TAMPERE UNIVERSITY OF TECHNOLOGY

AYŞE ÖZGE GÖKTÜRK

ENERGY STORAGE TECHNOLOGIES IN PV SYSTEMS

Master of Science Thesis

Examiner: Prof.Seppo Valkealahti
Examiner and topic were approved by the council of the Faculty of Computing and Electrical Engineering on 9 November 2016

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
AYSE OZGE GOKTURK: Energy Storage Technologies in Photovoltaics Systems
Master of Science Thesis, 50 Pages
November 2018
Master's Degree Program in Electrical Engineering
Major: Smart Grids
Examiner: Professor Seppo Valkealahti
Keywords: Photovoltaics, Energy Storage, Smoothing Fluctuations

Power demand of world increases significance of renewable energy resources for energy production. For being able to compensate energy requirement, renewable energy resources are needed to be used and one of these resources can be thought as solar power systems.

In solar power systems, photovoltaic cells are used for conversion from solar irradiance to direct current. They can be modeled as an ideal diode which is affected from some factors like parasitic resistance, temperature, and irradiance. This thesis will give an explanation about these main concepts and examine relationship between photovoltaic cells and these factors.

Efficiency of solar power systems can be improved by installation of electrical energy storage technologies into systems. For achieving this, mechanical, electrical or electrochemical systems can be used. Pumped hydroelectric storage systems, compressed air energy storage systems and flywheel energy storage systems are implemented systems to store electrical energy by using mechanical systems. In addition to these systems, battery energy storage systems can be implemented to solar power systems that are mainly lead-acid, lithium-ion, sodium-sulfur, and nickel-cadmium batteries. These battery energy storage systems and flow batteries store energy by using electrochemical reactions. Lastly, capacitors, supercapacitors and superconducting magnetic energy storage can be classified as electrical energy storage systems. In this thesis, these storage technologies will be analyzed and compared to be able to get an optimized storage solution in terms of different requirements.

Photovoltaic power fluctuations that are caused from cloud shading of sun or other environmental impacts is one of the main drawback of solar power systems. For smoothing these photovoltaic fluctuations several methods can be thought. In this thesis, moving average algorithm will be implemented into fluctuated signal and thesis will finalize by comparing difference between fluctuated and smoothed signals.

PREFACE

This master of thesis was worked in the Laboratory of Electrical Energy Engineering of Tampere University of Technology for the Smart Grids major. Professor Seppo Valkealahti was thesis examiner and topic of thesis was detailed and structured with him.

It was a great opportunity for me to pursue my thesis study in Tampere University of Technology. In each phases of my thesis study, I had an opportunity to improve my knowledge about this area. For this development, I want to express my gratitude to Professor Seppo Valkealahti. In this period my family and friends were always supporting and encouraging me. I want to thank all of them through their all support and friendship.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AA-CAES	Advanced Adiabatic CAES
AGM	Absorbed Glass Mat
BES	Battery Energy Storage
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CPV	Concentration Photovoltaic Cell
DC	Direct Current
D_{zone}	Dead Zone
EES	Electrical Energy Storage
ESS	Energy Storage System
FBES	Flow Battery Energy Storage
FES	Flywheel Energy Storage
LAES	Liquid Air Energy Storage
LPF	Low Pass Filter
MA	Moving Average
PCS	Power Converter System
PCM	Phase Change Material
PEM	Proton Exchange Membrane
PHS	Pumped Hydroelectric Storage
PVGS	Photovoltaic Power Generation System
OPV	Organic Photovoltaic Cell
PV	Photovoltaic
SMES	Superconducting Magnetic Energy Storage
STATCOM	Static Synchronous Compensator
SOC	State of Charge
VRFB	Vanadium Redox Flow Battery
VRLA	Valve Regulated Lead Acid
V2G	Vehicle to Grid
V2H	Vehicle to Home
I	Current
q	Electron Charge
V	Voltage
γ_i	Upper and Lower Bound Limitations of State of Charge
δ	Power Fluctuation Rate Limit Value
η	Efficiency
A_i	Accelerate Control Effect
C_{bat}	Range of Remaining Battery Capacity

E_G	Energy Gap
I_{bat}	Current of Battery
I_D	Dark Saturation Current
I_{MPP}	Maximum Power Point Current
I_{SC}	Short Circuit Current
I_{ph}	Photo Current
$k_{rise,PV}$	Rise Rate Limit Value of PV Cell
$k_{drop,PV}$	Drop Rate Limit Value of PV Cell
P_{ave}	Average Power of System
P_{fluc}	Fluctuated Power of System
P_G	Smoothed Power Injected to the Grid
P_i	Target Power of PCS i
P_{max}	Maximum Power of System
P_{MPP}	Maximum Power Point Power
P_{PV}	Power of PV Cell
Q_{bat}	Charge of Battery
R_{ch}	Charging Resistance
R_{dis}	Discharging Resistance
R_{int}	Internal Resistance
R_{PV}	Resistance of PV cell
T	Temperature
V_{bat}	Voltage of Battery
V_{MPP}	Maximum Power Point Voltage
V_{OC}	Open Circuit Voltage
W_{bat}	Remaining Battery Capacity

1 INTRODUCTION

Importance of usage of renewable energy resources become more dramatic in higher demand of energy in the world. Due to increment of energy and electricity requirement new energy resources started to be explored. For that purpose, one of the main resource can be considered as photovoltaic (PV) solar power systems.

When energy generation from this source is analyzed deeply it can be concluded that output from photovoltaic plants and ways of storage of this energy are needed to be improved. Variation of power outcomes will be observed in systems because of several external factors like cloud coverage, adjustments of sun's angle over the solar panels. Due to these impacts in PV power plant some fluctuations will occur and for smoothing these fluctuations in the system energy storage systems can be used.

Many different technologies for storage mechanisms can be considered in PV systems to be able to smooth fluctuations in solar power systems. Battery Energy Storage Station (BESS) can be analyzed as one solution that is combination of static synchronous compensator (STATCOM) and direct current (DC) power source to reach smoothed outcome for these power systems.

When different storage systems are analyzed it can be concluded that they can be classified according to their functionality such as mechanical, electrical and electrochemical. In this thesis, firstly, mechanical electrical energy storage technologies were stated that are pumped hydroelectric storage systems, compressed air energy storage systems and flywheel energy storage systems.

In addition to these mechanical storage systems, electrochemical battery energy storage systems could be preferred for same aim. For that purpose, lead-acid, lithium-ion, sodium-sulfur and nickel-cadmium batteries can be implemented to power systems. These different battery technologies can be preferred for different needs such as energy density, power density, specific power and specific energy. Furthermore, electrochemical energy storage systems such as flow batteries, capacitors and supercapacitors can be also used in solar power systems.

In this thesis, one of main aims is to explain different electrical energy storage technologies and analyze main differences among these different technologies. Lastly, one of the most efficient ways to smooth photovoltaic power fluctuations, moving average algorithm will be stated by analyzing simulation results.

2 PHOTOVOLTAIC SYSTEMS

2.1 General Operation of Photovoltaic Cells

In solar power systems, photovoltaic cells convert solar radiation to electricity by utilizing photovoltaic effect phenomenon. As shown in figure 1, in this concept, photovoltaic cells that are mainly semiconductors are used for photon absorption and energy of photon will be converted to potential energy of electron. After energizing electron, it can escape its bond to create electric potential which generates a hole. These holes are playing very important role in combined P-N junction that is a layer within photovoltaic cell and moving in opposite direction from electrons to produce an electric voltage (Energy.gov, 2013).

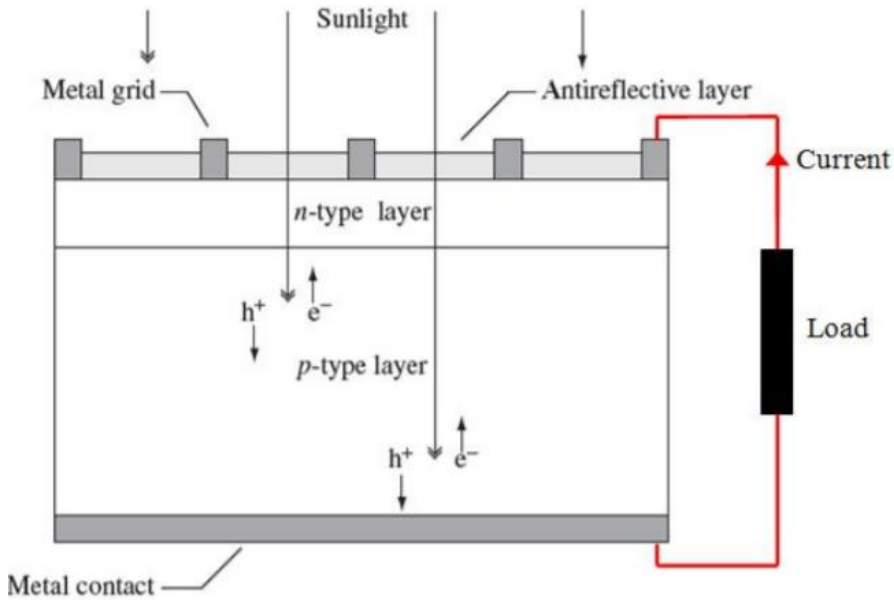

Figure 1. *Photovoltaic Effect (Valkealahti, 2016).*

There are several types of photovoltaic cells and as a first type, traditional PV cells could be considered. These cells are flat-made or silicon and create highest efficiency among all types of PV cells. Furthermore, second-generation photovoltaic cells are also named as thin-film cells consist of amorphous silicon or non-silicon materials such as cadmium telluride. In these thin-film cells, biggest advantage is layer thickness of semiconductor materials which is only a few micrometers. This flexibility in thickness extends usage areas like using at rooftop shingles and tiles, building facades, or the glazing for skylights.

In addition to these two types, third-generation PV cells are composed of several new materials like solar inks that is used in areas like solar dyes, and conductive plastics. For focusing on sunlight onto higher efficient parts of PV cells, plastic lenses or mirrors could be implemented to these solar cells (Energy.gov, 2013).

As another type of photovoltaic cells, Organic photovoltaic cells (OPV) are carbon-rick polymers and could be tailored to be improved in specific areas like certain type of light precision. In this type of cells, silicon or thin-film technologies have lower-cost for same amount of electricity production. However, in operations of OPV cells, shorter operating lifetimes is expected in comparison of crystalline silicon cells. Furthermore, concentration photovoltaic cells(CPV) can be thought as another effective solar cell and it focuses sunlight by implementing a mirror or lens. When sunlight is absorbed in smaller area, requirement of solar cell in system will be decreased. In this type of solar cell, materials become more effective at energy conversion in more concentrated light coming. However, in CPV system needs more costly materials, manufacturing techniques, tracking and this condition could create higher drawbacks for system (Energy.gov, 2013).

2.2 I-V Curve of Photovoltaic Cell

PV cells mainly can be considered as an ideal diode in the case of any light presence of current generation. This diode representation can be made as Figure 2. For ideal case, there is no impact on both resistances and short circuit current is equal to photovoltaic current I_{ph}.

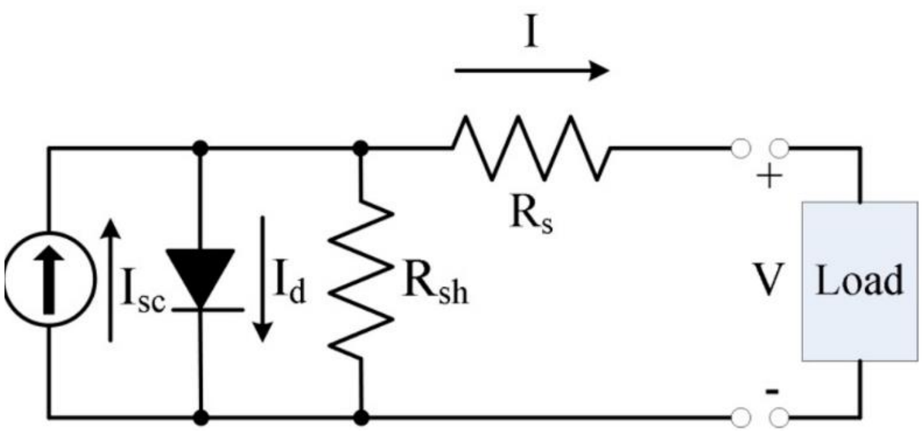

Figure 2. *Circuit Diagram of Photovoltaic Cell (Liu et al., 2017).*

Relationship of diodes and I_{SC} to reach output current can be formulated as equation (1) where I_{SC} represents short circuit current of system, I_{D1} and I_{D2} are dark saturation currents corresponding to two different diodes, T is temperature, k is Boltzmann's constant, V is voltage and q is electron charge.

$$I = I_{SC} - I_{D1}\left(e^{\frac{qV}{kT}} - 1\right) - I_{D2}\left(e^{\frac{qV}{2kT}} - 1\right) \quad (1)$$

In this formula I_{D1} is implemented to system for dark saturation current which is occurred as a result of recombination in quasi-neutral region and I_{D2} is used for dark saturation current because of recombination in depletion region (Valkealahti, 2016). Therefore, it could be concluded that output current of solar cell depends on these two diodes and short circuit current as symbolized as I_{SC} in Figure 2 when equation (1) is analyzed.
For being able to analyze performance of PV cells, current-voltage relationship is needed to be focused. To reach that aim I-V curve representations are created for PV cells which can be shown as figure 3.

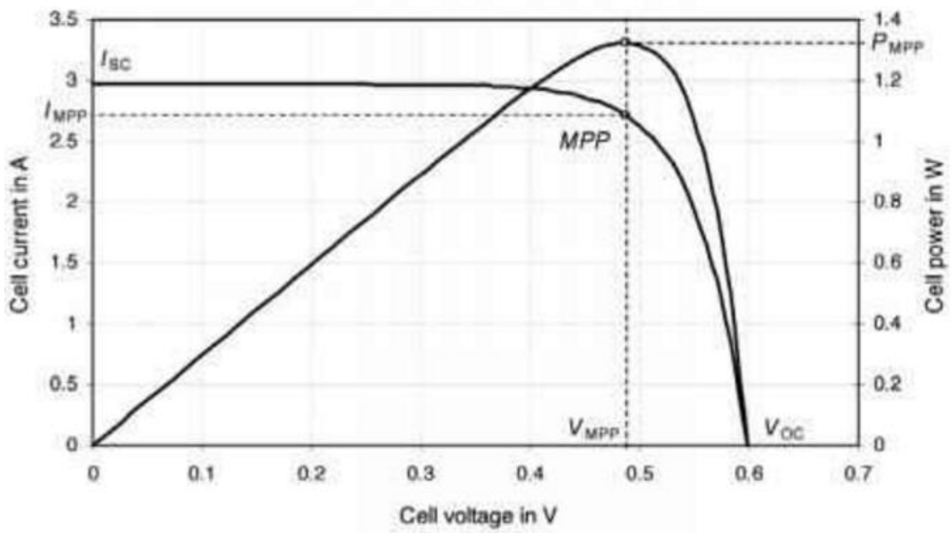

Figure 3. *I-V and P-V Representation of PV Cell (Freeenergyplanet.biz, 2017).*

For calculating short circuit current, I_{SC} voltage of the cell must be zero. I_{SC} is in the first phase of the forward-bias sweep and is equal to highest current value in the power quadrant. Under ideal circumstances, maximum current value is equal to total current production in the PV cell by photon excitation (Freeenergyplanet.biz, 2017). In figure 3, I_{MPP} is used for maximum power point current. Similarly, open circuit voltage, V_{OC} will occur in the case of no current flow through PV cell. Therefore, open circuit voltage can be reached in the case of no current in the cell and it also implements that V_{OC} is maximum voltage difference across PV cell for a forward-bias sweep in the power quadrant (Freeenergyplanet.biz, 2017). In addition to that in figure 3, V_{MPP} is used for maximum power point voltage.
Lastly power curve (P-V) can be reached by deriving from I-V curve by applying equation (2) as below where P represents power of system, V shows voltage of system and I is current of system:

$$P = VI \tag{2}$$

Like voltage and current in figure 3, P_{MPP} is used for maximum power point power.

2.3 Parasitic Resistance Effect

In ideal cases both parasitic series and parasitic shunt resistances are neglected. However, for real cases of PV cell integration as shown in figure 2 both resistances need to be taken into account. When origin of series resistance is considered, sources like the metal contacts, specifically to the front grid, and transverse flow of current through photovoltaic cell could be found (Valkealahti, 2016).

In analysis of series parasitic resistance impact, it can be observed that there is no impact on open circuit voltage of I-V curve directly. However, parasitic resistance decreases short circuit current of I-V curve at high voltages. Because of this fact maximum point of both voltage and power will be decreased.

In addition to parasitic series resistance there is impact of parasitic shunt resistance to I-V characteristics of PV cell. Similar to parasitic series resistance, parasitic shunt resistance has no impact on short-circuit current directly, however it decreases open circuit voltage of the PV cell at high current. Like parasitic shunt resistances, there will be a decrement of maximum point of both power and voltage.

2.4 Temperature Effect

Temperature has a very dominant impact on recombination of current carriers and increment of temperature leads to weakness in the photovoltaic cell. Main reason of this weakness in cell is band gap decrement of this cell as equation (3) shows below:

$$E_G(T) = E_G(0) - \frac{\alpha T^2}{T-\beta} \tag{3}$$

where E_G is energy gap, T is temperature and α and β are specific constants for each different semiconductor (Valkealahti, 2016).

