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Classification and assessment of energy storage systems

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ABSTRACT

The increasing electricity generation from renewable resources has side effects on power grid systems, because of daily and seasonally intermittent nature of these sources. Additionally, there are fluctuations in the electricity demand during the day, so energy storage system (ESS) can play a vital role to compensate these troubles and seems to be a crucial part of smart grids in the future. This study comparatively presents a widespread and comprehensive description of energy storage systems with detailed classification, features, advantages, environmental impacts, and implementation possibilities with application variations.

1. Introduction

Rapid increase in world population and variation of consumer habits are the two main reasons for the increase in energy use and electricity consumption for the last few decades. A significant part of total energy consumption is composed of industry, transportation, and construction sectors. World energy demand is projected to be more than double by 2050 and to be more than triple by the end of the century. Incremental improvements with conventional ways in existing energy networks will not be adequate to supply this demand in a sustainable way [1].

Because of their negative environmental effects (global warming, ozone layer depletion, ground-level ozone formation, pollution, and acid rain etc.) and rapid depletion of fossil fuels, preventive steps should be taken such as use of energy efficient methods in the processes from energy production to consumption, use of clean and renewable energy sources, and etc. All interested parties must consent to use renewable energies to cover the increasing energy deficit [2]. Renewable energy sources can be listed as follows: solar, ocean thermal, wind, tidal, wave, hydrokinetic (marine and river current), hydropotential, geothermal, biomass [3].

Electricity is consumed at the same time as it is generated. Therefore, the proper amount of electricity must always be provided to meet the varying demand. An imbalance between supply and demand will damage the stability and quality (voltage and frequency) of the power supply. Moreover, electricity generation places are usually located far from the locations where it is consumed [4]. Long transmission lines increase the investment cost and energy lost. On the other hand, daily and seasonal fluctuations of renewable energy sources complicate this situation. Short and long-term energy storage is considered one of the prominent solution methods for these difficulties.

Actually, energy storage means a formation of energy in different styles, which can be drawn upon in the future to perform some useful operation [5]. The energy being portable and storable of may open new horizons for the interested parties of the sector. Electrical energy can hardly be stored. In general, the storage of electrical energy requires its conversion into another form of energy [6].

Better ways to store energy are critical for becoming more energy efficient. One of the keys to advances in energy storage lies in both finding novel materials and in understanding how current and new materials function [7]. Energy could be stored via several methods such as chemical, electrochemical, electrical, mechanical, and thermal systems. Among these methods mechanical pumped hydro storage system (PHSS) and thermal energy storage systems based on latent heat and phase change materials come into prominence and are intensely investigated and also easily applicable [8–10].

The present study aims to explain energy storage systems with comprehensive classification, certain definition, different aspects such as referring to application fields, unique features, and partly comparison.

2. Energy storage system (ESS) classification

Energy storage methods can be used in various applications. Some of them may be properly selected for specific applications, on the other hand, some others are frame applicable in wider frames.

Inclusion into the sector of energy storage methods and technolo-

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gies are intensively expected in the future. The success parameter may be matching the application to the technology. Energy research is carried out in five main groups of applications (Electricity supply applications, Ancillary services, grid support applications, renewables integration applications) [11].

The form of converted energy widely determines the classification of energy storage systems [4]. ESS's may be divided into 5 main categories such as chemical, electrochemical, electrical, mechanical, and thermal energy storage [5].

2.1. Chemical energy storage systems

Chemical energy is stored in the chemical bonds of atoms and molecules, which can only be seen when it is released in a chemical reaction. After the release of chemical energy, the substance is often changed into entirely different substance [12]. Chemical fuels are the dominant form of energy storage both in electrical generation and energy transportation. Most commonly used chemical fuels which are processed are coal, gasoline, diesel fuel, natural gas, liquefied petroleum gas (LPG), propane, butane, ethanol, biodiesel and hydrogen. All of these mentioned chemicals are freely converted to thermal and mechanical energy and then to electrical energy by using heat engines as prime mover [5,13]. On the other hand, the stored chemical energy can be released through electron transfer reactions for the direct production of electricity [14]. Chemical energy storage is rather suitable for storage of large amounts of energy and for greater durations [13].

Chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers [4,6]. They could have a significant impact on the storage of electrical energy in large quantities [6]. Moreover than the hydrogen and SNG, the fuels derived from biomass can be taken into account as chemical energy storage methods [13].

In addition to the conventional chemical fuels, there are some studies about new chemical and thermo chemical energy storage technologies includes sorption and thermo chemical reactions such as ammonia system [15,16]. In thermo chemical energy storage, energy is stored after a dissociation reaction and then recovered in a chemically reverse reaction [17].

2.1.1. Hydrogen

Hydrogen is a clean, highly abundant and non-toxic renewable fuel and an energy carrier material [18–21]. Hydrogen, is a widely used industrial chemical, can be produced from any primary energy source [5] such as from water by thermolyses and electrolyses, reforming of fossil fuels, gasification of biomass, methanol, etc. [21]. It releases only water vapor as emission after combustion reaction [21–24]. Chemical energy of hydrogen is 142 kJ/kg which is higher than other hydrocarbon based fuel [21].

Hydrogen storage methods can be divided in two categories as physical (in gas or liquid phase) and material-based storage. Gas phase storage is generally made in high-pressure tank of 350–700 bars. Boiling point (at one atm.) of hydrogen is −252.8 °C. Hence, the liquid storage of hydrogen requires cryogenic cooling methods [25]. Materials-based storage is possible on metal hydride, chemical hydrogen storage, and sorbent materials [26]. Hydrogen storage is possible on the surfaces of solids by adsorption or within solids by absorption [25]. Material-based storage researches continue in the following areas; metal organic frameworks, metal hydrides, aluminum hydride, sodium alienate, magnesium hydride, reactive hydride composite of $LiBH_4$ and MgH_2 [27].

Hydrogen can be used to drive combustion turbines or fuel cells, in hydrogen cars with fuel cells or special internal combustion engines or for heat generation. A schematic diagram of hydrogen energy storage system is given in Fig. 1 [28].

