WEL-COME TO ALL T. Y. B. Sc. STUDENTS

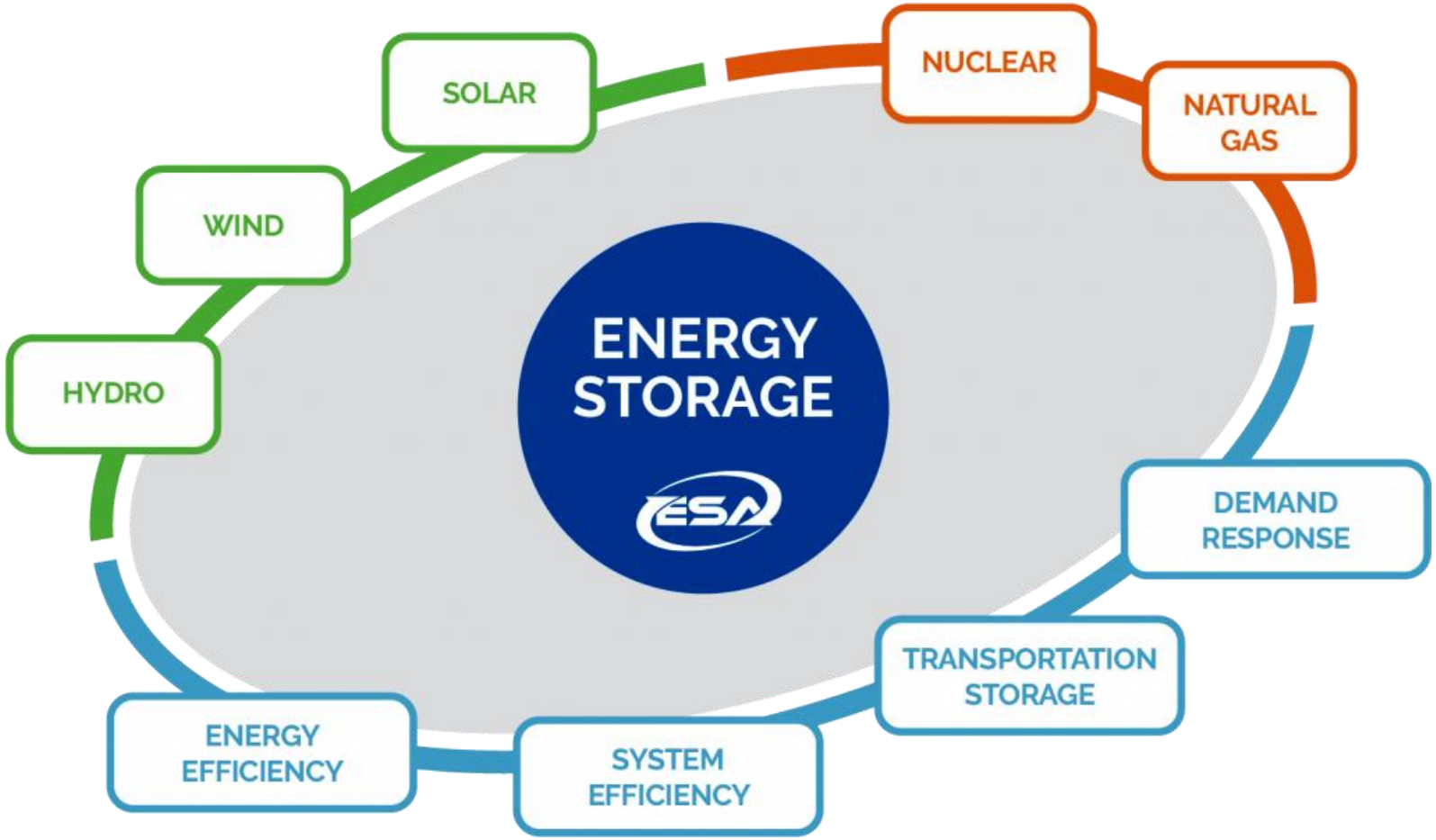
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PHYSICS DEPARTMENT

Name of Paper :- Renewable Energy Sources I

Topic:- Energy Storage

Energy Storage



Energy Storage

- One of the major goals of sustainable energy systems is to provide clean, affordable, accessible energy with benign environmental impact.
- Development of reliable energy systems without toxic by products to preserve the environment while powering the future is urgently needed.
- This need has led to the design and implementation of power generating systems using photovoltaics (PV) and energy storage devices. Currently, there is an excess increase in the fossil fuels cost due to increase in consumption of electric grid energy and its inability to meet up with the demand.
- Optimizing the generation, storage and use of electric power by using renewables (PV) and storage devices will enhance efficient, effective and reliable power consumption.
- This chapter proposes an efficient approach for the integration of renewable energy systems (PV) and energy storage devices as well as their safety and trade offs in the environment.