Therefore, it can be concluded that with increment of temperature in the environment, performance of solar cell become weaker due to narrowed band gap that can be seen from equation (3).

2.5 Irradiance Effect

Irradiance can be defined as total radiant power received by surface per unit area and there will be an impact of irradiance on PV cells. When relationship between I -V characteristics of PV cell and irradiance is analyzed, it can be reached that increment of irradiance provides increment on short circuit current. By increasing irradiance open circuit voltage will increase but very slightly when it is compared with short circuit current.

2.6 Effects of Internal and External Factors to Solar Cells in MATLAB Simulation

In analysis of different factors on solar cells firstly it is needed to implement a solar cell system in Simulink. For this purpose, temperature and irradiance blocks as external factors are added to system. When cell block is built series resistance, shunt resistance and ideality factor as internal factors that impacts operation of solar cell are used. Under the same conditions when series resistance is changed to analyze impact on solar cells it is observed that decrement of this value improves both voltage and current value of solar cell as shown in figure 4.

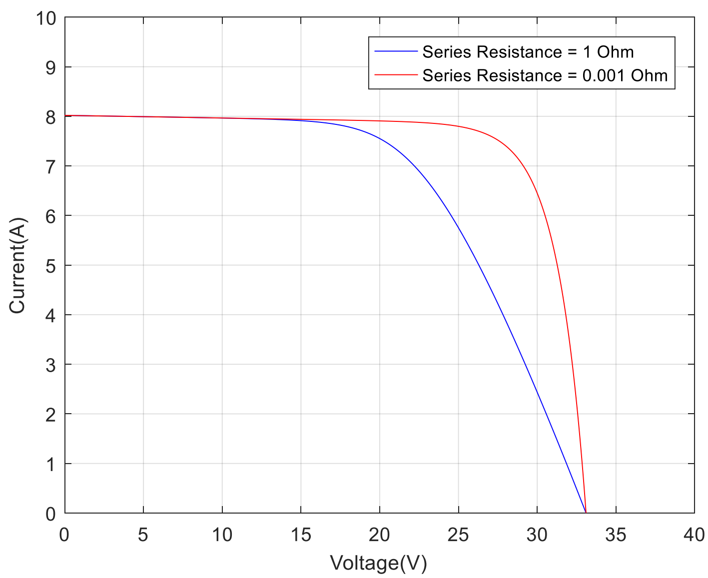

Figure 4. *Impact of Series Resistance on Solar Cell.*

Similarly, when effect of parasitic shunt resistance is analyzed, increment of shunt resistance value of solar cell increases its both voltage and current values in I-V curve as illustrated in figure 5.

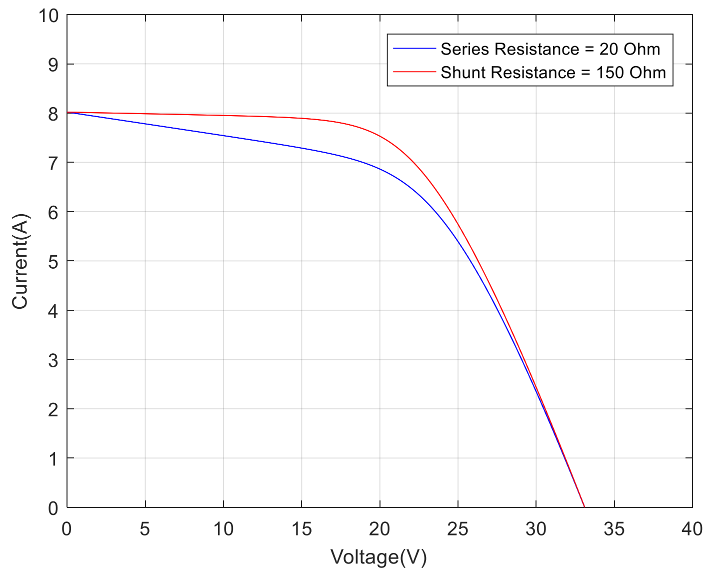

Figure 5. *Impact of Shunt Resistance on Solar Cell.*

For temperature impact on solar cell, different temperature values were tried in MATLAB simulation. As shown in figure 6, when temperature value of solar cells was increased, there will be a small increment in current value of solar cell. However, when voltage is analyzed it is observed that there is a sharp decrement and in overall, performance of I-V curve of solar cell is decreased in higher temperature values.

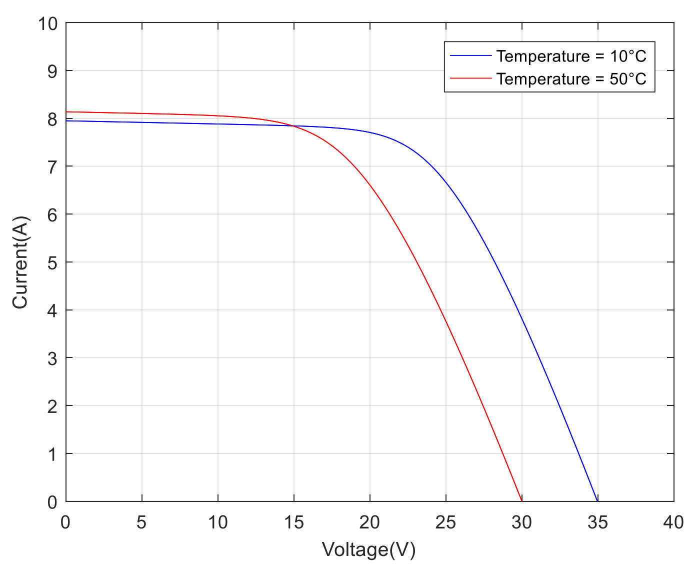

Figure 6. *Impact of Temperature on Solar Cell.*

Lastly, irradiance values were changed to see the corresponding effect on solar cell performance. As shown in figure 7, higher irradiance improves both voltage and current values of solar cells.

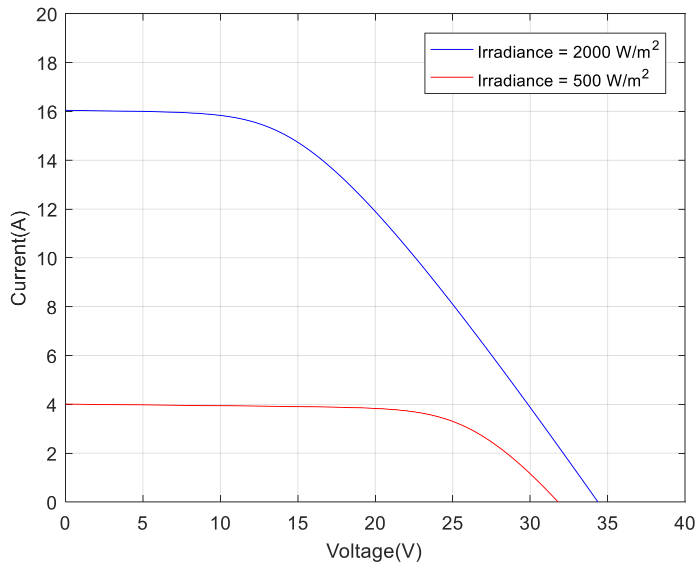

Figure 7. *Impact of Irradiance on Solar Cell.*

2.7 Photovoltaic Power Fluctuations

There are several factors that leads an inconsistency in solar radiation such as shadowing, dust gathering or sun angle. For intervals of less than ten minutes, these fluctuations are directly absorbed by PV electricity systems which results in variations in power frequency. Utility operators are powerless to correct these imbalances which can ultimately result in electrical power systems failure (Elp.com, 2017). Due to these environmental factors, there could be very rapid fluctuations in solar power systems as represented in figure 8. Having rapidly changing radiation in cells will decrease the ability of accurate prediction and that has impact on profit sustainability, revenue return estimations and customer service quality. Therefore, for improving the solar power systems fluctuations needed to be smoothed in that system.

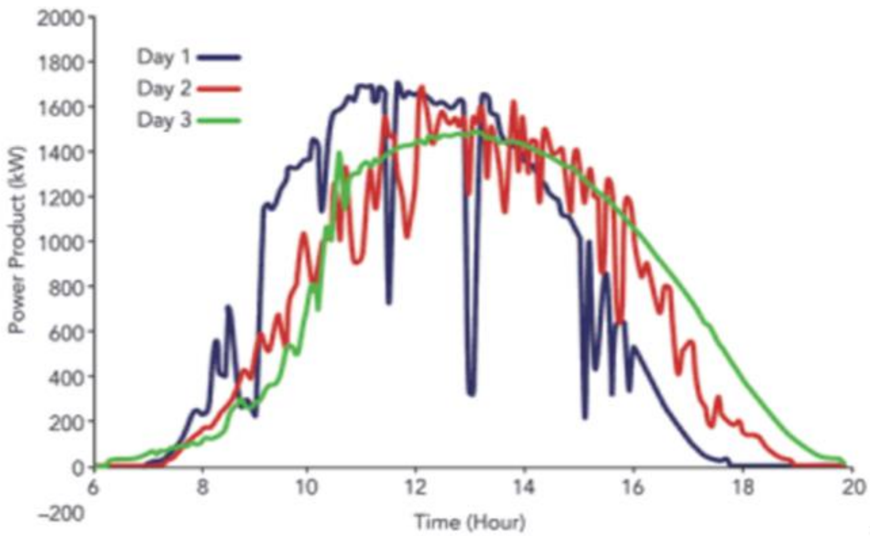

Figure 8. *Power Fluctuations in Southern California in 3 Days (Elp.com, 2017).*

3 ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Electricity generation over the world have increased rapidly due to several types of electricity resources. However, lack of ability to store this generated electrical energy can be considered as very important drawback of system. Therefore, for being able to increase efficiency of the system electrical energy storage technologies are needed to be implemented. In this section main electrical energy storage technologies will be examined.

3.1 Pumped Hydroelectric Storage

In regular pumped hydroelectric storage(PHS) technology, there are two reservoirs that are located vertically. In this storage system, location of pumped water is directly affected from demand hours, in the case of off-peak time, the water is pumped and be stored into the higher-level reservoir. Similarly, in the case of peak times, water could be released from higher reservoir to lower one (Luo et al., 2015). By using height difference between these two reservoirs, electricity can be generated for electrical machines of turbine units as shown in figure 9.

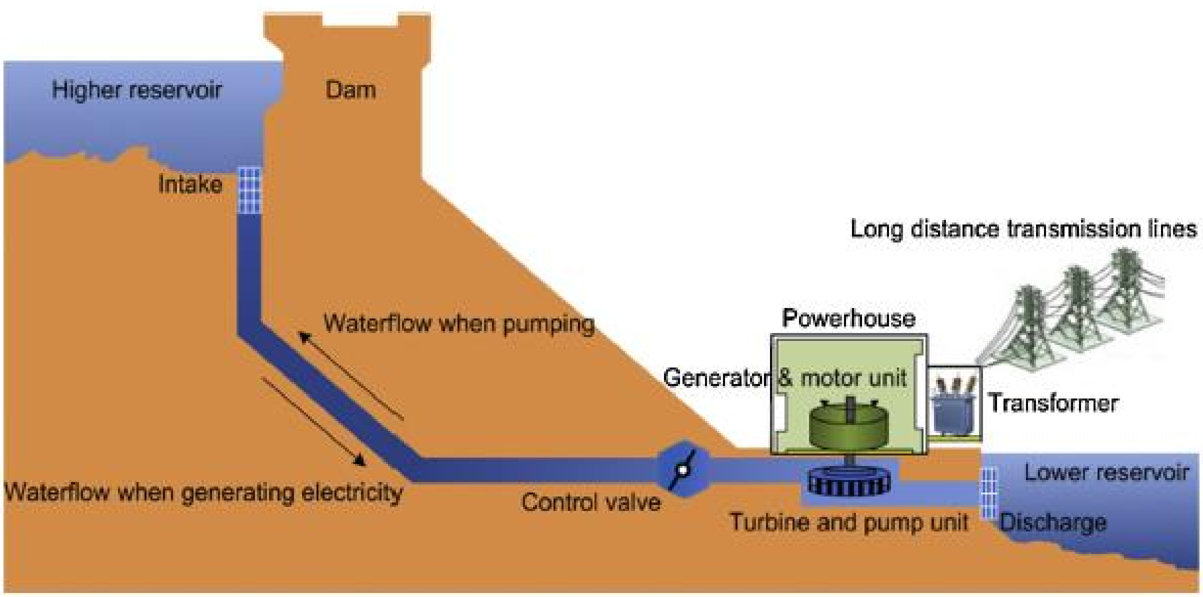

Figure 9. *Pumped Hydroelectric Storage Plant (Luo et al., 2015).*

Due to this process, in PHS, energy storage capability is critically affected by the vertical distance between higher and lower reservoirs of PHS and total volume of water storage capability. In addition to stored energy, in analysis for impacts of turbines flow ratio and pump/turbine and generator motor power ratio are considered as very significant factors for this system.

When electrical performances of PHS are analyzed it can be observed that in various PHS plants, range of power ratings can be between 1 MW and 3003 MW, with cycle efficiency up to 70-85% and more than 40 years lifetime (Luo et al., 2015).

In comparison of PHS among other storage technologies, one of the most significant advantages of this system is that storage plants are operated differently from any type of hydroelectric power plants as no requirement for water supply flow. When fulfillment of head and trail pond is happened once, only inflow is required to be able to compensate for the evaporation and separate losses. By using advantage of seasonal flow adjustment of water, stream flow can be used that might otherwise run to waste. In addition to this advantage of this storage system, in pumped storage plant there is no relationship between capacity and river flow and seasonally varied flow. Therefore, it represents that pumped storage plants can operate in all seasons of the year (Sánchez Muñoz, Garcia and Gerlich, 2016).

3.2 Compressed Air Energy Storage

Compressed air energy storage (CAES) system includes reversible generator unit which is driven by extra generated electricity during off-peak times and it activates compressors to inject air into a storage vessel. In this process, energy storage is implemented in form of high-pressure air and this will be used in case of load demand by being heated from either fossil fuel combustion or heat recovery of compression process. Lastly, turbines of system capture compressed air energy and the waste heat can be recycled by a recuperation unit which can be seen in figure 10.

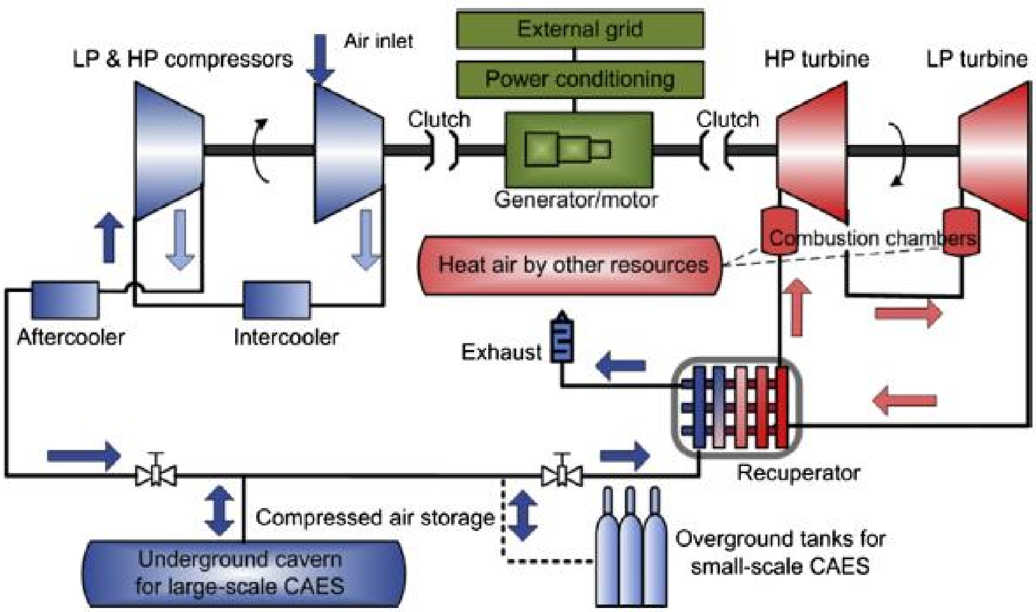

Figure 10. *Compressed Air Energy Storage (Luo et al., 2015).*

When advantages of CAES is analyzed it is understood that by implementing CAES into systems, request for purchasing, maintenance and dispose of waste chemicals can be provided by effective location of underground caverns. Additively supplying electrical power, heat for by-production might be utilized as cogeneration. Furthermore, one of the biggest advantage for system capacity factor is to minimize total cost of delivered electricity and this can be satisfied by using this storage technology. (Luo et al., 2015).

3.3 Flywheel Energy Storage

A modern Flywheel Energy Storage (FES) system includes five main units that are a flywheel, magnetic bearings, motor/generator, power electronic unit and vacuum housing as illustrated in figure 11 (Luo et al., 2015). FES systems use electricity for acceleration or deceleration of flywheel, which transfers stored energy to or from integrated motor/generator. To be able to increase efficiency of FES, reduction of wind shear and energy loss of air resistance is needed to be achieved by placing system to a high vacuum environment. In this system, total energy storage depends on both rotation speed and inertia of flywheel (Luo et al., 2015).

