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Factors Affecting the Performance of Photo-voltaic Solar Energy Storage

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FACTORS AFFECTING THE PERFORMANCE OF PHOTO-VOLTAIC SOLAR ENERGY STORAGE

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ABSTRACT

One of the most important factors in a nation's development is energy availability. All the aspects of its economy are directly proportional to the energy resources. Oil is one of the most sought energy resources currently. Solar energy is one of the most important renewable sources of energy available to us. With oil deposits depleting and current global warming, there is an emphasis on using more and more renewable sources or clean energy. This has led to immense research on solar cells and how it could better be used to get maximum output. Storage of energy is another aspect that is studied most as this stored energy could be used as and when required. This study aims to study the factors that affect the performance of solar energy storage. This study will be conducted by identifying and analyzing different factors that influence the solar energy storage. The goal of this research is to find the factors that affect energy storage and identify which factors has the greatest effect on its efficiency and suggest better and innovative ways that could help energy storage in a positive way.

Dedication

This work is dedicated to my parents Vimala and Ganapathi Bhat, who were always my support pillars. Also, this work is dedicated to my wife, Shail, who always stood by my side for all my adventures in life. My In-laws Jyoti and Som Derashri, were always role models and encouraged me to do better.

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CHAPTER 1: INTRODUCTION

There are over a billion people in the world who have no access to conventional energy whatsoever. The primary reason is the heavy dependence on grid-connectivity and considering the speed at which infrastructure adapts to population growth means that the waiting period for every person to be grid-connected is going to be a very long one.

The journey of the present energy system began from a light bulb. Ideas of Nikola Tesla and Thomas Edison did not just make a light bulb but created an entire industrial energy system to go with that light bulb. Today, every country around the world has this standardized energy system, where, to get the appliances working, one needs to have power stations and the infrastructure that ultimately provides electricity at user end.

The world we live in runs on energy. Any nation's economic and social development depends on several factors, one of them is energy availability. Energy is broadly classified as renewable and non-renewable energy. Today we are mostly dependent on the non-renewable sources of energy. According to International Energy Agency – IEA, 85% of the total energy consumption of the world is generated using non – renewable sources.(U.S. energy information administration - EIA.) Only 15 % of the total energy used is from a renewable source currently. Oil is one of the most used energy sources but with depleting oil pockets and increasing prices, there is emphasis on using cleaner fuel for energy generation. Global warming is another factor that has led to research in developing alternative clean source of energy.(Varianou Mikellidou, Shakou, Boustras, & Dimopoulos, 2018) In addition to using more cleaner fuels for energy generation, there are steps taken to improve the efficiency of energy generation and its storage.(U.S. energy information administration - EIA.)

In countries all over the world, including some of the fastest growing economies like India, the governments are taking steps to decrease their dependence on fossil fuels and encourage electricity generation from renewable resources. This is also evident from the fact that 193 countries have signed the Paris Agreement for climate change. The role of renewable energy is exponentially growing in the world and so is the need for infrastructure that can meet the growing demand for energy that comes from renewable sources.(Vidyanandan, 2017)

Solar energy, Wind Energy, Biomass, Hydro, etc. are all examples of renewable energy sources of which solar energy is the most abundantly available and hence is seeing rapid growth in terms of usage, research, and technological advancements. However, one of the major shortcomings of solar energy is its intermittent availability, meaning it is available only during the day.

According to the published data for the year 2016 by the US Energy Information Administration (EIA), the total energy production using all renewable sources was a mere 12%. (U.S. energy information administration - EIA.) The rest of the 88% energy production was done using non-renewable sources of energy. Among the renewable sources of energy hydro power is mostly used in US currently. Even though sunlight is available abundantly all over the planet, this energy source is not used extensively in most countries.(Newell, Qian, & Raimi, 2016)

1.1 Problem statement

The main problem of solar energy is its intermittent supply. There are shady days that massively hamper the output of the solar cells. To overcome this problem, solar energy is stored using various techniques, which helps in providing energy throughout the demand. There is extensive research focused on developing better technologies to convert sunlight into electricity. Due to the intermittent solar supply the storage of that energy is given equal importance. This has led to immense focus on energy storage and more research is currently done on the performance of the storage of solar energy.

The current usage can be shown in the following figure 1:

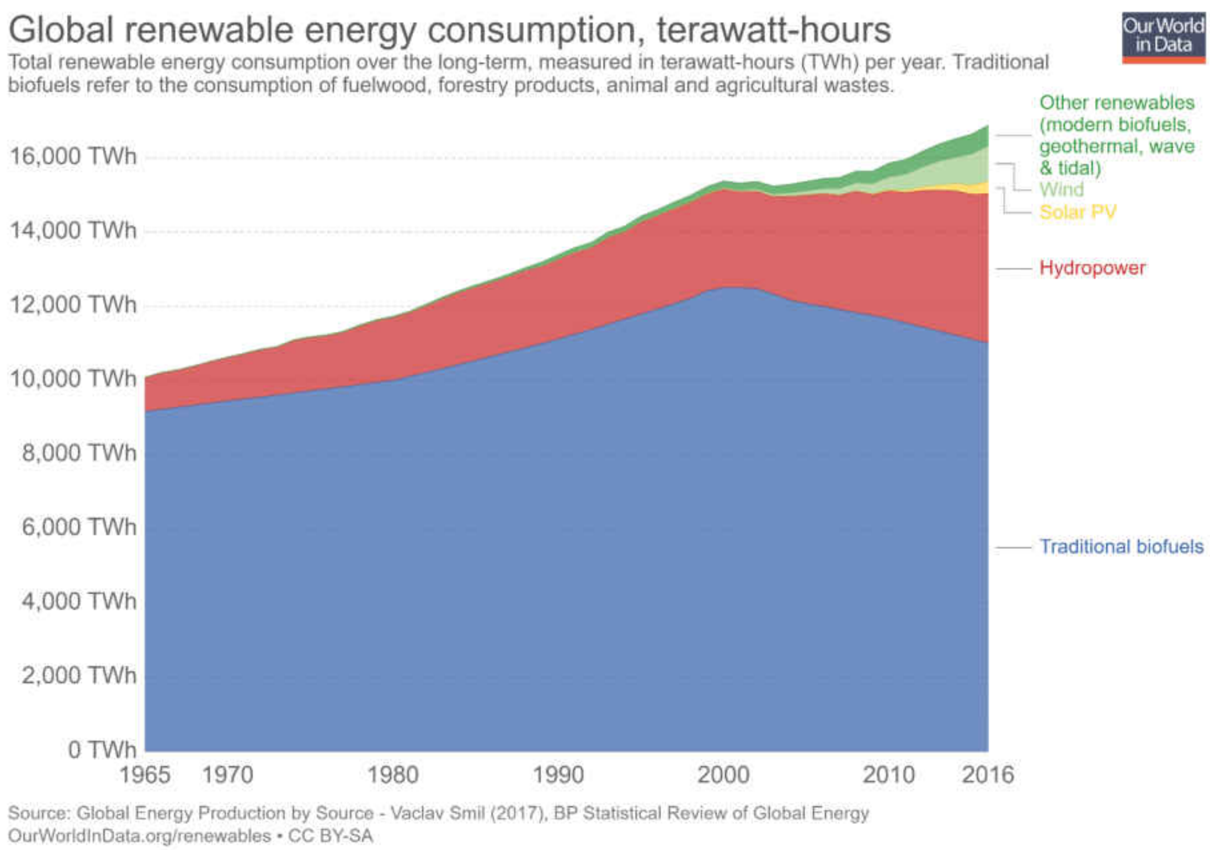


Figure 1: Global renewal energy consumption

Source: (Tandon & Mallik, 2017)

1.2 Research Questions

Given the challenges identified in the problem statement the research questions for this research are:

a) Which factors affect the performance of solar energy storage?

b) What are the factors that have the greatest impact on the performance of solar energy storage?

CHAPTER 2: LITERATURE REVIEW

This literature review has three main objectives. First, to identify different energy storage methods that are commercially or theoretically available. Secondly, to recognize different factors that affect the performance of energy storage process. Third, determine which factor effects the performance of energy storage. Therefore, this research will provide a detailed analysis of all the factors that affect solar energy storage methods.

2.1 Introduction

This chapter is the literature review of the need of energy storage systems, development in photovoltaic systems, types of energy storage systems and the future of solar power.

Solar radiation encompasses the entire electromagnetic spectrum. The electromagnetic spectrum is made up of Gamma Rays, X-Rays, Ultra-violet light, Visible Light, Infrared Light, Microwaves and Radio Waves. A distribution of the electromagnetic spectrum is seen in the figure 2:

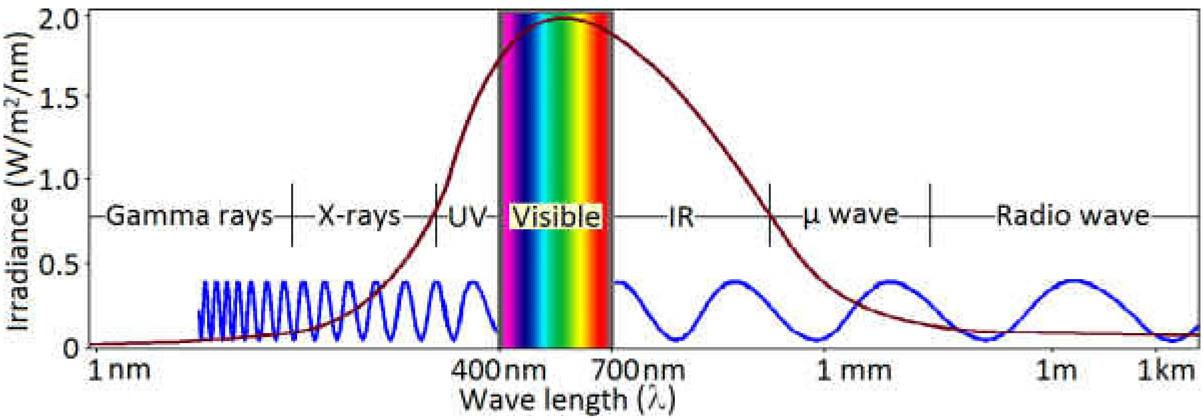


Figure 2: Electromagnetic spectrum

Source: *(Vidyanandan, 2017)*

Radiation is said to be made up of a group of particles called photons. Photons contain a specific amount of energy which is related to the wavelength of the radiation and is measured in electron volts (eV). As seen from Figure 2, Gamma rays have photons with the highest amount of energy while Radio waves have photons with the least amount of energy. Therefore, shorter wavelengths have a higher amount of energy, while longer wavelengths have a lower amount of energy.

Fossil fuel-based power generation has been the primary source of energy availability at the user end for a very long time. With the introduction of technologies that could harness the power of renewable energy sources such as wind, sun, tidal, hydro, etc. and convert it to usable electricity, and the ever-growing environmental concerns caused by the burning of fossil fuels, a new market for renewable energy-based power generation opened up. However, this market size is still significantly smaller than the fossil fuel-based power generation despite there being a good demand for it primarily because of the high-cost of set up for renewable technology and its supporting infrastructure. Solar PV technology was also a high-capital off-grid system when it was first introduced, but with research and improvement in technology, now solar PV systems are available at much lower costs and have higher efficiencies. The governments have also played a significant role in introducing and implementing policies like feed-in-tariffs and subsidized solar technology that has encouraged the growth of solar market. (Vidyanandan, 2017)

2.2 The need of energy storage system

The main issue of solar energy is its uncertainty. There are days with complete sunlight, and a cloud cover could reduce the sunlight to very little. Unfavorable weather conditions also add difficulties to capture solar energy. Secondly, energy requirement during nights when there is no sunlight pose another problem. Getting sunlight when and where required is the biggest challenge. These uncertainties create a problem for continuous supply of electricity. To overcome this issue, energy is stored in various methods discussed in this chapter.

