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Overview of Energy Storage Technologies: A Techno-Economic Comparison

S. Surender Reddy[(1)], Chan-Mook Jung[(2,*)]

[(1)]*Department of Railroad and Electrical Engineering, Woosong University, Daejeon, Republic of Korea.*
[(2)]*Department of Railroad and Civil Engineering, Woosong University, Daejeon, Republic of Korea.*
[(*)]*Corresponding Author*
[(1)]*ORCID: 0000-0002-3849-6051*

Abstract

This paper presents the necessity of energy storage technologies to help the Renewable Energy Resources (RERs) power the smart grid to meet the energy demands of the future. The paper identifies the different storage techniques that can be implemented in to a smart grid and a cost-benefit analysis of the different storage techniques. While explaining these different storage techniques the following items that will be covered are size, technology, protection, advantages, disadvantages, time scale for implantation and physical location of the storage. The cost-benefit analysis of different storage technologies have also been presented in this paper, the guidelines are also presented to select a storage technique based on a given power systems problem.

Keywords: Renewable energy resources, energy storage, cost-benefit analysis, battery storage, supercapacitors.

INTRODUCTION

As the world continues to expand and the develop, it brings an exponential increase on energy demand. On the above, it is a top priority that the available energy is utilized with the maximum efficiency possible and also that whatever energy is not being consumed immediately is stored employing any of the available storage techniques such as flywheels, batteries, supercapacitors, compressed air, hydrogen storage, pumped hydro, etc. This paper is going to explore each of the available storage techniques based on various characteristics including cost, impact, maintenance and protection, and potentially make a recommendation regarding an optimal storage technique [1].

More work has is being done to increase the assimilation of various energy storage methods into (smart) grids which are connected to the RERs. This is due to the intermittency that arises with these resources. Energy storage in these systems will help to provide a buffer for periods of imbalance with power demanded and supplied. Improved storage facilities will help RERs to address transmission issues that result from geographical challenges and easing availability for consumers. In these grids, generally, supercapacitors are used for the short-term storage, which runs is considered to be about a few microseconds, whereas the storage batteries are used for longer term storage. Usually, the energy storage devices can be categorized into two main groups, electrochemical and non-electrochemical storages. The electrochemical devices are mainly the rechargeable batteries of various types. These include lithium ion, lead acid, nickel metal hydride, sodium sulfur, nickel cadmium, and flow batteries. The non electrochemical storage devices include flywheels, Superconducting Magnetic Energy Storage (SMES), supercapacitors, Compressed air energy storage (CAES), and pumped hydro energy storage. This paper will address the characteristics and potentials of each of the storage devices and their capability to perform the following functions: grid operational support, grid stabilization, frequency regulation, voltage support, and load shifting. Storage sources of various sizes can be distributed throughout the grid ranging from end used loads to major substations and central power stations. This feature can be use for congestion management at both transmission and distribution levels [2].

Reference [3] has presented five energy storage technologies for cooling energy application in hot climates and to provide a comparison among them. The detailed analysis of flywheel energy storage technology innovation and diffusion processes is presented in [4]. Reference [5] presents the operation principle of technology and materials used for heat pumps and thermal energy storage. Reference [6] analyses the economic performance of an innovative storage technology, known as stored energy in the sea, and compares the findings of the economic analysis with the costs of alternative storage technology options, such as CAES and pumped hydro storage, which are comparable in capacity and their balancing performances. The concept of energy storage, the different technologies for the storage of energy with more emphasis on the storage of secondary forms of energy (electricity and heat) as well as a detailed analysis of various energy storage projects all over the world is presented in [7]. Reference [8] presents an overview of numerous forms of energy storage technologies under the investigation and development, with a focus on thermal energy storage through the adsorption. A combined assessment methodology enabling a benchmark comparison of stationary electricity storage technologies for different time and system scales, considering their technical, economic and environmental performance is proposed in [9]. The description of various energy storage techniques have been presented in [10].

