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Energy Storage Systems: Current Techniques and Future Prospects

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Abstract **-** Because of the depletion and scarcity of natural resources, energy storage systems have become the foundation of energy utilization today. Energy can be stored in a variety of ways, including kinetic, chemical, electrical, and thermal. The implementation systems and devices used for each process distinguish the various storage types. In addition, applications can specify the characteristics of the used energy as well as the consumption parameters. These systems generate energy during periods of high demand in order to meet the needs of the population and industries. In hybrid configuration plants, energy storage plants can store energy generated directly from one source or can combine two or more energy types to produce the required energy.
In this paper, we will discuss the various types of energy and describe the working principle of some systems using examples. Following that, we will discuss the development outlook based on the trends that have been examined.

Keywords: Energy storage system, Mechanical energy storage system, Electrochemical energy storage system, Chemical energy storage system, Thermal energy storage system, Electrical energy storage system.

1. Introduction

Energy is a physical quantity that measures the ability to generate work, radiation, or heat. In several systems, the energy causes the modification of the primary status due to movement, deformation, or other thermal or mechanical actions. In general, energy associates various parameters, including force, duration, the nature of the applied action, and the system's state at the end of the experience. The popular forms of energy are radiation, gravitational, thermal, chemical, electricity, latent heat, nuclear, potential, kinetic, sound, mechanical, and motion. Table 1 below contains the detailed specifications for each form.

Table1. Forms of energy

Radiation	Waves or particles through space or materials, Electromagnetic radiation, Particle radiation and acoustic radiation, Gravitational radiation…
Gravitational energy	Stored energy in objects in height (The higher and heavier the object, the more gravitational energy is stored).
Thermal energy	Atoms and molecules move in a substance, Geothermal energy.
Chemical energy	Atoms and molecules in batteries, Petroleum, Coal treatment, Natural gas, Biomass…
Electricity	Charged particles/electrons moving through a wave,
Nuclear energy	The nucleus of an atom, Nuclei combination or split…
Kinetic energy	Motions of waves, electrons, atoms, molecules, substances, and objects.
Mechanical energy	Stored energy in objects by tension, Compressed springs, and Stretched rubber bands.
Sound energy	Stored energy due to the movement of the objects (The faster the object moves, the more energy is stored),

The listed forms in Table 1 are critical to meeting the world's daily energy needs. As a result, energy storage for later uses is indispensable to reducing energy demand imbalances. The concept of energy storage entails converting energy from difficult-to-store forms to more convenient or economically storable ones. Moreover, it offers valuable flexibility in the choice of fuels and primary energy sources. Consequently, energy storage is a crucial component that approves the necessity of renewable energy sources, and it plays an essential role in maintaining a robust and reliable modern electricity system [1].

By 2030, the demand for energy storage will increase, necessitating some specialized devices and systems [2]. Rapid reductions in the cost of wind and solar power generation and an even higher reduction in electricity storage costs have made renewables plants more competitive with fossil resources alternative solutions [3]. Furthermore, by 2050, the demand for energy storage is expected to triple from its current level, especially in grid services, electromobility, and variable renewable energy systems [4]. This rising demand necessitates extensive research to develop new storage techniques to meet the needs of all sectors. ESSs are vital for the energy generation industry because their performance determines system efficiency, operational costs, and system lifetime based on storage characteristics [5]. Energy can be stored directly in its original form or converted later in the application process to another form. Several methods and principal systems are employed in this regard. Thermoelectric, photovoltaic, thermionic, and magnetohydrodynamic generators are some of the most common transformation systems [6]. Some new concepts emerge due to the rise of new transformation and conversion strategies, such as the concept of power to X, which aims to convert or store electricity using surplus power. Moreover, formulating an excellent energy conversion and management strategy has become an effective method to achieve established goals with the application of advanced information technology for the incorporation of electricity and natural gas systems [7].

2. Energy Storage Systems (ESS)

2.1. Mechanical Energy Storage Systems (MESS)

MESSs advance due to research done in materials, control systems, transmission devices, and innovation fields. They can be purely mechanical or include electrical/electronic components; the main difference is whether the stored energy is used directly or is transmitted via a generator [8]. For instance, isothermal compressed air ESS (CAESS), flywheel ESS (FESS), gravitational potential energy (GPE), hydraulic accumulators (HA), and pumped-storage hydroelectricity (PSH) are all common mechanical storage systems.