Owing to the intermittent nature of solar energy, it becomes essential to develop storage methods such that can harness the solar energy and make it available during times when the sun isn't available. Today, Solar energy is most widely used in generation of electricity and having a solar energy storage can mean that Demand Side Management and Supply Side Management will not have to be simultaneously balanced. This will give greater flexibility to utilities and facilities so conduct power transactions or operate machinery and optimize load-shifting through the method of stockpiling, wherein stored energy can be used to lower the operating costs of a facility. (Hasnain, 1998)

The benefits of developing a solar energy storage infrastructure are:

1. Take advantage of renewable credits from state or central regulating agencies by using stored solar energy instead of grid power or fossil fuels
2. Solar energy storage infrastructure for electricity would cost lesser than erecting a new electricity generation, transmission and distribution network.
3. Carbon offset/ Carbon credit-based regulations can be adhered to by using solar (and other renewable) energy storages

4. Improved load management due to lowering the capacity and operating costs of generators, because solar energy storage infrastructure could cater to demand peaks, thus allowing the generator to run on base load.
5. Stabilize electricity price in market by minimizing price peaks caused in the energy exchange/open grid electricity transmission and distribution systems.
6. Considerable techno-commercial advantages over the old technologies of storing renewable energy. (Schainker, 2004)

2.3 Energy types

There are two forms of energy. One is potential energy and other is kinetic (moving) energy which further can be classified into different types of energy. The different types of energy that is stored can be classified into mechanical, electrical and thermal energy. Based on these types of energy different storage methods are used. First, let's look at different types of energy that is relevant to this case. (Sharma, Tyagi, Chen, & Buddhi, 2009)

2.3.1 Mechanical Energy

Mechanical energy like kinetic, potential or gravitational energy can be stored and converted back to electrical energy when and where energy is needed. This mechanical energy can be stored as gravitational, compressed air or hydropower. The storage methods also depend on economic viability since most of this energy is large scale production and require large capital investment. During weekends and nights inexpensive off-peak power is abundantly available which is stored and discharged when there is a demand for more power. (Sharma et al., 2009)

2.3.2 Electrical energy

The solar energy is directly converted to electrical energy by solar cells which can be stored in batteries. Energy stored in batteries is an example of electrical energy storage. The batteries – either single use or re-chargeable ones, use the energy from chemical reactions and convert it to usable electrical energy. Once the re-chargeable batteries discharge, they can be charged up again by connecting them to a source of electric current that reverses the chemical reaction in the battery cell and makes the battery usable again. Batteries proved to be beneficial in applications like utilization of off-peak demand, load leveling, and storage of electrical energy generated by wind turbines or photovoltaic plants. Lead acid, Nickel-Cadmium (Ni-Cd), Nickel Metal Hydride (NiMH) and Lithium-ion are the most common types of re-chargeable batteries available today. (Sharma et al., 2009)

2.3.3 Thermal energy

Thermal energy or heat energy is primarily divided into three categories:

2.3.3.1 Sensible heat energy

The amount of heat stored depends on the specific heat, material mass and temperature difference between initial and final condition.

The amount of heat stored could be calculated by the following formula:

$$Q = m * C_p * \left(T_f - T_i\right) \, where$$

$$m = Density\ (\frac{kg}{m^3})$$

$$C_p = Specific\ heat\ (J/Kg\ K)$$

$$T_f - T_i = Difference\ in\ final\ and\ initial\ temperatures\ (°C)$$

Water is one of the best mediums to store such energy because of its high specific heat and substantial temperature difference potential. (Importance of phase change material (PCM) in solar thermal applications: A review.2016)

2.3.3.2 Latent heat energy

When heat is applied a solid can change to liquid or gas directly and a liquid can change to gas. This phenomenon is called phase change. Latent heat storage is based on the phase change phenomenon when either heat is absorbed or released. The amount of heat stored can be calculated by the following formula:

$$Q = m * \left[C_p(T_m - T_i) + L + m * C_p \left(T_m - T_f\right)\right] where$$

$$m = Density \left(\frac{kg}{m^3}\right)$$

$$C_p = Specific\ heat\ (J/Kg\ K)$$

$$T_m = Melting\ temperature\ (°C)$$

$$T_i = Initial\ temperature\ (°C)$$

$$T_f = Final\ temperature\ (°C)$$

2.3.3.3 Thermochemical energy

Thermochemical energy is a combination of thermal energy and chemical energy. When an endothermic reversable chemical reaction happens either heat is released or utilized. The concept of molecular bond energy and heat released during this process. A chemical reaction reforms bonds between molecules which in turn would either absorb or release energy depending on the chemical reaction.(Sharma et al., 2009)

2.4 Energy storage methods

Over the years there have been various methods of energy storage. Depending on the type of energy produced corresponding energy storage techniques are adopted. There are three major energy storage methods used commercially are mechanical energy storage, electrical energy storage and thermal energy storage. Electricity by itself in general is very difficult to store but this electricity produced can be converted into other forms of energy which in turn is easily and efficiently stored. Thermal energy is stored primarily as sensible heat or latent heat. The solar energy is used to change the temperature and then this heat is stored which could be used later. Examples of such energy storage methods are solar water and air heaters, graphite and concrete storage. The concept of solar water and air heater is to store solar energy in the medium of air or water is example of sensible heat storage. Latent heat storage which makes use of the energy stored when a substance changes from one phase to another by melting (just lice ice melting into water).(*Importance of phase change material (PCM) in solar thermal applications: A review*2016)

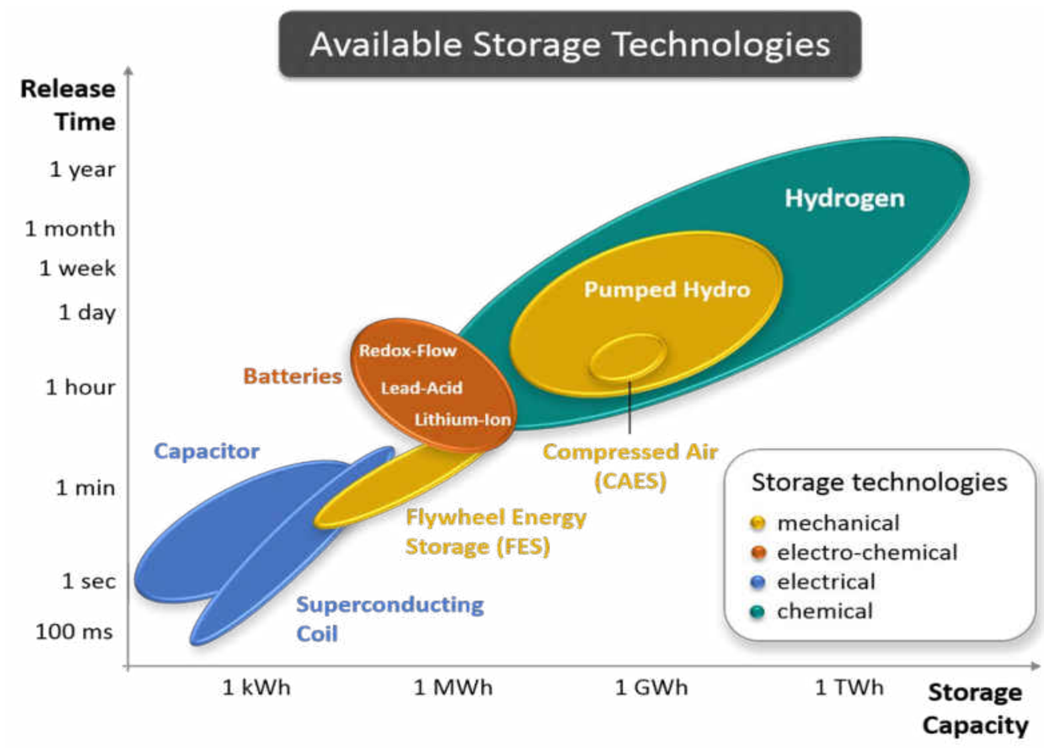


Figure 3: Available Storage Technologies

Source: (Joi Scientific, 2019)

2.4.1 Mechanical Energy Storage

This is one of the oldest energy storage methods available to mankind in its simplest form. One example of such energy storage and use is doing pottery. The wheel is pushed physically to rotate thus allowing some momentum to the wheel and helping the clay to be shaped in the desired shape. This same concept is used today in much more modern way. (Burheim, 2017)

Pumped hydroelectric storage, Compressed air energy storage, and flywheel are types of mechanical energy storage methods.

2.4.1.1 Pumped hydroelectric storage (PHS)

Pumped hydroelectric storage is the largest storage capacity that is available commercially. In this system two water reservoir is used one at a higher level and other at a lower level. The excess electrical energy that is generated during off peak hours is used to pump water from a lower reservoir to a higher reservoir. During peak hours when the demand is high this water is discharged from the higher reservoir to the lower reservoir through a turbine thus converting the potential energy of water into electricity again. The PHS system typically has an output as much as 1000 MW. The cost to build up such mega setup is large thus the output has to be large to make them economically viable. The capacity is depending on the size of the reservoir and the elevated distance between them. Typically, it is in the range of 70% to 80%. Accordingly, turbines can be placed between them to generate electricity when the water is released from the top reservoir to the bottom reservoir. The disadvantage of PHS system is there are very limited sites where such an operation can be performed. It requires a large area with a suitable geographical location where upper and lower reservoirs can be built or naturally occur. There have been cases of environmental groups opposing this technology.

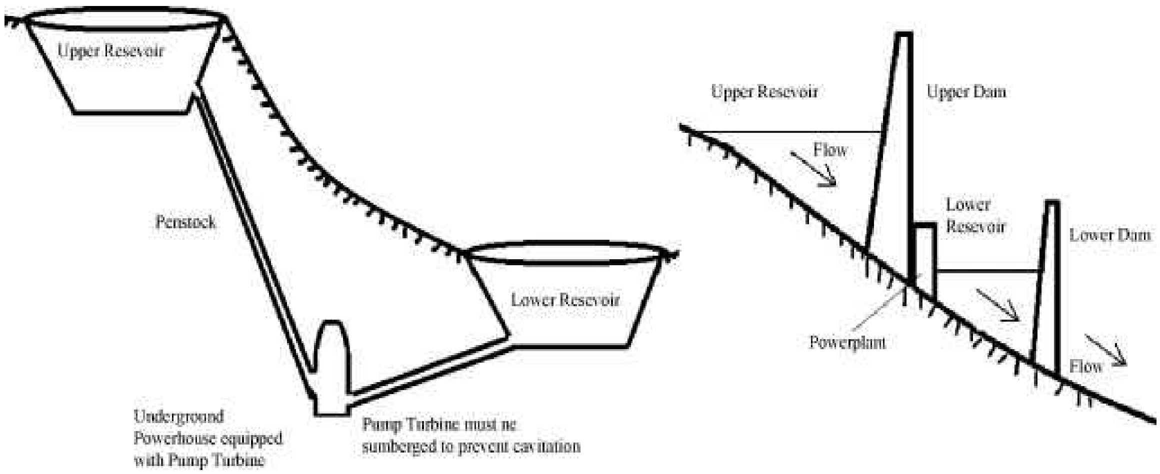


Figure 4: Pumped hydro-electric storage (PHS)

Source: *(Deane, Ó Gallachóir, & McKeogh, 2010)*

Due to limited availability of such location another method has been tested and tried. Underground pumped hydro, in which the lower reservoir is excavated through the rock bed underground. Several R&D efforts by DOE have shown that this method is economical feasible. (Schainker, 2004) Unfortunately, the capital cost for such projects is much higher than the conventional methods. This is one of the prime reasons why there is no underground pumped hydro plants exist today. Variable speed pumps can be used instead of regular pumps which help the plant to increase the overall efficiency. This energy saving equipment when used can help these plants increase their output efficiency. (Schainker, 2004)

2.4.1.2 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage system uses compressed air as a medium for energy transfer. Underground reservoir suitable for compressed air is used as a storage medium. The off-peak electricity is used to compress air and into those underground reservoirs. Even elaborate piping system, big vessels, caverns made of salt or rock formations, depleted natural gas fields etc. could be used to store this compressed air. When electricity is required this compressed air is released and heated and run through combination of low- and high-pressure turbines to generate electricity. Compressed Air Energy Storage just like Pumped Hydroelectric Storage provide large energy storage options. The disadvantage of this type of system is similar to the PHS system. The geographic location suitable for such process is hard to find. This system is also a hybrid system as fossil fuel is used to heat the air thus releasing some hydrocarbons back to the atmosphere.

EPRI has sponsored several technical and economic studies to determine the technical feasibility and economic viability of deploying CAES in the United States. These studies found that several sites across United States were conducive to such systems. Almost three fourth of all locations that were studied were a match for CAES systems. As mentioned before these are large systems with extensive large machineries like turbines etc. that are used. Most of the machineries used for CAES are available easily in United States. Any range from 10 MW to 350 MW can be designed for economic generation of electricity. All these favorable factors have helped CAES systems to increase their foot hold in United States. More private companies are venturing into the idea of commercial generation of electricity using CAES.

