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# COMPARISON OF ENERGY STORAGE OPTIONS AND DETRMINATION OF SUITABLE TECHNIQUE FOR SOLAR POWER SYSTEMS

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## ABSTRACT

The efficiency and cost of renewable solar and wind power systems using intermittent resources could significantly be improved by developing low cost, high efficiency and more sustainable energy storage systems. A comparison study between energy storage options is presented in this paper. The energy storage options include: (1) electro chemical storage: lead acid, Li-ions, Nickel-Cadmium, Nickel metal hydride, Sodium Sulfur, and vanadium flow batteries; (2) electro-magnetic energy storage: super capacitors and super conducting magnetic energy storage; (3) hydrogen storage: onboard systems and utility scale; (4) mechanical storage: compressed air, flywheel, pumped hydro, spring (composite and metal), and (5) thermal energy storage. The resource intensities and operational parameters of the energy storage options are compared in this study. The main objective is to review the various types of storage techniques and their characteristics and to determine the most appropriate technique for solar and wind energy applications: energy storage system with suitable discharge time, lowest resource intensities, best operation performance and lowest cost. Based on the results obtained in this study, super capacitors, super conducting magnetic, and flywheel energy storage systems could be a good option for solar and wind applications: they offer fast discharging/charging times, greater performance (high specific power, high cycle efficiency, high cycle life and they) and are very attractive with respect to the operating costs.

## INTRODUCTION

Today most of the global energy demand is derived from the combustion of gas, oil and coal. The reliance on fossil fuels is expected to diminish in the coming decades due to (1) the new emissions regulations – reduction of carbon dioxide and other greenhouse gases (Nitrogen oxides $NO_X$ and Sulfur Oxides $SO_X$ for example), (2) the reduction of the coal, oil and natural gas reserves, (3) the need to reduce the dependence on foreign imports (use local resources), and (4) the projected triple increase in the energy demands by 2050 [1]. How this energy will be generated when the oil, gas and coal reserves become depleted. Nuclear and renewable energies are the two alternatives to conventional power generation using fossil fuels [2].

Renewable energy could supply most of the energy demands (80%) by 2050 [1]. Renewable energy technologies that can be integrated in the present and future energy systems includes solar, wind, hydro, bioenergy, geothermal, and ocean (wave, current, temperature gradients) as source of renewable energy [3]. Solar and wind energy are among the most abundant and potentially readily available.

Solar and wind power technologies have grown quickly. Globally, the total electricity from installed wind power reached 336 gigawatts (GW) in June 2014, and wind energy production was around 4% of the total worldwide electricity usage [4]. The World Energy Council estimates that new wind capacity worldwide will total up to 474 GW by 2020. The output from photovoltaic (PV) module installations is currently growing at 40% per year worldwide [5]. By the end of 2013, worldwide installed PV capacity reached 139 GW and an estimated 40-50 GW was added in 2014 [5]. Solar power is expected to become the world's largest source of electricity by 2050 [5]. However, solar and wind are not constant and reliable sources of power. The variable nature of these renewable sources causes significant challenges for the electric grid operators because other power plants such as fossil fueled power plants need to compensate for the variability. For example, wind power profiles peak at night when demand is low and solar power is generated only during the daytime and varies when clouds pass by. The energy can be stored when the supply is high and demand is low. The energy can be recovered and used when the supply is low and the demand is high. Another concern is the fact that the renewable resources are localized and are often away from load centers. For example in the United States, wind sources are concentrated in the Midwest regions, and solar sources in southwest regions.

To smooth out the intermittency of renewable energy production, high performance and low-cost electrical energy storage will become necessary. Energy storage has been considered as a key enabler of the smart grid or future grid, which is expected to integrate a significant amount of renewable energy resources [6-7]. Energy storage technologies will (1) help electric utilities increase the grid efficiency, capacity, and reliability (balance load – shift energy consumption; bridge power – no break in service during the switch from one power generation source to another; and power quality management – control voltage and frequency), (2) meet the need of energy consumers and (3) help the integration of renewable energy into to the grid by managing the intermittency.

A comparison study between energy storage options is presented in this paper. The principal objective of this comparison study is to determine the most suitable energy storage techniques for power systems with intermittent resources such as solar and wind.

## DESCRIPTION OF THE ENERGY STORAGE SYSTEMS

A description of the energy storage systems for power systems is presented in this section. The energy storage options include: Electro chemical storage (lead acid Li-ions, Nickel-Cadmium, Nickel metal hydride, Sodium Sulfur, and vanadium flow batteries), electro-magnetic energy storage (super capacitors and super conducting magnetic energy storage), hydrogen storage (onboard systems and utility scale), mechanical storage (compressed air, flywheel, pumped hydro, spring), and thermal energy storage (See Fig. 1).

