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Comparative Review of Long-Term Energy Storage Technologies for Renewable Energy Systems

A. Andrijanovits, H. Hoimoja, D. Vinnikov
Department of Electrical Drives and Power Electronics, Tallinn University of Technology,
Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +3726203705, e-mail: sergejeva84@hot.ee

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Introduction

Energy storage systems for a long time have been utilized in many forms and applications. Today's energy storage technologies are used to achieve electric power systems of higher reliability and to contribute to the broader use of renewable energy. Wind power appears to be one of the most perspective and widespread renewable energy sources. Because of unregulated energy generation of wind generators, with the wind speed fluctuating, the output too is fluctuating, i.e. at some instances energy overflow and deficiency will appear (Fig. 1) [1].

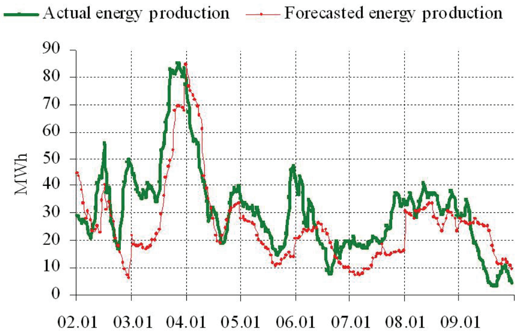

Fig. 1. An example of unpredictable energy generation by Estonian wind farms

An energy storage element introduced into a wind power plant will change the spectrum and statistical distribution of the output power. Increasing the amount of storage (power and energy) associated with a wind power plant will gradually make the output more controllable and predictable [2].

Energy storage technologies

A variety of technologies are available for energy storage in the power system. To identify the most relevant storage solutions it is necessary to include considerations of many relevant parameters, such as cost, lifetime, reliability, size, storage capacity, and environmental impact. All these parameters should be evaluated against the potential benefit of adding storage to reach a decision about the type of storage to be added. There may also be cases where the value of adding storage is not sufficient to justify such an investment.

Energy storage technologies can be generally divided into three main groups: mechanical, electrochemical and electromagnetic storage (Fig. 2). Mechanical storage includes pumped hydro storage, compressed air energy storage and flywheels. Electrochemical storage includes all types of batteries as well as a hydrogen based energy storage. Electromagnetic storage includes supercapacitors and superconducting magnetic energy storage.

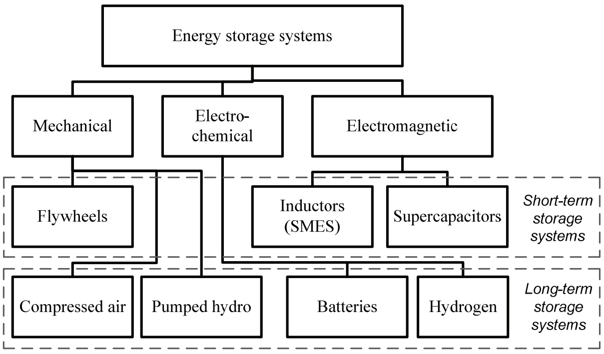

Fig. 2. Classification of energy storage technologies

Each technology has certain properties with regard to storage capacity, power, response time and cost. Grouping storage technologies with regard to storage capacity is relevant because it can be used to exclude those sizes not relevant in relation to renewable energy systems [3–7].

Different energy storage technologies have a wide range of energy release rates (discharge rates) that extend from seconds to many hours and days (Fig. 3) [7].

Based on their energy storage capacity, energy storages can be categorized as short-term and long-term energy storages. Short-term storage systems include the supercapacitor energy storage (SCES), flywheel energy storage (FES) and superconducting magnetic energy storage (SMES) (Fig. 2). The long-term storage systems could be subdivided into pumped hydroelectric energy storage (PHES), compressed air energy storage (CAES), battery energy storage (BES), and hydrogen energy storage (HES) (Fig. 2).