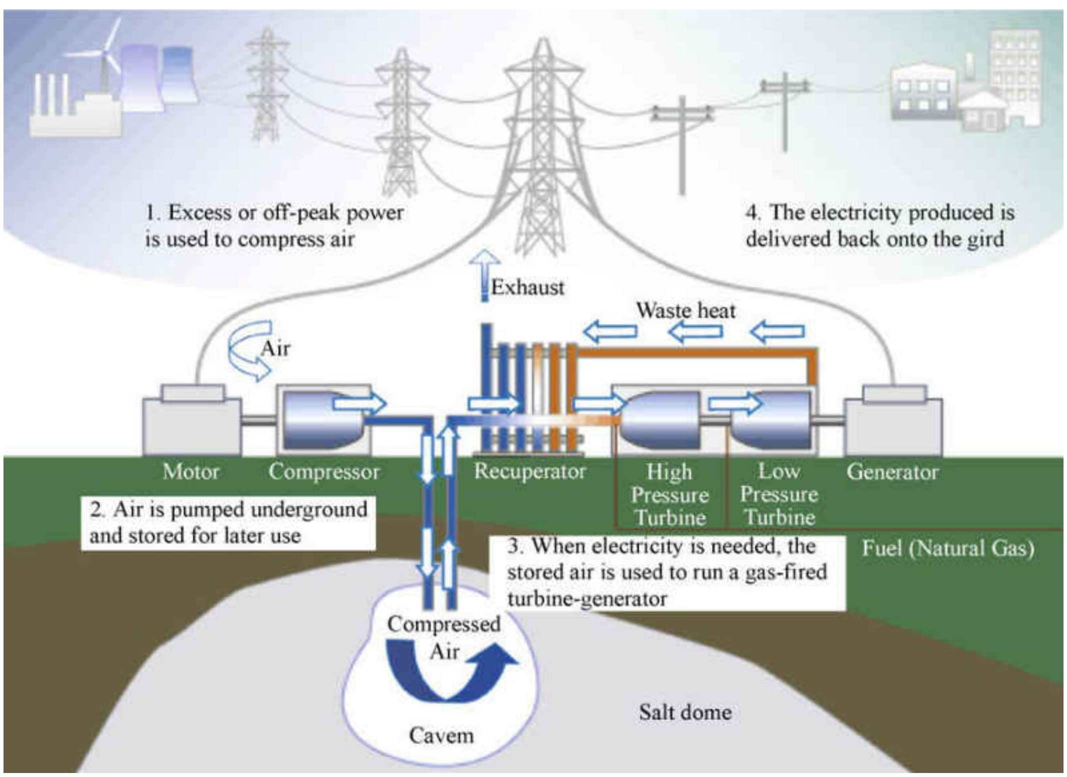


Figure 5: Compressed Air Energy System

Source: *(Chen et al., 2009)*

CAES systems have an efficiency range of 70% – 89% if used in tis optimum condition. Although there are not many CAES systems around the world but with better techniques that help in improving the efficiency we could be seeing more locations coming up in future.

2.4.1.3 Flywheel Energy Storage

A flywheel energy storage system stores the kinetic energy from a moving mass at an angle. Kinetic energy charge and discharge properties are used to produce electricity. During off peak hours the mass is rotated at an angle and when electricity is needed then this same kinetic energy is used to rotate a turbine to generate electricity. At discharge, the motor becomes a generator that produces electricity. There are high speed flywheels as well as low speed flywheels. The difference is in the material they are made of. High speed flywheels are made of composite material whereas low speed flywheels are made of metals. Because of its tensile strength high speed flywheel are more durable than low speed flywheel but that very fact makes it more expensive to make. The energy storage capacity depends on the speed, the mass of the spinning object and the size of the flywheel. Modern development of flywheels includes using them in vacuum. There are few flywheels with magnetic bearing instead of conventional bearing. These changes reduce friction thus increasing the efficiency of newer flywheels. The efficiency can reach up to 95% of their capacity.

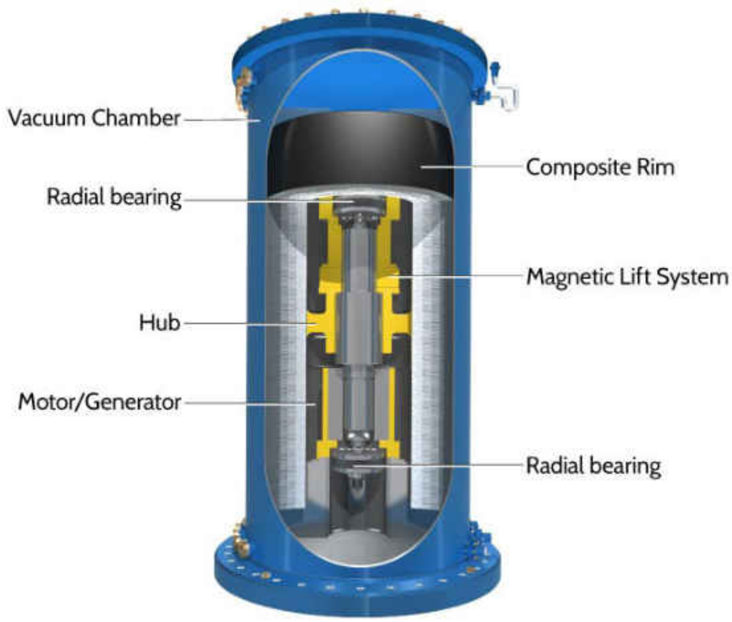


Figure 6: Flywheel

Source: (Chen et al., 2009)

Depending on its capacity flywheels can be made in a cost-effective manner. There are number of attributes like high power density, high energy density, no capacity degradation, no regular maintenance, short recharge time, and environmentally friendly materials are few reasons for flywheel system. (Bolund, Bernhoff, & Leijon, 2007) Even with high efficiency there are losses like eddy current losses that could be avoided. Therefore, many different methods are being researched to remove heat from the vacuum enclosure. Smaller flywheels have been a success commercially. Research is being done for larger wheels to be used commercially. (Schainker, 2004)

2.4.2 Electrical Energy Storage

Electrical energy can directly be stored in batteries or super-conducting magnetic devices.

2.4.2.1 Batteries, flow batteries and fuel cells

A battery is an electrochemical cell that converts stored chemical energy into electrical energy. This is one of the oldest methods of storing energy that is used today extensively. With advances in technology and increased usage there was a need of re-using batteries. The chemical reaction was reversed by introducing electricity back to batteries gave rise to rechargeable batteries. This technique also changed the usage of solar energy as now solar energy was converted into electrical energy and stored in batteries and used when electricity was needed. The efficiency of a typical battery is in the range of 60% - 80%, depending on how long they have been used (charging and discharging) and their chemical reaction efficiency.(Schainker, 2004)

A battery cell consists of a cathode, anode and a solid or liquid medium that separates them. When the batteries discharge there is a chemical reaction at the electrodes thus producing electrons. These electrons pass through external circuit thus generating electricity. When charging the process is reversed and electricity is provided at these electrodes and charge these batteries to be used again when needed. They respond quickly to load changes thus making it ideal for energy storage applications. (Chen et al., 2009)

Significant development has been made in battery technology because of its desirability, efficiency and commercial potential. The lead-acid battery is the oldest type of battery that is still widely used. Nickel cadmium battery is another type of battery that is as popular and efficient as lead-acid battery. They also have long maturity life. Other batteries include Sodium Sulphur or more commonly known as NaS battery and sodium nickel battery also knows as ZEBRA battery. More than 50% of small device market is taken by Lithium-ion batteries but currently there are few challenges to produce them on large scale.

A flow battery has two electrolytes which are stored in two separate tanks and is pumped through the cells of the reactor. This system converts chemical energy to electric energy. Similar to lead acid batteries these flow batteries can be charged and discharged multiple times thus can be used several times. One of the advantages of flow battery is they self-discharge very slowly thus can be used where long storage of energy is required. The flow batteries can provide electricity continuously due to their high rate of discharge. (Reddy & Linden, 2011)

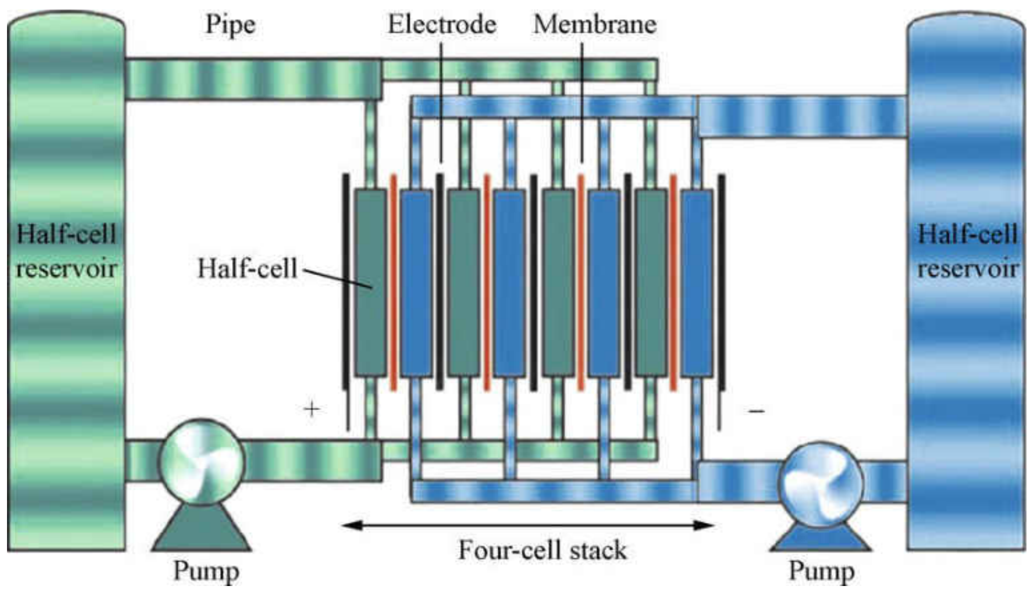


Figure 7: Schematic of flow battery

(Van, 2006)

A fuel cell is an electrochemical energy conversion device that is also popular as an energy storage technology. In this technology, the electricity is generated from external supplies of fuel and oxidant. A reversible fuel cell is formed when certain chemicals are used together with electricity to produce another chemical (for example, the production of hydrogen through the process of electrolysis), in this way it becomes a form of storage. Fuel cells are different from batteries because fuel cells consume reactants, which must be replaced.

The dawn of the 20th century has seen the advent of a storage technology that is flexible, has minimum response time (20 milliseconds or lower), can be used in conjunction with the grid, is adaptable to the consumer needs and has a silent operation. This revolutionary new technology is called the battery. From their time of invention, batteries have become more energy efficient and have increased their output power capacity to the measure that now even cars can be driven solely on battery power.

Battery is hugely popular due to its strength of a quick response time to load changes. Facilities usually install these "back-up power" technology near load centers or substations and keep them "cycled". A healthy cycled battery together with the kind of electrochemistry being used can assure that the AC – AC round trip efficiency of a battery can be maintained in the range of 60% - 80%.

Several experiments conducted by EPRI have proven the technical and economic feasibility of batteries in the role of energy storage technology.

2.4.2.2 Superconducting Magnetic Energy Storage (SMES)

An energy storage technology that capitalizes on the magnetic effect created by passing direct current through an electromagnetic coil is called the superconducting magnetic energy storage. Here, electrical energy gets stored in the magnetic field generated by passing a direct current (DC current) through a circular electromagnetic coil. The coil is maintained at low temperatures (between 55K and 77K) to promote low resistance (approaching zero) and hence the superconducting state. (Chen et al., 2009) The energy release rate is faster in SMES as compared to the other storage technologies and it boasts of a 98% or greater efficiency, however, SMES is also relatively costly, and the strong magnetic field that the system generates can be a deterrent in some applications. (Hou, Vidu, & Stroeve, 2011)

The amount of energy that can be stored by a SMES can be calculated by the formula:

$$Enery\ Stored = \frac{1}{2} \times Inductance\ of\ the\ Coil \times (Current\ passing\ throuh\ the\ Coil)^2$$

As with any system, there are inherent losses in the SMES system as well. The conversion from AC current to DC current and back to AC current results in about 2% – 3% losses each way Advances in recent technology have made it possible for the SMES to cater the energy that ranges from 1 MW up to several hundred of MW, although theoretically even 1000 MW is achievable. (Hou et al., 2011)

2.4.2.3 Capacitors

Supercapacitors, ultracapacitors or electrochemical double-layer capacitors (EDLCs) are terms for the same high-capacitance electronic component. Modern advancement in technology has made possible an output that is of the tune of thousands of Faradays. Higher capacitance is achieved by using porous electrodes with large surface area. (Hou et al., 2011)

Storage capacity of a capacitor is directly proportional to the square of its voltage. Higher and higher transmission voltages have been achieved over the past few years and this has also resulted in an exponential boost for capacitor energy storage. (Schainker, 2004)

Depending on its energy density one can opt for suitable storage methods. Figure 8 shows the comparison of energy and power density of various electrical storage options.