Storage devices save the energy that is not used and stores it for later use. They make this electricity available whenever it is needed. Storage devices provide frequency regulation to maintain the balance between the network's load and power generated, and they can achieve a more reliable power supply for high tech industrial facilities. Energy storage gathers the excess electricity produced at off-peak hours and releases the stored energy at peak hours. It provides voltage support, grid frequency regulation, and operating reserves. This enhances the grid stability and reliability. This paper presents the description of various energy storage techniques and their cost-benefit analysis.

DIFFERENT ENERGY STORAGE TECHNOLOGIES

Energy storage systems which are tied with renewable energy sources can overcome the problems of intermittency and high transmission cost, and can ultimately provide a stable source of base load electricity.

Battery Energy Storage (BES)

With the new technologically advanced batteries are being fabricated, designed, and built as the trend of using motor vehicles is increasing. It has a serious environment impact which is leading to the air pollution in large cities and densely populated areas. As a result, the manufacturers, power industry, battery researchers and exporters around the world have meetings to communicate and focus on the basis of distributing better and prevent the environment from hurting people. Batteries are can be found in many different forms which include lithium ion, sodium-sulfur, flow, and lead acid. Because of their high cost and/or short lifetime, they are only used in a limited number of applications. The main features of BES are:

- They are highly portable.
- Lead-acid batteries are commonly used to stabilize the electrical systems by supplying extra power and maintaining voltage and frequency levels.
- Lead acid batteries have very low life spans when charged and discharged frequently.
- Lithium-ion batteries are commonly used in mobile phones and laptop computers. Compared to nickel-cadmium and lead acid batteries, they have a much higher energy density. Their long lifetimes make them a very good cost option.
- Nickel-metal hydride have relatively low energy densities and are very sensitive. They tend to have problems with overcharging.
- Rural locations utilize portable sodium-sulfur battery systems to provide power for small time periods.

The cost of storage batteries varies depending on the type of battery chosen. At the low end, alkaline batteries cost $190/kWh. At the high end, nickel-cadmium batteries cost $1500/kWh [11].

The battery is charged by an external power circuit which supplies an over-voltage and reverses the regular flow of current in the battery and makes the positive ions migrate from the positive to negative electrode, therefore, it has a flow of current in the opposite direction. During the discharge, the positive ions carry current from the negative to positive electrode and hence the stored energy is given up. Batteries for energy storage can be easily constructed to fit specific needs and are thus available in various shapes and sizes.

Supercapacitors

These devices have an operating principle similar to a traditional capacitor, but their capacity and discharge current are much higher. Supercapacitors store energy using two oppositely charged electrodes which are separated using an ionic solution. Energy is stored when ions attach to the electrodes and released when ions return to the solution. The main difference compared to conventional capacitors is based on two critical aspects and they are [12]:

- Energy is stored at the interface between a porous conductive electrode and a liquid electrolyte ionic conductor.
- The surface is greatly increased due to the very high porosity of the electrode.

Supercapacitors are used for voltage drop compensation in weak networks. This allows a very intense power. In the complete cycle of charging and discharging, a supercapacitor can reach the efficiencies up to 95%. Figure 1 depicts the equivalent circuit of a supercapacitor [13].

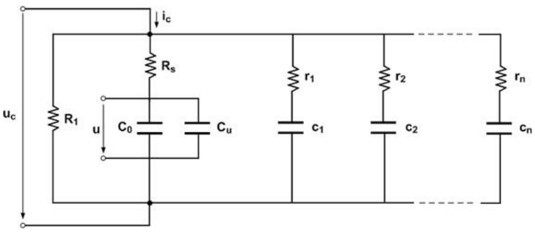

Figure 1: The equivalent circuit of supercapacitor.