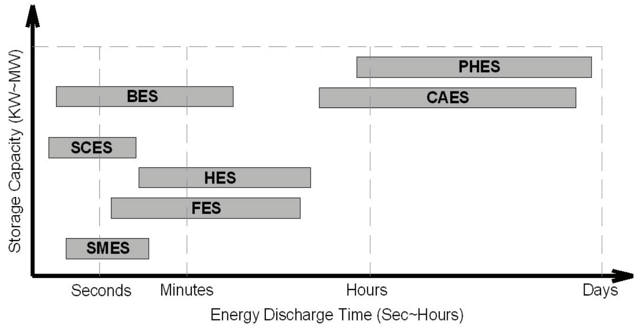

Fig. 3. Typical energy storage capacities and discharge times of different energy storage technologies

Renewable energy sources cannot be easily regulated or dispatched. Peak levels generated by a wind power plant may not coincide with the peak demand. In the case of instability of wind production, long-term storage technologies could be used. It allows wind farms to be used as a base load or enables an increase of predictability to nearly 100 % for a certain period of time. The time horizon could be days or weeks, depending on storage size and variations allowed.

General technical parameters of long-term energy storage technologies in the wind power context are summarized in Table 1 [6, 8].

Table 1. Comparison of long-term energy storages

Storage system	Capacity, MW	Efficiency, %	Technology
Pumped hydroelectric	100…1000	70 – 80	Mechanical
Compressed air	0.1…1000	75 – 85	Mechanical
Batteries	0.1 – 10	60 – 80	Electrochemical
Hydrogen	0.1 – 1	20 – 40	Electrochemical

Pumped hydroelectric energy storage

Pumped hydroelectric energy storage (PHES) has been in use worldwide for more than 70 years. These large-scale energy storage plants represent the most widespread energy storage technology in use today. Pumped hydro units operate on the principle of a hydro-electric power plant. However, their generator units serve also as motors. During off-peak hours surplus power is used to pump water from a lower reservoir to a higher level reservoir (Fig. 4) whilst pump/turbine (PT) operates as a pump and a motor/generator (MG) as a motor. At peak demand, water is released from the higher reservoir to turn the turbine and to produce electricity, and then the MG operates in the generating mode and the PT as a turbine [9].

PHS plants can produce a large amount of energy for sustained periods of time. In addition, these plants have round trip efficiencies in the range of 70 to 80 %. Their storage capacity is dependent only on the size of the reservoir. Thus, instead of having only a few hours of energy storage it could be days. The major drawback of this design is the significant area of land required to create the reservoirs and the elevation needed between them. Many of the desirable sites are already in use and other ones have encountered opposition from environmental groups. The environmental impact of large-scale PHS facilities is becoming more of an issue, especially where existing reservoirs are not available. Environmental considerations such as impacts on fisheries, recreation, water quality, aesthetics, and land use have sharply limited the further development of this technology [10]. There is, however, an alternative to avoid the environmental impacts of the large reservoirs by placing them underground. The use of underground PHS plants has proven to be technically feasible, but with the high costs associated with placing them underground none currently exist today [6, 11, 12].

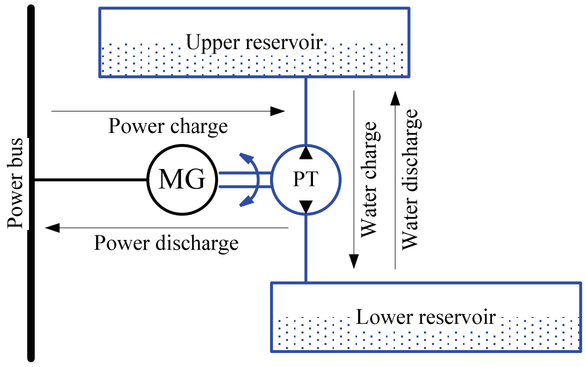

Fig. 4. Power and water flows in a PHS

Compressed air energy storage

Compressed air energy storage (CAES) systems use off peak electrical power generated from base load plants or renewable energy sources to compress air at high pressure (typically around 75 bar) into an underground reservoir or a surface vessel. Then, during times of high electrical demand this compressed air is combined with a fuel to drive a turbine generator set. The energy flow and air state changing of the CAES system is shown in Fig. 5 [9, 13].