A typical hydrogen storage system consists of a hydrogen generation unit such as electrolyzer, a hydrogen storage tank and a fuel cell (if applicable). An electrolyzer is an electrochemical converter, which splits water with the help of electricity into hydrogen and oxygen [4].

2.1.2. Synthetic natural gas (SNG)

Natural gas, is most popular gas fuel, mainly consist of CH_4. Biogas, Landfill gas, SNG, and bio-SNG are the other gas fuels. Biogas is produced by decayed organic matters and contains CH_4 and CO_2. Composition of landfill is similar to biogas [29]. Synthetic natural gas (SNG) means the partly conversion of solid feedstock with gasification followed by gas conditioning, SNG synthesis and gas upgrading or similar processes to natural gas [30].

The SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid. The production of SNG is preferable at locations where both CO_2 and excess electricity are available [6]. Steam-oxygen gasification, hydrogasification, and catalytic-steam gasification are the different processes that could be used to convert coal to synthetic natural gas. Biomass could also be utilized for SNG production [31]. The hydromethanation or catalytic steam gasification technology is considered more energy-efficient than the traditional methanation processes [32].

2.1.3. Biofuels

Biomass is the name given to any organic matter, which is derived from plants and animals. [33–35]. Biomass means the biodegradable fraction of products such as purpose-grown energy crops, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste [36,37]. Biofuels can be in gas or liquid form. They are generally classified as first-generation, second-generation, and third-generation. Biofuels such as biodiesel, straight vegetable oil, alcohol fuels, or biomass can be used to replace hydrocarbon fuels. Various chemical processes can convert the carbon and hydrogen in coal, natural gas, plant and animal biomass, and organic wastes into short hydrocarbons suitable as replacements for existing hydrocarbon fuels [6].

2.1.4. Thermo-chemical energy storage (TCES)

TCES is based on a reversible reaction, in which a thermo chemical material (C) absorbs heat energy in order to chemically conversion into two components (A and B). The reverse reaction is possible if these components (A and B) combined again, C is reformed. Energy is released during this combining reaction [17].

In the ammonia-based thermal energy storage system (Fig. 2), liquid ammonia (NH_3) is dissociated in an energy storing (endothermic) chemical reactor as it absorbs solar thermal energy. Later, the gaseous products hydrogen (H_2) and nitrogen (N_2) are reacted on demand in an energy releasing (exothermic) reactor to resynthesise ammonia and recover the stored solar energy.

2.2. Electrochemical energy storage systems

Electrochemical power sources convert chemical energy into electrical energy. At least two reaction partners undergo a chemical process during this operation. The energy of this reaction is available as electric current at a defined voltage and time [38,39].

There are two major branches of electrochemical storage technologies as electrochemical batteries and electrochemical capacitors [40]. The existing types of electrochemical storage systems vary according to the nature of the chemical reaction, structural features, and design [39]. Electrochemical cells and batteries can be classified into 4 categories based on the principle of operation; primary cell or battery, secondary cell or battery, reserve cell, and fuel cell [41,42].

A second useful classification refers to discharge depth; either shallow or deep cycle batteries [43]. Deep cycle batteries, have fewer

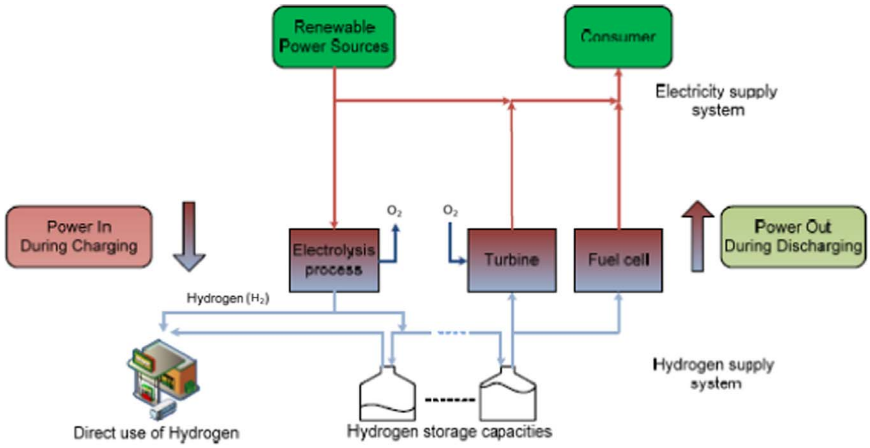

Fig. 1. Hydrogen energy storage system [24].

thick plates in structure, are suitable for renewable applications. The third classification refers to the characteristic of the electrolyte in the battery (flooded or wet and sealed). Flooded or wet batteries are widely used in renewable applications. There are two varieties of sealed batteries; the Gel Jel and Absorbed Glass Mat for renewable applications [43].

Transportation and micropower (stationary/portable) generation including wind and solar energy utilization are among the important application areas of electrochemical energy storage systems. [44].

2.2.1. Primary cell or battery

A primary battery generally is not rechargeable. Most primary cells utilize electrolytes, which are contained within absorbent material or a separator [45]. The type of electrolyte as aqueous and non-aqueous might categorize the primary batteries. Aqueous batteries contain water based electrolyte solutions. Batteries with aqueous electrolyte include Leclanche Zinc-Carbon and Zinc-Chloride, Alkaline Zinc–Manganese Dioxide, Zinc-Air, Zinc–Silver Oxide, and Zinc–Mercuric Oxide. Nonaqueous electrolyte kind includes Lithium–Thionyl Chloride, Lithium–Sulfuryl Chloride and Lithium–Sulphur Dioxide, Lithium–Manganese Dioxide, Lithium–Carbon Monofluoride, Lithium–Iron Disulfide, Lithium-Iodine, Lithium–Silver Vanadium Oxide, Lithium–Copper Oxide [46].

2.2.2. Secondary cell or battery

A secondary cell or battery is rechargeable by passing current through the circuit in the opposite direction to the current during discharge [45]. Rechargeable battery systems can be seperated by the electrolyte type into two groups. They have both aqueous and nonaqueous electrolytes, which are based on water and solvents respectively [46]. Batteries with Aqueous Electrolytes include Lead Acid, Nickel-Cadmium, Nickel–Metal Hydride, and Alkaline Zinc–Manganese Dioxide, Batteries with Nonaqueous Electrolytes include Lithium Ion, Lithium Metal, Metal Air, Sodium Sulphur, and Sodium Nickel Chloride [6,46].