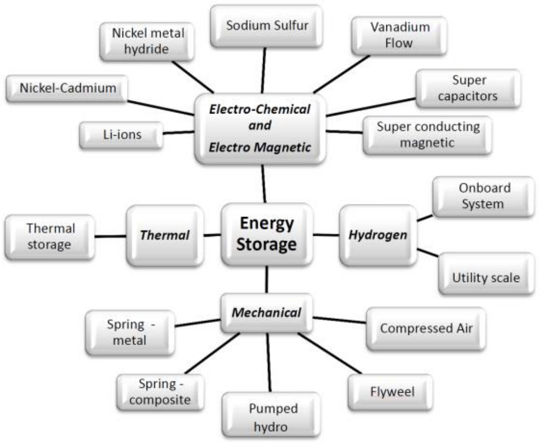


**Figure 1** Energy storage systems

### Mechanical Storage

**Compressed air energy storage (CAES):** When the energy demand is low and the supply is high, the energy is used for compressing and storing air. When the demand increases, the energy is released by expanding the air through a pneumatic motor or turbine, connected to a generator to generate electricity. The compressed air can be stored in small tanks for automotive applications, or in underground chambers for utility scale applications. During the compression process, the air temperature increases and this result in losses of energy as heat. To reduce or eliminate the energy loses during the compression processes, the compression air chamber should be well insulated (adiabatic compression) [14]. The other option is to have a compression at constant temperature. This can be accomplished by compressing the air slowly, and allowing the heat to escape and be stored separately so that the temperature of the compressed air remains constant (isothermal compression). During the expansion process, the air cools rapidly and can freeze the turbine. To avoid this problem, the air can be heated during the expansion process. If the heat generated during compression can be stored and used during the expansion process, the efficiency of the storage system will improve considerably. The compressed air can also be uses in gas turbine engine to produce electricity. This is a hybrid compressed air energy system and is similar to a conventional gas power plant. In a conventional gas power plant, up to 60% of the output from the plant is used to compress air. The remaining 40% is directed to the generator [14]. In hybrid compressed air system, the stored compressed air removes the need for this (all the power from CAES turbine is directed to the generator), increasing the efficiency of the gas plant up to 70% [14].

**Pumped Hydro Storage:** Energy is stored as potential energy. Low cost-off peak power is used to pump water from low to high reservoirs. The energy is then stored as gravitational potential energy in a mass m ($W = m\ g\ h$, where g is the acceleration due to the gravity). During periods of high electrical demand, the stored water is released through turbines to produce electric power [8]. The pumped hydro energy storage accounts for 99% (~127,000 MW) of the worldwide capacity [15]. The energy efficiency of the pumped storage Hydroelectricity varies between 70% and 80% [15].

**Flyweel Storage:** The Energy can be stored as kinetic energy ($W = \frac{1}{2} I \omega^2$, where I is the rotational moment of inertia and $\omega$ is the angular velocity of the flyweel) by spinning a flywheel. The stored energy is then released by allowing the flywheel to run a generator and produce electricity. The flywheel is designed to have as large moment of inertia as possible in order to spin fast and maximize the energy stored. Frictional losses (in the bearings and surroundings air) reduce the efficiency of the flywheel storage system. The flywheel systems are usually used for short term storage. To reduce the losses related to the air resistance, the flywheel can be placed in a vacuum. Superconducting magnetic bearings can be used to levitate the mass and reduce the bearings losses.

**Spring (composite and metal):** It is the storage of energy as mechanical potential energy by compressing or extending material elastically [9]. The springs have very low specific energy (MJ/kg). The specific energy is given by $W/m = \frac{1}{2} (\sigma_y^2/\rho E)$, where $\rho$ is the density, E is the Young Modulus and $\sigma_y$ is the yield stress for the material). There are no examples of springs being used as a utility scale device, nor to store energy in automobiles. The spring storage method with low energy density using today material was added in this paper just for comparison purpose. The development of new materials in the future will help to increase the energy density of the spring [9].

### Thermal Storage

It is the storage of energy by heating up a material [10]. The energy can be used to (1) heat a solid or liquid and the heat capacity Cp (J/kg K) of the material is used to retain the energy, or (2) heat a solid to melt and the latent heat of fusion $L_m$ (J/kg) is used to capture the energy. When excess energy is available, this energy is used to create a temperature gradient and the energy is stored as heat. Alternatively, the energy can be used to melt or freeze material, thereby storing energy as latent heat. The energy is released by using the temperature gradient either to directly heat/cool space, or to run an engine and generate electricity. Utility scale thermal energy storage is increasingly being used as part of concentrated solar plants. The sun's heat is used to heat up molten salt from a cold tank (typically 40% potassium nitrate, 60% sodium nitrate), which is then held in a hot tanks until the energy is needed. The molten salt from the hot tank then returns to the cold tank via a steam generator, which runs a turbine and generates power.