With the CAES plant fuel consumption is reduced by two thirds as compared to the conventional units and the plant is capable of starting up within tens of minutes. It does not require a lengthy startup time like other spinning reserves, such as thermal units.

CAES plants require a large volume of compressed air to operate for extended periods of time. The principle of storing a gas underground is based on a proven method developed by the oil and gas industry. Typical ratings for a CAES system are in the range of 50–300 MW, with an efficiency of about 85 %.

The main key to a CAES system is that the reservoir has to be air tight and very large. Smaller units using above ground storage tanks are usually limited in their energy storage capacity to only a few hours [11]. In order to achieve a higher efficiency or remove the need for an additional conventional fuel there are many new hybrid CAES technologies being developed. These new hybrid systems under development use supercapacitors, oil-hydraulics and pneumatics to increase the efficiency of the design [6, 12].

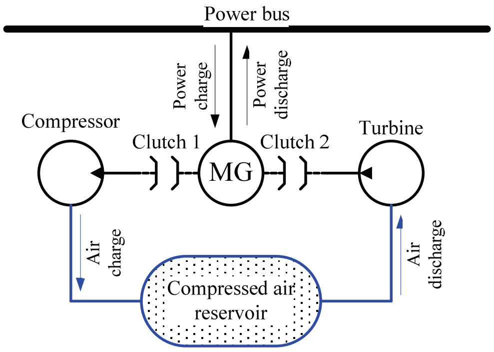

Fig. 5. CAES energy flow diagram

Battery energy storage

Batteries are one of the most cost-effective energy storage technologies available, with energy stored electrochemically [14]. Battery energy storage systems (BES) are modular, quiet, and non-polluting. They can be located almost anywhere and can be installed relatively quickly. Charging a battery causes reactions in the compounds, which then store the energy in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the grid, as shown in Fig. 6 [9]. Instead of two separate ac/dc converters for charging/discharging, a sole bidirectional converter may be utilized.

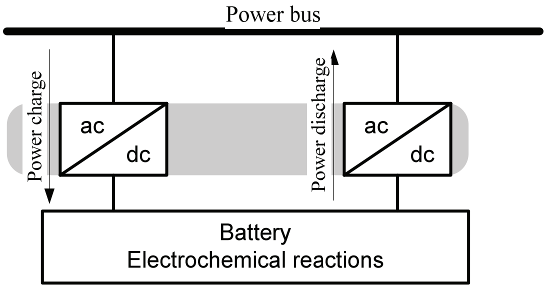

Fig. 6. Energy flows in a BESS

Fast response is one of the strong points of the battery technology: some batteries can respond to load changes in about 20 milliseconds. The efficiency of battery modules is in the range of 60–80 % [6, 11]. Batteries, however, have some very unique challenges. During an electrical charge and discharge cycle the temperature change in the battery must be controlled or it can affect the battery's life expectancy. The type of battery being used will determine how resistant it is to life degradation due to temperature.

Another major concern is the battery's life cycle. This is defined as the number of charge/discharge cycles that a battery can supply depending on the depth of discharge. The battery cycle application may require the BESS to charge and discharge multiple times a day. As long as the depth of discharge is relatively low the battery's cycle of life will remain unaffected. However, if the depth of discharge is large, then the battery's life cycle can be degraded. If the desired cycle of life of a battery is 20000 cycles, then the depth of discharge cannot be greater than approximately 15 % (Fig. 7) [6].