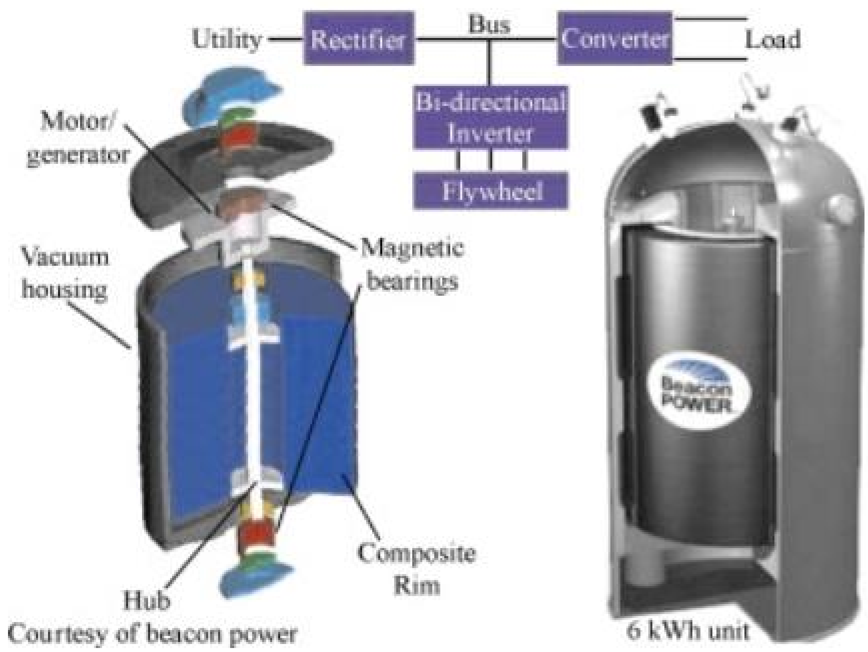

Figure 11. *Flywheel Energy Storage (Chen et al., 2009).*

Specific energy of flywheels will be between 5 Wh/kg and 100 Wh/kg and storage system has up to 95% cycle efficiencies at rated power, relatively high-power density, no depth-of-discharge effects and easy maintenance (Luo et al., 2015). Therefore, when advantages of flywheel energy storage are analyzed it can be concluded that this technology can be considered as very environmentally-friendly and effective storage technology of energy. Furthermore, it is also observed that system has flexibility of not using harmful chemicals. To the contrary of these advantages, loading up more energy than components can handle might cause considerable potential safety risk. This situation might cause a disaster and prevention of this issue needs security walls by increasing total weight of system's unit (Luo et al., 2015).

3.4 Battery Energy Storage

As another common energy storage technology, battery energy storage system(BES) could be considered. This technology can generate electricity with specified level of voltage by using electrochemical reactions on cells of system. Each cell of BES includes two electrodes, anode and cathode, with a solid, liquid or ropy state electrolytes.

3.4.1 Lead-Acid Battery

A lead-acid battery includes various series-connected cells, each of them is delivering a voltage around 2 V and there are lead cathodes, positive ionized lead oxide anodes and sulphuric acid electrolyte in battery system. In discharging phase, both the anode and cathode parts of battery reacts with electrolyte to release electrical energy with lead sulfate as product. During charging phase of battery, this chemical reaction will happen in opposite direction by applying electricity. (Oberhofer, 2012)

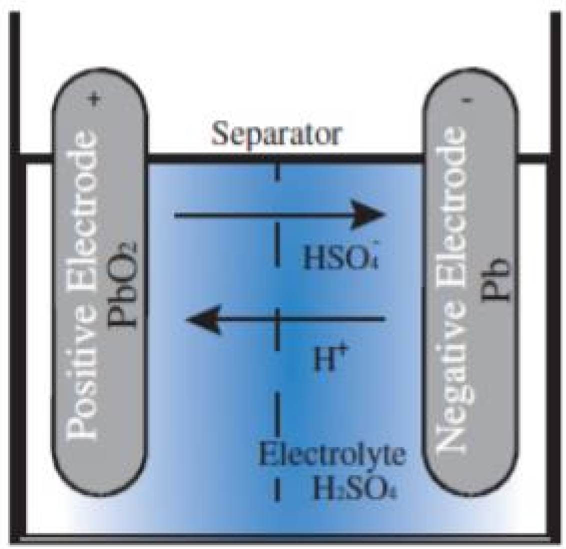

Figure 12. *Lead-Acid Battery (Sánchez Muñoz, Garcia and Gerlich, 2016).*

As shown in figure 12, during the discharge process, positive electrode of battery reaches electrons from the external circuit. Then, there will be reduction reaction that continues flow of charge through electrolyte to negative electrode between these electrons and active materials of positive electrode. In this reduction reaction, PbO_2 will be transformed to $PbSO_4$ by absorbing HSO_4^- and H^+ ions from the electrolyte.

In lead acid batteries, there is an oxidation reaction between negative electrode and charge and in this reaction Pb is oxidized to form $PbSO_4$ by absorbing HSO_4^- ion and releasing H^+ ions to the electrolyte while loading electrons to the negative electrode. All chemical reactions in this battery are reversible and by changing direction of reactions (Sánchez Muñoz, Garcia and Gerlich, 2016). When advantages of this storage system are analyzed, fast response time, approximately 0.3% daily self-charge rate, 63-90% cycle efficiency and low capital costs (50–600 $/kWh) could be considered (Luo et al., 2015). However, lead-acid batteries could have disability of being stored in discharged condition. In addition to that, both electrolyte and lead content can lead to environmental damage, which is not environmentally friendly.

In industry, there are several types of lead-acid batteries and valve regulated lead acid(VRLA) battery could be considered as one of the most commonly used. In VRLA, system provides reduction of the water loss during both discharge and recharge cycle, and water will not be required by keeping hydrogen close to plates to use for re-combination during discharging phase.

These VRLA batteries can be classified into two main kinds that are Gel Cell and the Absorbed Glass Mat (AGM). In Gel Cell Battery, immobile type of jelly electrolyte where sulfuric acid is blended with fumed silica is observed. Due to feature of this electrolyte, Gel Cell could be located in any position and represents a higher resistance to temperature adjustment and vibration.

As a second kind of VRLA, in AGM absorption of acid is observed and became immobile by implementing thin fiberglass mats between the plates in the system. By using AGM, a faster chemical reaction of acid with plate material could be observed. Furthermore, this battery system could be in any shape and make the design very flexible. One of the biggest advantage of AGM batteries is its low internal resistance and quicker acid movement between fiber and plates when it is compared with other types of batteries (Hoffman, 2014).

3.4.2 Lithium-Ion Batteries

In a lithium-ion(Li-ion) battery, lithium metal oxide and graphitic carbon will be used as cathode and anode respectively and a non-aqueous organic liquid will be an electrolyte. Li-ion battery is very advantageous storage system especially when response time, small dimension and/or weight of equipment are considered (milliseconds response time, 500000–10000000 W/m^3, 75–200 Wh/kg, 150–2000 W/kg). In addition to that, these batteries have high cycle efficiency that is up to 97% (Luo et al., 2015).

In other respects, reality of protection requirement could be considered as one of the main drawbacks of these batteries. Since robustness of Li-ion batteries are not well-performed among other storage technologies. Furthermore, this battery technology needs protection for case of over and discharging and it could be problematic when ageing is focused (Sánchez Muñoz, Garcia and Gerlich, 2016). There are several kinds of Li-ion batteries and as one type of lithium-ion cell, in lithium-air(Li-air) cell, voltage generation will be occurred with oxygen molecules (O_2) at the positive electrode of batteries as shown in figure 13. O_2 has reaction with positively charged lithium ions to create lithium peroxide (Li_2O_2) as an output for electric energy generation. If Li_2O_2 is not created in this battery, battery will become discharged (Simanaitis Says, 2015).

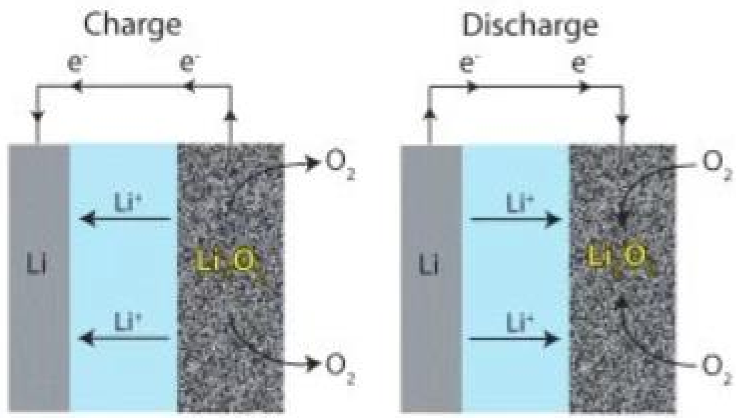

Figure 13. *Lithium Air Battery (Simanaitis Says, 2015).*

In this battery system, one of the main drawback is bad conductivity of Li_2O_2. If deposits of Li_2O_2 accumulate in electrode surface, this condition will prevent reaction on the battery and it will damage battery's power. This issue can be solved by storing Li_2O_2 molecules near to battery electrode but does not coat it.

Researchers from Cambridge University improve a system by using mixture of lithium iodide (LI). In addition to lithium iodide, electrode that are made of several thin layers of graphene and filled with large pores will be used. This combination of chemicals incorporate hydrogen stripped from the water for forming lithium hydroxide (LiOH) crystals which are used for fulfillment of pores in the carbon electrode. (Simanaitis Says, 2015).

3.4.3 Sodium-Sulfur Batteries

In Sodium-Sulfur(NaS) batteries, there are molten sodium and molten sulfur as electrodes of NaS battery, and beta alumina is used as solid electrolyte as shown in figure 14. During discharging phase of NaS batteries, sodium sends electrons through circuit in negative electrode of battery. Then Na^+ ion passes through electrolyte and has reaction with Sulfur to create sodium polysulfides at positive electrode of battery as shown in equation (4).

$$2Na + xS \rightarrow Na_2S_x \quad (4)$$

In charging phase, equation (4) will be reversed and sodium polysulfides decompose and Na^+ passes back through the electrolyte. The chemical reactions of sodium-sulfur batteries operate at temperature of 574–624 K to remain the electrodes in liquid states, to reach better reactivity. NaS battery usage in power systems can be considered as relatively high energy densities (150–300 Wh/L), almost zero daily self-discharge and high pulse power capability. Furthermore, in NaS battery, inexpensive, non-toxic materials are used that provide around 99% recyclability (Luo et al., 2015).

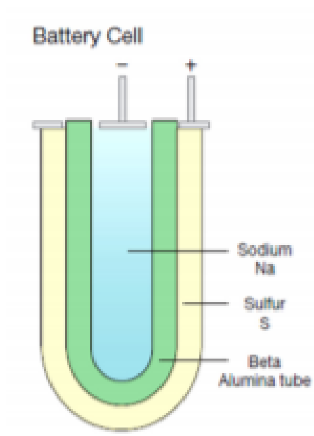

Figure 14. *Soduim-Sulfur Battery (Sánchez Muñoz, Garcia and Gerlich, 2016).*

3.4.4 Nickel-Cadmium Batteries

As shown in Figure 15, in Nickel-Cadmium(NiCd) battery, there are two electrodes that are nickel hydroxide and metallic cadmium and an aqueous alkali solution is included as the electrolyte. As shown in equation (5), in discharging phase, nickel oxyhydroxide is returned the lower valence state by accepting electrons externally.

$$2\ NiOOH+2H_2O+2e^- \rightarrow 2Ni(OH)_2+2OH^- \quad (5)$$

When negative electrode of battery is analyzed, it can be seen that in discharging phase, cadmium is oxidized, create cadmium hydroxide($Cd(OH)_2$) and releases electrons to the external circuit as represented in equation (6).

$$Cd+2OH^- \rightarrow Cd(OH)_2+2e^- \quad (6)$$

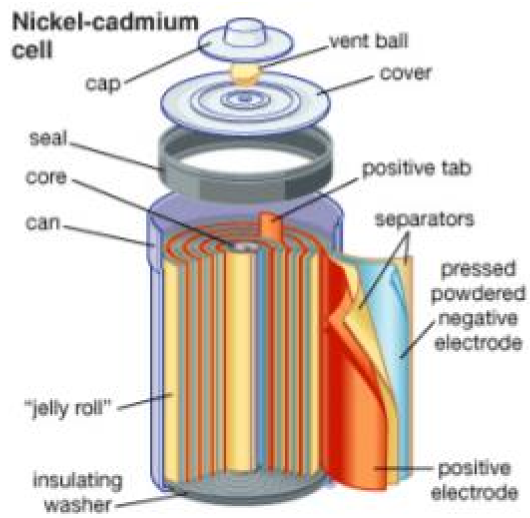

Figure 15. *Nickel Cadmium Battery (Sánchez Muñoz, Garcia and Gerlich, 2016).*

Therefore, overall equation during discharge phase can be concluded as shown in equation (7) and in case of charging all equations will be in reverse direction (Luo et al., 2015).

$$Cd+2H_2O+2NiOOH \rightarrow 2Ni(OH)_2+Cd(OH)_2 \quad (7)$$

NiCd batteries have higher robustness and lower maintenance requirements among all storage technologies. However, environmental damage which is resulted by using toxic heavy metals could be considered as one of the main drawback. In addition to that, battery is affected from the memory effect which states that partial discharging might lead to decrement in maximum capacity (Sánchez Muñoz, Garcia and Gerlich, 2016).

3.4.5 Nickel Metal Hydride Battery

As shown in figure 16, Nickel Metal Hydride(Nimh) batteries include a metal hydride and become a solid source of hydrogen reduction that could be oxidized to be able to form protons by using a nickel hydroxide(NiOOH) and metal alloy(MH) as active elements in electrodes. When electrolyte of battery is analyzed it is made from alkaline potassium hydroxide (Mpoweruk.com, n.d.).

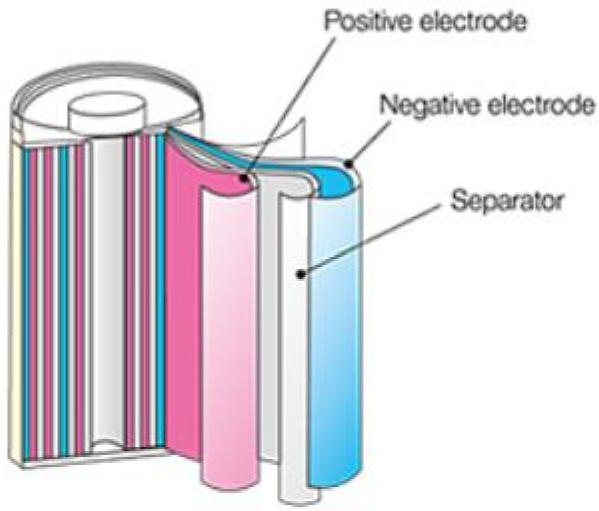

Figure 16. *Nickel Metal Hydride Battery (Global.kawasaki.com, n.d.).*

One of the main advantages of Nimh battery can be seen as its environmental-friendly structure which contains only mild toxins. In addition to that, this battery technology has a capability of recycling 30-40 percent higher than NiCd batteries. Lastly, Nickel Metal Hydride Battery provides very simple storage and transportation opportunity to users. Despite of all these advantages, there are some drawbacks of this battery technology. One of the main problems on this technology is its limited service life due to deep discharging of battery. In addition to that, another critical disadvantage is the requirement of complex charge algorithm (Mpoweruk.com, n.d.).

3.4.6 Carbon-Zinc Batteries

As shown in figure 17, zinc can is anode part of battery which is source of high potential electrons and is the negative pole. In cathode part of battery, there is a manganese and inert carbon rod is a positive pole which is a non-corrodible conductor (IamTechnical.com, n.d.).