### Electro Chemical Energy Storage - Batteries

The batteries store energy as chemical energy. The battery consists of two half cells, each containing a metal and a salt solution of that metal (e.g. metal sulfate) [13]. The half-cell with the more reactive metal (metal A, in this example) is the anode. The metal is oxidized, becoming a metal A ion ($A^{+2x}$) and releasing some electrons ($e^-$):

$A \longrightarrow A^{+2x} + 2xe^-$. The half- cell with the less reactive metal (metal B) is the cathode. The metal ions ($B^{+2x}$) from the solution are reduced: $B^{+2x} + 2xe^- \longrightarrow B$. The metals from each half cell are connected through a conducting circuit. The electrons are transported from the anode to the cathode through this circuit, where they provide electricity. In order to maintain balance of charge, anions (negatively charged ions) are allowed to pass through a porous disk or salt bridge from one solution to the other. These are some examples of batteries:

**Lead-acid batteries**: they have a lead anode and a lead dioxide cathode [13]. On discharge, both of these become lead sulfate. At the anode lead (Pb) reacts with bisulfate ions ($HSO4^-$) to form lead sulfate (PbSO4), hydrogen ions ($H^+$) and electrons:

$Pb + HSO_4^- \longrightarrow PbSO_4 + H^+ + 2e^-$

At the cathode, lead dioxide (PbO2) reacts with hydrogen ions and bisulfate ions to form lead sulfate and water ($H_2O$):

$PbO_2 + 3H^+ + HSO_4^- + 2e^- \longrightarrow PbSO_4 + 2H_2O$

**Li-ion batteries:** Lithium-ion batteries have an anode of graphite intercalated with lithium, and a cathode of lithium compounds [13]. During discharge, lithium ions $Li^+$ move from the graphite/lithium ($Li_xC_6$) anode: $Li_xC_6 \longrightarrow xLi^+ + xe^- + 6C$

and are inserted into the lithium compounds (typically a lithium metal oxide compound ($Li^{1-x}$ MO)), to become lithium compounds with more lithium (LiMO): $Li_{1-x}\,MO + xLi^+ + xe^- \longrightarrow LiMO$

**Nickel Cadmium batteries:** Nickel-cadmium batteries have a cadmium plated anode and a nickel oxide-hydroxide plated cathode [13]. On discharge, the cadmium (Cd) at the anode is oxidized with hydroxide ions ($OH^-$) to form cadmium hydroxide ($Cd(OH)_2$) and electrons: $Cd + 2OH^- \longrightarrow Cd(OH)_2 + 2e^-$

The nickel oxide-hydroxide (NiO(OH)) is reduced with water ($H_2O$) and electrons to form nickel hydroxide ($Ni(OH)_2$) and hydroxide ions:

$NiO(OH) + H2O + e^- \longrightarrow Ni(OH)_2 + OH^-$

**Nickel-metal hybrid batteries**: These batteries are similar to nickel-cadmium batteries, but the anode is plated with a metal hydride rather than cadmium [13]. The metal hydride can be one of a series of different metals, common examples of which are lanthanum, neodymium, praseodymium or cerium [13]. On discharge, the metal hydride (MH) is oxidized with hydroxide ions ($OH^-$) to form solid metal (M), water ($H_2O$) and electrons: $MH + OH^- \longrightarrow M + H_2O + e^-$. The nickel oxide hydroxide (NiO(OH)) is reduced with water and electrons to form nickel hydroxide ($Ni(OH)_2$) and hydroxide ions:

$NiO(OH) + H_2O + e^- \longrightarrow Ni(OH)_2 + OH^-$.

**Sodium-sulfur batteries**: Sodium-sulfur batteries have an anode of molten sodium (Na), and a cathode of molten sulfur (S) [13]. On discharge, the sodium is oxidized, and the ions pass through an alumina electrolyte to reduce the sulfur and create sodium polysulfide ($Na_2S_4$). The overall reaction is: $2Na + 4S \longrightarrow Na_2S_4$

**Vanadium flow batteries:** Vanadium redox flow batteries operate in a slightly different manner to other batteries [13]. The electrolytes are stored in tanks, and are pumped through the battery cell, where they are reduced or oxidized. The anode and cathode electrolytes are made up of a solution of vanadium in different oxidation states. The anode electrolyte is a solution of vanadium (II) ions ($V^{+2}$), which are oxidized to vanadium (III) ions ($V^{+3}$) on discharge: $V^{+2} \longrightarrow V^{+3} + e^-$

The cathode electrolyte is a solution of vanadium (V) oxide ions ($VO_2^+$), which are reduced with hydrogen ions ($H^+$) and electrons, to form vanadium (IV) oxide ions ($VO^{+2}$) and hydroxide ions ($OH^-$):

$VO_2^+ + H^+ + e^- \longrightarrow VO^{+2} + OH^-$

### Electro-magnetic Energy Storage

**Super-capacitors**: Capacitors store electrical energy directly. Conventional capacitors consist of two plates placed in close proximity, with a dielectric insulator between them [13]. Energy is used to remove charge from one and place it on the other, creating a potential difference between them. Energy is extracted by allowing the charge to return, after passing through an external circuit where it delivers energy. Although these can be charged and discharged very quickly, their specific energy is very small at 0.00005-0.0001MJ/kg. However, electric double-layer capacitors (EDLCs), or "super-capacitors" offer scope for further improvements. EDLCs store the charges at the interface between activated carbon and a liquid electrolyte, rather than between two plates. Because of the large surface area to volume ratio of activated carbon, and the vanishingly thin distance over which the charge is stored, ultra capacitors have much greater capacitance densities and consequently much greater energy densities of 0.01-0.1MJ/kg.