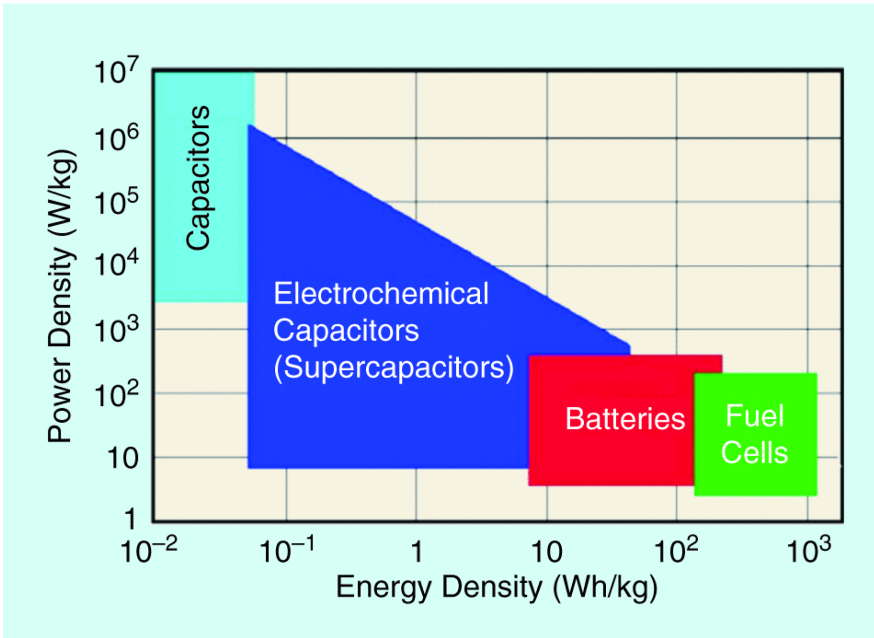


Figure 8: Comparison between Power and Energy density

Source: (Energy storage for electrified aircraft: The need for better batteries, fuel cells, and supercapacitors.2018)

2.4.3 Thermal Energy Storage

When considering the storing energy in the form of heat, two options are available: the sensible heat storage and the latent heat storage.

2.4.3.1 Sensible Heat storage

Sensible heat storage is done by raising the temperature of a medium. Use of sensible heat for energy storage is recommended for materials that are stable under thermal stress and have a higher specific heat. For example, water is the preferred medium for sensible heat energy storage with a specific heat capacity of 1 kcal/kg-°C versus air as a medium that has a specific heat capacity of 0.25 kcal/kg-°C to make the storage economically viable, the medium should be plentiful and not expensive. Sensible heat storage can further be classified on the basis of the heat storage media as liquid media storage such as water and solid media storage such as metal or rocks.

2.4.3.2.1 Liquid media storage

Sensible heat storage in liquids can be done in three ways: Storage in Water, Storage in salty water, and storage in other fluids. The advantages and disadvantages associated with these are:

a) Storage in water: Water is one of the most preferable solar energy storage mediums today owing to is low cost, higher availability and a higher specific heat as compared to most other mediums. However, water at higher temperatures develops a substantial vapor pressure, thereby requiring special handling equipment which can result in higher operating costs. It has higher specific heat than other materials, and it is cheap and widely available.(Hasnain, 1998)
b) Storage in salty water: When salt is added to water, its specific heat decreases, meaning that salty water gains and loses heat faster than

un-salted water. The faster heat gain capability of salty water is used in storing solar energy by the use of solar ponds which are simply salt-water ponds where the concentration of salt increases with the depth of the pond. Sea water can also be used here. These solar ponds are used for space heating and cooling applications, supplying industrial process heat and in electric power generation.

c) Storage in other fluids: in absence of availability of salty or water, Petroleum-based oils and molten salts are used as sensible heat storage mediums. Such fluids are very effective when high temperatures in the range of 300°C to 350°C are desired since the vapor pressure of such fluids is very low. Molten salts like sodium hydroxide are widely used when desired temperatures are up to 800°C. however, the corrosive nature of such molten salts requires higher amount of specialized equipment. Liquid metals behave similar to water in terms of sensible heat storage and also offer a higher thermal conductivity; however, they also pose higher chances of reactivity with container owing to their lower specific heat and a corrosive nature. An oxide free environment, which is usually difficult to achieve, is incorporated in the energy storage process.(Hasnain, 1998)

2.4.3.2.2 Solid media storage

Solid media is another stable material that is used to store energy. Their unique advantage is they do not change phases thus it becomes easier to handle as the media handling equipment have to be equipped to handle one medium. With liquid media which turns into gaseous state, the equipment designed to handle these mediums have to be apt for high pressure gaseous state when liquid changes phase. Rocks, metals, concrete, sand, and bricks are commonly used solid media storage mediums. Another advantage of using solid media is they do not leak thus reducing the risk of accidents or losses due to leakage. In metals cast iron is the most preferred medium due to its high energy density level, which is even greater than water storage.(Hasnain, 1998)

Sensible heat storage in solids can be distinguished in three different mediums. They are: Storage in rocks, storage in metals, phase change materials (PCM), storage in salt hydrates, and storage in paraffins.

a) Storage in rocks: Pile of rocks are used to create a bed which is enclosed by an insulated vessel. The insulated vessel helps in keeping the heat inside and increase efficiency by reducing heat lost in air. Hot air when passed through this loosely packed bed of rocks heat the rocks which retain the heat based on their size, packing density and material. This retained heat or stored energy is then used by circulating ambient air through the bed. This method of storage is used when low temperatures up to 100 °C is required. Typical applications are solar air heaters where this method can be implemented. Normally 300 – 500 k rock is used per square meter of solar collecting area. Fluidized beds are similar to rock beds and can be used for low, medium or higher temperature solar applications.

b) Storage in metals: For higher temperature energy storage inorganic salts and metals are mostly used. Among the metals, aluminum, magnesium and zinc have mostly done well in various experiments. The advantage of using metals is they have high thermal conductivity and heat transfer can be done more efficiently. The disadvantage of using metals is it is very costly to use especially the ones that are most favorable. Thus, metal energy storage is only used when cost is not a factor. To reduce the cost solid industrial wastes like copper slag, iron slag, cast iron slag, aluminum slag and copper chips could be used as storage material for energy storage.

c) Storage in building fabric: Heat storage in buildings is usually done by combining air and water systems. Ceramic bricks and building mass are used to design and store energy. One of the most common application for such energy storage is floor warming. Water is the most common heat transfer medium currently. During off peak loads electricity is used to heat the medium which in turn is used to warm the building when needed.

2.4.3.2 Latent Heat storage

Latent heat energy storage is associated with using the advantage of phase change of material, while sensible heat energy storage uses the temperature differential, also called the Delta T, within the same phase of a material. This provides high density energy storage option and stores heat in the form of latent heat of fusion at a constant temperature.

a) Phase change materials (PCMs): Depending on their temperature range to be heated and be cold again there are different. PCMs can be classified into the following major categories: inorganic compounds, organic compounds and eutectics of inorganic and/or organic compounds. Inorganic compounds include salt hydrates, salts, metals and alloys (Abhat, 1983), whereas organic compounds are comprised of paraffins, non-paraffins and polyalcohol.(Pillai & Brinkworth, 1976)
b) Storage in salt hydrates: A number of salt hydrates, such as sodium sulfate decahydrate (Glauber's salt), calcium chloride hexahydrate, sodium thiosulphate pentahydrate, sodium acetate trihydrate and barium hydroxide octahydrate, were investigated largely because of

their low cost. One interesting fact is that most companies like to rely on the data available for the analytical grade material rather than doing any tests on the thermophysical properties.

Supercooling is a problem phenomenon that salt hydrates face. Another problem that is prevalent is phase segregation (Memon, Cui, Zhang, & Xing, 2015). Supercooling can be prevented by adding nucleating agents or by promoting nucleation by rough container walls (Carlsson & Wettermark, 1980). Similarly, phase segregation I avoided by techniques such as the use of thickening agents as well as use of rotating storage devices and direct contact heat transfer have been successfully implemented (Lane, 1983). The encapsulation of PCMs in metal and plastic matrices has been tried extensively. The macro-encapsulation of PCMs can (i) avoid large phase separations, (ii) increase the rate of heat transfer and (iii) provide a self-supporting structure for the PCM. Plastic containers and tin-plated containers are the most cost-effective containers that can be used. One problem is corrosion in these containers and could lead to disastrous consequences. This happens when internal and external lacquer finishes are not applied properly to the mild steel metal cans.

c) Paraffins: Paraffins are the most ideal in terms of the characteristics that they have as PCMs for storage applications. Characteristics such as high heat of fusion, negligible supercooling, low vapor pressure in the melt, chemically inert and stable, self-nucleating, no phase segregation and commercial availability at reasonable cost make them very desirable (Abhat, 1983). However, the problem lies in properties like low thermal conductivity and large volume change especially during phase change. These properties are undesirable and create issues. Use of metals in the form of Metallic fillers, metal matrix structures, finned tube and aluminum shavings are used to improve their thermal conductivity. The volume change problem is overcome by using different container sizes. Pure paraffin waxes are very expensive, therefore only technical grade paraffins can be used for latent heat storage. Technical grade paraffins are mixtures of many hydrocarbons and, therefore, have a melting temperature range rather than a sharp melting point.

The problem is one cannot rely on the data for technical grade PCMs for designing an effective heat storage device, as thermophysical properties vary from manufacturer to manufacturer, mainly due to different levels of impurities in technical grade PCMs. It is, therefore, recommended by Hasnain to measure thermophysical properties of technical grade PCMs and not rely on published data unless at least the name of the supplier and purity level of the PCM are specified.(Newell et al., 2016)

d) Non-paraffin organics: Organic materials like fatty acids, esters, alcohols and glycols are used as non-paraffin organics. There are many fatty acids which have ideal temperature ranges suitable for such applications. These fatty acids have melting points suitable for heating applications as compared to salt hydrates. They exhibit excellent melting and freezing characteristics without any supercooling. Their major drawback is their cost which is about three times greater than paraffins. The compatibility of fatty acids with conventional materials of construction is another area which requires further investigation.

e) Eutectics: Eutectics are mixtures of two or more salts which have definite melting/freezing points. They have great potential for thermal energy storage applications. A highly crystalline polymer, such as high-density polyethylene (HDPE) offers definite advantages as a potential thermal energy storage material if it is rendered form stable by crosslinking. Researchers at the Electrotechnical Laboratory performed several investigations to demonstrate the suitability of crosslinked HDPE for thermal energy storage systems. Kamimoto et al. concluded that crosslinked HDPE is an excellent thermal energy storage material and can be used in direct thermal contact with ethylene glycol and silicone oil.

f) Salt mixtures. The composite salt/ceramic thermal energy storage media concept offers the potential of using phase change materials via direct contact heat exchange and, therefore, the potential of significant cost improvement through elimination of heat exchanger material, reduction of storage materials and containment vessel size. This salt/ceramic approach may be explained as micro-encapsulation of a PCM within the submicron pores of a ceramic matrix. The liquid salt is retained within the solid ceramic network by surface tension and capillary forces. Heat storage occurs as latent heat of the PCM and as sensible heat of the basic ceramic material and the PCM. Therefore, the use of salt/ceramic materials represents not a pure latent heat but a latent/sensible hybrid storage concept.

PCM has been successfully impregnated in gypsum wall board to enhance the thermal energy storage capacity of buildings with particular interest in peak load shifting. Some composites have been prepared from abundantly available low-cost materials, like coarse aggregates, sand, gypsum, cement, vermiculite and polyester resin. Six potential implementations of thermal energy storage by PCM have been identified for energy conservation in buildings. All potential implementations of PCM technology are not equally advanced: experimental prototypes of PCM wall boards have been produced, but most other technologies are still at a conceptual stage.