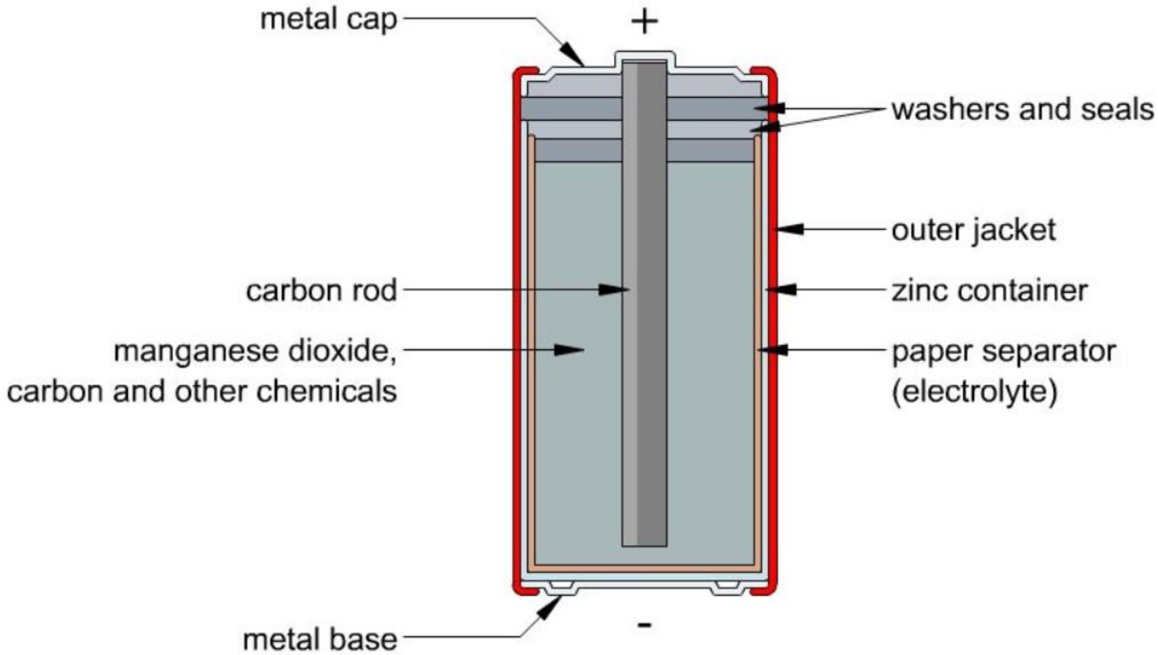

Figure 17. *Carbon-Zinc Battery (IamTechnical.com, n.d.).*

Overall reaction of this battery is observed as shown in equation (8).

$$Zn + 2MnO_2 \rightarrow ZnO + Mn_2O_3 \quad (8)$$

Half reactions of battery will be like equations (9) and (10) and where anode and cathode will be represented respectively (Luo et al., 2015).

$$Zn \rightarrow Zn^{2+} + 2e^- \quad (9)$$

$$2NH_4^+ + 2MnO_2 + 2e^- \rightarrow Mn_2O_3 + H_2O + 2NH_3 \quad (10)$$

When advantages of this battery are examined, being cheap and convenient can be considered as two effective characteristics. However, in carbon-zinc batteries, several drawbacks can also be observed. First of these disadvantages could be its lack of environmentally friendly features due to leaking out of the battery. In addition to that, battery’s short life time and small current can be two other significant weaknesses. Lastly, in this battery, voltage stability is hard to achieve and resistance of battery is higher when it is compared with other battery energy storage systems (Slideplayer.com, 2011).

3.4.7 Comparison of Battery Energy Storage Technologies

Both power and energy densities are playing very important role for understanding efficiencies of these battery energy storage technologies. Comparison of energy and power densities can be observed as shown in table 1.

	Power Density(W/kg)	Energy Density(Wh/kg)
Lead Acid Battery	75-300	30-50
Lithium-Ion Battery	150-315	75-200
Nickel-Cadmium Battery	150-300	50-75

Table 1. *Power and Energy Densities of Battery Energy Storage Technologies (Chen et al., 2009).*

It is observed that among these three technologies lithium-ion battery has highest value in terms of both power and energy density. When both lead-acid and nickel-cadmium batteries are analyzed, their power and energy density values are very close and less than lithium-ion batteries. Therefore, it can be concluded that lithium-ion batteries have more advantageous in terms of both density values.

Specific power and specific energy are two important variables when comparison of battery technologies is analyzed. Specific energy, or gravimetric energy density, is used for definition of battery capacity in terms of weight(Wh/kg). Higher specific energy provides longer runtimes at moderate-level load but ability of delivering higher current loads could not be achieved. As another significant specification of battery, specific power, or gravimetric power density, is used for loading capability. In batteries for power purpose, specifications are focused with higher specific power and lower specific energy (capacity). Analysis of these two parameters for different battery technologies can be seen in figure 18 (Chen et al., 2009).

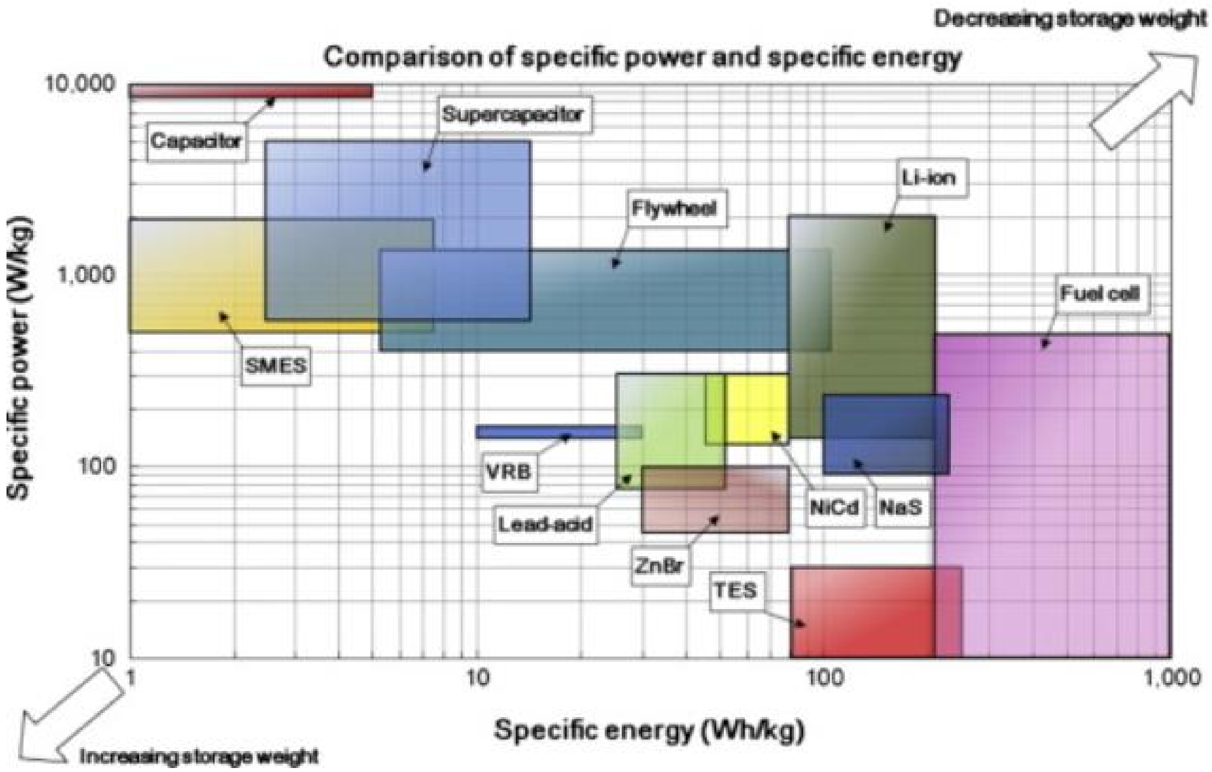

Figure 18. *Specific Power and Specific Energy Values for Battery Energy storage Technologies (Luo et al., 2015).*

When these two variables are analyzed among these battery technologies, it is observed that lead acid has lowest value in both specific energy and specific power values. When lithium-ion battery is examined, it reaches highest value in both variables. Lastly Ni-MH battery is in the between li-ion and lead-acid batteries.

3.5 Flow Battery Energy Storage

Flow battery energy storage(FBES) systems include external liquid electrolyte stores as shown in figure 19 and these stores are used for pumping electrolytes to reaction cell. Chemical operations happened at cell depend on reduction-oxidation operations of the electrolyte solutions.

In charging phase, conversion of electrical energy to chemical energy will be made with oxidization of electrolyte at anode and reduction of electrolyte at cathode. In discharging phase of FBES, all process will happen in reverse direction.

In analysis of this storage system's advantages, one of the most important one is that power of this system and its storage capacity are not depended to each other. In FBES, system power capability is impacted by electrodes' size and number of cells in stack storage capacity of FBES system is performed better with higher concentrated electrolyte. In addition to these features, FBES could have smaller self-discharge because storage of electrolytes could be made in separate sealed tanks (Luo et al., 2015).

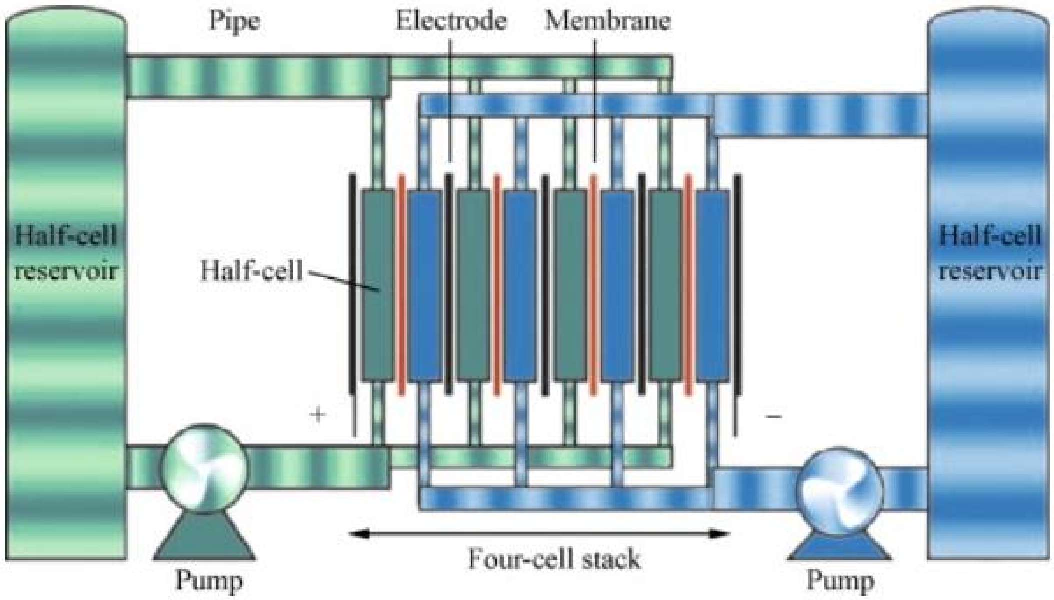

Figure 19. *Flow Battery Energy Storage (Chen et al., 2009).*

When possible drawbacks of FBES are analyzed, it can be stated that requirement for pumps, flow controllers and storage tanks make operation of the system more complicated and decrease the storage units' overall energy density. In addition to that, this technology also requires more complex electronics when it is compared with basic lead-acid battery designs (Chen et al., 2009).

3.5.1 Vanadium Redox Flow Batteries

As shown in figure 20, in vanadium redox flow battery(VRFB) there is the ion-selective membrane that is used for separation of catholyte and anolyte receivers. These two parts of battery are circulated with two electrodes including different valence states, VO_2^+/VO^{2+} and V^{2+}/V^{3+} in the positive electrolyte and negative electrolyte respectively (Luo et al., 2015).

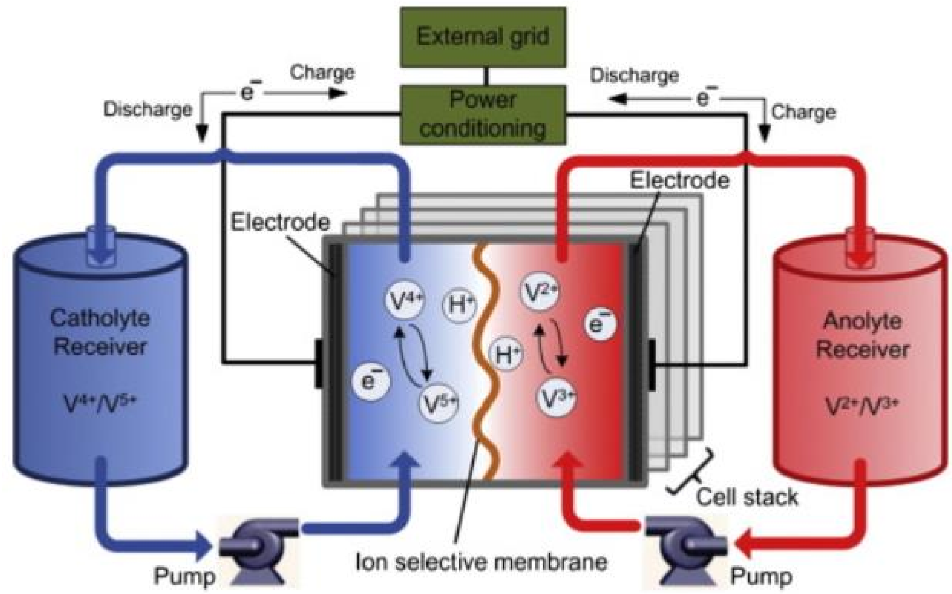

Figure 20. *Vanadium Redox Flow Battery (Luo et al., 2015).*

When discharge process of VRFB is analyzed it is observed that VO_2^+ ion is reduced to VO^{2+} ion at the positive electrode of battery and V^{2+} is oxidized to V^{3+} at the negative electrode, which is represented in equations (11) and (12).

$$VO^{2+} + H_2O - e^- \rightarrow VO_2^+ + 2\ H^+ \tag{11}$$

$$V^{3+} + e^- \rightarrow V^{2+} \tag{12}$$

Charge process of battery is the reactions in opposite direction. In process of charging, active species are dissolved in a strong acid, and the protons transfer across ion-selective membrane to balance the charge (Luo et al., 2015).

When advantages of vanadium redox flow batteries are analyzed, it is observed that in these batteries, charge and discharge of other ions is not happened and that results in a longer lifetime than other battery technologies. In addition to that VRFB could be designed as a full automated system, and whole operation is environmentally friendly with easy maintenance and low operation cost. Although, there are several advantages of these batteries, some drawbacks are also observed. One of these disadvantages is that this battery needs costly ion-selective membrane usage, that can contribute more than 40% of the overall system expense. Furthermore, low stability and solubility of electrolyte decreases quality of energy density in this storage system (Sánchez Muñoz, Garcia and Gerlich, 2016).

3.5.2 Zinc Bromine Flow Batteries

The zinc-bromine battery is a sort of hybrid redox flow battery and during charging phase, zinc metal plate will be used for energy storage in phase of solid into anode plates of electrochemical stack. Therefore, total energy storage capacity of these flow batteries depend on area of electrode and size of the electrolyte storage reservoirs. (Butler et al., n.d.)

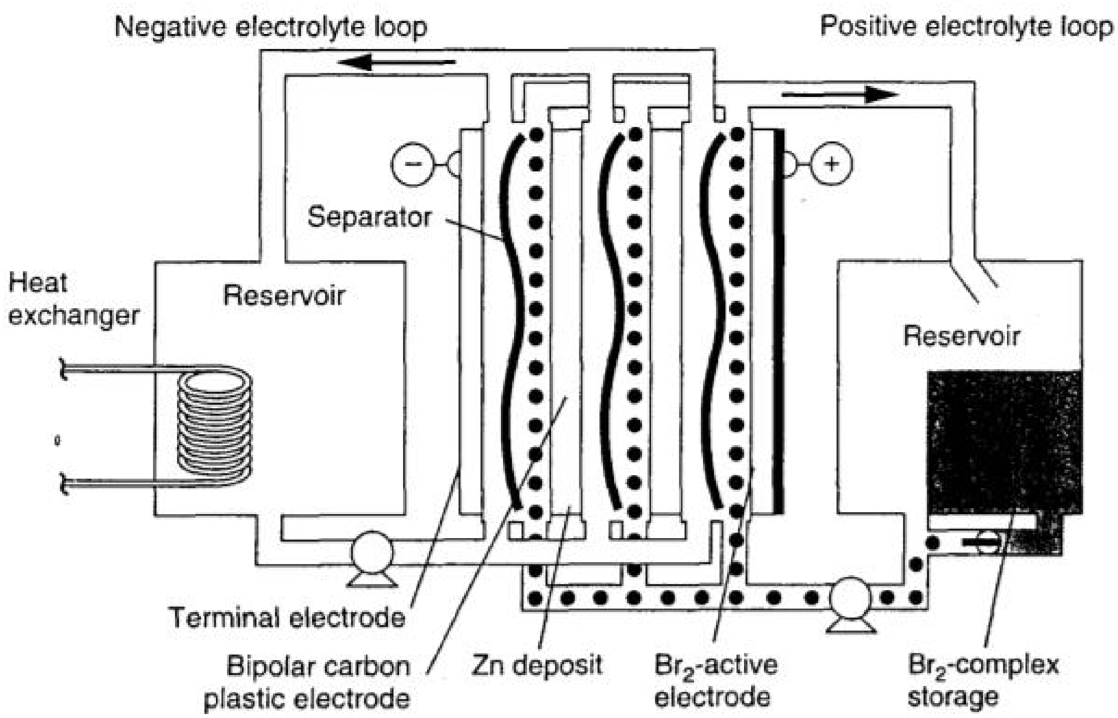

Figure 21. *Zinc Bromine Flow Battery (Butler et al., n.d.).*

As shown in figure 21, during charging phase, overall chemical reaction of zinc bromine battery includes zinc reduction and bromine evolution. Similar to this case, during discharging period, recombination of zinc and bromine creates $ZnBr_2$. One hand, when advantages of this battery is considered, well specific energy and energy efficiency, usage of low-cost materials, less environmental damage and system design flexibility can be listed. On the other hand, circulation and temperature control requirements and power capability development requirements have to considered in design of these storage systems (Butler et al., n.d.).

3.6 Solid Oxide Fuel Cells

Solid oxide fuel cell is a type of storage system that takes chemical energy and converts it to electrical energy directly. Main components of these fuel cells are electrolytes and electrodes that act as catalysts for electrical chemical reaction.