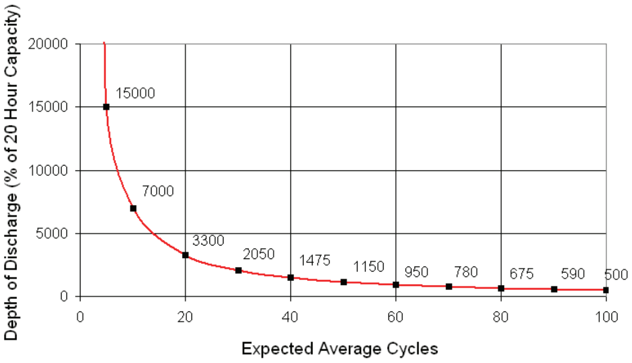

Fig. 7. Life cycle of batteries

The maximum discharge rate of the battery is also of concern because the battery can also be damaged by using too high discharge rates. Depending on the type of battery and its application, the discharge rate maybe its capacity divided by 4, 6 or even 10. This limits the available current in the battery for immediate use.

There are also environmental concerns related to battery storage due to toxic gas generation during battery charge/discharge. The disposal of hazardous materials presents some battery disposal problems [6, 14].

There are many new battery technologies that are being developed to store more energy, last longer, and cost less than the Lead-Acid battery. Some of these new battery technologies are lithium ion, Hydrogen Vanadium Redox, Regenesys Redox (both of the two also known as flow-through batteries), Sodium Sulfur, Nickel Metal Hydride, Nickel Cadmium, and Zinc Bromide.

Hydrogen energy storage

Hydrogen is one of the promising alternatives that can be used as an energy carrier. The universality of hydrogen implies that it can replace other fuels for stationary generating units for power generation in various industries. Having all the advantages of fossil fuels, hydrogen is free of harmful emissions when used with dosed amount of oxygen, thus reducing the greenhouse effect [15].

Essential elements of a hydrogen energy storage system comprise an electrolyzer unit which converts electrical energy input into hydrogen by decomposing water molecules, the hydrogen storage system itself and a hydrogen energy conversion system which converts the stored chemical energy in the hydrogen back to electrical energy (Fig. 8) [9]. The major application of the stored hydrogen is the electricity production by help of fuel cells. Water to hydrogen conversion efficiency is averaged at 65 % and fuel cell conversion efficiency is 65 – 70 % which ends up to 20 – 40 % overall system efficiency [6, 7, 11].

It must be kept in mind that in terms of storage, hydrogen is not used as a fuel, but as an energy carrier in a wider sense.

There are five basic methods for hydrogen storage:

- Compressed and stored in a pressure tank;
- Cooled to a liquid state and kept cold in an insulated tank;
- Physisorpted in carbon;
- Metal hydrides;
- Complex compounds.

In order to select the optimal integration method of hydrogen base energy storage in the wind power system the hydrogen storage capacity of each method has been compared. Fig. 9 [16] shows how much volume is needed to store a mass unit. As it can be seen, metal hydrides and complex compounds occupy a smaller volume to store the same amount of hydrogen; however, this method is not suitable for this application due to its high adsorption/absorption temperature. Both liquid hydrogen and compressed gas at high pressure were better candidates for suitable methods for this project, however, liquid hydrogen requires more expensive equipments and very low temperature.