Here, the parameter analyzed is the capacity of supercapacitor (C), which defines its behavior and the energy stored. This capacity is not constant and it depends on the voltage across its terminals. Therefore, it's capacity is modeled as a constant value (C_0), in parallel with a conventional capacitor (C_u), showing a linear dependence on voltage (u). This has been shown mathematically in the following equations [13]:

$$C = C_0 + K \cdot u \quad (1)$$

$$C_u = K \cdot u \quad (2)$$

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In addition, the resistance R_{est} represents voltage drops during charge and discharge, and resistance R_1 loss of charge when the device is in stand-by [13].

Flywheel

The flywheel is a very versatile energy storage device. It is constructed with a rotor suspended by magnetic or mechanical bearings and rotates inside a vacuum chamber (to reduce friction), all within a shell for safety. This is then connected to a system (usually a generator). Based on the principle of conservation of energy, the flywheel stores the energy when it spins and supplies energy when needed. When the flywheel is charging, it accelerates to speeds from 20,000 to 50,000 rpm.

Flywheels are very effective in providing quality control, and are usually employed to provide frequency and voltage steadying and are utilized in various applications dealing with: rail electrification, decreasing harmonics in low voltage power networks, UPS systems, aerospace applications and wind-diesel generator. The costs to be considered in undertaking this storage technique include [14]:

- Capital Cost: It refers to the cost of installing a complete system. This also covers the cost of the individual parts such as high temperature superconductor bearings, carbon-fiber composite rotors, diamagnets, and so on. Beacon Power did a study on a 20MW power system and estimated the cost for the flywheel will be about $1,630/kW.
- Operational Costs: These costs include staffing, maintenance and fuel costs.
- Regulation costs, and
- Depreciation costs.

The modelling for the flywheel takes into account the energy is stored in the rotating mass within the flywheel. When the flywheel is acting as motor, electric energy supplied to the stator winding is converted to torque and applied to the rotor, causing it to spin faster and gain kinetic energy (KE). In generator mode, the KE stored in the rotor applies a torque, which is converted to electric energy. The KE stored in a flywheel is expressed as,

$$E_K = \frac{1}{2} I \omega^2 \qquad (3)$$

where E_K is the KE stored in flywheel, I is the moment of inertia and ω is the angular velocity. Moment of inertia (I) is a function of shape, and for a cylindrical rotor, we have:

$$I = \frac{1}{2} r^2 m = \frac{1}{2} r^4 \pi \alpha \rho \qquad (4)$$

where r is the radius, m is the mass of cylinder and ρ is the density of cylinder material. The maximum energy of a flywheel rotor is expressed by,

$$\frac{E}{m} = K \left(\frac{\sigma}{\rho}\right) \qquad (5)$$

whee σ is the tensile strength of the material (Pa), ρ is the material's density (kg/m^3), K is the rotor's geometric shape factor (dimensionless). The main applications for the flywheels include the grid-connecting application and power supply. Grid connecting application strengthens power quality and filtered power supply, and the power supply is used on the vehicles.

Compressed Air Energy Storage (CAES)

CAES is a way to store energy generated at one time for use at another time. More often, the compressed air is mixed with natural gas and they are burnt together, in the same fashion as in a conventional turbine plant [15]. A CAES operates by means of large electric motor driven compressors that store energy in the form of compressed air in the reservoir. The compression is done outside periods of peak demand. As part of the compression process, the air is cooled prior to injection to make the best possible use of the storage space available. The air is then pressurized. To return electricity to the customers, the air is extracted from the reservoir.

Figure 2 depicts the typical CAES system. The CAES is used for compressing air that is stored deep under the ground. The CAES prevents the wind production from hurting people, plants, and animals. It also has the potential to reduce the risk for renewable projects and to reduce of the wind curtailment and increased the possibility. As a result, the combination of the wind production and CAES overall value is increased and produce the best wind power which is being delivered to the market as daily basis.