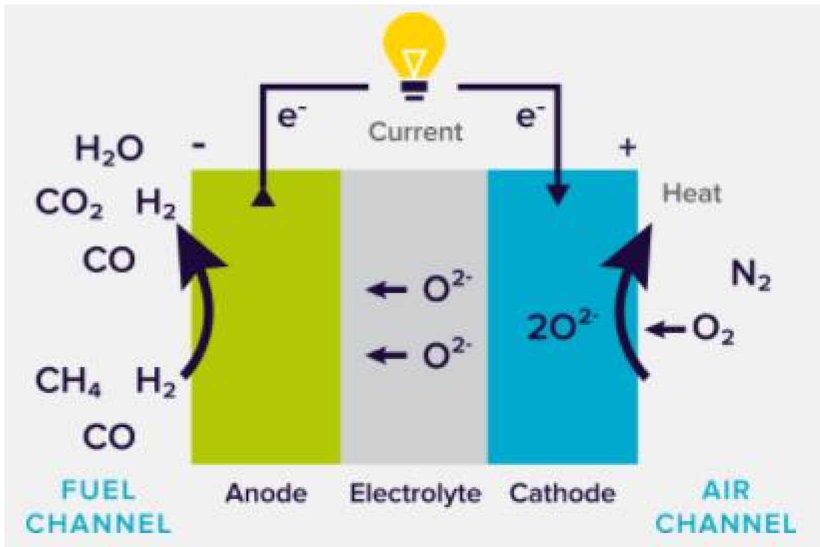

Figure 22. *Working Principle of Fuel Cell (Convion, n.d.).*

As shown in figure 22, fuel and air are supplied to anode and cathode sides of electrodes, respectively, where fuel gets electrochemically oxidized while oxygen decreased and that leads to DC current in an external circuit (Convion, n.d.). From figure 22, it can be also understood water and carbon dioxide are products of these chemical reactions and it is type of exothermic reactions that create heat to environment. Similar approach to solar cells, to be able to reach higher voltage in fuel cells they can be connected in series.

In advantage analysis of solar oxide cell, one of the main benefit could be its improved reaction kinetics due to high operation temperature. In addition to that, its high temperature operation creates possibility of reforming fuels within fuel itself and that eliminates requirement for external reforming (Convion, n.d.).

3.7 Capacitor and Supercapacitor

As another significant electrical energy storage, capacitor is made of two electrical conductors which are separated by insulator that is generally materials like plastic film, ceramic or glass. In charging phase of capacitor, energy storage is happened in the dielectric material in an electrostatic field. In this storage system, maximum operation voltage is related to breakdown characteristics of dielectric material. In addition to that, they are preferable for smaller energy storage requirement and varying voltage conduction because these storage systems provide a higher power density and shorter charging time among other battery technologies (Luo et al., 2015).

Supercapacitors, also named as electric double-layer capacitors or ultracapacitors, comprise two conductor electrodes, an electrolyte, and a porous membrane separator. Because of their characteristics, these supercapacitors have capability of characteristics combination of both electrochemical batteries and capacitors. In this system, static charge between electrolyte and electrodes of capacitor create energy storage. Increment of supercapacitors' performance are mostly related with chosen nano materials by extending electrode surface area. These capacitors are very advantageous especially with more than 10^5 cycles cycling times and 84-97% cycle efficiency. Furthermore, it can be observed that supercapacitors merge energy storage features of battery systems with power discharging qualifications of capacitors. By using electrodes of capacitor which are made of very high surface area activated carbon, with a molecule-thin layer of electrolyte high energy density can be achieved. Since total amount of stored energy in capacitor will impact from the surface area of electrode positively and decreasing the gap between electrode and electrolyte will improve energy density (Luo et al., 2015).

In addition to these advantages, since, flexibility of no need of chemical reactions for both charging and discharging phases of supercapacitor, these two phases can happen very quickly (milliseconds to seconds) and cycle life of supercapacitor is almost unlimited (Sánchez Muñoz, Garcia and Gerlich, 2016). When main drawback of super capacitor is considered, one of its disadvantages can be its low energy density. In addition to that when it is compared with other chemical batteries, high-self discharge will be observed.

3.8 Superconducting Magnetic Energy Storage

In superconducting magnetic energy storage(SMES) system, there are three main parts that are superconducting coil unit, power conditioning subsystem and refrigeration and vacuum subsystem as shown in figure 23.

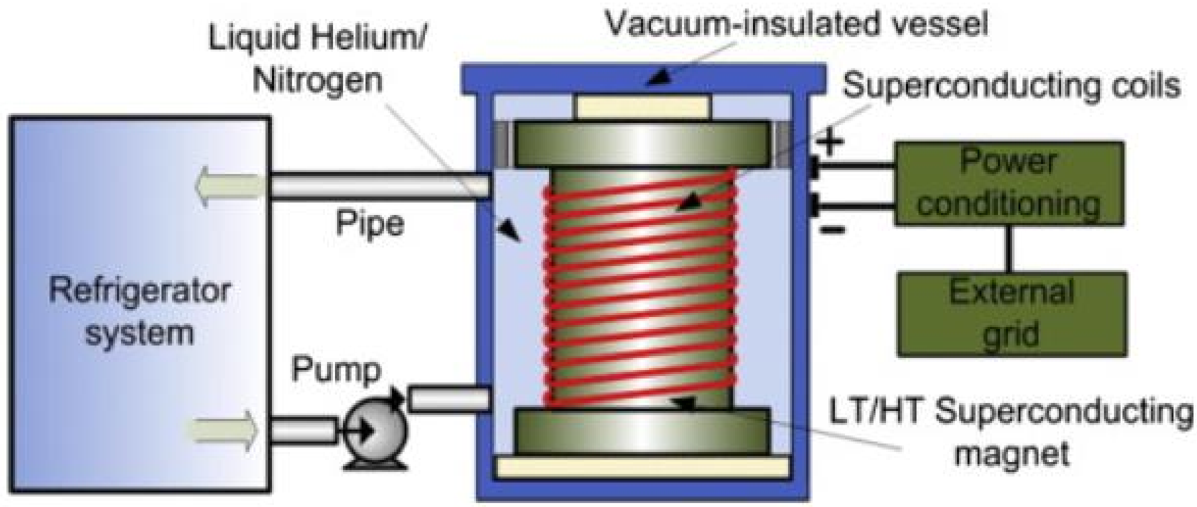

Figure 23. *Superconducting Magnetic Energy Storage (Luo et al., 2015).*

In SMES, energy storage is in magnetic field form that is generated by the current in the superconducting coil as represented in equation (13). This could be released by discharging the coil of battery. These coils generally include materials of niobium-titanium (NbTi) filaments. Due to high effectiveness of this system, SMES can be adjusted from full discharge to full charge phases very quickly and vice versa (Luo et al., 2015).

$$E = \frac{1}{2}LI^2 \tag{13}$$

In general mechanism of system, when current passes through superconducting coils, resistance of wire will cause energy dissipation in form of heat, but if superconducting material is used, it creates almost zero resistance in superconducting state and this power losses of system could be minimized. When main advantages of SMES are analyzed, system's up to 4000000 W/m^3 power density, millisecond-level response time, less than 1-minute full discharge time, 95-98% cycle efficiency, up to 30 years lifetime can be stated (Oberhofer, 2012). However, SMES technology has large amount of power requirement to keep coil at low temperatures that leads to increment in overall cost for unit. Economic advantage of SMES can be satisfied in case of short cyclic periods only with maximum duration of storage. Since, SMES has higher self-discharge ratio for long periods (10- 15% per day) and mechanical stability issues (Luo et al., 2015).

3.9 Liquid Air Energy Storage

In liquid air energy storage (LAES) technology, medium for energy storage will be made of liquid air or liquid nitrogen. As shown in figure 24 liquid air is kept in insulated low-pressure tanks at extremely low temperatures. Importing of liquid air tank could be done in two ways that are either obtaining from existing supply chains or manufacturing on site via a liquefaction plant. In this energy storage system, energy need will be satisfied by pumping liquid air from the tank by using heat exchangers for expansion and driving of generating turbine. Waste heat can be implemented in this system for incrementing the efficiency of the conversion process for LAES. Further gain of system efficiency can be satisfied by recovery of the cold air from conversion process (English, 2017).

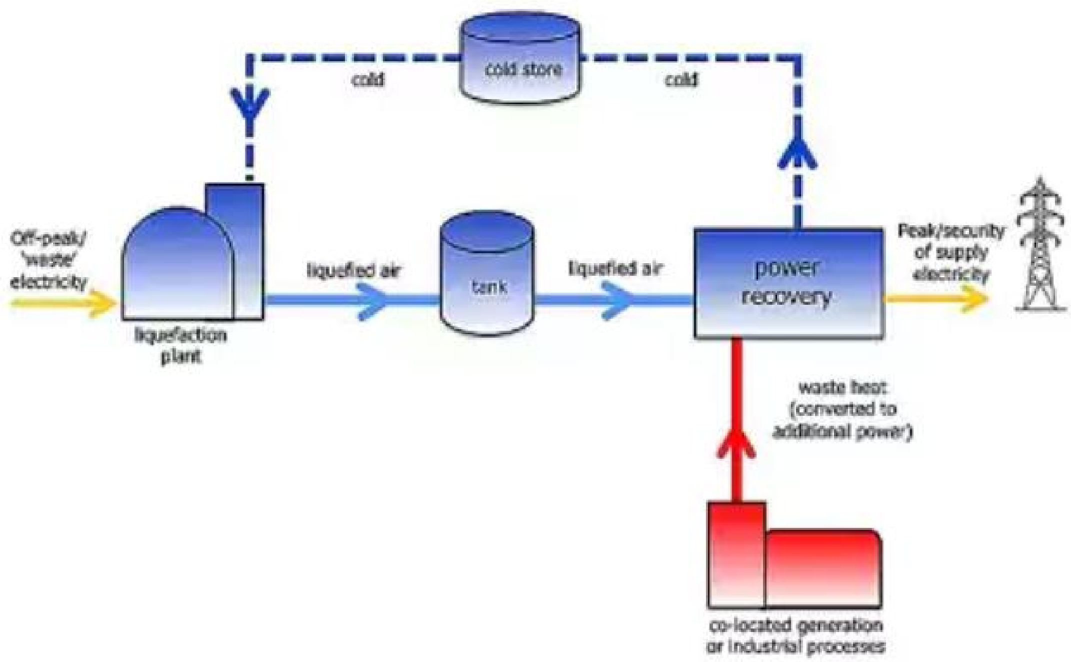

Figure 24. *Liquid Air Energy Storage System (English, 2017).*

When advantages of this technology are examined one of the main points can be a fact that LAES boasts competitive pricing with low amount of capital and operating costs. In addition to that, unlike traditional air storage systems, this system uses underground caverns which can be mounted in anywhere. When LAES is compared with battery storage systems, it is realized that in these storage systems life expectancy is longer which is around 25 years. Furthermore, in liquid air energy storage systems, integration of waste industrial heat and cold is possible that could develop the overall efficiency of the system. Lastly, due to fast process of LAES there is no scarce materials or harmful emissions happened and this creates clean energy possibility for electrical energy storage technologies.

In addition to these advantages of liquid energy storage system there are some disadvantages of same system. One of these drawbacks is its smaller efficiency when it is compared with battery and pumped-hydro storage systems. Another important issue of LAES is lack of ability of implementation for communities and individuals' homes and offices. Lastly, when this technology is compared with other battery storage systems it is observed that LAES takes few seconds to minutes longer than batteries for responding power demand (English, 2017).

3.10 Latent Heat Storage Systems

In latent heat storage systems, heat will be stored while changing phase as represented in figure 25. In this system, mostly common used phase change is solid-to-liquid, but also solid-to-solid changing is of interest. Theoretically, during these phase changes, temperature will remain same and in real systems, temperature stabilized around melting point which is the main characteristic of latent heat storage systems. Due to this fact, materials that are used on this storage system, is known as phase change materials(PCM) (Large.stanford.edu, 2010).

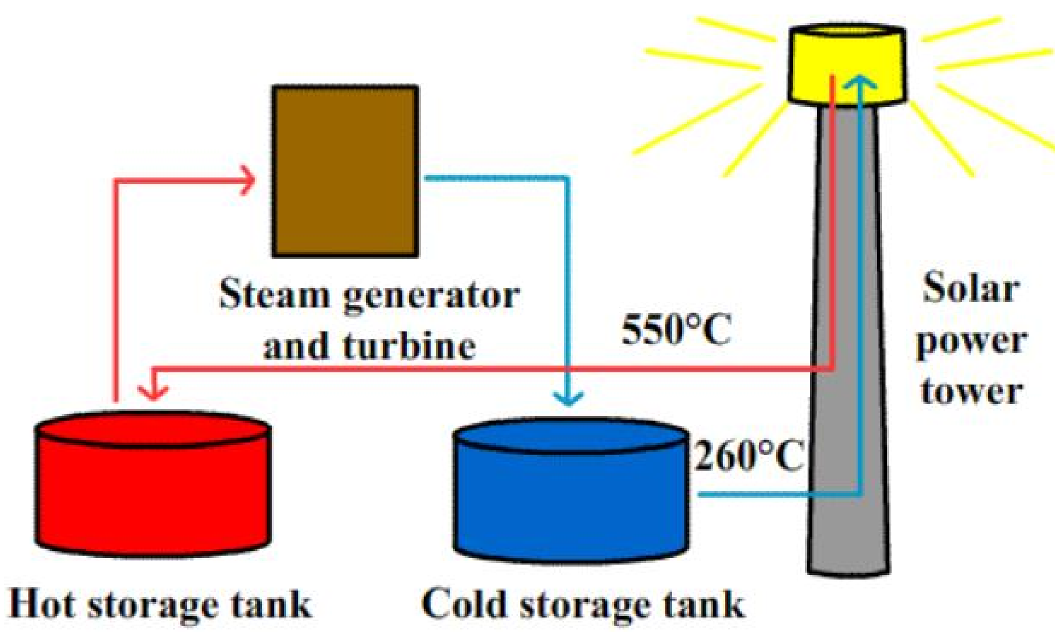

Figure 25. *Latent Heat Storage Systems (Large.stanford.edu, 2010).*

When this technology is analogized with other thermal storage systems, it usually has higher energy storage densities. This situation is occurred because the enthalpy difference associated with change of phases is larger compared to sensible heat storage systems with a material across a typical temperature range. Despite of these important advantages, there are some drawbacks of latent heat storage systems. Phase changing materials of systems are expensive and heat generation storage capacity will be diminished after several cycles due to incongruent melting. In addition to that, because they solidify, an additional heat transportation medium with a heat exchanger should be implemented to this storage system (Large.stanford.edu, 2010).

3.11 Molten Salt Technology

Molten salt is a sort of salt that tends to be a solid under standard conditions of temperature and pressure but transforms a liquid at elevated temperatures. This salt type is widely used in industry for several applications such as power generation, material science, heat transferring in industrial processes. A significant qualification of these salts is its ability to conduct electricity and this makes these salts very good candidate for electricity generation from renewable sources.

As shown in figure 26, in this storage system, molten salt will be circulated through special piping system of heat exchanger during the day and stored in storage tanks at night. Usage of molten salt in storage systems have several advantages especially in both heat transfer and thermal energy storage minimization of number of storage tanks and required salt volumes. Furthermore, molten salt has environmental-friendly sodium nitrate and potassium nitrate mixture which has ability of utility as high-grade fertilizer when the plant is eventually decommissioned (Roman et al., 2011).

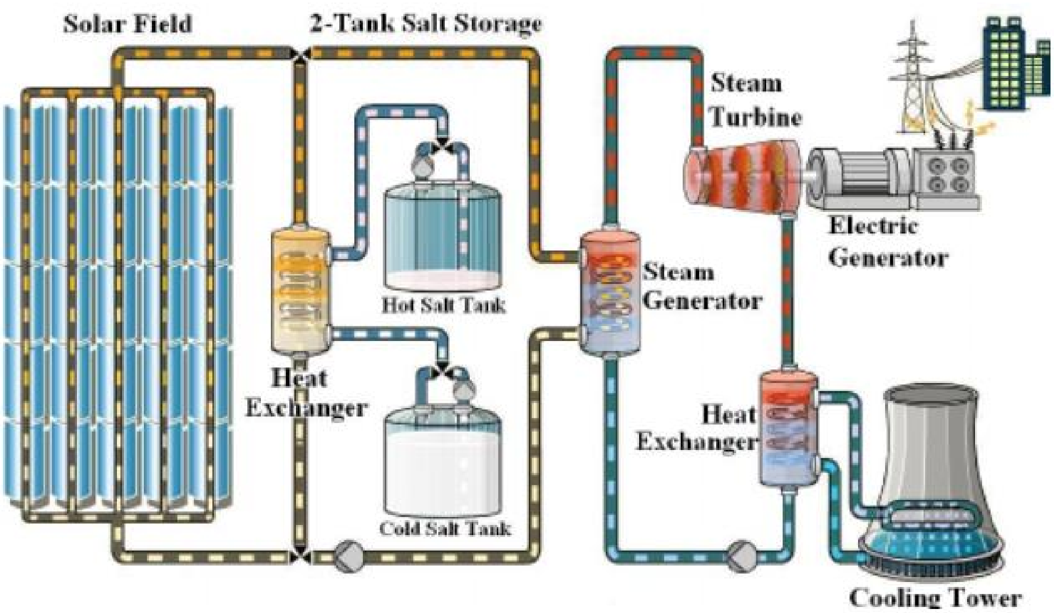

Figure 26. *Molten Salt Technology (Roman et al., 2011).*

As another advantage of molten salt storage technology, its ability to be heated to 1050°F can be thought. This characteristic allows high energy steam to be created at utility-standard temperatures reaching high efficiency of 40 percent of thermodynamic cycles in turbine systems. Furthermore, molten salt transfers loop through the receiver and isolation between main stream temperatures and

this receiver will be satisfied. In this way, system will become less expensive through low-pressure salt pipping usage (Renewableenergyworld.com, 2008).
Despite of all these advantages, this salt mixture has higher melting point. Due to this condition, this salt mixture can freeze and block the pipeline during winter time. To be able to solve this problem, auxiliary facilities are required to be installed that leads to investment and operation costs increment (Renewableenergyworld.com, 2008).