**Superconducting magnetic energy storage:** It is the storage of energy as magnetic energy by charging up a superconducting magnet with current, which creates a magnetic field [11]. Because there is no resistance, the current continues to flow. Energy is then released by discharging the current through an external field. The difficulty with this system is that the superconducting material needs refrigeration, which reduces the efficiency, especially over large periods. For this reason, it tends to be used for short term storage (e.g. for frequency regulation). However, high temperature superconductors (HTS) (e.g. YBCO – Yttrium Barium Copper Oxide), which become superconducting below ~77K require less power for refrigeration than low temperature superconductors (LTS) which only become superconducting below ~4K.

### Hydrogen Storage

Energy can be stored as the chemical energy of hydrogen [12]. Energy is used to electrolyze water into hydrogen and oxygen, and the hydrogen stored. When energy is needed again, the stored hydrogen can be passed through a fuel cell to generate electricity. The water electrolyzer works by passing a current through water. The only way this current can flow is if the water ($H_2O$) is broken up into positive hydrogen ions ($H^+$) and oxygen ($O_2$). At the anode: $2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$

The hydrogen ions then recombine at the cathode to produce hydrogen (H2): $2H^+ + 2e^- \longrightarrow H_2$

The fuel cell works in a similar way to a battery. Hydrogen passes the anode, where it is oxidized into hydrogen ions and electrons at the anode: $H_2 \longrightarrow 2H^+ + 2e^-$

At the cathode, oxygen is reduced with hydrogen to form water:

$O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$

An electrolyte sits between the anode and cathode, and only allows hydrogen ions to pass. The electrons are then forced through an external circuit, where they deliver energy. Catalysts are required at the cathode and anode of the hydrogen fuel cell to encourage these reactions to occur. At the anode, platinum is used; at the cathode, nickel is typically used. An overview of the hydrogen storage methods available today with respect to their progress made recently and problems are summarized in the study by Zhou [ ].

## RESOURCE INTENSITIES AND OPERATIONAL PARAMETERS

A deep understanding of the resources intensities and operational parameters is needed for the development of sustainable, efficient and cost effective energy storage systems. A review and comparison of resource intensities is very important for the economic and sustainability accounting. The operational parameters review and comparison are needed for the design and performance evaluation studies and the development of more efficient storage system.

### Resource Intensities

The resource intensity is a measure of the resources needed for the energy storage systems [13]. This is a measure of the efficiency of the resource used and the carbon released to the atmosphere per unit of storage capacity (MJ). The resource intensities are the key concepts used for sustainability measurements. The resource intensities for the energy storage systems include the type and amount of material the energy storage system requires; the total area of land the system occupies; the total energy required (material, fabrication, and transport) of the energy storage system; the amount of $CO_2$ released to the atmosphere during the construction of the system, and the cost for building or purchasing the storage system [13].

- Capital intensity (\$/MJ) is the ratio of the total money value of capital equipment (cost of building or purchasing the storage system - \$) to the total potential output (storage capacity - MJ).
- Material intensity (kg/MJ) is the ratio of the total mass of material (kg) that the storage system typically requires to the total potential output (storage capacity – MJ).
- Area Intensity ($m^2$/MJ) is the ratio of the total area of land ($m^2$) that the storage system typically occupies to the total potential output (storage capacity – MJ).
- Energy Intensity (MJ/MJ) is the ratio of the total energy required to create the storage system (energy needed to extract and process raw materials, fabricate components, and construct the storage system, with transport at different stages of the construction process taken into account - MJ) to the total potential output (storage capacity – MJ).
- Carbon intensity (kg/MJ): The ratio of the $CO_2$ (equivalent) released to the atmosphere (kg of $CO_2$) during the construction of the storage system to the total potential output (storage capacity – MJ).

## Operational Parameters

The development of energy storage devices will dependent on the cost and efficiency of these systems. It is necessary to know the operational parameters during the design, analysis and performance evaluation of the energy storage systems. The operational parameters are usually selected as the design basis, performance evaluation and the cost analysis of a given storage system. These parameters include: the specific energy, energy density, specific power, economic storage capacity, cycle efficiency, cycle life and the operational cost [13].