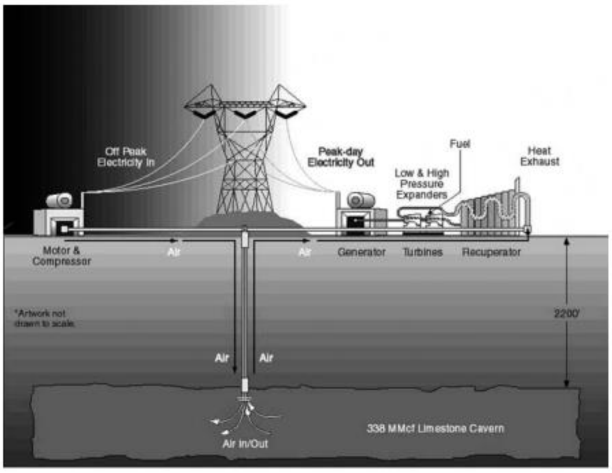

Figure 2: Compressed Air Energy Storage System.

The overall efficiency of the CAES system is provided by the reduction of carbon emission. The decrease of reliance on thermal production and increase overall efficiency leads to the vast reduction of carbon emission provided CAES. It is used for energy generated at one time and utilized it for many days.

When it comes out of the ground, it is released through the turbines, which drives the rotor of an electric current generator, in the form of heat. The modelling of CAES system is presented next:

$$pV = nRT = \text{constant} \quad (6)$$

$$W_{A\rightarrow B} = nRT(\ln V_B - \ln V_A) \quad (7)$$

where n is the number of moles, R is the ideal gas constant, T is the temperature, V_B is the volume of second state, V_A is the volume of initial state.

The above equations show the mathematical modelling of isothermal compression/ expansion [16]. The work that is necessary to compress or expand the gas is computed using the ideal gas law. This isothermal expansion works on the principal that heat exchangers remove excess heat during compression and during expansion heat is allowed to be released. This process must be reversible if it is to be completely isothermic. The heat that is exchanged must occur over infinitesimally small temperature differences. The cost of CAES system is about $1500/kWh of capacity [17]

Superconducting Magnetic Energy Storage (SMES)

The SMES system has fast response times but the costs are very high. Electric current is stored indefinitely inside of superconducting windings. There are very low resistive losses. Also, SMES has the capability to quickly discharge high power for short time spans. Larger coils correspond to more power capacity. As the coils become larger, the magnetic field increases. At a point, the superconducting properties of the windings begin to break down and the coolant is necessary to for the machine operation. Hence, it is very expensive. The key features of SMES include:

- Altering the current in the windings allows the energy to be put in or taken out of the system.
- During the steady state, the energy can be maintained indefinitely.
- High power can be released instantaneously for a short period of time.
- Networking several SMES systems together can increase the energy availability.
- SMES has high reliability and low maintenance.

The SMES is modeled as,

$$E = \frac{1}{2} L I^2 \quad (8)$$

where E is the energy stored, L is the inductance, and I is the current.

SMES stores energy in a superconducting coil in the form of a magnetic field. The magnetic field is created with the flow of a direct current (DC) through the coil. To maintain the system charged the coil must be cooled adequately, so as to manifest its superconducting properties. This enables the current to circulate indefinitely with almost zero loss, and hence, the energy remains stored in the form of a magnetic field. The stored energy can be released back to a connected power system by converting the magnetic energy to electricity, discharging the coil [18]. The cost of SMES is approximately $4.2 million for a 3.3kw prototype [19].

Chemical Energy Storage

New substance capable of holding the potential energy (PE) for later use can be created through the suitable chemical reactions. They are: hydrogen, synthetic natural gas, methane, hydrocarbons, ethanol, methanol and butanol. However, the Hydrogen is considered as the major chemical compound which can be easily produced from electricity [20].

Hydrogen Energy Storage

The Hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is a converter which parts water with the assistance of electricity into hydrogen and oxygen electrochemically. To create power, both gasses flow into the fuel cell where an electrochemical reaction which is opposite to the water splitting happens: oxygen and hydrogen react and deliver water, heat is discharged producing electricity [20].

Off peak power is utilized to electrolyze water to create hydrogen for energy storage application. Storing hydrogen in different forms as compressed gas, liquefied gas, carbon nanostructures or metal hydrides is also possible. However, the disadvantage is the considerable energy loss amid a single cycle in utilizing hydrogen for energy storage.