3.12 Hydrogen Energy Storage

Hydrogen atom can occur only in combination with other elements to form a chemical product such as oxygen in water and carbon, nitrogen and oxygen in organic materials and fossil fuels. Although it is not primary energy production source, hydrogen becomes a good way for energy carrier by splitting other elements. Due to this feature, hydrogen energy storage is considered as clean fuel of future. Main advantages of using this storage can be listed as, developing sustainability by implementing renewable energy sources, reducing pollution and reaching better urban air quality by generating near-zero carbon, hydrocarbon (Luo et al., 2015).
In hydrogen energy storage, water electrolysis technology usage provides very flexible energy storage on a large, long-term scale. As shown in figure 27, in this technology, Proton Exchange Membrane (PEM) electrolyzer splits water into its basic constituents, hydrogen and oxygen, and storage of these constituents could be done in common tanks of this storage system (Schiller, 2014).

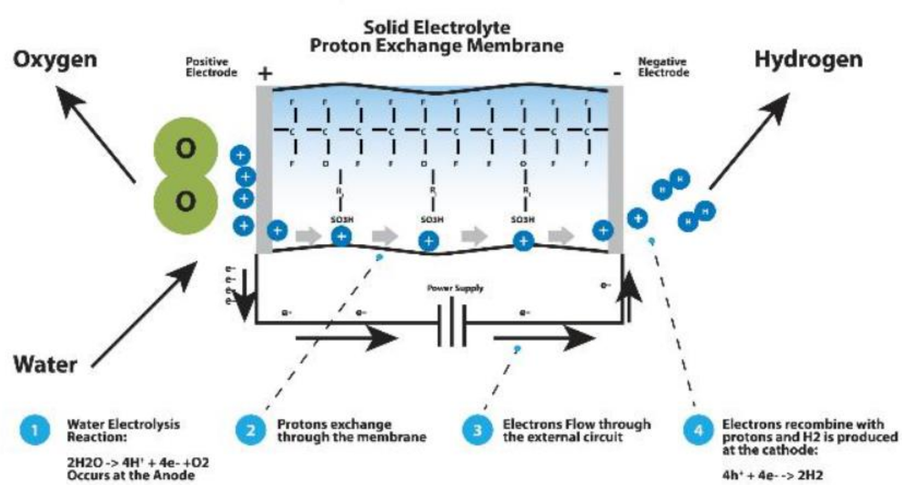

Figure 27. *Proton Exchange Membrane (Schiller, 2014).*

3.13 Thermochemical Energy Storage

In thermochemical energy storage, thermal energy is used for driving endothermic chemical reaction to store energy as potential chemical energy. In high solar radiation, when energy is required energy-consuming reactions store thermal energy in chemical bonds. Reversely, chemical reaction recombines chemical reactants to release energy.

In this type of electrical storage, main purpose is to develop system for dispatchable and effective concentrated solar power generation via combined power cycles. As represented in figure 28, thermochemical energy storage significantly depends on the manganese-oxide redox cycle in a system which includes two fluidized-bed reactors that are for solar higher-temperature endothermic reduction and non-solar lower-temperature exothermic oxidation. In this system, stable and durable redox materials will satisfy high reaction rates and high-efficient solar reduction reactor improvement. Under favor of symmetric vertical orientation, solar reactor allows to suppress convective heat losses from receiver caves and high optical efficiency will be observed in this thermochemical storage system (ANU College of Engineering & Computer Science, 2018).

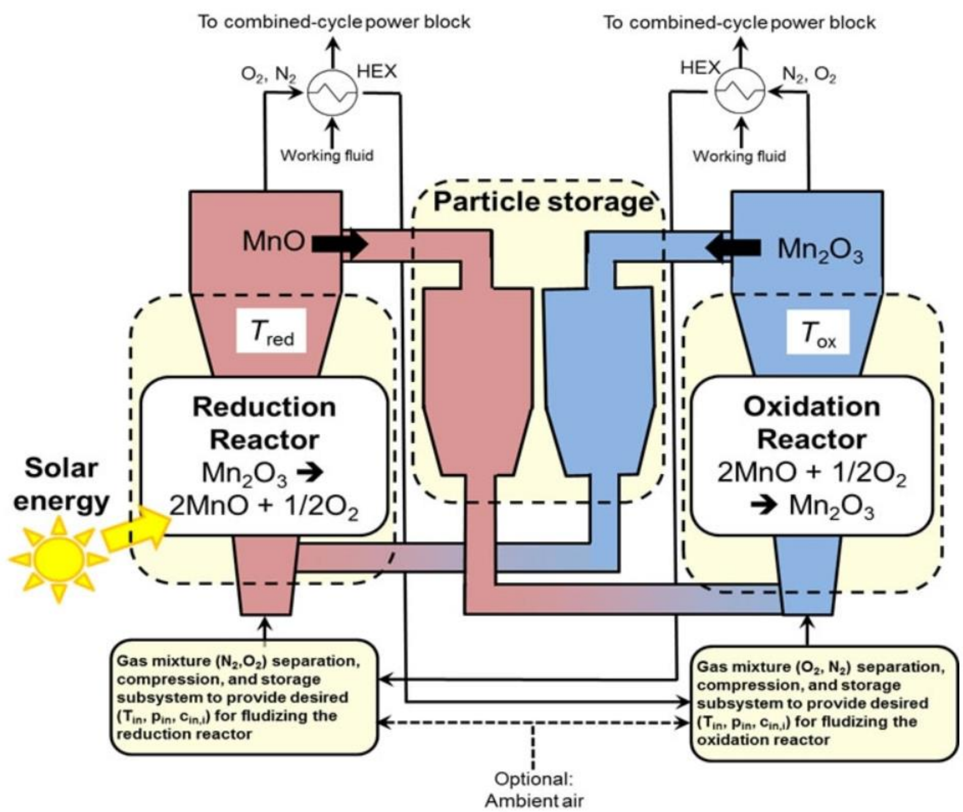

Figure 28. *Thermochemical Energy Storage (ANU College of Engineering & Computer Science, 2018).*

When advantages of thermochemical energy storage are considered, it has higher energy density than latent heat storage systems because, in addition to sensible heat, energy is stored as chemical potential energy. When endothermic reactions of thermochemical energy storage is compared with molten salt technology, it can operate at higher temperatures. In higher temperatures, operation provide higher efficient power cycles in energy storage. These two advantages reduce cost for energy storage for solar power systems. However, there are some drawbacks of thermochemical energy storage which are shorter service life and material compatibility problems in high-temperature chemically reactive system conditions (AuYeung and Kreider, 2017).

4 COMPARISONS BETWEEN ELECTRICAL ENERGY STORAGE TECHNOLOGIES

4.1 Electrical Storage Capacity and Discharge Time

When all electrical energy storage technologies are compared in terms of power capacity, it is observed that PHS, SMES and CAES have higher capacity. However, for pumped hydroelectric storage and compressed air there is need for higher discharge time as can be seen from figure 29.

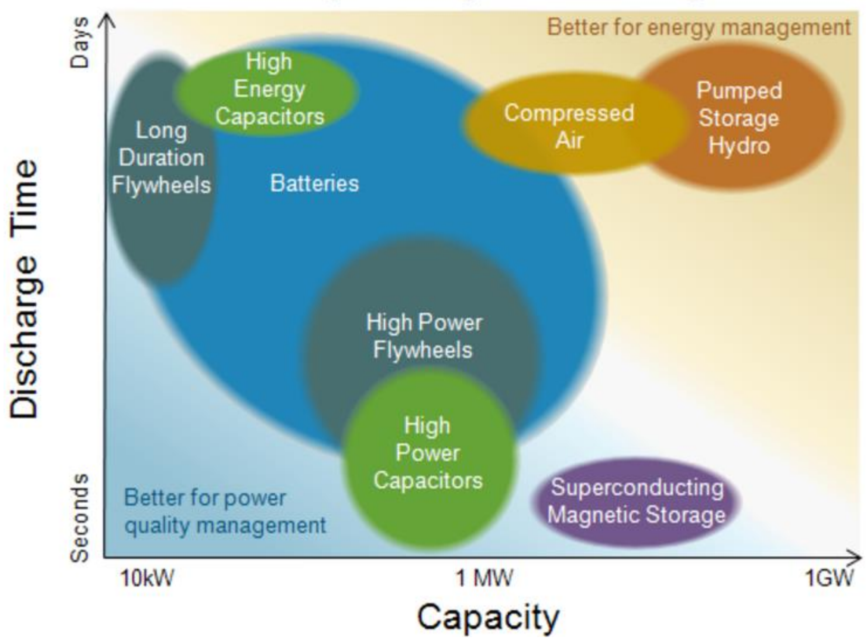

Figure 29. *Power Capacity and Discharge Time Relationships Among Electrical Storage Technologies (Oberhofer, 2012).*

In addition to that flywheels and capacitors have comparably less power capacity but specially for high power capacitors and high-power flywheels there is no huge amount of discharge time requirement. Therefore, I can conclude that in terms of power capacity pumped hydroelectric storage and compressed air systems can be considered as more advantageous storage technologies. When I analyze discharge time, I reached that superconducting magnetic storage system and high-power capacitors need shorter time among other storage technologies.

4.2 Energy Density and Power Density

Energy density and power density terms are very significant variables to be able to analyze power and efficiencies of electrical storage technologies. As shown in figure 30, especially capacitors have higher power density. When battery energy storages are analyzed it is seen that they have lower power density values.

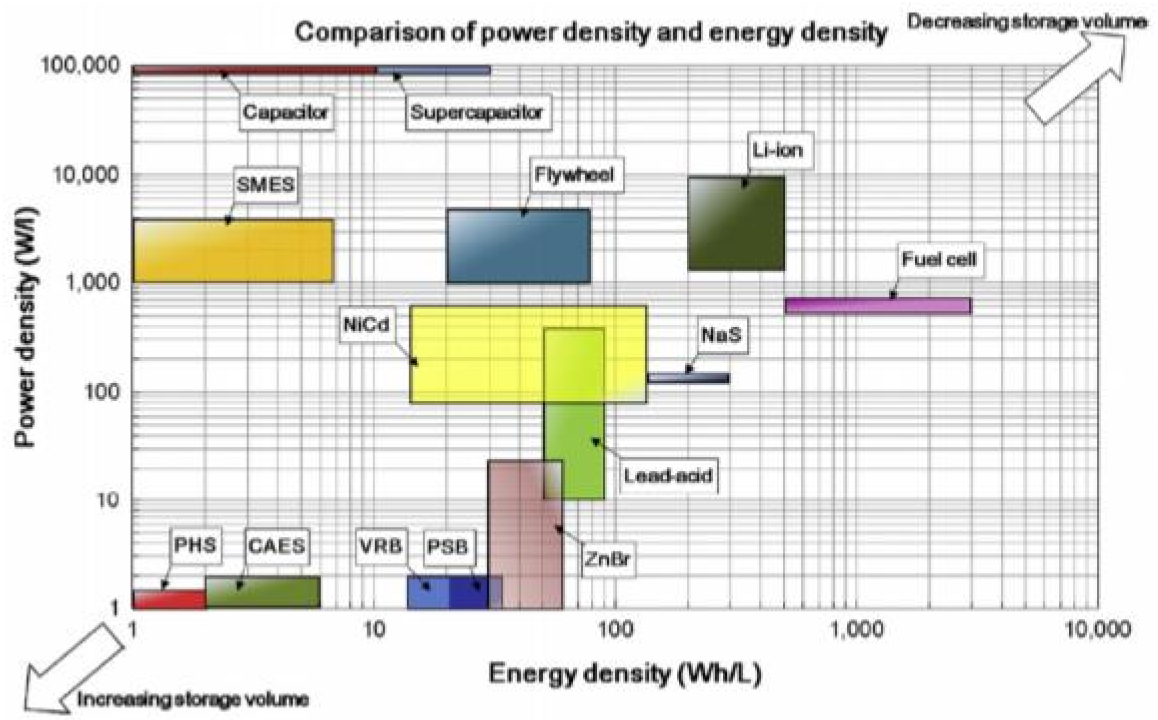

Figure 30. *Energy Density and Power Density Relationships Among Electrical Storage Technologies (Sánchez Muñoz, Garcia and Gerlich, 2016).*

In analysis of energy density, it is observed that battery energy storage systems have higher energy density values especially for lead-acid and NiCd batteries. On the contrary to these storage systems, capacitors with high power density, have very low values in terms of energy density.

Lastly, for flywheel storage systems, it has average values on both power and energy density. Therefore, for higher power or energy density requirement specification either capacitors or battery energy storage systems such as lead-acid, NiCd batteries can be preferred.

4.3 Cost of Electrical Storage Technologies

For being able to analyze systems' advantages and drawbacks, financial impacts are needed to be examined. When building electrical storage systems for power networks is considered, cost of these technologies can be analyzed in figure 31.

Figure 31. *Cost of Power Capacity Among Electrical Storage Technologies (Esource.com, 2017).*

As shown in figure 31, in terms of cost of power capacity, capacitors and thermal storage systems are cheaper than other storage technologies. When mechanical storage systems are analyzed such as flywheels, PHS and compressed air energy storage technologies they could be considered as medium-level expense technologies. Lastly, when battery energy storage systems and flow batteries are analyzed they are more expensive technologies than other storage systems.

4.4 Scale of Storage vs. Duration of Storage

Scale of storage and duration of storage are two important focuses for comparisons among electrical energy storage systems. When figure 32 is analyzed, it is observed that in terms of scale of storage, battery energy storage systems mostly have smaller scale and energy storages like SMES and flywheel energy storage systems have medium scale of storage. In addition to that, CAES and PHS have larger scale of storage.

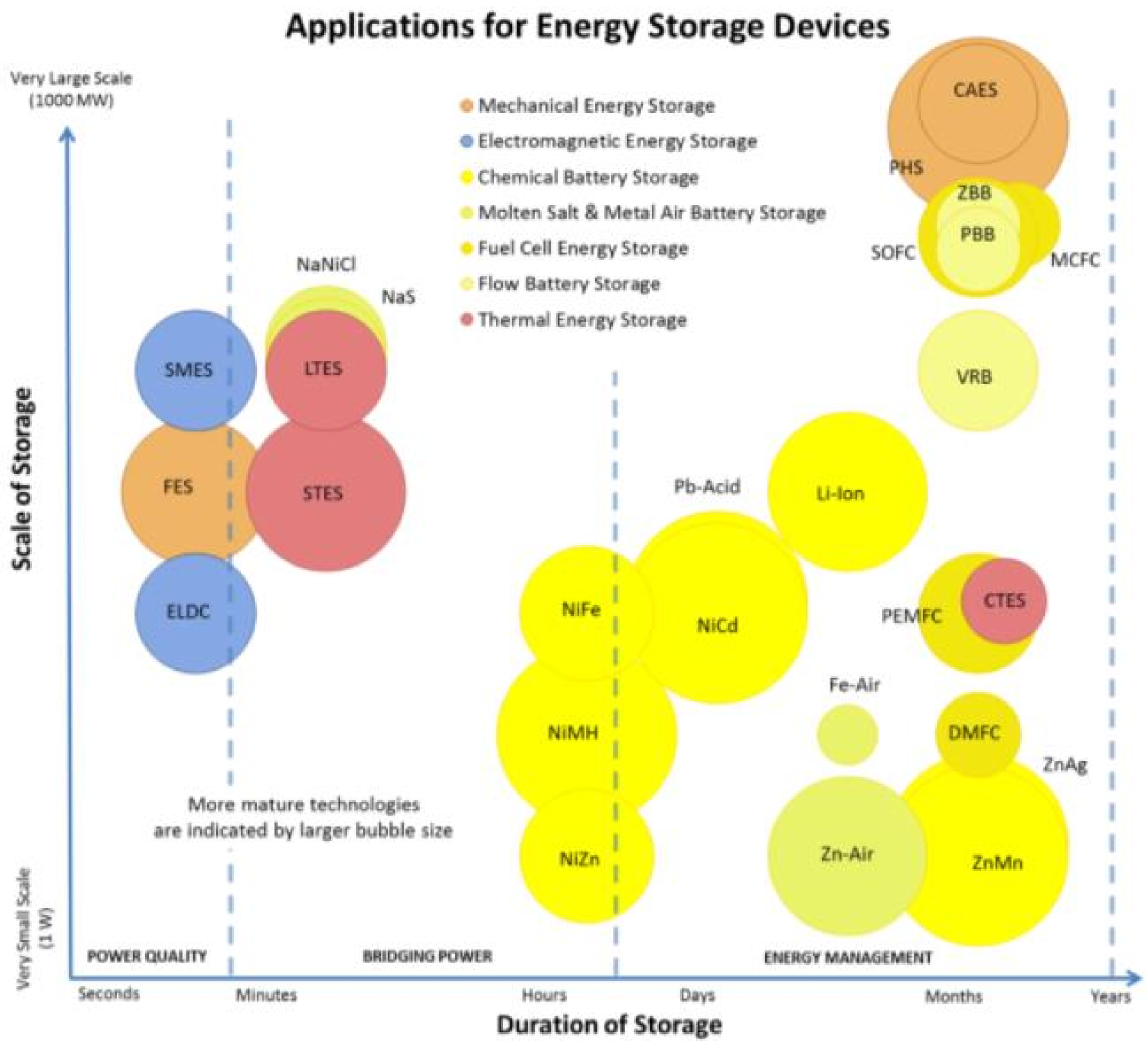

Figure 32. *Scale of Storage and Duration of Storage Relationships Among Electrical Storage Technologies (Sabihuddin, Kiprakis and Mueller, 2014).*

Similarly, as shown in figure 32, in terms of duration of storage SMES and flywheel energy storage systems have smaller duration of storage. However, when CAES and PHS systems are analyzed, it is observed that they have longer duration of storage. Lastly, mainly battery energy storage technologies have medium-scale of duration of storage.