2.2.3. Reserve cell

A reserve cell or battery is a kind of primary batteries. Reserve batteries are often used for long storage. The active chemicals of the cell are segregated and isolated until required [41]. Reserve batteries are assembled without electrolyte. They can be reliably stored under a variety of adverse conditions that would compromise the performance of fully activated cells. The missing element of the battery can be added before use [46].

2.2.4. Fuel cell

Fuel cells are electrical generation devices, which mainly use the chemical energy of hydrogen or another fuel to unleash a fuel's latent chemical energy and convert to produce electricity [47,48]. Fuel cells work like batteries. They, however, do not run down or need recharging, also produce electricity and heat as long as fuel is supplied [47]. A fuel cell is composed of an anode, a cathode, and an electrolyte membrane. A fuel cell works by passing hydrogen through the anode of a fuel cell and oxygen through the cathode Fig. 3 [48]. The hydrogen molecules are split into electrons and protons at the anode site. The protons pass through the electrolyte membrane, while the electrons are forced through a circuit, generating an electric current and excess heat. The protons, electrons, and oxygen combine to produce water molecules at the cathode site [49].

Mainly the type of electrolyte classifies fuel cell as follows:

- Polymer electrolyte membrane (PEM) fuel cells
- Direct methanol fuel cell,
- Alkaline fuel cell,

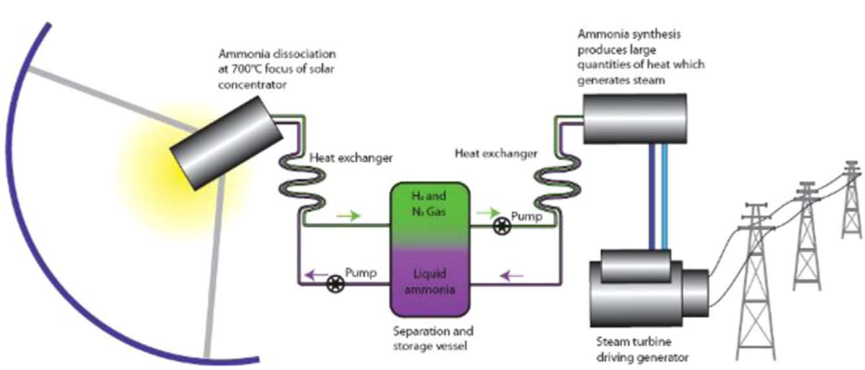

Fig. 2. Solar thermo chemical energy storage using ammonia cycle (Diagram:Tim Wetherell).

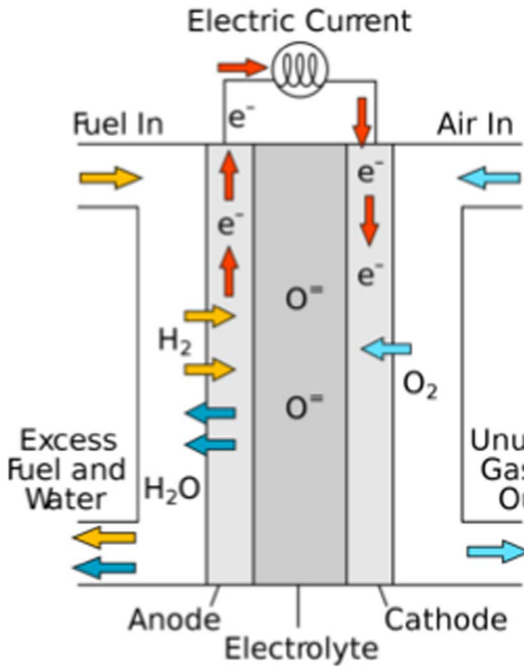

Fig. 3. Working principle of typical fuel cell [44].

– Phosphoric acid fuel cell,
– Molten carbonate fuel cell,
– Solid oxide fuel cell,
– Reversible fuel cell [50,51].

2.3. Electrical energy storage systems (EESS)

EESS can be categorized as electrostatic including capacitors and supercapacitor, and magnetic/current energy storage system [52]. Electrical energy storage systems can be used in some following situations. The capacitors can be used in the case of high currents, but only for extremely short periods, due to their relatively low capacitance generation. The supercapacitor can replace a regular capacitor except that it offers very high capacitance in a small package. Superconducting magnetic energy storage systems can be preferred on the exit of the power plants to stabilize output or on industrial sites where they can be used to accommodate peaks in energy consumption (e.g. steel plants or rapid transit railway) [53].

2.3.1. Capacitor

Capacitors are the most direct method to store electricity [54]. A capacitor consists of two metal plates separated by a nonconducting layer called a dielectric. As one plate is charged with electricity from a direct-current source, the other plate will have induced in it a charge of the opposite sign [52]. They store energy on the surfaces of metalized plastic film or metal electrodes. Since the energy density of capacitors is very low, they are able to deliver or accept high currents, but only for extremely short periods [5].

2.3.2. Supercapacitor

Supercapacitor, electrochemical double-layer capacitors fill the gap between classical capacitors used in electronics and general batteries [6]. Supercapacitors use a molecule-thin layer of electrolyte and have very large surface area activated carbon structure [5]. Comparing with conventional capacitors, the energy storage capabilities of supercapacitors are quite greater [52]. Energy storage of supercapacitors is differed from electrochemical battery system by means of static charge [5]. Rather than the more common arrangement of a solid dielectric between the electrodes, the supercapacitors store energy by means of an electrolyte solution between two solid conductors [47]. Besides, they can provide high peak power output, they can also be recharged and discharged up to millions of times without damage (in contrast to batteries) [55].