Pumped Hydro Energy Storage

Generally, the hydro pumped storage reservoirs are not considered to generate the electrical power. They are a way of storing energy, so that we can release it quickly when we need it. This storage method stores energy in the form of water, pumped from a lower elevation reservoir to a higher elevation. During the periods of high electrical demand, the stored water is released through turbines to produce electric power [21]. When the electrical demand and prices are low, the water is pumped back to the upper reservoir [21]. Figure 3 depicts the schematic diagram of pumped hydro energy storage system.

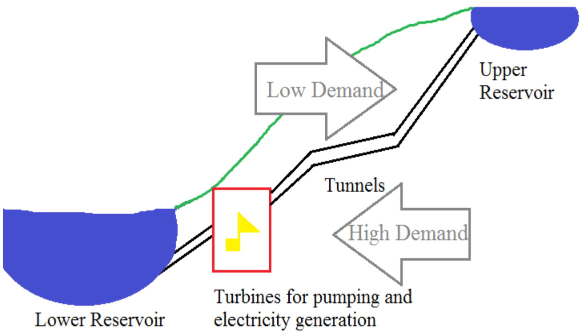

Figure 3: Schematic diagram of pumped hydro energy storage system.

This storage system stores the energy as gravitational potential energy by moving large amounts of water between tapered reservoirs.

$$\text{Potential energy} = gm_wH \qquad (9)$$

where g is the acceleration due to gravity (9.81 m/s^2), m_w is the mass of water in (kg), H is the elevation over a reference plane.

The power capable of being generated in one hour while the pump hydro system is in generation mode while bringing water from the upper reservoir to the lower reservoir can be described as,

$$E_g = \rho g H V^g \xi_g \qquad (10)$$

where ρ is the density of water (kg/m^3), V^g is volumetric flow rate (m^3/s), g is the acceleration due to gravity (m/s^2), H is difference in elevation (m), ξ_g is the conversion coefficient for power generation, ξ_p conversion coefficient for pumping.

COMPARISON OF DIFFERENT STORAGE TECHNOLOGIES

In this section, the different energy storage technologies are compared in terms of their applications, cost, location, advantages and disadvantages.

Battery Energy Storage (BES):

The lithium-ion batteries have the following advantages:

- They can be produced in various shapes or sizes to fit whatever need they are to meet.
- Lighter weight in comparison to other equivalent secondary cells.
- Low self-discharge rate.
- It is relatively safe for the environment, and helps to reduce carbon emissions from vehicles.

However, the disadvantages are:

- High charge levels and elevated temperatures hasten capacity loss.
- They possess relatively high internal resistance.

The cost of lead-acid battery is $0.17/Wh. The U.S. Advanced Battery Consortium has set a $150/kWh target for the cost of Li-ion battery to make it accessible by the mass market by year 2020. A set of 4 alkaline batteries costing $2.74 with capacity 0.0171 kilowatt-hours. This corresponds to a cost of $160.23 per kilowatt-hour.

Supercapacitors

They need batteries to store the energy. They are basically used as a buffer between the battery and the device. Super capacitors can be charged and discharged hundreds of thousands of times unlike a battery which can only be recharged multiple times. The advantages of Supercapacitors include:

- Low cost per cycle.
- Good reversibility.
- High specific power and efficiency (up to 95%).
- Very high rates of charge and discharge.
- Improved safety, no corrosive electrolyte and low toxicity of materials.
- Long life with little degradation over multiple cycles.

However, the disadvantages include:

- High self-discharge.
- Though having a high power density, it's energy per unit weight is relatively low.
- High dielectric absorption.
- Cannot be singly implemented, except in series connection with other capacitors
- The voltage across any capacitor, including super capacitor drops significantly as it discharges.

Supercapacitors are relatively expensive in terms of cost per watt. Supercapacitors cost approximately $2400-$6000/kWh of storage capacity [22]. Similar to batteries and capacitors, the supercapacitors are also highly portable because of their size.