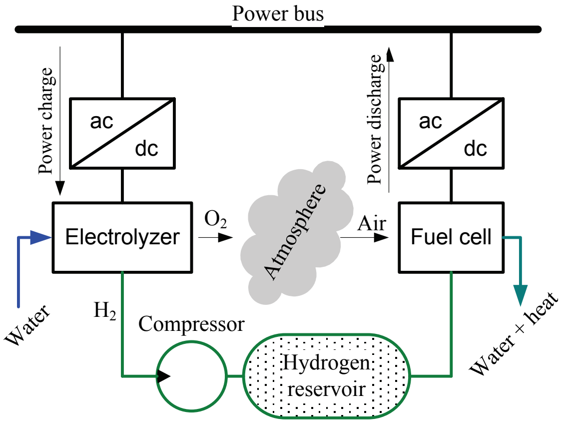

Fig. 8. Energy exchange processes of the hydrogen based energy storage

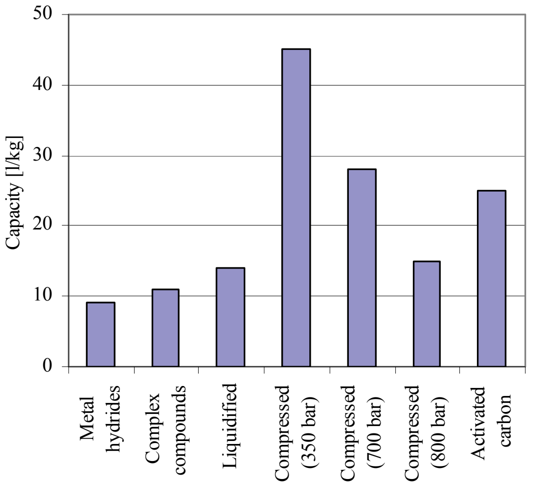

Fig. 9. Comparison of hydrogen storage capacity by different methods for the same occupied volume

There are various inefficiencies involved with storage and recovery of electrical energy via the use of hydrogen. Energy is consumed to place the hydrogen in storage. This varies with the different energy storage approaches, the efficiency of each method is summarised in Table 2 [16].

From Fig. 9 and Table 2 it can be seen that the energy lost to compress the gas is relatively low and therefore yields higher conversion efficiency. Activated carbon also has a high efficiency; however, a very low temperature is required during the process. Because the required energy storage time could be long due to the strong wind periods lasting extended periods of time, a low leak rate is critical to preventing additional dynamic energy loss.

It can be seen from Table 2 that the compressed gas method has a very low leakage rate compared to the other methods, high hydrogen capacity and dynamic energy efficiency [16].

Table 2. The energy required to place the hydrogen in storage varies between the various energy storage approaches and the corresponding efficiency

Hydrogen storage approaches		**Energy intensity (MJ/kg)**	**Efficiency**	**Leakage rate (/day), %**
Compressed gas	300 bar	0.915	0.92	0.000024
	700 bar	0.905	0.91	0.000033
Liquid		28-45	0.63-0.77	1
Activated carbon		8-10	0.92-0.93	0.2
Hydrides	Low temperature (<100°C)	0.9-0.93	0.9-0.93	-
	High temperature (>300°C)	0.79-0.83	0.79-0.83	-

Application example

Researchers at the Department of Electrical Drives and Power Electronics have introduced the concept of using hydrogen for compensating the instability of wind production. A typical configuration of a wind turbine connected to the transmission grid was formed by a set of wind generators electrically connected to a distribution grid, sharing one single infrastructure for access and control.

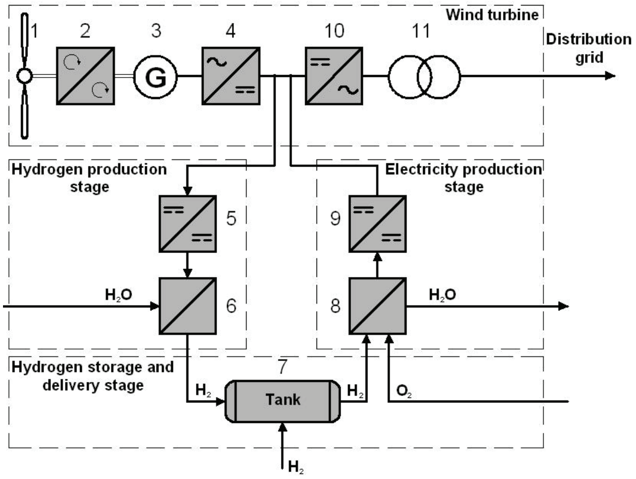

Fig. 10. Block diagram of the proposed hydrogen buffer for wind turbines: 1 – blades, 2 – gearbox, 3 – generator, 4 – rectifier, 5 – interface dc/dc converter for the electrolyzer, 6 – electrolyzer, 7 – hydrogen storage tank, 8 – fuel cell, 9 – interface dc/dc converter for the fuel cell, 10 – inverter, 11 – power transformer

As mentioned above, the hydrogen buffer used to stabilise unregulated energy production consists of hydrogen production, hydrogen storage and delivery as well as electricity production stages. In hydrogen production stage excess electrical energy from the wind generator is converted into chemical energy by using water electrolysis and stored in a tank. In electricity production stage during wind stills, hydrogen is converted into electrical energy by using a fuel cell. Combining energy storage and distributed generation results in a system which can produce controlled power [17].