- Specific energy (MJ/kg): is the energy the system can store (MJ) per unit of its mass.
- Energy density (MJ/$m^3$) is the energy the system can store per unit of volume.
- Specific power (W/kg): represent the rate at which the energy can be drawn from the system per unit of its mass.
- Economic energy storage capacity (MW) is the range of energy capacity for which a particular storage system is economically viable.
- Cyle efficiency (%): is the percentage of the energy put into a storage system that can be recovered when the energy is retrieved. The cycle efficiency = (Energy output / Energy input) x 100. The cycle efficiency is measured for a typical cycle time, and will usually decrease if the cycle is usually long.
- Cycle life (cycles) is the the number of times an energy storage system can be charged and discharged before the capacity of the system drops below 80% of its initial capacity. The cycle life is limited by factors such as fatigue in mechanical systems and electrolyte degradation in electrochemical systems.
- Operating cost (\$/MJ/cycle) is the approximate cost of one charge/discharge cycle per unit of energy, and includes the cost of maintenance, heating, and labor.

## RESULTS

A comparison between energy storage options (electro chemical and electromagnetic, mechanical, hydrogen, and thermal) for power systems is presented in this paper. The comparison includes the resource intensity (capital, material, area, energy and carbon foot print intensities), and operational parameters (cycle efficiency, cycle life, specific energy, specific power, and discharging/charging times).

Figure 2 shows the material intensity in kg/MJ for the energy storage systems. The results show that some of the energy storage systems such as spring, pumped hydro, flywheel, super capacitor and super conducting magnetic use more materials per energy storage capacity. The electro chemical batteries, compressed air, hydrogen and thermal energy storage systems have the lowest material intensity. The material intensity is one of the metrics used for sustainability accounting. Using less material for the construction of the energy storage system will help not only to reduce the material consumption but also reduce the energy consumption and $CO_2$ emissions during the extraction and processing of the material and reduce the cost of the energy storage system depending on the type of material used. It is noted that solar power systems have the lowest material intensities compared to the other renewables, fossil and nuclear power systems [3]. It is important to select the energy storage system with the best material intensity for the solar power systems with respect to sustainability and economic criteria.

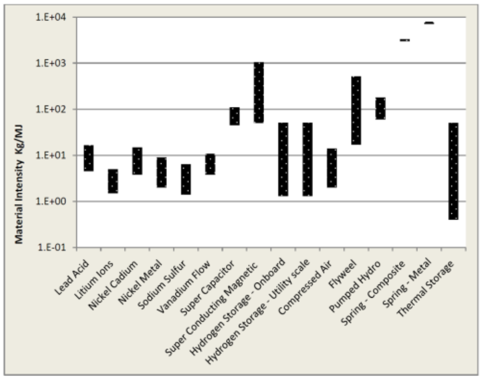


**Figure 2** Material intensity

Figure 3 shows the energy intensity or the total energy used for the construction of the energy storage systems per unit of energy storage capacity. Spring, Super capacitor, and super conducting magnetic use more energy for the construction of the energy storage systems per energy output. Compressed air is the energy storage system with the lowest energy intensity. It is also noted that renewable power systems such as hydro power (steel reinforced concrete), tidal power (barrage), deep geothermal power, and solar power plants have high energy intensities ( MJ/kW: energy used for the construction of the power plants per power output) compared to conventional power plant such as natural gas power plants. Solar power systems use more energy during the construction of the power plant (high energy intensity). Compressed air energy storage system is the best option to reduce the total energy used for the construction of the integrated system (solar power plant and energy storage system).

The $CO_2$ (kg/MJ) intensities during the construction of the energy storage system show a linear variation of the $CO_2$ intensity with the energy intensity. The high energy used during the construction of the energy storage systems for spring storage system is associated with high carbon footprint or $CO_2$ emissions released in the atmosphere. The compressed air storage system with the lowest energy intensity has the lowest $CO_2$ intensity. With respect to electricity generation, renewable power systems are not carbon free if we look for the life cycle of the system. Emission of $CO_2$ is released in the atmosphere during their construction and their maintenance. The energy and $CO_2$ intensities are two metrics for sustainability accounting. The goal is to develop an integrated system (renewable power systems such as solar and energy storage system) with the lowest energy and $CO_2$ intensities.

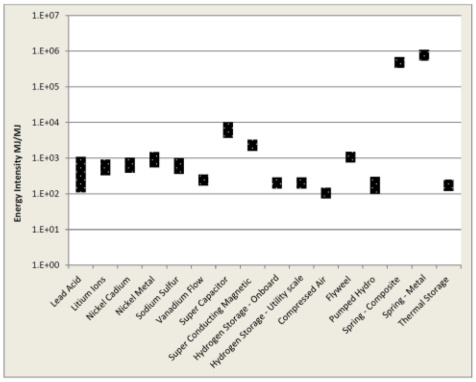


**Figure 3** Energy intensity

The area intensities ($m^2/MJ$) of the energy storage systems are presented in Figure 4. Renewable power system such as wind and solar require land area far in excess to conventional power generation technologies. Most of the renewable energy systems use more area: 50 to 150 times than conventional (coal and natural gas) and nuclear power systems except geothermal power based plant [3]. It is important to select more efficient energy storage system with the low total area of land the storage system typically occupies. Thermal, compressed air, hydrogen, and electrochemical batteries are examples of energy storage systems with low area intensities.