CHAPTER 3: FACTORS AFFECTING SOLAR ENERGY STORAGE

3.1 Cable thickness

We generally have electrical appliances working at 220V which is significantly higher compared with the usual PV system DC voltages of 12V, 24V or 48V. For the same wattage much, higher currents are involved in the PV systems. This brings into picture resistance losses in the wiring.

3.2 Temperature

Solar cells perform better in cold rather than in hot climate and as things stand, panels are rated at 25°C which can be significantly different from the real outdoor situation. For each degree rise in temperature above 25°C the panel output decays by about 0.25% for amorphous cells and about 0.4-0.5% for crystalline cells. Thus, in hot summer days panel temperature can easily reach 70°C or more. What it means is that the panels will put out up to 25% less power compared to what they are rated for at 25°C. Thus, a 100W panel will produce only 75W in May/June in most parts of India where temperatures reach 45°C and beyond in summer and electricity demand is high.

About 0.5% loss of efficiency occurs for every degree Celsius rise in temperature. Hence, temperature plays a vital role in the performance of solar photovoltaic modules. As the temperature rises, the output of photovoltaic module decreases which means a lower input to the energy storage medium. A lower energy input will produce a lower energy output at the user end, thus presenting a lower performance of the storage medium.

To counter the effect of high temperature exposure to photovoltaic modules in areas like India, Brazil, etc., a floating photovoltaic system known as Floatovoltaics is now being used. Floatovoltaics not only move away from land to make use of the real estate on water surface, but also prove to be more efficient as compared to land based photovoltaic systems as these photovoltaic modules are naturally cooled by water body. This decrease in operating temperature and lower impact of dust leads to about 10% increase in power generation from a floating photovoltaic as compared to a land based photovoltaic module.

Flotovoltaics also proved to be useful to the water body itself by decreasing the rate of evaporation and growth of algae. This system has the capacity and advantage of being used in conjunction with other power generation technologies like hydro power plants, where, the solar photovoltaic can supplement the hydro power generation during the daytime.

3.3 Shading

Ideally solar panels should be located such that there will never be shadows on them because a shadow on even a small part of the panel can have a surprisingly large effect on the output. The cells within a panel are normally all wired in series and the shaded cells affect the current flow of the whole panel. But there can be situations where it cannot be avoided, and thus the effects of partial shading should be considered while planning. If the affected panel is wired in series (in a string) with other panels, then the output of all those panels will be affected by the partial shading of one panel. In such a situation, an obvious solution is to avoid wiring panels in series if possible. Thus, when the output of the photovoltaic module is not optimum, it translates to a below optimum performance of storage mediums owing to lower input energy available, which will be used as a lower output energy at the consumer end.

3.4 Charge controllers and solar cell's IV characteristics

An inherent characteristic of solar silicon cells is that the current produced by a particular light level is virtually constant up to a certain voltage (about 0.5V for silicon) and then drops off abruptly. What it means is that mainly the voltage varies with light intensity. A solar panel with a nominal voltage of 12 volts would normally have 36 cells, resulting in a constant current up to about 18 volts. Above this voltage, current drops off rapidly, resulting in maximum power output being produced at around 18 volts. When the panel is connected to the battery through a simple charge regulator, its voltage will be pulled down to near that of the battery. This led to lower watt power (watt = Amp x Volt) output from the panel. Thus, the panel will be able to produce its maximum power when the battery voltage is near its maximum (fully charged). So, it helps to design a system in such a way that the batteries normally don't remain less than full charged for long. In times of rainy or heavy clouded days a situation may occur when the batteries remain in the state of less than full charge. This would further pull down the panel voltage thus, degrading the output further.

3.5 Inverter efficiency

When the solar PV system is catering to the needs of the AC loads an inverter is needed. As things stand, in real world nothing is 100% efficient. Although inverters come with wide ranging efficiencies, but typically affordable solar inverters are between 80% to 90% efficient.

Centralized inverters also called string inverters are used to convert the DC power generated by photovoltaic cell into AC power. There are two types of string inverters: Transformer-based type and Transformer-less type. The transformer-less type inverters have higher efficiency of 97% as compared to the transformer-based type inverters which have about 2% lesser efficiency. In order to maximize their power output, these inverters use the maximum power point tracking (MPPT) system wherein a point on the Current-Voltage (I-V) and Power-Voltage (P-V) curves is located such that it corresponds to maximum power of photovoltaic module to the available solar radiation.

Hybrid inverters can direct the power generated using photovoltaic to the load or the grid when required or to a storage system like batteries when the power is not required. Such inverters are also called bidirectional inverters and have the capability of isolating the system from the grid, whenever the grid is down. When the inverters run at optimum efficiency, this results in higher available output power from the batteries.

Figure 9: Components of a photovoltaic system

3.6 Battery efficiency

One of the factors that affect the performance of a battery storage system is the efficiency. In terms of battery storage, it essentially means the response time with which a battery storage system can respond to load changes. With the technologies currently available, it takes an average of 20 milliseconds for a battery to respond to load changes, making the efficiencies in the 60% to 80% range, depending on the electrochemistry.

Lead acid batteries are most commonly used. All batteries discharge less than what go into them; the efficiency depends on the battery design and quality of construction; some are certainly more efficient than others. A lead-acid battery has an efficiency of only 75-85% (this includes both the charging loss and the discharging loss). From zero State of Charge (SOC) to 85% SOC the average overall battery charging efficiency is 91%- the balance is losses during discharge. The energy lost appears as heat which warms the battery. It can be minimized by keeping the charge and discharge rates low. It helps keep the battery cool and improves its life.

3.7 Flywheel speed

A flywheel is a mechanical device that can store energy in form of rotational energy. The energy stored is proportional to the square of the speed of its rotation. Controlling the flywheel speed can boost or degrade the performance of the energy storage system.

Ways to improve the flywheel speed are being researched in areas such as the following:

- Building composite materials that have a high tensile strength instead of using a single material to build the flywheel
- Operating the flywheel in a vacuum space for zero friction effect
- Reducing the weight of the flywheel
- Optimizing the size of the flywheel

- Using magnetic levitated bearing to counter the energy lost in bearing heat
- Reducing the eddy current losses on the flywheel
- Improve the cooling of the flywheel such that heat from the flywheel is removed entirely

All these developments are being done with the factor of low-cost being kept in mind. The efficiency of flywheel is better as compared to the battery storage technologies since they lie in the range of 80% to 85% depending on various losses such as bearing, cycling, winding, etc. (Schainker, 2004)

3.8 Change in outlook for storage

While energy storage systems have conventionally been used to counter the peaks in the energy system and improve capacity factor of base-load generation, with the advent of various energy storage technologies that can store much greater amount of power and deliver it at user end with improved efficiencies, it has become a matter of change of outlook and perspective towards how the storage technologies are being used, and how the older technologies can be replaced with modern technologies for improved performance. The advantages of using an energy storage network strategically as an integral part of an energy management system are being acknowledged and this is leading to energy storage systems increasingly playing a vital and broader role in the energy generation and distribution system. (Schainker, 2004)

3.9 Soiling

When dirt and dust accumulate on the surface of a Photovoltaic module, a thin film forms on surface and impacts the solar radiation that falls on the photovoltaic module. This phenomenon is called soiling and it ultimately affects the electrical output of a photovoltaic cell. A lower photovoltaic output translates to a smaller electrical input available for storage.

Dust is comprised of particles which measure less than 500 μm. The amount of dust that gathers and settles on a surface is depends on factors like:

- Weather condition (rainy, cloudy, dry, etc.).
- Speed of wind
- Shape of dust particle (finer particles, coarse particles)
- Weight of dust particle
- Size of dust particle (smaller particles like cement, engine exhaust, or larger particles)

- Location of Photovoltaic Cells (high altitude, desert, costal, near highways, areas of high rainfall, ground-mounted, roof-top, etc.)
- Finish of surface (smooth, glossy, glass, abrasion-free)
- Tilt angle of the photovoltaic module
- Cleaning frequency of photovoltaic module (depends on location, season, type of mounting for the module)

Collection of dust particles in high-humidity condition over a period of time without cleaning can lead to permanent soiling, especially in the lower portion of a tilted photovoltaic module. This can lead to shading for the lower row of cells and cause damage to the coating and seals. Smaller and finer dust particles have a greater impact on soiling rather than larger and coarse particles. This happens because the finer particles are very efficient at reducing the inter-particle gap and therefore have much greater ability of blocking the path of solar light/ radiation toward the photovoltaic module.

Soiling has been known to cause an annual power loss of 5% to 17%. Regular cleaning by means of electrostatic curtain, manual washing, self-cleaning glass, cleaning robot, wiping, cleaning with water, etc. can greatly reduce the power loss of photovoltaic modules. The graphs below show the impact of dust density on input solar radiation and output of the photovoltaic. The graphs help in understanding the impact that a lower photovoltaic output means that lower energy is available for storage. Figure 10 and figure 11 depicts the dust density over solar radiation and PV output respectively.

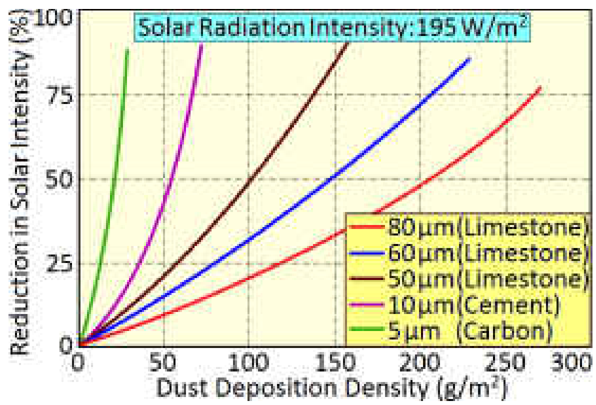


Figure 10: Impact of dust density on solar radiation

(Vidyanandan, 2017)

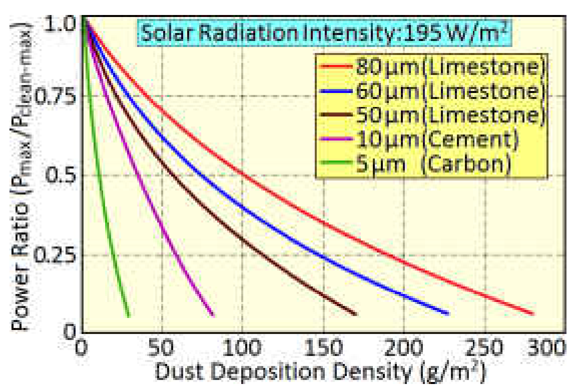


Figure 11: Impact of solar density on PV output

(Vidyanandan, 2017)

3.10 Air mass factor

The optical path length of the Earth's atmosphere is called the Air Mass. For example, during noon at sea-level, the air mass is 1. An air mass of 1.5 will suggest that the light would have to travel an atmospheric depth of 150% than that at noon.

Air Mass thus affects the energy yield of a photovoltaic module and will ultimately affect the amount of energy available for storage. A lower available storage input will translate to even lesser available storage output owing to several conversion and efficiency losses. Storage technology will degrade over time when its optimum capacity is not utilized. (Vidyanandan, 2017)

3.11 Type of PV technology

A number of photovoltaic technologies are today available on the market to cater to a broad spectrum of consumers and end users. The popular technologies among them include mono-crystalline silicon, poly-crystalline silicon, thin-film technologies of amorphous silicon (a-silicon), cadmium telluride (CdTe), copper-indium-gallium-diselenide (CIGS), multi-junction and emerging technologies such as Organic PV (OPV) and Concentrating PV (CPV). Silicon based crystalline modules are currently represent a majority of the world photovoltaic market. They have a higher efficiency as compared to other photovoltaic technologies since they have higher silicon content which means a higher energy yield per unit area. These photovoltaic modules also degrade at a slower rate as compared to other thin film modules like CIGS, CdTe, etc. Mono crystalline silicon has a better efficiency (18% –22%) and a lower area requirement as against the poly crystalline silicon efficiency (14%–18%).and a higher area requirement.

The figure 12 below is a comparison of the photovoltaic technologies available in the market today.