4.5 Technical Maturity

Technical maturity involves readiness of technology for operations through a spectrum of environments with a final aim of transition to the user. This qualification includes determination of fitness for a specific technology to be able to meet customer's needs and desired outcome for operations. In electrical energy storage systems, technical maturity is significant variable that needs to be taken into account for comparison among these systems. As shown in figure 33, mechanical storage systems are in or close to mature-level. When battery energy storage systems are analyzed, they also reached maturity level. However, when technologies like fuel-cells, superconducting magnetic energy storage and supercapacitor are examined, their technologies are still developing.

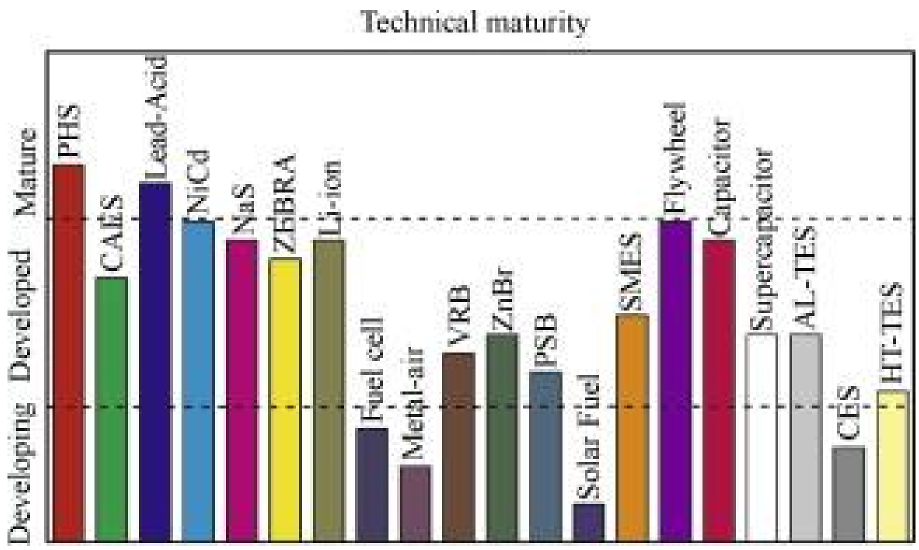

Figure 33. *Technical Maturity Among Electrical Energy Storage Technologies (Chen et al., 2009).*

4.6 Cycle Efficiency

As another important factor, cycle efficiency can be defined as shown in equation (14).

$$g = E_{out}/E_i \tag{14}$$

where g represents cycle efficiency, E_{in} and E_{out} is used for electricity input and electricity output, respectively. In figure 34, cycle efficiency of electrical energy storage systems is compared.

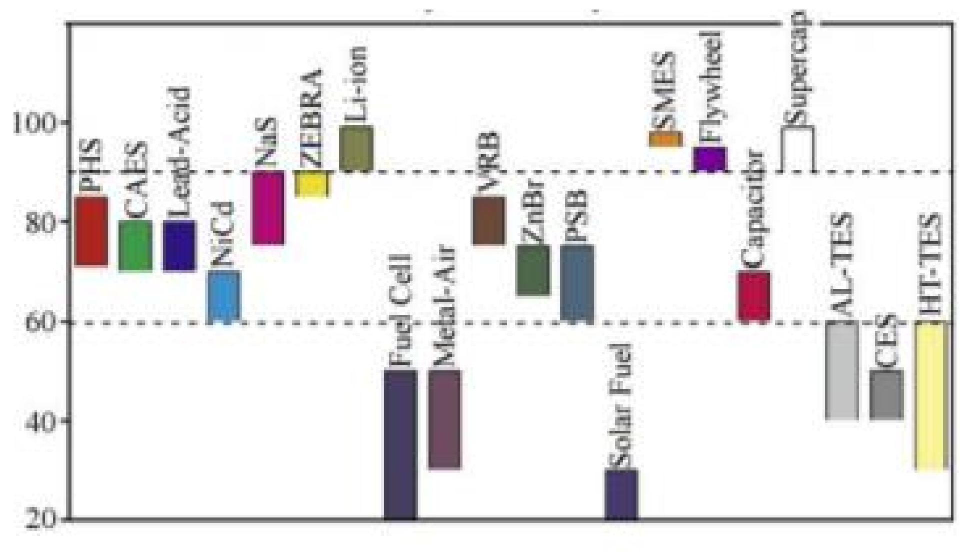

Figure 34. *Cycle Efficiency Among Electrical Energy Storage Technologies (Chen et al., 2009).*

In this comparison, it is understood that storage systems like supercapacitors, flywheels and SMES have highest cycle efficiency values. Battery energy storages like lead acid, Li-ion, NiCd and NaS have medium-valued cycle efficiencies. Lastly, storage systems like capacitors and thermal energy storage systems have lowest cycle efficiency among other technologies.

5 MAIN ROLES OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Roles of EES technologies can be classified mainly in two parts which are roles from the viewpoint of a utility and roles from the viewpoint of consumers.

5.1 Roles from Viewpoint of Utility

One of the most important duty of utilities is preparing supply capacity, both transmission and distribution lines to control annual increment of peak demand and develop electricity generation systems from primary energy sources. According to some utilities it is better idea to store electricity at off-peak times to reduce cost of generation. Reaching larger demand gap between peak and off-peak times creates higher requirement for electrical storage systems. Since, using these technologies will provide less gap between these two-time periods and reach flatter electricity generation outcome that is resulted with higher efficiency in operation and cost reduction in fuel. In addition to that, one of the main service of power utilities should have higher-tolerance supply power voltage and frequency by changing supply to adjusted demand. Frequency control will be implemented by adjusting power generators' outcome and electrical energy storage technologies can provide frequency control functions. When voltage control is considered it can be realized that taps of transforms are playing very significant role. Similarly, for reactive power control, phase modifiers can be used. For being able to improve power quality of system, these technologies can be implemented at the end of a heavily loaded line which might control both voltage drops and decreasing voltage increment, by discharging and charging electricity respectively. Furthermore, congestion might be observed if transmission and distribution lines cannot be matched to satisfy power demand increment. Under this condition, large-scale batteries located at appropriate substations might ease the congestion and therefore support utilities to hold over or suspend consolidation of network (Electrical Energy Storage, 2011).

When utility companies supply electricity from small, isolated power networks output power of small-capacity generators like renewable energy sources must satisfy the power demand. By installing electrical energy storage systems, a utility can supply stable power to consumers. Lastly, having a stable and reliable power supply to both protect and control is very significant in power utility companies. Several batteries are preferred as power supply for emergent situations in case of any outage.

5.2 Roles from Viewpoint of Consumers

In power systems, utilities might decide prices that can change continuously with time. By using this flexibility on decision, they can get lower prices during night-time and higher prices in day-time for giving consumers an incentive to flatten electricity load. Because of this system, consumers of electricity may decrease their own costs by implementing electrical energy storage technologies to decrease peak power required from grid in day-time and to purchase electricity during off-peak periods. In this way, total cost of electricity purchase can be minimized. Another important role from customer view is that customers might require continuous power supply like fire sprinklers and security equipment. Electrical energy storage systems might be located as a substitute for emergency generator to be able to activate in case of outage. Because of lightning, semiconductor and liquid crystal manufacturers are impacted by rapid change or any outage which might reduce quality of their own products. Under these situations, some electrical energy storage technologies like large-scale batteries, ultra-capacitors and superconducting magnetic energy storage can be mounted to prevent impacts of a momentary outage due to rapid change on the load of the network to the electrical energy storage supply.

Lastly, electric vehicles include high-efficient battery systems such as NiCd, Nimh, Li-ion which are installed on these vehicles and considered as power supplies. Electrical vehicles' batteries could be used power in-house appliances by combining with solar power and fuel cells and researches are improved to analyze possible connection of these batteries to power networks. These chances are often named as vehicle to home (V2H) and vehicle to grid(V2G) (Electrical Energy Storage, 2011).

6 SMOOTHING PHOTOVOLTAIC POWER FLUCTUATIONS

6.1 Battery Energy Storage Station

In solar systems, produced energy can be very unstable in different periods of days due to position of sun, clouds, and other environmental impacts. In these unstable conditions, very rapid fluctuations will be occurred in very short time periods. To be able to use this solar power in different systems feeding power by using different smoothing methods for fluctuations become more essential. For this purpose, BESS technology can be used as combination of conventional Static Synchronous Compensator (STATCOM) technology and Direct Current (DC) power source. In BESS technology, STATCOM is used to be able to achieve control of reactive power flow by altering amplitude modulation ratio of converters (Li, Hui and Lai, 2013).
BESS battery systems can be implemented for several reasons such as frequency regulation, grid stabilization, transmission loss reduction, diminished congestion, and increased reliability (Li, Hui and Lai, 2013). This technology can be used for solar power smoothing to be able to compensate fluctuations. In this way, BESS energy capacity request will be decreased by preventing drawbacks from nature of PV system's outcomes.

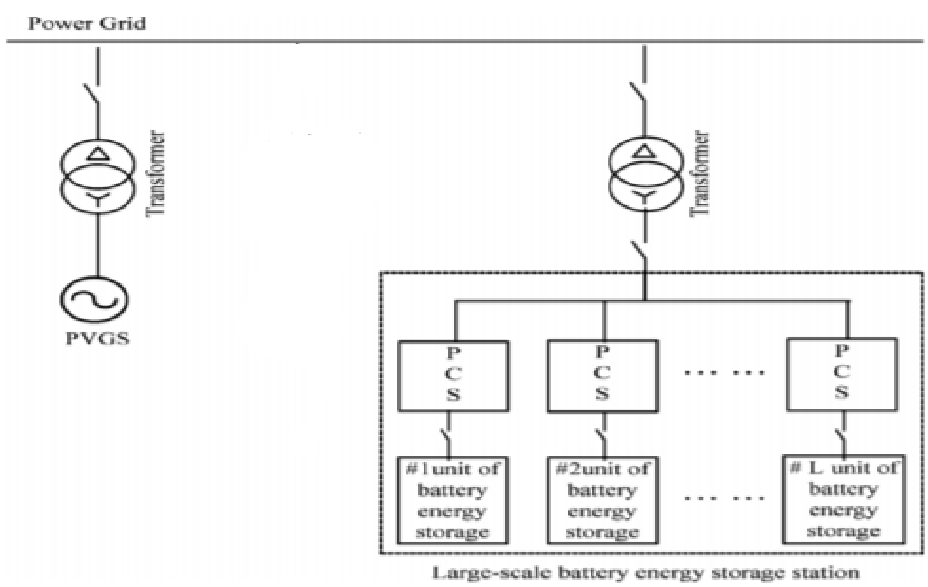

Figure 35. *Photovoltaic-BESS Hybrid Power Generation System (Li, Hui and Lai, 2013).*

For being able to reach satisfied measurement in storage systems, state of charge is required to be used. State of charge(SOC) might be used to define system's remaining capacity which is a very significant value for a control strategy and it represents performance of the battery. In addition to that, SOC satisfies accurate estimation of the state of charge that can not only preserve battery, prevent over discharge, and develop battery life but also allow the system to create control strategies to save energy (Li, Hui and Lai, 2013).

PV-BESS combined power generation system as represented in figure 35 where PVGS represents photovoltaic power generation system and PCS is used for power converter system along with a SOC-based smoothing control strategy was implemented to be able to flatten photovoltaic fluctuations. This could be achieved by adjusting required output and providing flexible feedback system of battery SOC in real-time (Li, Hui and Lai, 2013). Therefore, open circuit voltage and charging and discharging resistances of the BESS system will depend on SOC which is shown in figure 36:

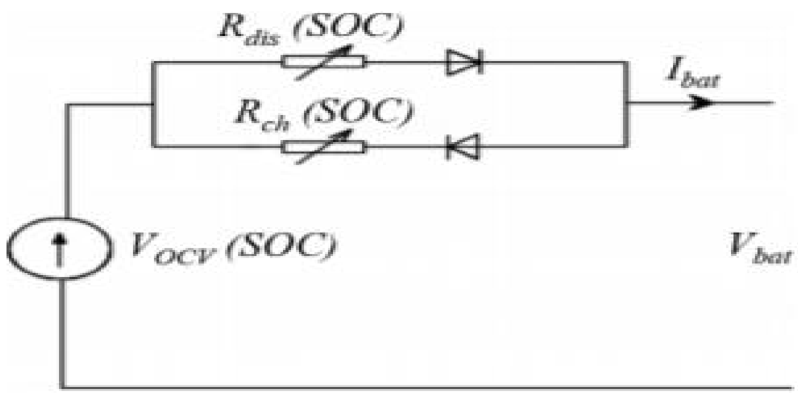

Figure 36. *Equivalent Circuit of BESS (Li, Hui and Lai, 2013).*

Internal resistance of BESS system can be calculated as below where V_{ocv} is an open circuit voltage, V_{bat} is a battery voltage, I_{bat} is a current of battery and R_{int} is an internal resistance.

$$R_{int}=(V_{ocv}-V_{bat})/I_{bat} \tag{15}$$

This internal resistance will be affected separately from both discharging and charging resistances which is shown in equation (15). Efficiency rates for charging and discharging periods can be formalized by using equations (16) and (17).

For charging

$$\eta = \frac{V_{OCV}}{V_{OCV}-I_{bat}R_{ch}} \tag{16}$$

where R_{ch} is charging resistance.

And for discharging

$$\eta = \frac{V_{OCV}-I_{bat}R_{dis}}{V_{OCV}} \tag{17}$$

where R_{ch} is discharging resistance.

These two efficiency values are very significant to be able to control the fluctuations of hybrid power generation unit which includes both PV and BESS system. Since this system is SOC-based and SOC is directly related with efficiency of this hybrid system as given in equation (18) where Q_{bat} is charge of battery:

$$SOC = SOC_{ini} - \int \frac{\eta I_{bat}}{Q_{bat}} dt \tag{18}$$

If the single storage unit of SOC is higher or lower, the adaptive coordination of the smoothing level of the power distribution between ESSs in the system must be deliberated based on state of charge and the maximum available charging or discharging power limitations of BESS. For providing smoothing storage systems in integrated PV units, the following 4 steps can be considered (Li, Hui and Lai, 2013).

In first step determination initial target power of BESS is needed to be considered. For that purpose, target power for BESS system, rate of power change of time can be reached as given equation (19) where r_{PV} is rate of power change in PV cell and P_{PV} is power of PV cell.

$$r_{PV} = \frac{P_{PV}(t) - P_{PV}(t - \Delta t)}{\Delta t} \tag{19}$$

If this rate is between rise and drop limiter rates target power will be assigned as P_{PV} value for the system. If it is not between these rises and drop limits it can be added or subcontracted multiplication of time intervals and these two drop limits that can be formulated as shown in equations (20) and (21):

$$k_{rise,PV} = \frac{P_{PV}(t) \times \delta_{PV}}{T} \tag{20}$$

Where $k_{rise,PV}$ is rise rate limit value of PV Cell and δ_{PV} is fluctuation rate limit for PV cell.

$$k_{drop,PV} = -\frac{Ppv(t) \times \delta pv}{T} \tag{21}$$

Where $k_{drop,PV}$ is drop rate limit value of PV Cell and in T period (Li, Hui and Lai, 2013).