Flywheel

The advantages of Flywheel include:

- High power density and life cycle.
- Quick recharge.
- They can handle high power levels and they are not affected by the temperature changes.
- As it operates within a vacuum, the mechanical and

electrical efficiencies are observed to be quite high (up to 90%).

The disadvantages of Flywheel include:

- Gyroscopic effects.
- Large power standby losses.
- Low energy density.
- Short energy storage time, due to energy loss through friction due to the dynamic orientation of the earth.
- Potentially dangerous failure modes.

The cost of a flywheel energy storage is approximately $1,630/kW. This includes operational costs, regulation costs, and depreciation. The location of flywheel can vary but must be able to support the size of the flywheel system. Their applications include the rail electrification, decreasing harmonics in low voltage power networks, and wind-diesel generator.

Compressed Air Energy Storage (CAES):

The advantages of CAES system include:

- Low start-up time.
- Easily enhanced to meet any requirement.
- Can be optimized easily to fit any specific site.
- Can start up from shut down condition without the help of power from a grid .
- CAES systems are capable of black starts.
- It provides a great economic benefit as it stores energy while demand is low and supplies this energy in times of peak demand, when the cost is higher.

The disadvantages of CAES system include:

- The underground caverns are a big risk.
- The efficiency of the system is relatively low.

According to the Electric Power Research Institute, the price of CAES system is about 1000$/kWh. The capital costs are $600 to $700 kW range. The locations with salt caverns or domes.

Superconducting Magnetic Energy Storage (SMES) The advantages of SMES include:

- It has quick response time with its ability to switch from charge to discharge state within seconds.
- Long service life.
- It has high efficiency for short duration storage.
- No significant negative environmental impact.
- As the coil has a virtually zero resistance, it stores current at almost no loss.

The disadvantages of SMES include:

- Cannot handle very high current as the superconducting properties of most materials break down with increased current.
- It needs of a large amount of power to keep the coil at low temperatures, combined with the high overall cost for the employment of a unit.
- Limitation of superconductivity based on magnetic field levels.
- Low energy density.
- Large parasitic losses and expensive.

Pumped Hydro Energy Storage System

The advantages of pumped hydro energy storage include:

- They are environmentally safe.
- High power density and high life cycle.
- Can be used on a very large scale to provide high levels of power.
- Quick recharge.
- It is a relatively efficient form of energy storage.

The disadvantages of pumped hydro energy storage include:

- The generator must be below the sea level.
- Lower energy density expensive.
- Can only be implemented in certain areas close to water.
- Sloped voltage curve requires power electronics.
- It will conflict with aquatic life in the area and will either damage their habitat, or the equipment could get damaged.

The cost of a pumped hydro storage system is about $1500/kWh of capacity. The pumped hydro storage system must be located in a place that can allow for the water to be raised to a considerably high elevation. It also requires sufficient space for the storage facility to be built.

CONCLUSIONS

Renewable energy resources (RERs) produce energy when it is not needed and, when needed, the generation output cannot be enough. For this, the energy storage technologies are used, as they can be integrated in the power system structure with various RERs. Energy storage plays a key role to minimize the transmission losses in the cases where it provides a closer geographical proximity to the consumers. With various storage technologies discussed based on their characteristics such as modeling, size, technology, advantages and disadvantages, etc., there is no one single solution to energy storage. Pumped hydro has been around for a long time and has matured as a technique, and hence provides a safe bet for new companies going into the field. Though the capacity of this method is very high, it can only be used in areas close to water and elevations as well. Flywheels have been in use for a long time, enjoy a long service life, and have little negative environmental impacts. However, their significant standby losses as well as high maintenance cost for all the components pose a slight drawback. Super capacitors on the other hand are safe, portable, the least inexpensive at 20$/Wh, low maintenance, and have the shortest charge time. This storage technique is ideal as it delivers the most benefits with the least costs. From the comparison of various storage technologies, it can be concluded that the best way to use these storage devices is through hybridization. This is to prevent depending on only one form of storage.