The CAESS is a technique for storing compressed air energy or potential mechanical energy that is grafted onto gas turbines. Air is compressed and stored under extreme pressure in underground geological storage facilities using electrical energy [9]. During times of high demand, expanding air causes expansion turbine blades to spin, which allows the generator to turn that motion into electricity. In addition to the various experiments conducted by laboratories on this side, the most popular plants are McIntosh and Huntorf. Both installations use salt caverns as storage tanks for compressed air, which is processed at night when energy demand is low. The generated power is about 110 MW for Alabama Electric Corporation in the McIntosh plant and 290 MW for Kraftwerk Huntorf installation [10]. Instead of using this technology during peak demand periods, researchers are expanding its use into other domains. Some examples are; renewable power generation plants, smarts-grids applications, wind energy networks, compressed air engines, and continuous power supply to maintain energy in some other sectors [11]. The technology has been continuously improved, particularly in China, where researchers have developed new systems to create supercritical CAESS and introduce hybrid installations based on multiple regeneration systems [12]. Actual studies compare CAESS to hydroelectric energy storage systems to improve performance, efficiency, and regeneration capacity.

PSH plants, like CAESS, are used for peak power demands and are based on storing the potential energy of water by pumping it to a higher tank and reflowing it to a lower one. The primarily used energy is purchased at night from thermal power plants or collected during the day from renewable installations. During energy release cycles, the operation process is very flexible, with a high level of dispatchability. This installation serves as a water management facility and a flood protector in addition to supplying energy to houses and plants. During the process, two factors can affect the quality of the energy generated: the air flow rate, which is affected by air pressure, and the water flow rate, which is affected by the stability of the groundwork [13]. However, recent technological advancements have focused on improving their ability to provide load-frequency control by researching variable speed PSH installation and short circuit performances [14]. In Australia, various studies are being conducted to improve the capacity and performance of PSH installations, particularly with the advantage of having many ground infrastructures suitable for the implantation process. Tumut 3, Wivenhoe, and Shoalhaven have a combined capacity of 2.5 GW as a primary result that will be expanded to cover other applications and sectors [15]. The Francis turbine is a water-mixed flow turbine that operates on a radial and axial flow combination principle. The peak efficiencies of modern Francis turbines range from 80% to 95%, which can be increased by changing the design [16]. These turbines control water from 40 to 600 m in height, producing electricity ranging from one or two kW to 800 MW, which can be reduced in small installations [17]. Furthermore, the integration of hybrid systems solves vibration, dynamic risk, and control problems that may arise during installation; the most commonly used hybrid system is the solar-wind-hydro configuration [18]. With advancements in wind and nuclear energy, many hybrid configurations are being researched for future use in conjunction with the actual PSH plant. China, for example, has been interested in developing its installations since 1960 in order to increase capacity and effectively exploit its hydro resources while avoiding the most critical issues such as power grid load adjustment and frequency control [19].