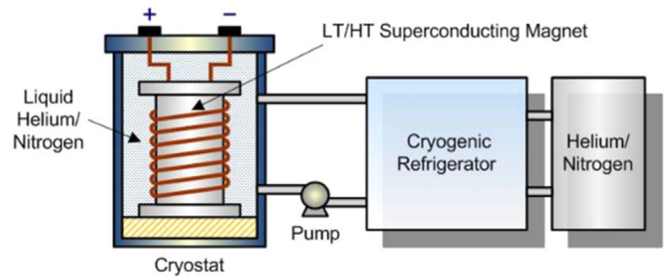

Fig. 4. Structural view of superconducting magnetic energy storage system [56].

2.3.3. Superconducting magnetic energy storage

Superconducting Magnetic Energy Storage (SMES) systems work based on electrodynamics' principle [6]. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature [5,6,54]. Superconducting material has been cryogenically cooled and the stored energy can be released back to the network by discharging the coil [5]. Structural view of superconducting magnetic energy storage system is given in Fig. 4 [56].

2.4. Mechanical energy storage systems

Mechanical energy storage is classified by working principal as follows: pressurized gas, forced springs, kinetic energy, and potential energy. The most useful advantage of mechanical energy storage is that they can readily deliver the energy whenever required for mechanical works [57]. Mechanical energy storage methods are easily adaptable to convert and store energy from water current, wave, and tidal sources. They mainly comprise of flywheel, pumped storage, and compressed air storage Technologies.

2.4.1. Flywheel system

A massive rotating cylinder (a rim attached to a shaft) that is supported on a stator by magnetically levitated bearings is the main part of most modern high-speed flywheel energy storage systems [52]. Principal view of flywheel system is given in Fig. 5 [58].

A flywheel can mechanically store energy as kinetic energy of the rotor mass spinning at very high speeds. [58,59]. This stored energy can be reused by slowing down the flywheel through a decelerating torque and returning the kinetic energy to the electrical motor, which is used as a generator. The faster a flywheel rotates the more energy it

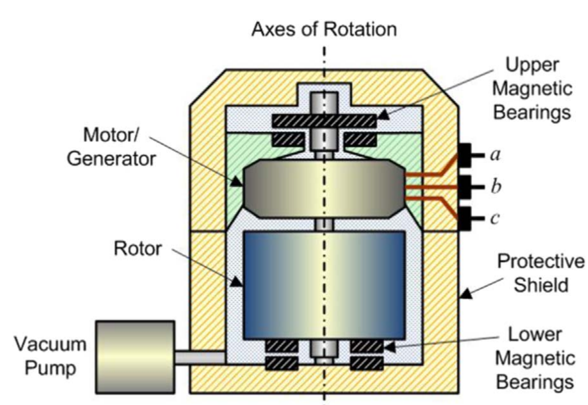

Fig. 5. Principal view of flywheel energy storage system [58].

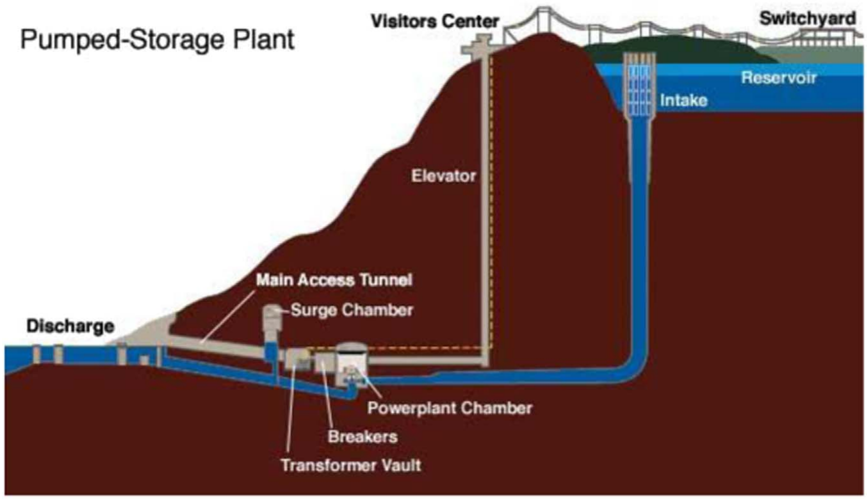

Fig. 6. Schematical view of pumped storage systems [61].

stores. Flywheels can be classified as high speed and low speed [59]. They have been employed to store energy in electric locomotives to guarantee motion along non- electrified sections of rail lines. Interest has been growing on the employment of flywheels as static batteries by the rail side. They can be used to stabilize the electric current feed to locomotives and also to store energy locomotives feed back to electric lines when braking [60].

2.4.2. Pumped hydro storage system (PHSS)

Pumped storage systems store and generate energy by moving water between two reservoirs at different elevations to compensate high and peak demand, Fig. 6 [59,61]. Creating large-scale reservoirs of energy with water is possible by pumped hydro energy storage systems [62].

Pumped storage now is being applied to firm the variability of renewable power sources, such as wind, solar, and wave power. Pumped storage can absorb excess generation (or negative load) at times of high output and low demand and release that stored energy during peak demand periods [63]. In a pumped-storage plant, pump turbines transfer water to a high storage reservoir during off-peak hours. The stored water can be later used to generate electricity to cover temporary peaks in demand from consumers or unplanned outages at other power plants [64].

Pumped storage has been categorized further into three main types:

- Closed-loop: consists of two reservoirs that are separated by a vertical distance, neither of which is connected to another body of water.
- Semi-open: consists of one artificial or modified reservoir and one modified lake or river impoundment with continuous through flow.
- Open-system (pump-back) is a system where there is continuous flow of water through both the upper and lower reservoir [65].