REFERENCES

[1] Y. Ma, P. Yang, X. Zhou, Z. Gao, "Research review on energy storage technology," *IEEE International Conference on Mechatronics and Automation*, Harbin, 2016, pp. 159-164.

[2] J.C. Beardsall, C.A. Gould, M. Al-Tai, "Energy storage systems: A review of the technology and its application in power systems," *50th International Universities Power Engineering Conference (UPEC)*, Stoke on Trent, 2015, pp. 1-6.

[3] G. Comodi, F. Carducci, J.Y. Sze, N. Balamurugan, A. Romagnoli, "Storing energy for cooling demand management in tropical climates: A techno-economic comparison between different energy storage technologies", *Energy*, vol. 121, pp. 676-694, Feb. 2017.

[4] S. Wicki, E.G.Hansen, Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage, *Journal of Cleaner Production*, vol. 162, pp. 1118-1134, Sept. 2017.

[5] L.F. Cabeza, A. Sole, C. Barreneche, "Review on sorption materials and technologies for heat pumps and thermal energy storage", *Renewable Energy*, vol. 110, pp. 3-39, Sept. 2017.

[6] H. Hahn, D. Hau, C. Dick, M. Puchta, "Techno-economic assessment of a subsea energy storage technology for power balancing services", *Energy*, vol. 133, pp. 121-127, Aug. 2017.

[7] M. Aneke, M. Wang, "Energy storage technologies and real life applications – A state of the art review", *Applied Energy*, vol. 179, pp. 350-377, Oct. 2016.

[8] D. Lefebvre, F.H. Tezel, "A review of energy storage technologies with a focus on adsorption thermal energy storage processes for heating applications", *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 116-125, Jan. 2017.

[9] A. Abdon, X. Zhang, D. Parra, M.K. Patel, C. Bauer, J. Worlitschek, "Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales", *Energy*, Jul. 2017.

[10] A.G. Olabi, "Renewable energy and energy storage systems", *Energy*, Jul. 2017.

[11] Available. [Online]: Accessed: Sept. 10, 2017.

http://www.allaboutbatteries.com/Battery-Energy.html

[12] Available. [Online]: Accessed: Sept. 10, 2017. http://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor

[13] Available. [Online]: Accessed: Sept. 10, 2017. http://www.supercapacitors.org

[14] Available. [Online]: Accessed: Sept. 10, 2017. http://library.corporate-ir.net/library/12/123/123367/items/278586/KEMA_CostComparisonReport.pdf

[15] Available. [Online]: Accessed: Sept. 10, 2017. http://dotyenergy.com/Markets/CAES.htm

[16] Available. [Online]: Accessed: Sept. 10, 2017. http://en.wikipedia.org/wiki/Compressed_air_energy_storage

[17] Available. [Online]: Accessed: Sept. 10, 2017. https://phys.org/news/2010-03-compressed-air-energy-storage-renewable.html

[18] Available. [Online]: Accessed: Sept. 10, 2017. http://www.lowcarbonfutures.org/sites/default/files/Pathways%20for%20Energy%20Storage%20in%20the%20UK.pdf

[19] I. Mazurenko, A. Pavlyuk and Y. Vasetsky, "Application of superconducting magnetic energy storage (SMES) in electric power grids," *16th International Conference on Computational Problems of Electrical Engineering*, Lviv, 2015, pp. 113-115.

[20] A.K. Rohit, K.P. Devi, S. Rangnekar, "An overview of energy storage and its importance in Indian renewable energy sector: Part I – Technologies and Comparison", Journal of Energy Storage, vol. 13, pp. 10-23, Oct. 2017.

[21] Available. [Online]: Accessed: Sept. 10, 2017. https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

[22] J. Dixon, I. Nakashima, E. F. Arcos and M. Ortuzar, "Electric Vehicle Using a Combination of Ultracapacitors and ZEBRA Battery," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 943-949, Mar. 2010.