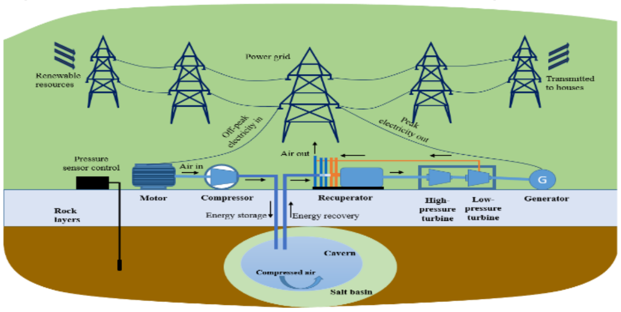

Fig. 1: Compressed air energy storage method

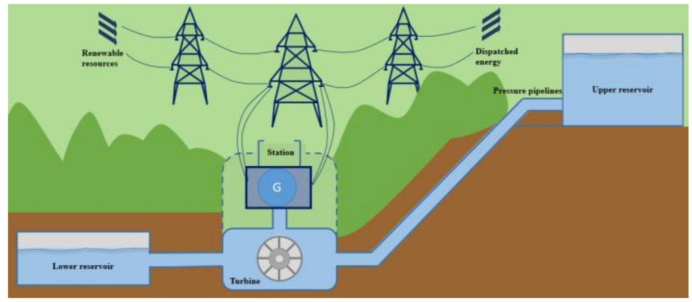

Fig. 2: Pumped–storage hydroelectricity technique

GPE storage systems regenerate electric energy by utilizing gravitational energy for objects that remain in height. The energy is released by holding objects at a height and then dropping them under natural gravitational force to create motion, which turns generators and produces electricity that can be distributed to the grid. Multiple companies are investing in GPE, a technology that uses solid materials at different elevations to store potential energy [20]. A start-up in Switzerland, Vault, has created a new energy storage method that uses a six-arm crane to raise and lower 5000 concrete blocks of 35 tons while exploiting the power of the earth's gravitational pull [21]. Vault offers a grid-scale gravitational renewable ESS. It expands its work by providing this technology in the form of buildings. Composite blocks are replacing concrete blocks as eco-friendly and recycled materials [22]. They simplified their system by incorporating heavy-weight lifting and lowering into an elevator-style building design that meets international building codes [22]. Actually, researchers are working to improve efficiency, technological performance, and commercial potential.

HAs are used as a supplementary energy source to reduce pressure in hydraulic circuits. As a result, they are combined with small pumps, shortening their cycles and conserving energy. They are also used to decrease vibration-induced pulses. Some researchers have focused on overcoming the system's major limitation to increase storage capacity. In this context, Liu Yanxiong, Xu Zhicheng, Hua Lin and Zhao Xinhao created a mathematical model of a controllable accumulator to manage the four working modes; this research is supported by simulated pneumatic, mechanical, and hydraulic models [23]. Others are considering developing new hybrid systems by combining various devices to increase capacity and lifecycle. A new solution flywheel-accumulator based on increasing the moment of inertia and the angular velocity is presented for this, and a numerical model is used to differentiate between the hydraulic system pressure and the quantity of stored energy [24]. Furthermore, in the aircraft industry, accumulators are regarded as an important component of the hydraulic circuit that must be continuously developed. In general, they deliver a transient flow in a limited time, keep a continuous pressure, and act as an emergency power supply [25].

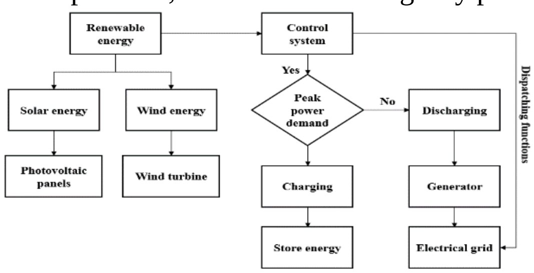

Fig. 3: Gravitational potential energy storage system diagram

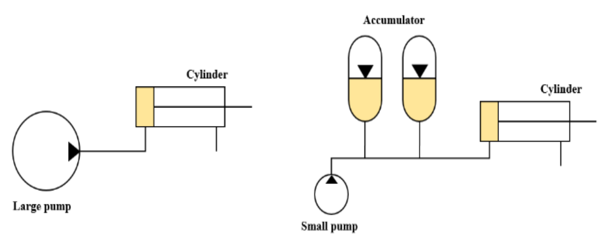

Fig. 4: Illustration of the impact of an accumulator in a hydraulic circuit

With the advancement of the electric grid, considerable developments have limited the utilization of flywheels, however, recent improvements in materials and power electronics have increased the necessity of building new storage systems based on some mechanical components [26]. Actually, flywheel systems are used as an interruptible power supply system in hospitals and datacenters to prevent grid outages and backup electrical power. Moreover, this system is used in the Join European Torus research program to conduct fusion tests for plasma pulses. The system provides the JET device with a maximum power of up to 400 MW and energy of up to 2600 MJ per pulse in order to generate and isolate the multimega-ampere plasma current [27]. Another application is the use of pulsed power in electromagnetic aircraft launch systems. The flywheel employs a synchronous motor to generate energy for the operating condition of the electromagnetic aircraft launch system; the energy is stored kinetically and launched in a series of pulses during the process [28].