2.4.3. Compressed air energy storage (CAES) system

CAES systems create a potent energy reserve [62]. Conventional (CAES) uses a compressor to pressurize air and pumps it into underground geological formations [66]. Compressor, air storage reservoir and expander are the three main components in CAES system [67]. CAES systems have been mainly thought and applied according to Brayton Cycle driven gas turbine power plants, which require compressed air before the gas entering the combustion chamber. CAES can be combined directly to wave energy system (Oscillating Water Column) as well. The Wells turbine, uses air flow produced by the pressure change inside the oscillating water column, is the main part of Oscillating Water Column energy plant [68]. Through this methods, most of renewable energy generated would be used if not immediately, then at the time when there is increased demand, or when renewable resources are experiencing periods of low production [69]. Storing fresh air in salt caverns is a proven, reliable and safe method of ensuring that excess energy is not wasted. This fresh air is stored in

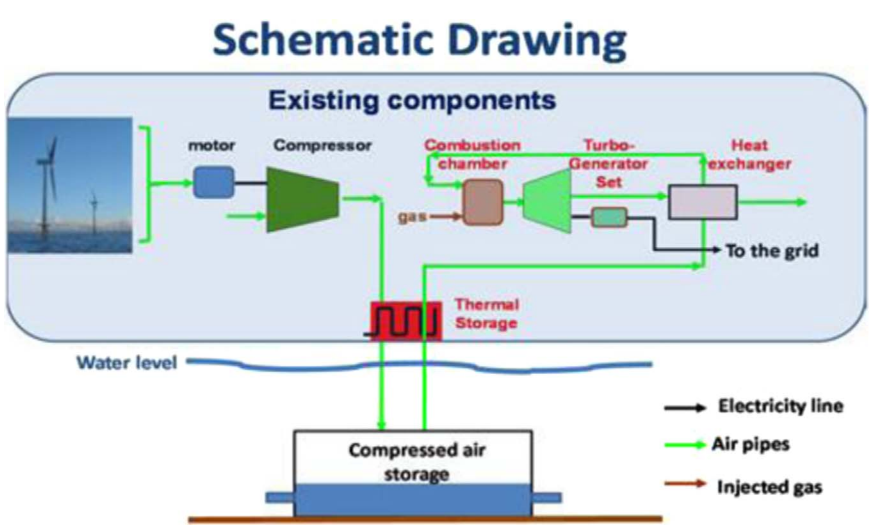

Fig. 7. CAES system schematic [64].

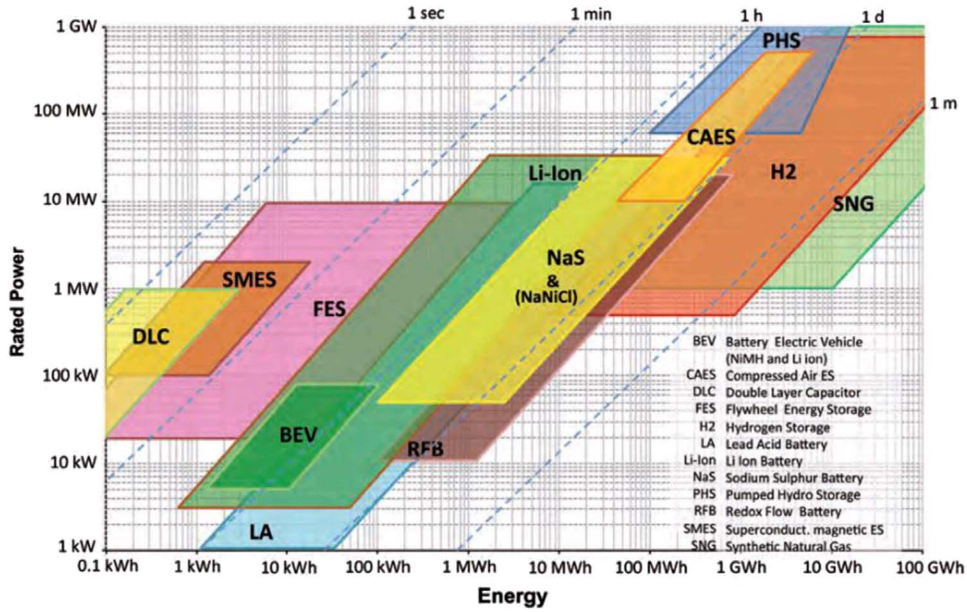

Fig. 8. ESS's comparison by rated power, energy, and discharge duration.

caverns deep underground within geological salt deposits up to one kilometer beneath the ground [70]. System working principle is given in Fig. 7 [71].

Because the compression stage normally uses up about 2/3 of the turbine capacity, the CAES turbine-unhindered by the compression work-can generate 3 times the output for the same natural gas input [72].

Due to heat recovery system after compression process is possible to achieve an important higher efficiency of up to 70%. because of decreasing in consumption rate of natural gas. [72]. Pneumatic storage technologies can use either compressed air or compressed gas to achieve energy storage. In compressed gas applications, a system similar to a hydraulic accumulator is employed which can store and release energy through its integration with a motor/generator and a pump/motor. A hydraulic accumulator is very similar to a pressure storage device made up of a reservoir in which a non-compressible hydraulic fluid is held under pressure by compressed gas [59]. Modern CAES systems overlap with the energy density offered by chemical batteries, and can offer higher power densities when needed while operating at higher efficiencies [73–75].

By another innovative system, the mechanical energy used for compression generates heat that is captured by the water spray. To deliver energy, we reverse the process-the air compressor becomes an expander, and the electric motor becomes a generator. Heat from compression is stored or routed to nearby buildings, providing heating. On the other hand, heat is extracted from energy storage system during expansion process, or buildings providing air conditioning. By this way, it is possible to achieve some important improvements in building energy efficiency [76].

2.5. Thermal energy storage (TES) systems

TES systems are suitable systems to store heat or cold in a storage medium at a temperature for further usage, under different conditions such as temperature, place or power [77]. TES systems are applicable in various industrial and residential purposes, such as space heating or cooling, process heating and cooling, hot water production, or electricity generation. TES system can be classified into three different categories, such as sensible heat, latent heat, absorption and adsorption system [4,77].

2.5.1. Sensible heat system

Sensible heat storage leads temperature changes in the process [78]. The specific heat capacity and the mass of the medium used determined the capacity of a storage system [4]. The storage medium can be in different phases as liquid (water, molten-salt or thermal-oil), solid (stone, concrete, metal or the ground), or liquid with solid filler material (molten-salt/stone) [4,78].