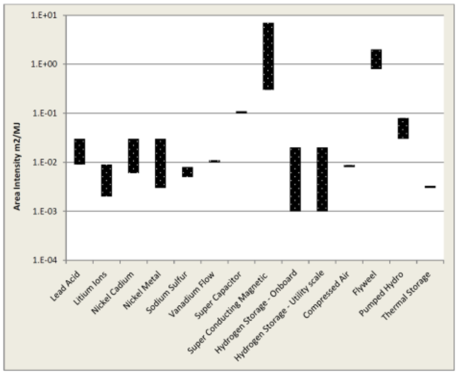


**Figure 4** Area Intensity

The results of the capital intensity or the ratio of the total money value of capital equipment (cost of building or purchasing the storage system) to the total potential output or storage capacity are presented in Figure 5. Solar power systems not only use more energy during the construction of the power plant (high energy intensity) but also present the highest capital intensity (US$/kW) compared to all power systems. Based on the results presented in Figure 5, compressed air is the best energy storage system to be integrated with solar power with respect to the capital intensity. The energy storage system with the highest capital intensity is the super conducting magnetic.

Figure 6-8 show the results of the operational parameters (specific energy, specific power, average charging time, and cycle efficiency) of the energy storage systems. The results presented in Figure 6 show the specific energy or the energy the storage system can store per unit mass. Hydrogen, electrochemical batteries, compressed air and thermal storage systems show high specific energy. The energy storage systems with high specific energy (MJ/kg) and high energy density ($MJ/m^3$) are suitable for small and light storage systems.

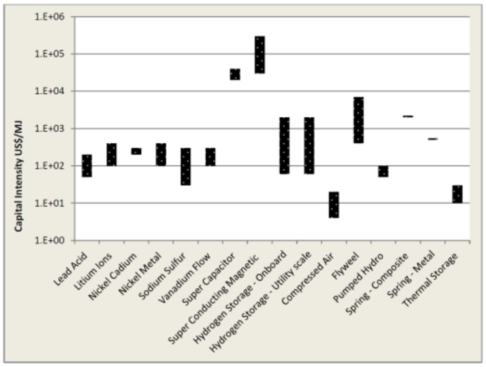


**Figure 5** Capital Intensity

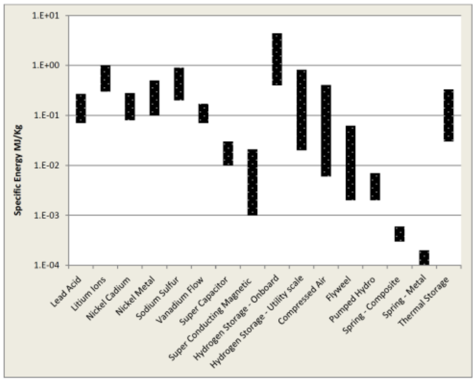


**Figure 6** Specific energy

Figure 7 shows the results of the specific power of the energy storage systems. The specific power defines how fast the energy stored in the system can be discharged or charged. Energy storage system with high specific power provides peak power requirements: fast response frequency regulation and short bursts of power that stabilize the grid. Super capacitors, super conducting magnetic, flywheel and Lithium ions batteries are examples of energy storage systems that can be used for energy storage and provide peak power requirements.

The average discharging/charging time for the energy storage system is presented in Table 1. The average charging time is the ratio of the average specific energy and the specific power. The results show average charging times between few seconds to days. Super capacitors, super conducting magnetic, and flywheel energy storage systems have charging time of few seconds. Energy storage systems with fast discharging/charging times or short bursts of power are suitable for fast response frequency regulation and to stabilize the grid. Lead acid, Nickel metals, compressed air, and vanadium flow energy storage systems have charging time of hours. Pumped hydro and thermal energy storage systems have charging times of day. Pumped hydro and thermal energy storage systems are more suited for long duration power systems.

Figure 8 shows also an important operational parameter for the energy storage systems – the cycle efficiency. It is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging and discharging cycle. The cycle efficiency is measured for a typical cycle time, and will usually decrease if the cycle is long. Hydrogen storage systems show the lowest cycle efficiency. The low efficiency of the energy storage systems is due to the losses during the recovery of the stored energy. Super-capacitors, superconducting magnetic and flywheels energy storage systems show high cycle efficiency with the lowest energy losses. Super-capacitors, superconducting magnetic and flywheels not only have high cycle efficiency but also high cycle life. The cycle life is the number of times an energy storage system can be charged and discharged before the capacity of the system drops below 80% of its initial capacity. Energy storage systems with low cycle life such as Lead acid, Lithium ions, Nickel Cadium and Nickel Metal will make the system less attractive due to the inconvenience of replacement and cost.