2.2. Electrochemical Energy Storage System (ECESS)

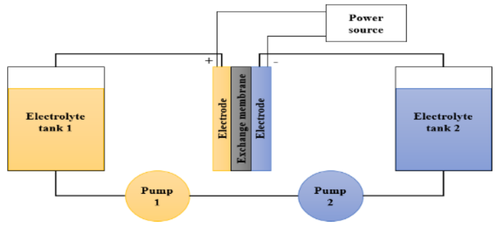

Fig. 5: Illustration of a flow battery components (Reproduced from [29])

ECESS are the foundation of modern batteries; they are classified based on the electrolyte used and the operating parameters and they are used in the automotive, aerospace, household appliances, and computer industries [30]. In the charging mode, renewable energies such as wind and solar systems are used; in the discharging process, the extracted electricity is stored in the tanks and pumped through electrodes to retrieve electrons [29]. The process ensures high efficiency due to the advanced rechargeability rate of chemicals stored in reservoirs in liquid form. These batteries are based on reduction-oxidation reactions between two chemicals and they are similar to regenerative electrochemical cells. Generally, the storage capacity depends on the size of the tank and the concentration of the elements. The electrolyte in redox batteries contains the active redox substance, and the cells are organized in bipolar layers so the electrolytes can circulate through in charge/discharge modes with an exchange membrane that prevents the solutions from mixing [31], [32]. Recently, researchers around the world have developed several types of redox batteries, particularly those based on vanadium, sodium, and zinc, which offer high efficiency and optimal cell voltage [33]. Furthermore, iron redox flow batteries are appealing due to their low cost, particularly for iron-chromium types [34]. Most rechargeable batteries face challenges in terms of durability, safety, and rates; these issues can be addressed by developing aqueous electrolytes and utilizing sodium ions conductivity to develop other electrolyte concepts [35].

2.3. Chemical Energy Storage System (CESS)

Some important CESSs are biofuels, hydrated salts, hydrogen storage, hydrogen peroxide, power to X, and vanadium pentoxide. Salts hydrates are frequently used in heat storage at low temperatures and are classified as an inorganic phase change material [36]. Their main advantages are good thermal conductivity due to higher density and the possibility of recycling; on the other hand, they require reinforcement with additives for more stability and can be corrosive [37]. Metal hydrides and complex hydrides are investigated for the potential development of on-board and off-board energy storage components for future use [38]. Furthermore, they are the most important techniques because they use materials to absorb hydrogen in various ways; the process requires an analysis of several materials to find the best fit for each application [39]. Chemical energy can also be stored using hydrogen peroxide H_2O_2, which has a high viscosity. Energy storage-based aqueous solutions of H_2O_2 have numerous advantages, including chemical stability, nontoxicity, and high energy density [40]. Furthermore, hydrogen peroxide plays an important role in oxidation reactions, acting as an electron acceptor and donor during oxidation and reduction reactions, respectively [41]. Similarly, Vanadium pentoxide V_2O_5 is used to improve supercapacitor performance, particularly for energy storage solutions, and research is ongoing to combine it with carbon nanomaterial's to improve its electrochemical structure and performance [42].

2.4. Thermal and Electric Energy Storage System (TESS - EESS)

TESS employs high-sensitivity materials in hard or liquid form, with the benefit of high capacity and density even at low temperatures [43]. Based on chemical reactions with high density and reversibility, TESS can be divided into sensible heat, latent heat, and thermochemical systems. Their applications are diverse, including energy insurance for use during cold periods and vice versa, and energy conservation for industrial power plants, particularly those that are synchronized with solar implantations [44]. As shown in Fig. 6, the captured energy from solar power plants is connected to a TESS, which converts it and stores it in a tank to be used later in the electric grid. Steam accumulators, molten salt storage, and phase change materials are all intriguing TESS features to develop and demonstrate.

EESS refers to all systems capable of storing and regenerating electricity for later use, particularly during peak demand periods. A variety of techniques are employed, the most important of which has proven profitable in the global market [45]. Superconducting magnetic energy storage SMES is a technology that stores energy in DC form from a magnetic field; It is primarily based on cryogenic temperatures and superconductivity [46] . Because SMES systems provide less power loss, the coil is used for storage with the need for a protection system to deal with anomalous conditions [47].