2.5.2. Latent heat system

In contrast to the storage of sensible heat, latent heat cannot be sensed by the change of temperature [78]. Latent heat storage use phase change materials (PCMs) as storage media [4]. Thermal conductivity (k) is a key instrument in latent heat system. Additionally, the density and the enthalpy at the phase transition are important as they determine to capacity of the volumetric storage [78]. Both organic (paraffin), inorganic, and bio-based PCM's (salt hydrates) are available to use in latent heat storage systems [4,79].

2.5.3. Absorption and adsorption System

This kind of thermo-chemical storage is one of the indirect way to store heat. The heat is not stored directly as sensible or latent heat but by means of a physico-chemical process. Absorption and adsorption are two good examples for this process, which consumes and releases heat in charging and discharging mode respectively [80]. High energy density (approx. 1000 MJ/m^3) resulting in small volume of material is taken in account as the main advantage of sorption energy storage [78,80]. Many absorption systems act as heat pumps making cooling as well as heating possible [80].

3. Comparison, assessment and environmental impacts of energy storage systems

Figs. 8–10 present some comparisons of ESS by means of three different ways [81].

Fig. 8 explain by rated power, energy, and discharge duration. Fig. 9 shows how high their power output is and how quickly they can discharge it. Fig. 10 compares the cycle life and the efficiency of storage technologies [81].

Implement of electricity storage can be possible in all five major subsystems in the electric power system: generation, transmission, substations, distribution, and final consumers [81]. The electricity is

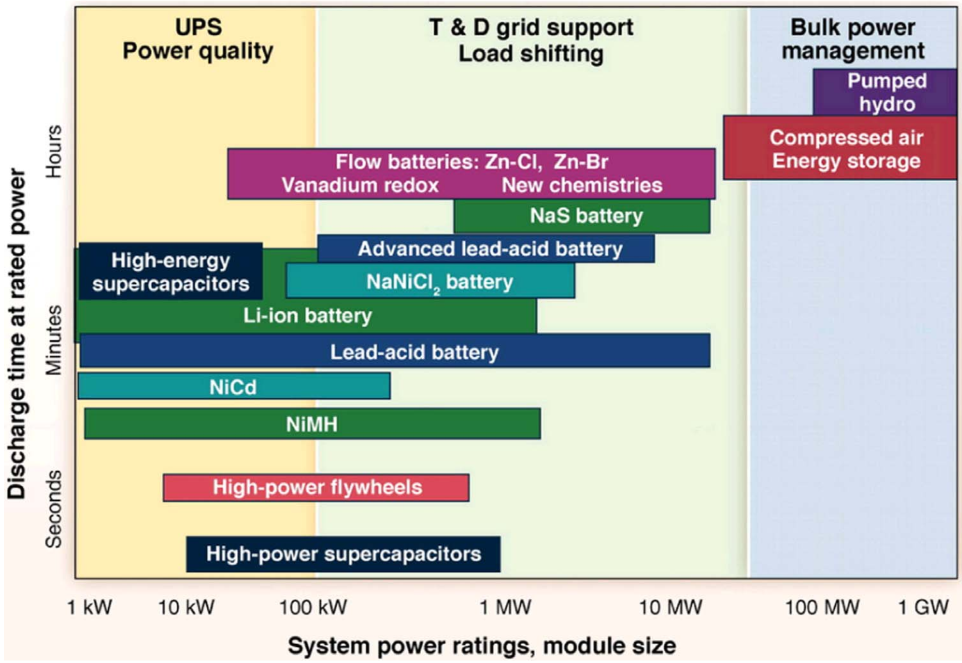

Fig. 9. ESS's comparison by power output and module sizing.

converted into another form of energy during the storage process then reconverted into electricity in many storage devices. On the other hand, this is not a case in the capacitor, which is very basic electrical storage devices, but electricity stores as an electric field [82]. As energy storage capacity increase, several positive impacts of the systems also seem to increase on environmental concerns. Some of the positive effects of bulk energy storage technologies include: black start capabilities, grid flexibility and stability, spinning reserve, auxiliary reserve, peak shaving and regulation control [65].

On the contrary, some negative impacts of ESS's include: occupying large areas and climate change impact of formed lakes of pumped energy storage systems, causing chemical pollution because of batteries, occurrence of losses due to the conversion and reconversion efficiency, creating environmentally harmful by-products by chemical transformations, and etc.

In some cases, it seems plausible and relevant to distinguish ESS's as long and short-term storage systems. Table 1 shows a comparison made as SWOT analyses [83].

Flywheels are preferred to be use for starting and braking locomotives due to their lightweight and high-energy capacity. However, it is not economical since their limited amount of charge/discharge cycle with the energy density of 0,05 MJ/kg and efficiency of η=0,8. CAES's can start up fast, draw back-geological structure reliance, and have higher energy density of 0,2–2 MJ/kg, but lower efficiency of η=0,5 compared to flywheels. PAES system: the most effective ESS with the largest electricity capacity over 2000 MW, energy density of 0,001 MJ/kg, and efficiency η=0,8. Some disadvantages of the PAES systems are as follow: geographical dependence, massive capital cost, soil erosion, land inundation, silting of dams. Superconductors are environmentally friendly, they work at low temperatures and electric currents encounter

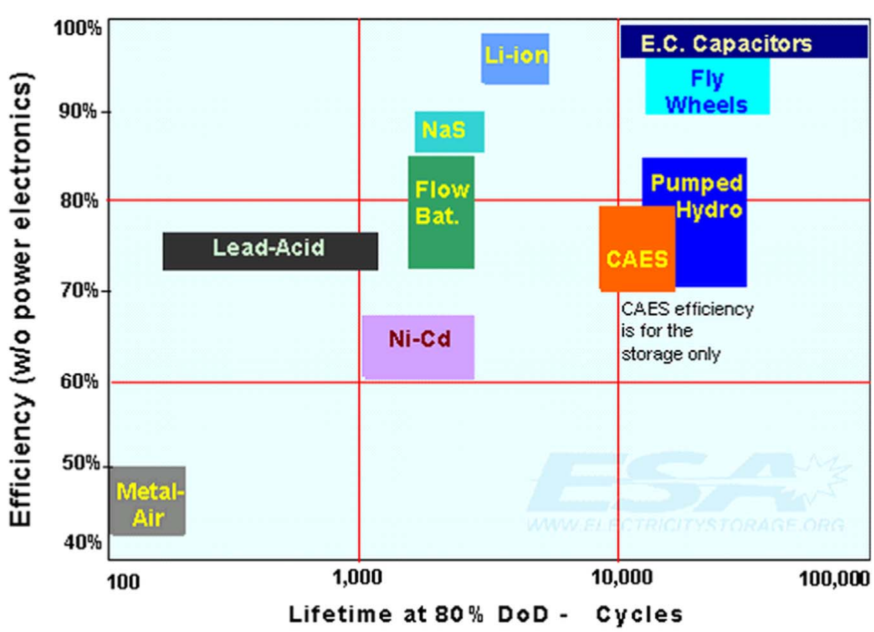

Fig. 10. ESS's comparison by cycle life and efficiency.