	Mono-Si	Poly-Si	Thin Film
Efficiency	Most efficient (18 - 22%)	Less efficient (14 - 18%)	Least efficient (10 - 12%)
Manufacturing	From single Si crystal	By fusing Si crystal	Many layers of PV material
Suitable for	Standard temperature	Moderately high temperature	High Temperature
Area need/kW	Least	Less	Large
Energy yield per unit area	Hi due to high Si content	Hi due to high Si content	Low due to low Si content
Performance at low light	Low	Low	Moderate
Gap between Voc and Vmp	15 - 20% (less is better)	15 - 20%	22 - 28%
Temperature coefficients	High	High	Low
Fill-factor	70 - 80%	70 - 80%	60 - 68%

Figure 12: Comparison of common PV technologies

(Vidyanandan, 2017)

3.12 Available Space

Photovoltaics today adorn the rooftops for house-hold generation of electricity. However, when the generation and storage is on large scale like solar farms, space availability is one of the primary requirements, because owing to low energy density of solar radiation, for the same capacity of a thermal power plant, a solar farm will require at least 10 times more space. Silicon based crystalline photovoltaic modules come with a space requirement of at least 7 to 8 m2/kW which roughly translated to about 5 acres/MW of generation. Thin-film photovoltaic modules need about 10 to 15 m2/kW, translating to about 10 acres/MW. Amount of electricity generated will act as input energy for storage technology, and hence, the larger the space, the bigger can be the scale of storage. (Vidyanandan, 2017)

3.13 Degradation of Solar PV module

The quality and amount of energy available for storage will be affected by the health of photovoltaic panels. Solar photovoltaic panels usually degrade at a faster rate in the first few years of their life. The degradation of the rated power output is usually pegged at 0.5% per year. The lesser power a photovoltaic module can produce, the lesser is the available energy for storage. Thus, this will affect the performance of storage media in a way that lesser energy will be available at user end. Thin film modules degrade faster. (Vidyanandan, 2017)

3.14 Variation in solar radiation

Solar radiation is the key input for any solar photovoltaic module. Any variations in the solar radiation will directly affect the output of photovoltaic module. Output energy of the photovoltaic module is the input for energy storage device, and a low input to the energy storage device will translate to a low energy output to the end user. Hence, any variation in solar radiation will be directly affecting the storage medium performance. (Vidyanandan, 2017)

3.15 Fill Factor

Fill factor is a measure of the squareness of the photovoltaic cell. A good quality photovoltaic module usually will have a fill factor more than 70%. Higher the fill factor better is the energy yield of the photovoltaic module. For better performance of the storage medium in terms of higher energy output available at user end, the fill factor of the photovoltaic module needs to be high. (Vidyanandan, 2017)

3.16 Potential Induced Degradation

PID or Potential Induced Degradation is a performance degradation mechanism in photovoltaics that is caused by stray currents that can be responsible for up to 30% of output power loss. This phenomenon is common in inverters that have not been earthed and as a result there is loss of useful power and cell damage. PID hence essentially can affect both the input as well as the output power of a storage system rendering it to perform below its capacity.

3.17 PV Module Orientation and Tilt Angle

Photovoltaic modules should get maximum solar radiation in order to provide the maximum output power. This can be achieved when incident sunlight on the photovoltaic module is always perpendicular to the module. However, this is not always possible due to daily and seasonal variation in the position of the Sun, and one of the easiest ways to work around this requirement is to provide minimum variation in solar radiation. Ideally, locations in the northern hemisphere should be oriented towards the true south, which is not the magnetic south, so there are minimum variations in solar radiation. A variable tilt angle can then be employed to help optimize the position of the photovoltaic module to receive maximum solar radiation.

CHAPTER 4: IMPACT ON STORAGE SYSTEM QUALITY AND PERFORMANCE - STORAGE CAPACITY AND STORAGE SIZE

Companies are increasing preferring solar PV modules with energy storage capacities as the cost of adding long-duration energy storage to solar PV modules continues to fall, making the solar energy storage systems the new "normal". The office of Energy Efficiency and Renewable Energy estimates that the solar-plus-storage systems that had a 4% presence in the market at the end of 2018 would reach 27% by 2023.

Cost of energy storage is directly dependent on the duration of the storage system, meaning that a solar energy storage system will decrease in cost per megawatt-hour (MWh) as the duration of storage increases. This is because cost of auxiliaries like inverters is higher in shorter duration storage. Figure 13 below shows the storage system costs breakdown by time.

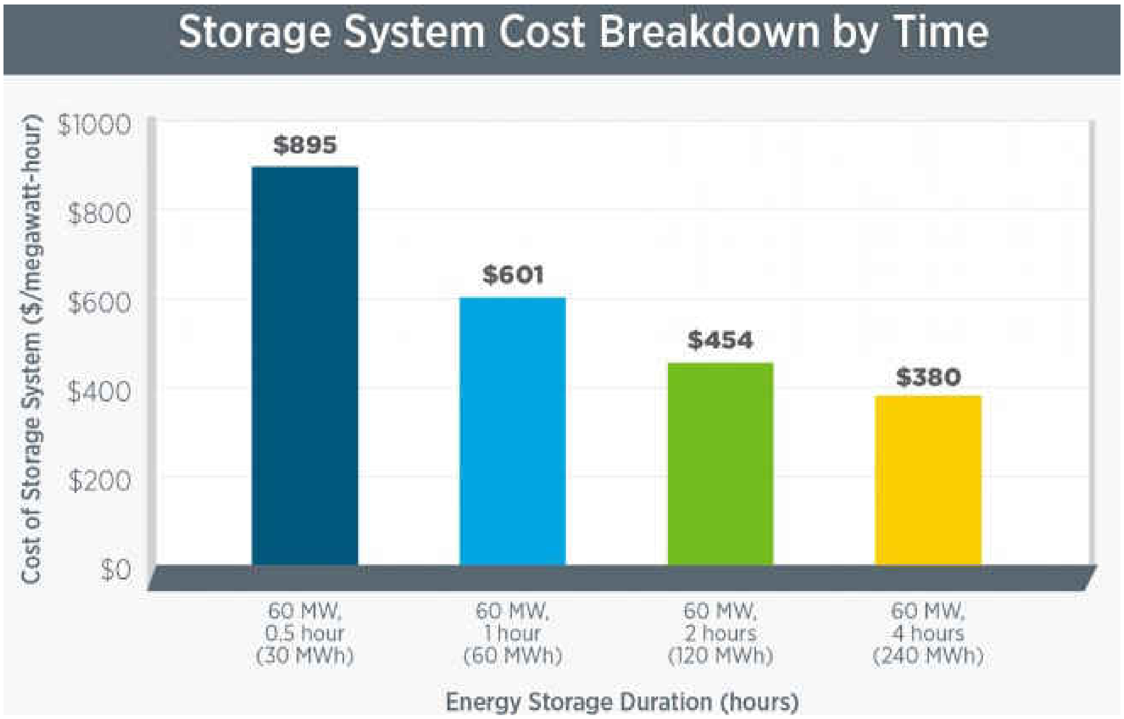


Figure 13: Storage system cost breakdown by time

Source: (Denholm, Eichman, & Margolis, 2017)

When storage system is located at the same location as the solar PV modules, some of the auxiliary systems can be shared between the two, and such an arrangement is known as co-location. (Denholm et al., 2017)

The chart below shows the cost implications of having stand-alone PV system and storage system, having an interconnected PV module and Energy storage system at different locations and the benefit of having a co-location PV module and energy storage system.

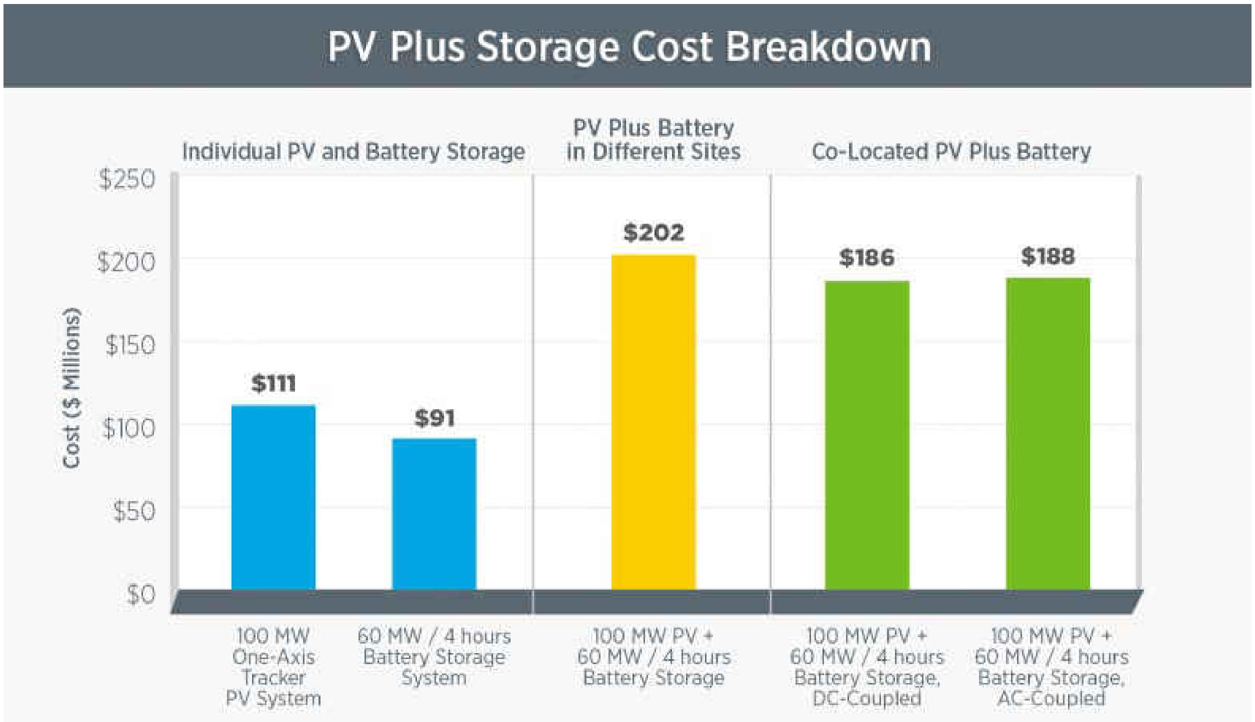


Figure 14: PV plus storage cost breakdown

Source: (Office of Energy Efficiency and Renewable Energy, 2019)

The buildup of energy storage in the queue of energy capacity in Gigawatts that it comes fourth as it stands with 18.9 GW energy capacity at the end of year 2017, while solar leads with188.5 GW. Figure 15 below represents the increase in energy capacity over the years 2014 till 2017. (Bolinger & Seel, 2019)

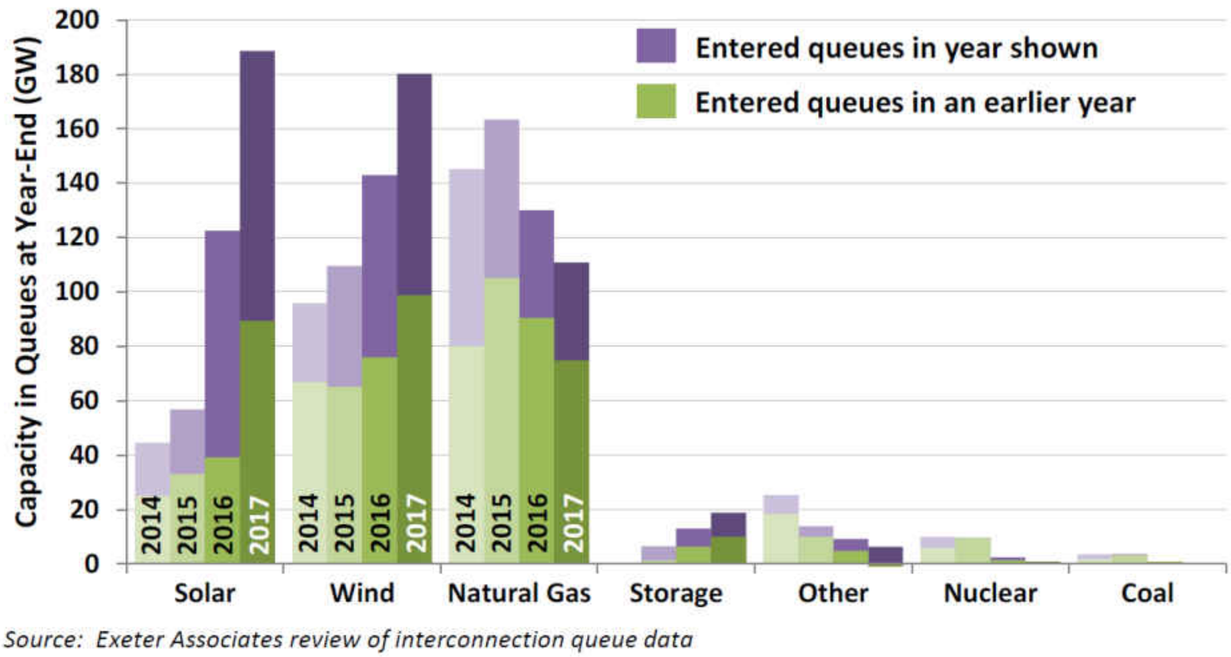


Figure 15: Capacity of non-conventional energy

Building a performance metric is a simplified method to understand the impact of various factors that have a significant effect on the performance of storage system. Many studies have been undertaken to develop such a metric which not only benefits the end user, but also the manufacturing company and its financers. Studies carried out by Lawrence Berkeley National Laboratory (LBNL) (Bolinger, Seel, & Wu, 2016) have been undertaken to build a multi-variate regression analysis of the factors that affect the performance of solar PV systems to statistically identify the factors that have the maximum impact on storage performance.(Bolinger et al., 2016)

