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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