Table 1
Comparative SWOT analysis of long-term storage possibilities.

	Strengths	Weaknesses	Opportunities	Threats
CAES	High capacity. Low cost per kWh. Minor needs for power electronic converters.	Need for underground cavities. Need for fuel.	Can prospectively be adopted for distributed storage.	Popularity related to thermal power plants.
PHES (Pumped hydro energy storage)	High capacity. Low cost per kWh. Minor needs for power electronic converters	Centralized storage. Geographical restrictions.	Can be used for offshore wind parks and with lower reservoir under seabed.	Can become obsolete when distributed storage preferred.
BES (Battery energy storage)	Distributed storage. Good configurability	High investment costs. Cycle life. Temperature dependent.	Emerging technologies.	Constant development phase complicates selection. Raw materials limited
HYDROGEN	Distributed storage. Other uses for produced hydrogen. Minor environmental issues.	Low efficiency. High investment costs. Need for power electronics and control. Need for stable load.	Market penetration. Perspective nanotube storage media. Dedicated converters.	Maturing battery technologies. EMI issues related to the use of power electronics converters.

Table 2
Comparison of different battery types.

	Lead acid	Nickel cadmium	Sodium sulphur	Lithium ion	Sodium nickel chloride
Achieved upper limit power	Multiple tens of MW	Tens of MW	MW scale	Tens of kW	Tens/low hundred of kW
Specific energy (Wh/kg)	35–50	75	150–240	150–200	125
Specific power (W/kg)	75–300	150–300	90–230	200–315	130–160
Cycle life	500–1500	2500	2500	1000–10000	2500+
Charge/discharge energy efficiency	−80	−70	up to 90	−95	−90
Self discharge	2–5% per month	5–20% per month		−1% per month	

almost no resistance which provides high efficiency. It can reduce the effect of fluctuations and have longer lifetime with the average power of 200 kW and maximum power of 800 kW. Electrochemical storage can be differentiated from small to large scale. Lead-acid batteries have energy density of 0,6 MJ/kg, and cell efficiency of 15%, and they are mostly used. Table 2 presents a comparison among the different battery types given in Table 2 [84].

TES systems are preferred for small to medium scale storage with the energy density of 0,25 MJ/kg with efficiency rate of η=0,8. De-ice of frozen roads can be given as an example for its environmental impact, if storage places are created beneath the roads. Fuel cell converts fuel to electricity directly, has energy density of about 38 kWh/kg for hydrogen systems for instance. Longer operating time, having no green house gases and not much political dependence would be counted as its advantages. On the other hand, storage problems because of inflammable nature and high investment cost can be accepted as its disadvantages [84].

Table 3 shows an assessment of the potential environmental impacts of various energy storage systems. Most of energy storage systems seems relatively benign from an environmental standpoint as presented in the Table 3. The primary impacts of concern are manufacturing emissions associated with battery systems [85].

Negative impacts of ESS's can be enumerated as follows:

- Energy lost in conversion and reconversion processes
- Cost and complexity increases
- Some challenges in creating of infrastructure and space requirements [86].

Challenges and barriers to the development and extensions of energy storage systems emerge following issues:

- Placement flexibility of energy storage systems can provide for widespread use of renewable energy.
- Energy storage system should meet the requests of industry and regulators as an effective option to resolve issues of grid interruptions and discontinuities.
- Energy storage system should make some tangible and concrete contributions to smart-grid concepts [87].

4. Discussion

Besides the differences in system diversity, energy storage methods vary considerably in size from starter battery in cars to water storage ponds at high altitude. In addition to the expected technical specs, the impact and repercussions of the selecting system to ecology and natural resources should be analyzed in detail during an appropriate system selection. In a more globally perspective, ESS's can be analyzed in terms of whether it requires chemical substance conversion (CSC). Environmental impacts of ESS's that require (CSC) should be examined in detail carefully. Moreover, CSC are either endothermic or exothermic. In that case, recovery or conversion of these energies to useful forms would require some challenging processes. The systems, not requiring CSC, would also be divided in two categories. The first is sensible heat thermal systems with high total heat capacity or latent heat thermal systems based on phase change material. The second systems are based on the conversion of energy forms (kinetic to potential, or vice versa), namely, the energy is converted from substance to substance for instance, wave power of marine currents to air pressure. In any occasion, energy storage systems are performed by chemical substance conversion, energy transfer from substance to substance, converting the energy forms, etc., or some combinations of them.

All these process stages should be investigated in detail comprehensively. Efficient energy storage processes could be designed, checked, and controlled only by this way. Meanwhile, conversion, storage, and reconversion processes should be taken into consideration elaborately. Particularly, system preferences, design parameters, conversion rates, and standby durations with environmental impacts and design should be taken into account as priority.

Electrical grid has to balance demand and supply of electricity amount. Fluctuations in electricity generation from renewable resources might occur because of intermittent nature of them. In that case, operation in larger capacity and adequate system flexibility seems to be crucial. The compensation of these fluctuations in generation phases have some challenges. Hence, increased electricity generation from renewable resources requires fundamental and long-standing approaches. All these uncertain and volatile issues on renewable

Table 3
Qualitative environmental impacts of energy storage systems [84].