In order to understand the impact that various factors have on energy storage systems, it is necessary to know the kind of storage system being employed to supplement the solar PV module. As an example, consider the figure below, which depicts the daily charging and discharging of a battery-based energy storage system. (Comello & Reichelstein, 2019)

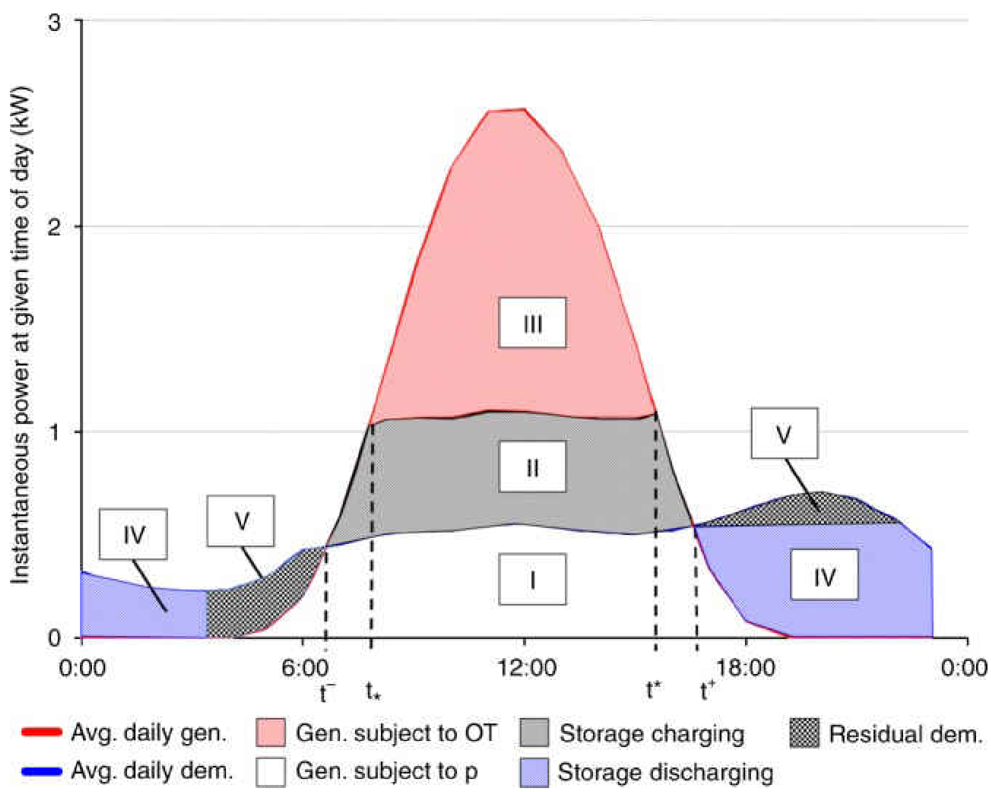


Figure 16: Instantaneous power in a day

Source: (Comello & Reichelstein, 2019)

In figure 16, Region I represent self-consumption from solar generation; region II is surplus energy that can be stored and subsequently discharged as region IV (minus efficiency losses); and region III is surplus energy sold to the grid. Region V is residual demand that would not be met by the battery and must be met through purchases from the grid at the going retail rate. While section 3 has highlighted various factors that affect the performance of a solar energy storage medium, this section will discuss the impact that each factor has on the performance of solar energy storage.

A regression analysis study was carried out on factors that were believed to have a significant impact on the performance of solar energy storage. These factors were identified as:

i. Availability of solar radiation
ii. Inverter Efficiency or the Inverter Load Ratio
iii. Temperature of the solar PV module
iv. Commercial Operation in a year (COD)

Out of these, the factors of "availability of solar radiation" and "Inverter efficiency" together were found to be statistically significant to the performance of solar energy storage, such that together they had an R^2 value of 0.920, which meant that the impact of these two factors on the performance of solar energy storage was 92%. "Availability of solar radiation" alone had an R^2 value of 0.811, meaning that the availability of solar radiation has 81.1% impact on the performance of the solar energy storage. The results of the regression analysis can be seen in figure 17 below:

	Model 1	Model 2	Model 3	Model 4	Model 5
2014 GHI	0.0604***	0.0521***	0.0478***	0.0479***	0.0423***
	(0.00280)	(0.00265)	(0.00199)	(0.00202)	(0.00245)
Tracking		0.0337***	0.0429***	0.0421***	0.0405***
		(0.00443)	(0.00296)	(0.00303)	(0.00285)
ln(ILR)			0.2391***	0.2146***	0.2158***
			(0.01911)	(0.02206)	(0.03393)
COD Year				0.0033**	0.0023*
				(0.00138)	(0.00132)
R^2	0.716	0.811	0.920	0.926	0.938

Figure 17: Regression results

Source: (Bolinger et al., 2016)

4.1 Availability of solar radiation

Availability of solar radiation includes the following:

2014 GHI – the 2014 Global Horizontal Irradiance and Tracking which can be explained by four factors of PV module orientation and tilt, shading, soiling and variation in solar radiation. (Bolinger et al., 2016)

Amount of sun hitting the solar PV module, as shown by various studies, has been identified as one of the biggest contributing factors to the performance of solar PV systems and thereby energy availability to the storage system. As per the factors highlighted in the paper, availability of solar radiation, also called the solar irradiance, can be identified as a mix of

a. PV module orientation and tilt
b. Shading
c. Soiling
d. Variation in solar radiation.

4.1.1 PV module Orientation and Tilt:

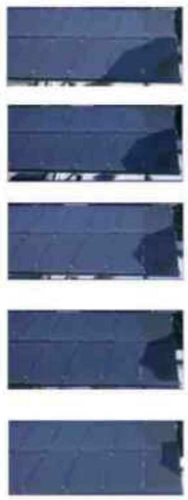
Flexible tracking PV modules that change their orientation and direction on axis as per the movement of sun in order to keep the plane of array as perpendicular to the sun as possible have proven to give a better performance as compared to fixed axis PV modules. Experiments conducted in the field of fixed-tilt versus tracking-tilt PV modules have shown that tracking tilt setup has an average output of 5.33 $kWh/m^2/day$, while the fixed-tilt setup has an average output of 4.83 $kWh/m^2/day$. (Bolinger et al., 2016)

4.1.2 Shading:

Power output of the whole solar PV module in series is dependent on the lowest power output of a single cell, meaning that shading even on a single cell is going to significantly reduce the performance of an entire solar

PV system, which also includes the energy storage system. Experiments have been conducted in order to study the impact that shading has on performance of a solar PV plus storage system, and the findings show that there is a substantial power loss because of non-uniform availability of solar irradiance on PV modules connected in series. The power generated by cells with availability of high solar irradiance is wasted in form of excess heat to the cells that have a lower availability of solar irradiance. (Ekpenyong & Anyasi, 2014)

Loss in system efficiency is disproportionately affected by the percentage of PV module that is shaded. As a thumb-rule, just 10% of shading can lead to almost 50% decline in PV module performance. Shading losses are known to go even up to 70%. The chart below shows test results of impact of shading on a solar PV system that includes storage.



% of Array Shaded	Power Loss Due to Shade
13%	44%
11%	47%
9%	54%
6.5%	44%
3%	25%

Figure 18: Impact of shading on PV module

Source: (Muenster, 2019)

4.1.3 Soiling:

While soiling cannot be eliminated completely due to various environmental factors, it can be reduced by simple steps such as daily washing of the panels during dry season. Soiling or dust accumulation has known to affect the performance of a solar PV system in the range of 2% to 50% depending on the area where the PV module is located. In 2001, Kimber et al. studied the effects of soiling on large grid-connected PV panels in California, United States. This study showed that there was a 0.2% daily reduction in PV system performance in days of dry weather with no rainfall. The annual loss in performance of the solar PV system in such conditions ranged from 1.5% to 6.2%. The picture below highlights the dust-density as observed around the world – darker the region – higher the dust density.

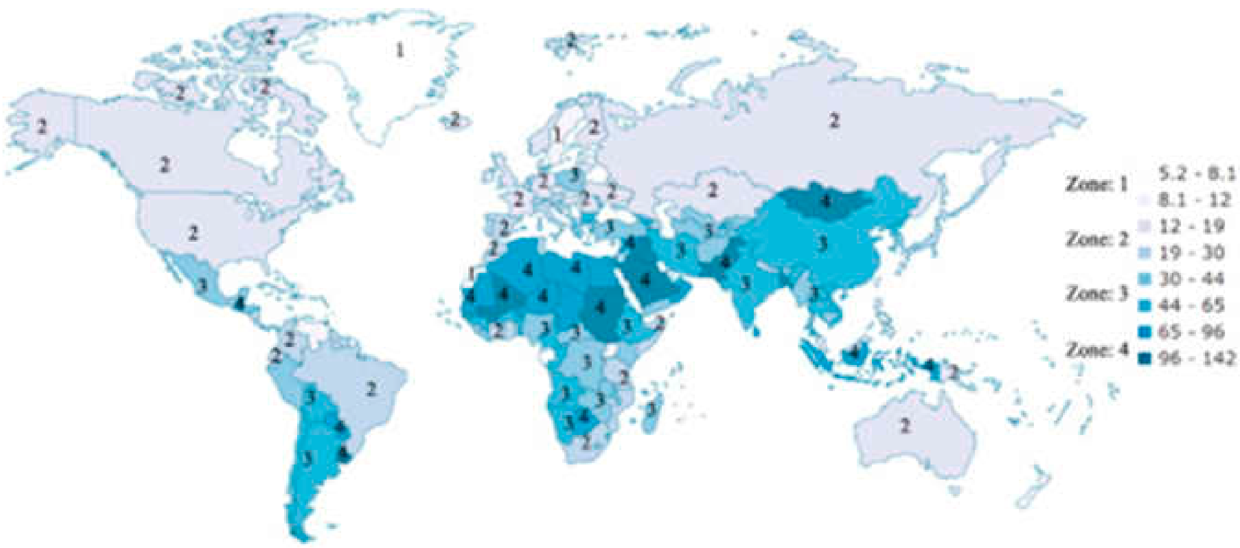


Figure 19: Dust intensity around the world

Source: (Maghami et al., 2016)

The study concluded that at least 20mm of rainfall was required to clean the surface of the solar PV panels which would improve the overall performance of the solar PV module.

