. ESSs to be used in this application have to offer an instantaneous response to provide backup during power disruptions. FES and BESS (mainly LA battery) have been extensively used in UPS facilities. Apart from these technologies, HESSs and super capacitors have potential applications in UPS.

3.2.6. Electric service reliability
On par with power quality applications, electric service reliability helps in keeping the sensitive loads energized in the event of electric grid not being operational. This service also allows for proper shutdown of equipment and processes with the objective of limiting the losses and damage to equipment. ESSs having fast response and discharge duration of several minutes can be used to minimize the adverse effects of power outages. BESSs, FBESSs, FES, and HESSs are the suitable technologies for maintaining the electric service reliability.

3.2.7. Forecast hedge mitigation
RERs create new challenges in planning and operation of the electric grid, in particular, uncertainty and variability of the weather-dependent RERs must be properly accounted for. Although weather forecasting is one of the key solutions to the efficient operation of weather-dependent RERs along with load forecasting, inaccuracies in forecasting can lead to more problems rather than solutions. ESSs can provide applications in forecast hedging mitigation and hence balancing the demand and supply. BESS, FBESS, HESS, CAES, and PHES can be utilized in these applications [182,251].

3.2.8. Mitigating RERs integration issues
Apart from the concerns discussed earlier in this paper, integration of RERs cause some other technical issues like islanding, equipment control, and protection etc. Moreover, the practice of islanding in the likely event of a fault may result in unnecessary blackouts and consequently may make

the DG power system unreliable. These situations can be eliminated if DG power system has the capability of continuously feeding the islanding system and by introducing ESSs this can be effectively achieved. Medium discharge duration ESSs like BESS, FBESSs, HESS, and CAES can serve in mitigating the RERSs integration issues.

3.3. Energy management applications

The ESSs technologies cab been utilized in energy management applications by providing energy time-shift on the time scale of hours to several days or even months. Several such applications are described as under:

3.3.1. T&D investment deferral

Transmission and distribution (T&D) investment deferral involves deferral of investment in transmission and/or distribution system upgrade where load growth is slow and system expenditures are large, using relatively smaller size ESSs (4% to 5% of T&D equipment's load carrying capacity). It is also to be noted that for most of the distribution infrastructure, the highest load occurs for a few days in a year and a few hours daily, therefore, ESSs used in these applications can be used simultaneously in other applications also. PHES, CAES, TES, HESS, BESS, and FBESS are the technologies which can provide their significant benefits for this application.

3.3.2. Energy time shifting (Arbitrage)

In electricity market, price of electricity varies from time to time and energy time shift (arbitrage) involves purchasing low price electricity when its off-peak hours, charging the ESSs and subsequently selling at on-peak hours when electricity price is high by discharging the ESSs. Alternatively, ESSs store excess energy from RERs which can be used later when demanded, otherwise curtailed and wasted, thus provide energy time shift duty. The long-term ESSs, which also have low self-discharge, in particular PHES, CAES, and TES are suitable for achieving energy time shift (arbitrage).

3.3.3. Peak shaving/valley filling

The purpose of peak shaving/valley filling is very similar to energy arbitrage application with the only difference that ESSs here are used to soften the peak and valley shape of the load curve whereas in energy arbitrage there are economic targets to achieve. ESSs used in peak shaving can effectively reduce the events of peak capacity operation of the utility system, thus increase its life. Valley filling increases the load factor of the generation and consequently overall efficiency increases. Well suited ESSs for these applications are PHES, CAES, TES, BESS, FBESS and HESS.

3.3.4. Load following

Load following is the ability to change the output in response to change in end-user demand (load). ESSs have a quick response to cover the load variations (both up and down) as compared to generation types. ESS to be used in this application has to perform its duty on an hourly basis (mainly during morning pickup and evening drop-off). Large-scale ESSs such as CAES, PHES, BESS, FBESS, and HESS are the key providers of this service [11,83,259].

3.3.5. Demand charge management

End users can reduce the demand charges by reducing the power drawn from the utility during specific period of time i.e. demand charge period (usually during on-peak hours). ESSs can be significant in demand charge management. They store electricity during the period when demand charge is not applied and discharge during the period when demand charge is applied. The ESSs having discharge period of five to six hours are suitable for this application.

3.3.6. RERs capacity firming

The main objective of RERs capacity firming involves providing sufficient support to the output of RERs by using energy storage facilities so that the combined output of RERs and storage is somewhat-to-very constant and firm. Surprisingly, the rating of ESSs required for this application is very small equivalent to the variations in output power of RERs. ESSs as used in RERs capacity firming need to have modest discharge duration and power rating in the range of MWs. PHES, CAES, BESS, TES are the preferable options for RERs capacity firming.

From the above discussion, it is clear that different ESSs are suitable for different applications and there is no single device that can fulfill all requirements of the DG power system incorporating RERs. Figure 4 shows the suitability of different ESSs as per their characteristics discussed in section 3. Further, Figure 5 depicts, in the form of bar charts, the worldwide power capacity shares by application and type of ESS, as of 2017 end.

Figure 4 Suitability of ESSs for different applications. The level of suitability is marked from 0 (least suitable) to 3 (most suitable), (a) Power quality applications, (b) Bridging power applications, (c) Energy management applications

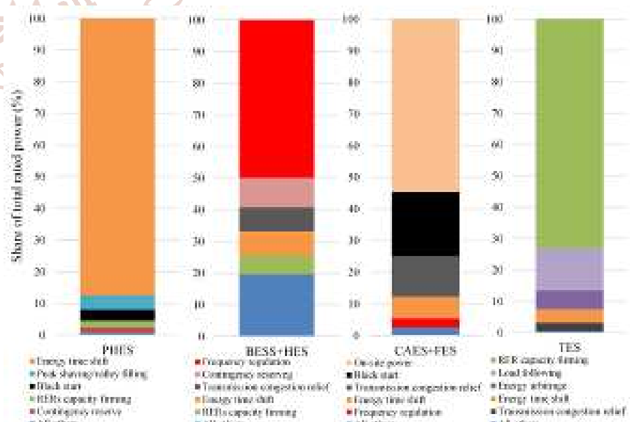

Figure 5 Worldwide power capacity shares by application and type of ESS by the end of 2017

4. Conclusions

In this paper, the working principles and important characteristics of several ESSs, that are currently being used and are expected to be used in future in DG power system applications, are descriptively provided. ESSs are categorized according to the form of energy they can store and their technical and economic characteristics are compared. The potential applications of ESSs in power system have been defined and discussed through an extensive review. These applications of ESSs are categorized, arguably a novel proposition, according to power chain (grid side, generation side, end-user/load side and RERs integration) and duration of discharge (power quality, bridging power and energy management). Comparative assessment of specific applications of ESSs and some of their installations world over have been presented. Challenges and future prospects in respect of ESSs have been clearly brought out and discussed.

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