A comparative SWOT analysis of storage technologies

In the analysis of the advantages and disadvantages of long-term energy storage possibilities, a SWOT (strengths, weaknesses, opportunities, threats) approach can be performed. Strengths and weaknesses are related to the present state-of-the-art, opportunities and threats with a view towards the possible future developments.

In Table 3 [7, 9, 11, 14, 18, 19] the storage technologies discussed are compared side by side. In terms of distributed storage it becomes clear that the main competitors to the hydrogen technology are the electrochemical batteries. The emerging technologies such as flow-through batteries may have characteristics similar to the hydrogen-based solutions; however, in the analysis of the material costs, the price and availability of the rare-earth metals and other resources to produce advanced batteries are to be discussed.

The future of hydrogen storage depends mostly on the improved efficiency of the energy conversion cycle, the storage media and advanced power electronic converters for grid interfacing. The recent developments in the converter design, especially regarding the implementation of the qZS topology make the hydrogen based energy storage systems attractive to many industrial applications [17]. Another advantage is the co-production of heat, which contributes to the popularity of the hydrogen based energy storages even in residential use.

Conclusions

The quality of wind energy may be improved by introducing energy storage. Ensuring availability and reducing variability are two strongly coupled ways of looking at improvements. Making energy more available means making it more predictable, reliable and controllable. The prospect of energy storage is to remove fluctuations on shorter timescales (seconds to hours). A good idea is to implement hybrid solutions, where long-term deviations are compensated by fuel cell systems and shorter fluctuations by supercapacitors [20].

Utilization of energy storage systems will be a major step in the solution to the use of renewable energy along with the current issues of reliability, stability, and power quality. A new wind power design methodology that identifies the optimal use of hydrogen energy storage in order to balance the electricity production to load demand has been proposed. Different hydrogen storage methods were carefully compared and the compressed gas approach was chosen as the best solution for this study due to its relatively high conversion efficiency, easy operation and low leakage rate.

Ultimately, the SWOT analysis revealed some advantages and disadvantages of hydrogen as compared to the other long-term storage possibilities. Though battery systems are preferred in the present situation, the hydrogen and fuel cells are likely to increase their share with a faster or at least equal pace.

Table 3. 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	High capacity. Low cost per kWh. Minor needs for power electronic converters.	Centralised storage. Geographical restrictions.	Can be used for off-shore wind parks and with lower reservoir under seabed.	Can become obsolete when distributed storage preferred.
BES	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.

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Sustainability of electric power systems will involve very large use of renewable energy sources for power production. Wind power is one of the cleanest and safest of all the renewable methods of generating electricity. However, wind power fluctuations have adverse impacts on power quality, such as local voltage and system frequency. Energy storage devices will be needed at different locations in the power system, to store the surplus of power from renewable sources for later use during non-generation time periods or low power generation time periods. This paper will give an overview of different storage technologies. Ill. 10, bibl. 20, tabl. 3 (in English; abstracts in English and Lithuanian).

A. Andrijanovits, H. Hoimoja, D. Vinnikov. Ilgalaikio energijos kaupimo technologijų taikymo atsinaujinančioms energijos sistemoms lyginamoji analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 2(118). – P. 21–26.

Energetikos sistemų išsilaikomumui užtikrinti gaminant energiją reikės naudoti daug atsinaujinančių energijos šaltinių. Vėjo energija yra vienas iš švariausių ir saugiausių atsinaujinančių elektros energijos šaltinių. Tačiau vėjo energijos fliuktuacijos turi neigiamą poveikį energijos kokybei (įtampai ir sistemos dažniui). Energijos kaupimo įtaisai bus reikalingi skirtingose energijos sistemos vietose perteklinei energijai iš atsinaujinančių šaltinių kaupti ir vėliau jai panaudoti. Pateikiama skirtingų kaupimo technologijų apžvalga. Il. 10, bibl. 20, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).