Energy storage system	Manufacturing impacts	Operational impact			Disposal impact
		Air	Water	Soil	
Compressed Air	Relatively low	Not significant, except from associated combustion turbine	Not significant	Not significant	Relatively low
Flywheels	Relatively low	Not significant	Not significant	Not significant	Relatively low
Hydrogen Electrolyzer/ Fuel Cell	Relatively low depending on technology and materials used	Not significant	Likely not significant — discharge water can have low pH	Not significant	Relatively low, depending on technology and materials
Lead Acid Battery	Lead and SO2 emissions can be significant but are tightly controlled in U. S.	Not significant	Not significant	Not significant	Lead contamination and sulfuric acid electrolyte are of significant concern but disposal relatively well regulated in the USA
Nickel Metal Hydride Battery	Relatively high air emissions from electricity needed for nickel smelting (can be reduced by battery recycling) as well as p	Not significant	Not significant	Not significant	Relatively low compared to other battery technologies
Pumped Hydro	Relatively low	Not significant if pumping energy comes from clean renewable source	Not significant	Not significant	Relatively low
Zinc Bromine Flow Battery	Relatively low compared with other battery types	Bromine leak locally toxic	Bromine leak locally toxic	Likely not significant	Relatively low with electrolyte less toxic than most other batteries and recyclable plastic components

electricity generation could be eliminated by ESS significantly. Moreover, stand-alone renewable energy generation has to be supported by ESS in many occasions.

Consumer's sensitivity to decrease their energy bill has been raising each day. The decrease in the energy consumption bills depends on the creation of smart-grid and energy management systems where generation, consumption, distribution are managed under one hand. The ratio of stored energy in the whole electricity grid is a sensitive issue that should be attentively assessed.

The main design parameters of energy storage technologies would be enumerated as follows;.

Capacity, - duration (short or long-time storage), impact degree on overall system performance (storage losses, conversion efficiency, reconversion efficiency), fast response, compatibility to automation requirements, being stationary or portable, storage costs, storage security, storage time limits, conversion rate, energy density, environmental impacts, and purpose of use (grid connected or stand-alone) [83,84].

The fulfillment of all these expectations simultaneously seems very difficult, meaning none of them are optimum for all purposes. Storage methods would be assessed according to capacity and maximum usable storage time.

Underground thermal, pumped hydro and compressed air ESS's are favorable for large scale storage. Energy losses of superconductors are insignificant. PHES would be swiftly adapted to power requirement of the grid with an efficiency factor of 70–85% [29]. Because of their high efficiency, fuel cells are considered as prospective alternative to petrol engines due to their high efficiency. Flywheels would not fulfill the large scale operations because of restricted structure [29,85]. On the other hand, fast-moving power transmission response to the grid seems to be an advantage for flywheels [29,85]. CAES system influences overall efficiency in power plants more effectively greater than 100 kW [29,64,88]. Battery Storage System (BSS), respectable due to their high efficiency and remarkable in applications of solar and wind power systems, ranges from lithium-ion, advanced lead-acid to flow batteries such as sodium sulphur and zinc bromine [64]. Moreover, advanced batteries would answer the fast response requirements [29]. Fuel cells should be emphasized attentively because of operational flexibility, if long-term storage and portable solution is demanded [4,89]. In portable and/or large scale implementations, chemical energy storage systems seems to be preferable and valuable [4]. PHES is more appropriate to use mainly in utility-scale energy storage with their easily manageable structure. CAES systems are used in a number of large power plants, based on gas turbines. BSS is not commonly practiced in power plants Sodium sulphur batteries (NaS) is applicable in size of hundreds of megawatts mostly in Japan. Additionally, there are some experiments with banks of lithium-ion batteries, nickel-cadmium batteries and regenerative fuel cells (flow batteries). Some researches have been still carried on energy storage by means ammonia synthesis [68].

5. Conclusion

An energy storage system (ESS) will enable smart grid concepts which is one of the encouraging technologies in the future. Eliminating the fluctuations related with their power production, ESSs may facilitate the integration of renewable energy systems. ESSs may support system reliability and additionally offer some auxiliary facilities such as load following, spinning reserve, black start capability. Furthermore, ESSs may contribute to compensate for peak loads, and by this way reduce generator breakdowns. The amount of stored energy may play a significant role to compensate for peak load. The capacity factor of base generation units can be increase by this way, also it is a positive factor for stored energy utilization with low price [90].

EES seems to be key component for adaptation to the diversity of new technologies, varying consumer habits and activities, and the alternating mechanism of the electricity generation and changing delivery system over the past decade. Moreover, it can provide several improvements in grid performance such as reliability, quick response, load-matching capability etc [91].

Major problems of energy issues such as sustainability and protection of environment are directed us to diversify the energy sources and increase the use of renewable energy. The variation of energy/ electricity generation amounts due to short and long term fluctuations of renewable resources require some critical measurements. Thus, energy storage becomes significantly important to improve the response capacity of the electric grid system due to their easy in manageability, controllability, predictability and flexibility.

Effective energy storage would compensate the difference of the levels between electricity generation and consumption in short and long term spans, precisely. All these technologies would strengthen the reliability and stability of electricity distribution systems. However, some parameters such as investment costs, inclusive construction, capacity, energy density, power and energy ratings, cycle life, respond rate and efficiency should be considered for proper ESS selection. Additionally, usage variation either stationary or portable should be taken in account. Commonly, energy storage density is gaining priority in portable applications. On the design of stationary applications either to be stand alone or grid connected should be considered. The amount of energy storage is a milestone for an effective decision on system selection.

Mechanical systems seem to be preferable due to their large amount of storage capacity. Batteries are preferred in stand-alone system, while both batteries and fuel cell would be chosen in portable system. The conversion rate and compliance to sudden load changes would be essential factors. Namely, the electrical systems would be responsive essential grid requirements. The above-mentioned issues and various other specific points according to the user purposes have significant impacts on the selection processes. Covering a lot of space, providing some sensitive security measures, relatively higher initial investment costs, compensation of mismatching between the generation and consumption rate of electricity, some negative impacts of chemical material transformations are among the weaknesses of building an ESS. Consequently, in any case, requirement and importance of ESS will gradually increase in every aspect of life such a in industrial processes, electricity generation, transportation sector, mobile applications, and etc.

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