Based on the results obtained in this study and the data [13] summarized in Table 1, super capacitors, super conducting magnetic, and flywheel energy storage systems offer the best option for solar power systems based on their fast discharging/charging times and greater performance even they don't offer the best resource intensities.

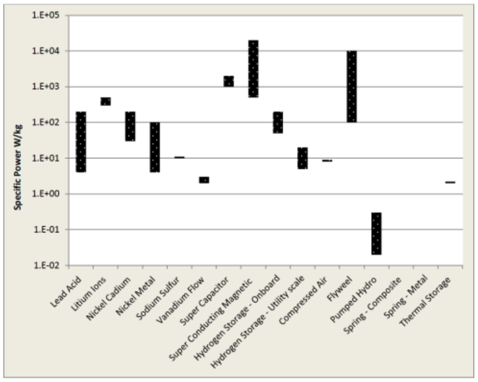


**Figure 7** Specific power

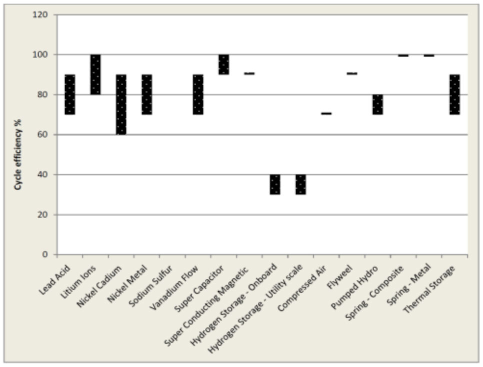
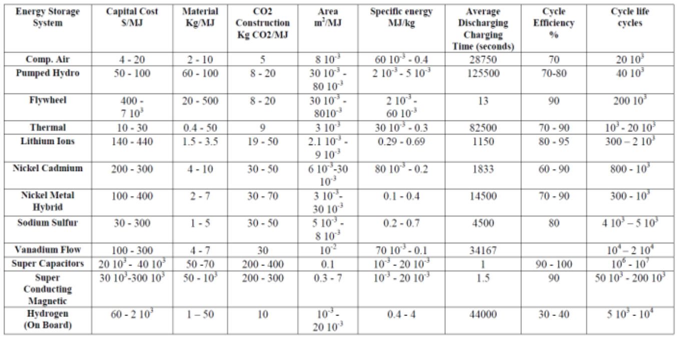


**Figure 8** Cycle efficiency



| Energy Storage System | Capital Cost \$/MJ | Material Kg/MJ | CO2 Construction Kg CO2/MJ | Area $m^2$/MJ | Specific energy MJ/kg | Average Discharging Charging Time (seconds) | Cycle Efficiency % | Cycle life cycles |
|---|---|---|---|---|---|---|---|---|
| **Comp. Air** | 4 - 20 | 2 - 10 | 5 | 8 $10^{-3}$ | 60 $10^{-3}$ - 0.4 | 28750 | 70 | 20 $10^{3}$ |
| **Pumped Hydro** | 50 - 100 | 60 - 100 | 8 - 20 | 30 $10^{-3}$ - 80 $10^{-3}$ | 2 $10^{-3}$ - 5 $10^{-3}$ | 125500 | 70-80 | 40 $10^{3}$ |
| **Flywheel** | 400 - 7 $10^{3}$ | 20 - 500 | 8 - 20 | 30 $10^{-3}$ - 80$10^{-3}$ | 2 $10^{-3}$ - 60 $10^{-3}$ | 13 | 90 | 200 $10^{3}$ |
| **Thermal** | 10 - 30 | 0.4 - 50 | 9 | 3 $10^{-3}$ | 30 $10^{-3}$ - 0.3 | 82500 | 70 - 90 | $10^{3}$ - 20 $10^{3}$ |
| **Lithium Ions** | 140 - 440 | 1.5 - 3.5 | 19 - 50 | 2.1 $10^{-3}$ - 9 $10^{-3}$ | 0.29 - 0.69 | 1150 | 80 - 95 | 300 – 2 $10^{3}$ |
| **Nickel Cadmium** | 200 - 300 | 4 - 10 | 30 - 50 | 6 $10^{-3}$-30 $10^{-3}$ | 80 $10^{-3}$ - 0.2 | 1833 | 60 - 90 | 800 - $10^{3}$ |
| **Nickel Metal Hybrid** | 100 - 400 | 2 - 7 | 30 - 70 | 3 $10^{-3}$- 30 $10^{-3}$ | 0.1 - 0.4 | 14500 | 70 - 90 | 300 - $10^{3}$ |
| **Sodium Sulfur** | 30 - 300 | 1 - 5 | 30 - 50 | 5 $10^{-3}$ - 8 $10^{-3}$ | 0.2 - 0.7 | 4500 | 80 | 4 $10^{3}$ – 5 $10^{3}$ |
| **Vanadium Flow** | 100 - 300 | 4 - 7 | 30 | $10^{-2}$ | 70 $10^{-3}$ - 0.1 | 34167 |  | $10^{4}$ – 2 $10^{4}$ |
| **Super Capacitors** | 20 $10^{3}$ - 40 $10^{3}$ | 50 -70 | 200 - 400 | 0.1 | $10^{-3}$ - 20 $10^{-3}$ | 1 | 90 - 100 | $10^{6}$ - $10^{7}$ |
| **Super Conducting Magnetic** | 30 $10^{3}$-300 $10^{3}$ | 50 - $10^{3}$ | 200 - 300 | 0.3 - 7 | $10^{-3}$ - 20 $10^{-3}$ | 1.5 | 90 | 50 $10^{3}$ - 200 $10^{3}$ |
| **Hydrogen (On Board)** | 60 - 2 $10^{3}$ | 1 – 50 | 10 | $10^{-3}$ - 20 $10^{-3}$ | 0.4 - 4 | 44000 | 30 - 40 | 5 $10^{3}$ - $10^{4}$ |