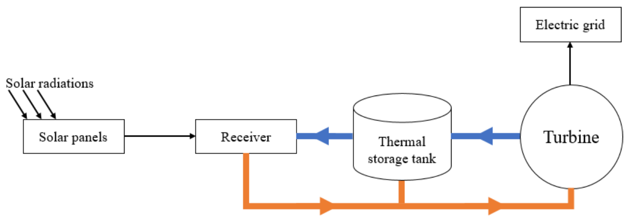

Fig. 6: Illustration of solar plant with TESS (Reproduced from [48])

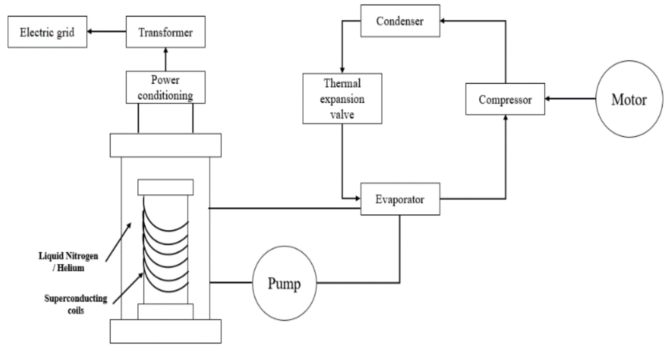

Fig. 7: Illustration of the superconducting magnetic energy storage system (Reproduced from [49])

3. ESSs Development and Trends

The global energy transition is under pressure due to the risks of energy supply shortages and energy access, sustainability, affordability, and security [50]. According to Enerdata statistics, there is a strong increase in coal consumption in Europe of +11,9%, a surge in global natural gas demand of +13,6%, a strong rebound in European power consumption of +4%, a sharp drop in crude oil production in the UK of -16,6%, and a decline in oil product consumption in Germany of -2,9% [51]. Moreover, power consumption is expected to triple by 2050, as electrification is frequently projected to be the first lever to achieve emission-reduction goals, being the cheapest and easiest to implement in most sectors [52].

On the other hand, this transition to a cleaner and safer future affects all countries. Morocco is one of these countries that aims to achieve net global zero goals through significant initiatives and investments in the energy sector. According to the leading data and analytics corporation, Morocco had 3.9 GW of renewable installed capacity in 2020 and is expected to reach 4.3 GW in 2021, a 9% increase [53]. Predictive statistics show that Morocco's renewable installed capacity will increase by 5.3 GW by 2030 compared to 2021, with a compound annual growth rate of 9.3% during 2020-2030 [53]. Morocco has established a program to reduce greenhouse gas emissions by 2030; this strategy is available in the renewable energy sectors including wind, solar, and hydroelectric [54]. With several programs to generate electricity from renewable sources, the Kingdom of Morocco is currently regarded as one of the world's leading countries in the energy transition, particularly in Africa [55]. Despite rising costs, the worldwide market for energy storage systems doubles. Despite rising energy storage costs, the worldwide energy storage market will expand, adding around 28GW/69GWh of energy storage by the end of 2023. Compared to installations in 2022, the market will almost treble in gigawatt-hours [56].

Finally, the field of energy management and regeneration can benefit greatly from the expansion of digitalization. Wastes can be reduced and effectively handled by combining technological and digital methods. Still, digitalization and the Internet of Things strategy make more significant contributions to technological progress in energy storage [57].

4. Conclusion

In this paper, we explore the many sources of energy, describe the operating principles and innovations in several installations, and discuss the newest trends and developments in the globe at large, as well as in Morocco specifically. It provides a solid foundation for analyzing ESSs and comprehending their applications in various industries. In the future, I'd like to identify appropriate technologies for electric vehicles, which are being developed to store and regenerate energy to address depletion difficulties. Many systems can benefit from advances in energy storage and manipulation to solve major problems. These conversion and storage techniques, on the other hand, have the potential to accelerate the adoption of electric vehicles. To be widely used, these vehicles require regenerative onboard systems supplemented by refueling stations. As a result, research into these storage technologies may aid in the adoption of electric vehicles by identifying compatibilities between various systems. Furthermore, hybrid configurations must be studied in order to be compatible with the vehicle structure, easy to implement in a limited space, and easy to synchronize with the various other control systems in the vehicle.

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