In second step determination of target power each converter systems is needed to be implemented. Target power of each separate power converter system can be reached by division of total target power to each system which can be formalized as below for k separate units where P_i^{ini} initial power of unit i, u_i start-stop status of unit i and SOC_i is state-of-charge of unit I as shown in equation (22).

$$P_i^{ini} = \frac{u_i SOC_i}{\sum_{i=1}^{k}(u_i SOC_i)} P_{BESS}^{ini} \tag{22}$$

As a following step determination of modified target power of each power converter systems need to be applied. It can be formulated for each PCS as represented in equation (23):

$$\Delta P_i = A_i u_i \gamma_i \tag{23}$$

Where A_i is being used to be able to accelerate control effect, γ_i which is computed in equation (24), to avoid upper and lower bound limitations of state of charge for BESS integrated PV system (Li, Hui and Lai, 2013). For reaching this limitation value for system following control effect needed to be calculated which is formalized as below:

$$\gamma i = \frac{SOC_i - SOC_{ref}}{0.5(SOC_{i,max} - SOC_{i,min})} \quad \text{where } SOC_{ref} = \begin{cases} 0.2 & if\ SOC_i \leq 0.1 \\ 0.8 & if\ SOC_i \geq 0.9 \\ SOC_i & otherwise \end{cases} \tag{24}$$

As a last step after modifications of all these three steps, modified initial power for each unit can be modified as given in equation (25):

$$P_{ini,new} = P_{ini} + \Delta P_i \tag{25}$$

After calculation of each unit's initial power summation of all these units' initial power of BESS can be reached. To sum up after modifications of initial power for new condition, control systems to smooth PV output can be achieved (Li, Hui and Lai, 2013).

6.2 Moving Average Algorithm

In this strategy to be able to smooth fluctuations in ESS integrated PV systems, one of the strategies could be Moving Average Strategy. By using this algorithm, smoothed power of grid could be calculated as average value in period of T as shown in equation (26).

$$P_G(t) = \frac{1}{T}\int_{t-T}^{t} P_{PV}(t)dt \tag{26}$$

It can be concluded that the greater period for window T, the higher performance of smoothing fluctuations at $P_G(t)$. In this strategy one of the most important advantages is that if the system is equipped in ideal conditions, efficiency of both battery and converter will be same at the beginning and end of any given day. Thus, SOC control is not required to avoid the continuous battery discharge. However, it should be also considered that in non-ideal cases this advantage of strategy will be removed and at the end of the day, the battery is discharged to a value equal to energy loss of both charging and discharging processes in the energy storage systems (Marcos et al., 2014).

6.2.1 MATLAB Simulation Results of Moving Average Algorithm

For being able to analyze efficiency of moving average algorthm, noisy signal is created in MATLAB as shown in figure 37. In this way, I reached a simulated fluctuated power signal to implement moving average algorithm on it.

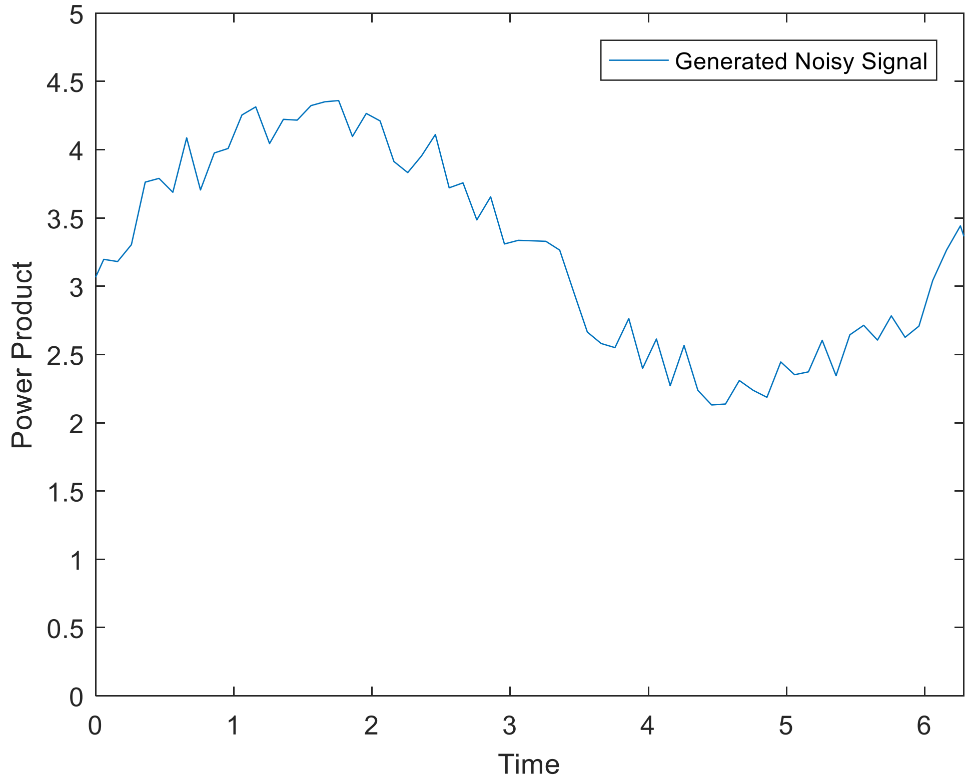

Figure 37. *Plot of Generated Noisy Signal in MATLAB.*

For implementing moving average algorithm in a period *T* mean of power signal was taken at these time intervals as shown in equation (26). When I observe difference between, signal and its smoothed version by using moving average algorithm as in figure 38, smoothed signal was eliminating most of fluctuations. Therefore, by using this algorithm power fluctuations can be smoothed effectively.

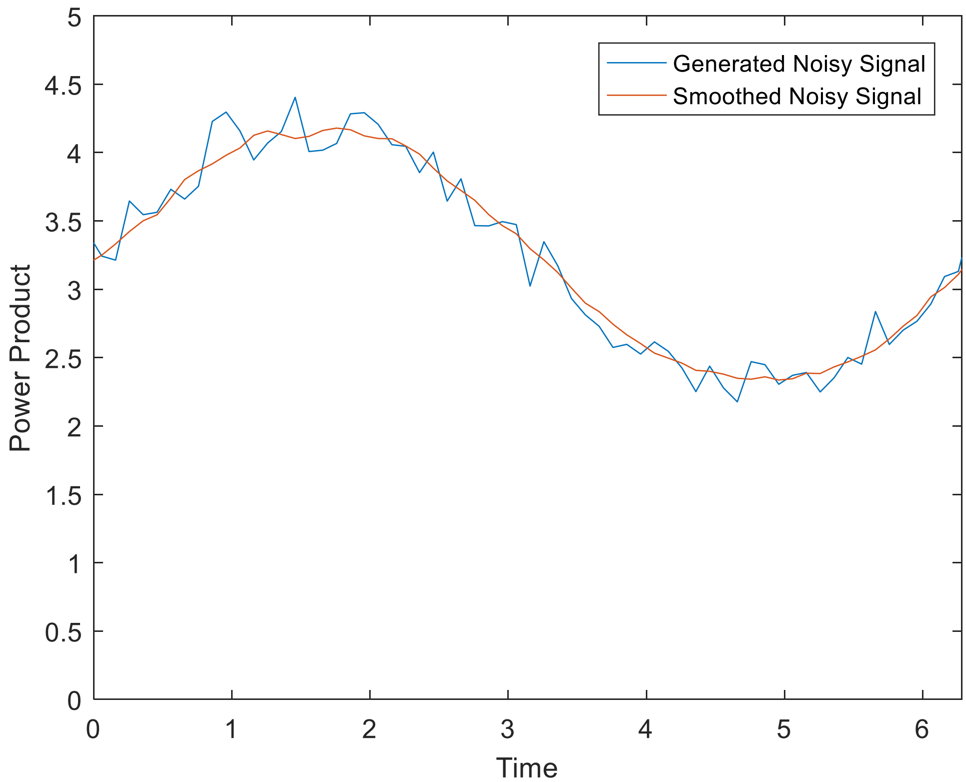

Figure 38. *Comparison of Generated Noisy Signal and Smoothed Noisy Signal.*

7 CONCLUSIONS

Solar power systems are considered as one of the renewable energy resources and these systems' outcomes required modifications. Since solar systems create fluctuated output by impact of sun angle, cloud cover etc. As a unit of solar power systems, photovoltaic cell is implemented for conversion of solar radiation to electricity. In these photovoltaic cells, I-V curve is impacted by temperature, irradiance, series resistance, shunt resistance and ideality factor.
In this thesis, different electrical energy storage technologies for solar power systems are analyzed. As mechanical storage systems, PHS, CAES and FES can be considered. In addition to that, battery energy storage systems such as, lead-acid battery, lithium-ion batteries, sodium-sulfur batteries, nickel-cadmium batteries, nickel metal hydride batteries and carbon-zinc batteries can be used for storage of solar power systems. Furthermore, for solar power systems, flow battery energy storage systems, solid oxide fuel cells, capacitor and supercapacitors, SMES, LAES, molten salt technology, hydrogen storage and thermochemical energy storage systems could be preferred.
In comparison of energy storage systems, first focus was electrical storage capacity and discharge time. In analysis of this comparison, it is concluded that pumped hydroelectric storage systems and compressed air storage systems have both highest capacity and discharge time. One hand, superconducting magnetic storage systems, high power capacitors are more advantages in terms of low discharge time and high capacity. On the other hand, high energy capacitors and long duration flywheels have lower capacity at higher discharge time. In addition to this comparison, power density and energy density was examined among these storage systems. In terms of power density, highest values can be reached at capacitors and flywheel energy storage systems. Among all energy storage systems, fuel cells, lead-acid battery, lithium-ion battery, and nickel-cadmium battery will have highest energy density. As another side of this comparison cost of power capacity was considered in this thesis. It is observed that flow battery energy storage, battery energy storage and pumped hydroelectric storage systems reach highest power capacity cost. Contrary to this condition, capacitors and thermochemical energy storage systems have lowest power capacity cost. As another comparison, scale and duration of storage could be analyzed. In analysis of scale of storage, it is observed that CAES, SMES and FES have highest values. When, duration of storage is examined, systems like thermal energy storage systems and superconducting magnetic energy storage systems have lowest duration which is in range of minutes. However, when I analyze, battery energy storage systems like lithium-ion or nickel cadmium batteries, compressed air energy storage systems and pumped hydroelectric storage systems, they have higher duration of storage values in scale of months. In addition to all these comparisons, technical maturity is another key point and in technical maturity it is observed that storage systems that reached mature level are lead-acid batteries, pumped hydroelectric storage systems, nickel cadmium batteries and flywheel systems. When I analyze solar fuel cells and fuel cells, I observed that they are still in developing

phase. Lastly, in analysis of cycle efficiency, lithium-ion batteries, SMES, flywheels and supercapacitors are close to 100% cycle efficiency. When fuel cells, solar cells and thermochemical energy storage systems are analyzed, these systems have lower value cycle-efficiency.

In this thesis, main roles of electrical energy storage systems that are roles from viewpoint of utility and roles from viewpoint of consumer are also stated. In viewpoint of utility, time shifting, power quality, making more efficient network usage, isolated grids and emergency power supply for protection and control equipment are five main factors that analyzed. Furthermore, roles from viewpoint of consumers are examined which includes time shifting/cost savings, emergency power supply and electric vehicles and mobile appliances (Electrical Energy Storage, 2011).

Lastly, moving average algorithm as a smoothing method for fluctuations is stated in this thesis. In this algorithm generated power will be calculated as the average value in a time window with a duration of T. When implementation of this systems is made in MATLAB with generated noise, it is observed that fluctuations will be smoothed significantly by using this methodology.

REFERENCES

AuYeung, N. and Kreider, P. (2017). *Solar Thermochemical Energy Storage*. [online] Aiche.org. Available at: https://www.aiche.org/resources/publications/cep/2017/july/solar-thermochemical-energy-storage [Accessed 28 Apr. 2018].

ANU College of Engineering & Computer Science. (2018*). High-temperature solar thermal energy storage via manganese-oxide based redox cycling.* [online] Available at: https://cecs.anu.edu.au/research/research-projects/high-temperature-solar-thermal-energy-storage-manganese-oxide-based-redox [Accessed 8 Oct. 2017].

Butler, P., Eidler, P., Grimes, P., Klassen, S. and Miles, R. (n.d*.). CHAPTER 37 ZINC/BROMINE BATTERIES*. [ebook] Sandia National Laboratories. Available at: http://www.sandia.gov/ess/publications/SAND2000-0893.pdf [Accessed 18 Apr. 2018].

Chen, H., Cong, T., Yang, W., Tan, C., Li, Y. and Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science, 19(3),* pp.291-312.

Convion. (n.d.). *Technology - Convion*. [online] Available at: http://convion.fi/technology/ [Accessed 10 Jan. 2018].

Electrical Energy Storage. (2011). [ebook] Geneva: International Electrotechnical Commision, pp.13-15. Available at: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf [Accessed 16 Sep. 2017].

Elp.com. (2017). *Solutions for Integrating PV into the Grid*. [online] Available at: http://www.elp.com/articles/powergrid_international/print/volume-16/issue-5/features/solutions-for-integrating-pv-into-the-grid.html [Accessed 27 Mar. 2017].

Energy.gov. (2013). *Solar Photovoltaic Cell Basics*. [online] Available at: https://www.energy.gov/eere/solar/articles/solar-photovoltaic-cell-basics [Accessed 29 Apr. 2018].

English, A. (2017). *Liquid Air ? the future of motoring?*. [online] Telegraph.co.uk. Available at: http://www.telegraph.co.uk/motoring/green-motoring/10087205/Liquid-Air-the-future-of-motoring.html [Accessed 1 Jun. 2017].

Esource.com. (2017). *Battery Killers: How Water Heaters Have Evolved into Grid-Scale Energy-Storage Devices | E Source*. [online] Available at: https://www.esource.com/ES-WP-18/GIWHs [Accessed 1 Jul. 2017].

Freeenergyplanet.biz. (2017). *Ai A f ep rr - Renewable Energy Systems - Free Energy Planet*. [online] Available at: http://www.freeenergyplanet.biz/renewable-energy-systems/ai-a-f-ep-rr.html [Accessed 31 Jan. 2017].

Global.kawasaki.com. (n.d.). *Structure | Kawasaki Heavy Industries.* [online] Available at: http://global.kawasaki.com/en/energy/solutions/battery_energy/about_gigacell/structure.html [Accessed 3 Mar. 2018].

Hoffman, S. (2014). *Valve Regulated Lead Acid (VRLA) Batteries - UPS Battery Center*. [online] UPS Battery Center. Available at: https://www.upsbatterycenter.com/blog/valve-regulated-lead-acid-vrla-batteries/ [Accessed 27 Jan. 2018].

IamTechnical.com. (n.d*.). Zinc-Carbon Battery*. [online] Available at: http://www.iamtechnical.com/zinc-carbon-battery [Accessed 18 Apr. 2018].

Large.stanford.edu. (2010). *Solar Thermal Energy Storage Systems.* [online] Available at: http://large.stanford.edu/courses/2010/ph240/barile2/ [Accessed 1 Mar. 2018].

Li, X., Hui, D. and Lai, X. (2013). Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations. *IEEE Transactions on Sustainable Energy*, [online] 4(2), pp.464-473. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6473871 [Accessed 1 Dec. 2016].

Liu, C., Chen, J., Liu, Y. and Yang, Z. (2017). *An Asymmetrical Fuzzy-Logic-Control-Based MPPT Algorithm for Photovoltaic Systems*.

Luo, X., Wang, J., Dooner, M. and Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137, pp.511-536.

Marcos, J., de la Parra, I., García, M. and Marroyo, L. (2014). Control Strategies to Smooth Short-Term Power Fluctuations in Large Photovoltaic Plants Using Battery Storage Systems. *Energies*, 7(10), pp.6593-6619.

Mpoweruk.com. (n.d.). *Nickel Metal Hydride NiMH Batteries.* [online] Available at: http://www.mpoweruk.com/nimh.htm [Accessed 29 Feb. 2018].

Oberhofer, A. (2012). Energy Storage Technologies & Their Role in Renewable Integration. *Global Energy Network Institute (GENI)*.

Renewableenergyworld.com. *(2008). Storing the Sun: Molten Salt Provides Highly Efficient Thermal Storage.* [online] Available at: http://www.renewableenergyworld.com/articles/2008/06/storing-the-sun-molten-salt-provides-highly-efficient-thermal-storage-52873.html [Accessed 3 Nov. 2017].

Roman, C., Fireteanu, V., Etay, J. and Fautrelle, Y. (2011*). An overview on solar energy, molten salts and electromagnetic pumping technologies. 2011 10th International Conference on Environment and Electrical Engineering.*

Sabihuddin, S., Kiprakis, A. and Mueller, M. (2014). A Numerical and Graphical Review of Energy Storage Technologies. Energies, 8(1), pp.172-216.

Sánchez Muñoz, A., Garcia, M. and Gerlich, M. (2016). Overview of storage technologies. *Siemens, THN, USE*.

Schiller, M. (2014). *Hydrogen Energy Storage: A New Solution To the Renewable Energy Intermittency Problem*. [online] Renewableenergyworld.com. Available at: https://www.renewableenergyworld.com/articles/2014/07/hydrogen-energy-storage-a-new-solution-to-the-renewable-energy-intermittency-problem.html [Accessed 6 May 2018].

Simanaitis Says. (2015). *LITHIUM-AIR—THE BEST OF BATTERIES, THEORETICALLY*. [online] Available at: https://simanaitissays.com/2015/12/01/lithium-air-the-best-of-batteries-theoretically/

Slideplayer.com. (2011). *The Zinc-Carbon Battery - ppt download*. [online] Available at: http://slideplayer.com/slide/7729913/ [Accessed 18 Apr. 2018].

Valkealahti, S. (2016). *Solar Cells,* PowerPoint Presentation, DEE-53117: Solar Power Systems, Tampere University of Technology. Available at: https://webhotel2.tut.fi/units/set/opetus/kurssit/Materiaalisivut/DEE-53117/4%20Solar%20cells.pdf