Table 1 Resource intensities and operating parameters of energy storage systems

## CONCLUSIONS

A comparison study between energy storage options for power systems is presented in this paper. The comparison study will help to select the best energy storage option for power systems with intermittent resources. The results show that:

Discharging/charging time: Super capacitors, super conducting magnetic, and flywheel energy storage systems have fast discharging/charging times. They can be used for short bursts of power and are suitable for fast response frequency regulation and to stabilize the grid. Batteries and compressed air can be used to store energy for hours. Pumped hydro and thermal energy storage systems have charging times of day.

Operation performance: Super-capacitors, superconducting magnetic and flywheels offer greater performance: high specific power, high cycle efficiency and high cycle life. These energy storage systems have high charge/discharge cycles and are more attractive with respect to the operating costs.

Resource intensities: Super-capacitors, superconducting magnetic and flywheels do not offer the best resource intensities. The material, energy, storage area, $CO_2$ and capital cost are higher during the construction of these energy storage systems. Hydrogen, compressed air and thermal storage offer the lowest resource intensities.

Based on these results super capacitors, super conducting magnetic, and flywheel energy storage systems offer the best option for solar power systems based on the fast discharging/charging times and greater performance even the resource intensities are not the best.

## REFERENCES

[1] UNEP International Resource Panel Report, Decoupling natural resource use and environmental impacts from economic growth, ISBN: 978-92-807-3167-5, 2011.

[2] Sims, R.E.H., Rognerb, H.H., and Gregoryc, K., Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation, *Energy Policy*, 31, pp. 1315–1326, 2003.

[3] Ghenai, C. and Janajreh, I., Comparison of Resource Intensities and Operational Parameters of Renewable, Fossil Fuel, and Nuclear Power Systems, *Int. J. of Thermal & Environmental Engineering* Volume 5, No. 2, pp. 95-104, 2013.

[4] The World Wind Energy Association (2014). *2014 Half-year Report*. WWEA. pp. 1–8.

[5] International Energy Agency, *"Technology Roadmap: Solar Photovoltaic Energy*", 2014

[6] Ginley, D.; Green, M. A.; Collins, R. , *MRS Bulletin*, 2008, 33, 355.

[7] Lee, B. S.; Gushee, D. E. Chem. *Eng. Prog*. 2008, 104, S29

[8] Ribeiro, F.M., and da Silva, G.A, 2010, Life cycle inventory for hydroelectric generation: a Brazilian case study, *Journal of Cleaner Production*, Vol. 18(1) pp. 44-54.

[9] Hill, F.A., Havel, T.F., and Livermore, C., 2009, Modeling mechanical energy storage in springs based on carbon nanotubes, *Nanotechnology*, 20.

[10] Heath, G., Turchi, C., Burkhardt, J., Kutscher, C., and Decker, T., 2009, Life cycle assessment of thermal energy storage: two-tank indirect and thermocline, *American Society of Mechanical Engineers (ASME)*, *3rd International Conference on Energy Sustainability*, San Francisco

[11] Hartikainen, T., Mikkonen, R., and Lehtonen, J., 2007, Environmental advantages of superconducting devices in distributed electricity generation, *Applied Energy*, Vol. 84 (1), pp. 29-38.

[12] Granovskii, M., Dincer, I., Rosen, M.A., 2006, Life cycle assessment of hydrogen fuel cell and gasoline vehicles, *International Journal of Hydrogen Energy*, vol. 31(3), pp. 337-352.

[13] CES EduPack software, 2011, Energy Storage Systems, *Granta Design Limited, Cambridge,* www.grantadesign.com.

[14] Nakhamkin, M., Wolk, R., Compressed Air Inflates gas Turbine Output, *Power Engineering*, March 1993.

[15] "Energy storage - Packing some power". *The Economist*. 2011-03-03. Retrieved 2012-03-11.

[16] Zhou, Li., Progress and Problems of Hydrogen Storage Methods, *Renewable and Sustainable Energy Review*, Vol. 9, Issue 4, pp. 395 – 408, 2005.