Figure 19 above shows the various problems that lead to dust accumulation, along with some of the correlating factors that cause the problems.(Maghami et al., 2016)

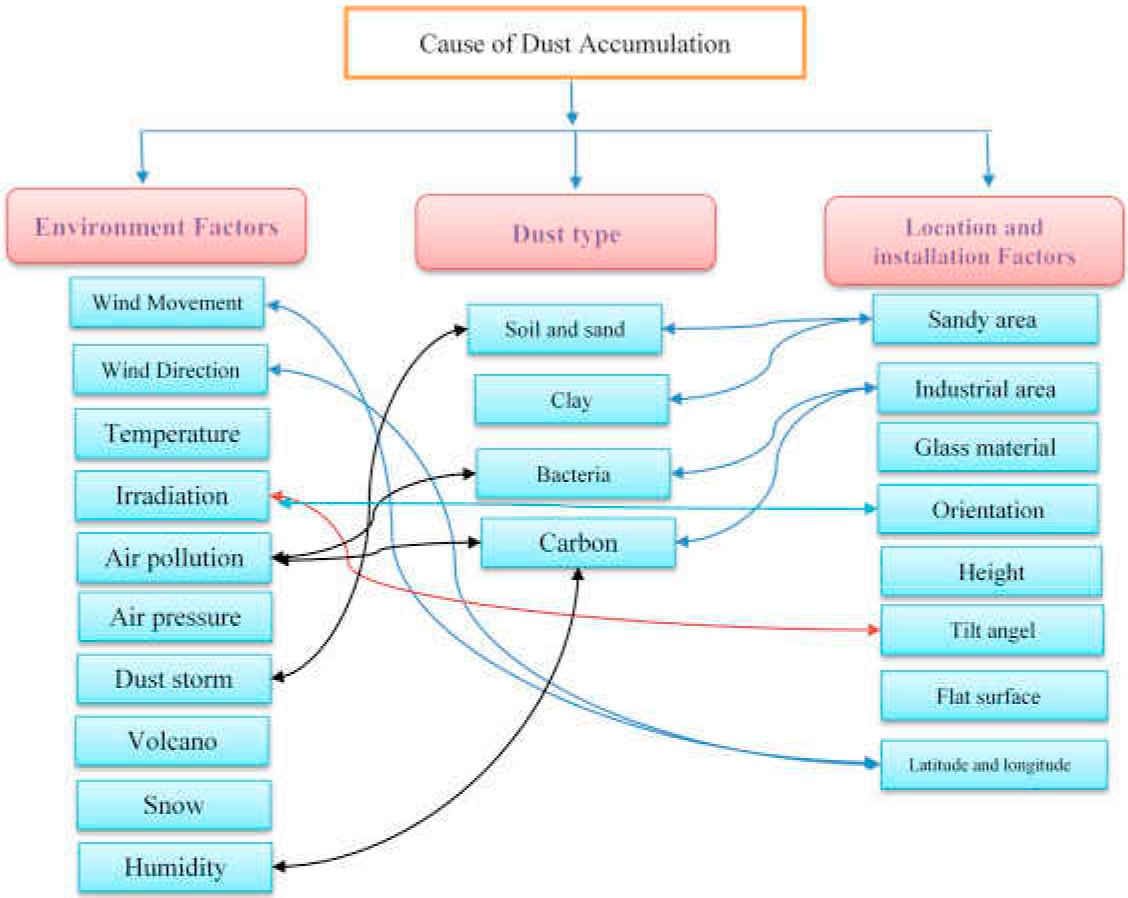


Figure 20: Cause of dust accumulation

Depending on the location of PV module + storage, the related environment factors and the type of dust, the power output of the PV module anywhere between 2% and 50%, thus affecting the power availability to the energy storage system. (Laajimi & Go, 2019)

4.1.4 Variation in Solar Radiation:

The ratio of solar radiation available for solar cell utilization, to global solar radiation, changes from season to season. It has been observed that the power output of a PV module is directly proportional to the amount of solar irradiance available to the PV module. Output variation for polycrystalline silicone technology PV module was found to be 4%, while for amorphous silicon technology PV module had a variation of 20%. This shows that an amorphous silicon technology PV module is more severely affected by the variation in solar radiation. Hence, seasonal changes in solar radiation cause variation in the amount of irradiation available to the PV modules, and this affects the total available power to the energy storage system. (Hirata & Tani, 1995)

4.2 Inverter Efficiency

Inverter Efficiency which can be understood by "load on inverter" or the "inverter loading ratio", is established as the second biggest factor making an impact on the performance of solar PV plus storage system as identified by the LBNL study. Electricity generated by solar PV module is in the form of DC current, and the energy stored is also in the form of DC current. In order for the stored energy to be transported to the grid, it has to be converted to AC current. The Inverter loading ratio is simply defined as the inverter's DC capacity rating to its AC capacity rating. It is found to be economically advantageous to increase the DC capacity rating of the PV array to the AC capacity rating of the inverters. This would enable the inverters to operate closer to full load for extended durations, in turn boosting the capacity factor AC terms and decreasing the capacity factor in DC terms. Regression analysis study has showed that the impact of inverter efficiency, in combination with the availability of solar radiation, on the performance of solar energy storage, amounts to 92%. (Bolinger et al., 2016)

It can thus be concluded that inverter efficiency and availability of solar radiation – which is a combination of PV module orientation and tilt, shading, soiling and variation in solar radiation, have a 92% impact on the variation in performance of solar energy storage system, making it imperative to focus on these two factors when aiming to improve the performance of solar energy storage systems. (Thaker, Oni, Gemechu, & Kumar, 2019)

CHAPTER 5: RECOMMENDATIONS AND FUTURE WORK

5.1 Summary

To summarize, a number of factors were reviewed that were believed to be important to the performance of solar energy storage systems. Environmental factors remain one of the biggest impacts on the performance of solar energy storage systems. These environmental factors include Shading, Soiling, Variation in solar radiation and the tracking of the sun – meaning the PV module orientation and tilt angle. The second biggest impact was that of the inverter efficiency. Together these two factors had 92% statistically significant impact on the performance of solar energy storage system.

5.2 Up-coming Trends in the Solar Energy System

One of the primary forces driving innovation in the solar industry are the customers. After having a light bulb or a radio that runs on solar energy, the customer challenges the companies to innovate so as to provide say a TV or a fridge that run on solar energy.

This progression can be compared to an energy ladder that may begin with an energy ladder, and gradually climbs up to solar appliances, and goes further up to distribution systems that have the right infrastructure to provide power for schools, hospitals, industries.

The companies that are actively innovating in the solar energy system are also credit-finance companies. So, they are bringing the people into an economy by putting their products, which are efficient and cheap, in the hands of the people.

In locations around the world where solar energy is in abundance, the governments are now encouraging solar rooftop programs so that every household and industrial facility is a proud producer as well as a consumer of the solar energy. Many state utilities around the globe have adopted technologies that allow the excess power generated through solar energy to be fed back into the conventional connected grid and passing the benefits to the household/ industrial facility. This setup means that the conventional utilities need to produce less energy to be fed into the grid, and ultimately ensure lesser burning of the fossil fuels.

5.3 Direction for Future for research

This study reviewed a number of parameters important to performance of solar energy storage. Solar energy storage systems can primarily be evaluated on three performance parameters namely Technical, economic and environmental health and safety. These performance parameters gauge the storage systems through its entire life cycle i.e. from the start of operations till the end of operations.

5.3.1 Life-Cycle Assessment of Solar Energy Storage Systems

Life cycle Assessment (LCA) technique is employed to define the characteristics of a product, service or a process in terms of the environmental impact through each stage of “womb-to-tomb”. Two methods are widely used for LCA namely:

1. Process-based Life Cycle Assessment, and
2. Economic-Input-Output Life Cycle Assessment

While the process based LCA focuses on inputs and outputs of a process leaving out the human labor, the Economic-Input-Output LCA method is solely focused on the monetary value of input and output of a process, and this includes accounting for human labor.

Recently, Life Cycle Assessments have been performed to evaluate the life cycle efficiencies and user phase efficiencies of storage systems like rechargeable batteries, pumped hydro and compressed air energy storage.

It was established that the total rechargeable battery storage system efficiency over its lifetime is calculated in the net energy ratio (kWhin/kWhout) which is a function of the following:

i. AC-AC round trip efficiency of the storage conversion process

ii. Storage medium energy ratio (kWhin/kWhout)

iii. Transmission energy ratio (kWhin/kWhout)

In addition to the energy ratios, Life Cycle Assessment also considers the total greenhouse gas emission factor (tons of CO2 emitted per GWh of energy) which is a function of the following:

i. Total electrical energy delivered by a storage facility over its lifetime

ii. Emission factor of primary electricity generation

iii. Operational emission factor per unit of energy delivered by the storage facility

iv. Emission associated with storage plant construction per unit of storage constructed

v. Storage plant size

Sandia national Laboratories conducted an Economic-Input-Output Life Cycle Assessment for various solar energy storage technologies like, a variety of batteries, fuel cells, pumped hydroelectric storage, compressed air energy storage, superconducting magnetic energy storage, capacitors and many more, to present an annual cost (cost per kW-year) for each storage technology. It was found that in the bulk storage category, Compressed Air Energy storage had the lowest cost, while in the distribution generation category hydro engine had the lowest cost. Nickel-Cadmium batteries proved to be drawing the highest annual cost in both the bulk storage category as well as the distribution generation category. High speed flywheel attracted the lowest annual cost, while Low Speed flywheel demanded the highest annual cost in the Power Quality category.

Apart from the Economic-Input-Output based Life Cycle Assessment, it is also important to factor in the process-based life cycle assessment since efficiency of a storage technology in conjunction with its environmental impact is the factors that affect the choice of a storage technology. For example, the pumped hydroelectric storage, compressed air energy storage and battery systems have a high operational cost, while the operational cost of super capacitors is negligible. The advantage of a super capacitor is its high storage efficiency owing to the fact that the capacitor can be re-used many-a-times. Although the energy required for the production of super capacitor's component is relatively small, the availability of raw materials required for the super capacitor is very limited. Therefore, to compare the technologies, a common denominator of energy cost per storage capacity is looked at rather than the energy ratio of energy input for every output of energy.

While it is necessary to construct robust and reliable energy storage techniques that not only succeed in realizing energy security, but also have negligible environmental impact, it should also be noted that no energy storage technology utilized in isolation can help achieve this goal. Techniques like Life Cycle Assessment help in comparing the various storage technologies on common grounds of technology cost over lifetime, environmental impact of the technology and storage capacity.

5.3.2 Storage capacity calculation

Solar energy is increasingly being used to generate electricity on a large scale using solar farms. Solar Photovoltaic energy (PV) in combination with an energy storage infrastructure is a game-changer in helping achieve the goal of reducing grid and fossil fuel dependency even during nights and bad weather. The size of a solar farm depends on the generation capacity expected from the farm, and moving forward, as the demand for solar energy increases, it is essential to understand that a solar farm needs to be sized in such a way that factors influencing the decrease in its performance have minimum impact. Since there is unavailability of sun during night, the solar energy harnessed during the day is also stored to be made available at night. The net electricity that can be generated from a solar farm thus depends not only on installed photo-voltaic capacity, but also on the installed energy storage capacity of the farm. Storage technology ensures that there is electricity even in the absence of the sun in a way that ensures grid stability and reduces the demand for back-up capacity. The net electricity output from a solar PV farm in a year can thus be calculated as follows:

Net Electricity Output = Gross Electricity Produced – Invested electricity

- (1)

Now,

$$\text{Gross Electricity Produced per yr} = 8760\ \text{hrs/yr} * \text{Total Capacity Factor} * \text{Total Photovoltaic Capacity}$$

Here,

Capacity Factor in a year is the ratio of the actual output in a year to its nameplate capacity output in a year

$$\begin{aligned}\text{Invested Electricity}\\ &= (\text{Total Embodied electricity in a Photovoltaic System}\\ &* \text{New Photovoltaic capacity added in the year})\\ &+ (\text{Total Embodied Electricity in Storage}\\ &* \text{New Storage Capacity added in the year})\end{aligned}$$

Here,

$$\begin{aligned}\text{New Photovoltaic Capacity added in the year (NCA)}\\ &= (\text{Total Photovoltaic Capacity in the year}\\ &- \text{ Total Photovoltaic Capacity in the previous year})\\ &+ \text{Retired Photovoltaic Capacity in the year}\end{aligned}$$

And,

$$\begin{aligned}\text{New Storage Capacity added in the year (NSA)}\\ &= (\text{Storage System's Total Capacity in the year}\\ &- \text{ Storage System's Total Capacity in the previous year})\\ &+ \text{Retired Storage Capacity in the year}\end{aligned}$$

In the equations above, the retired capacity is the total capacity that needs to be replaced with additional new capacity and is equal to the PV system or storage capacity added lifetime years ago. It is important to note that the Lifetime of both PV system and Storage system are taken to be 30 years. 65% out of the gross total embodied electricity in a PV system is electricity, while 50% out of the gross total embodied electricity in a storage system is electricity.(Jain, Jain, & Vaughn, 2018)

Also,

$$\text{Storage Capacity (in GWh)}$$
$$= \text{Storage Systems's rated Capacity in GW x Required number of storage hours}$$

Based on research, it is suggested that for designing a storage to support a 100% renewable energy system, the storage system's rated capacity may be taken as equal to the average power demand, while the required number of storage hours should be at least 240 hours (or 10 days) to counter any fluctuations in the weather.

However, if the storage is not for a 100% renewable system but used in conjunction with the grid, then, in such a case, the storage capacity required every year may be calculated as follows:

$$\text{Storage Capacity in the year (in GWh)}$$
$$= \text{Total Installed Capacity of PV in the year x Required number of storage days x 24}$$

(Jain et al., 2018)

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