Energy Storage

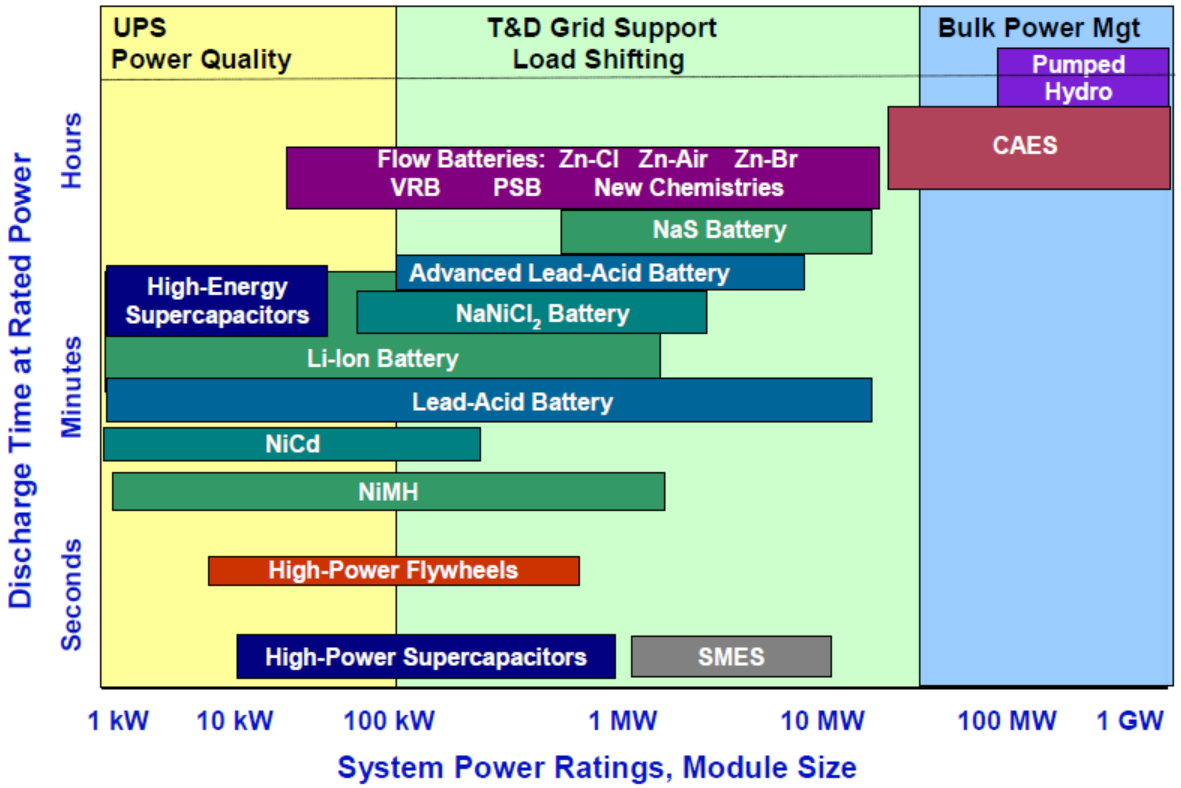
- A major goal of sustainable energy system using renewable energy is to provide clean, affordable, accessible energy with efficient energy storage with depleting the earth resources.
- There is a need to develop reliable energy systems that do not depend on fossil fuel to preserve the environment while powering the present and the future.
- This has led to the development of power generating systems utilizing renewables (photovoltaics and wind)
- There has being rapid increase in the power generation from PV over there the years
- Due to the rapid increase in PV generation, energy storage is serves as a storage medium for excess generation which can use when needed.
- Energy storage systems also serve as a means of increasing the power utilization and consumption rate. Implementing battery storage is limited due to relatively high cost.

Energy Storage

- Energy storage is the ability to capture energy at one time for use at a later time.
- Storage devices can save energy in many forms (e.g., chemical, kinetic, or thermal) and convert them back to useful forms of energy like electricity.
- Although almost all current energy storage capacity is in the form of pumped hydro and the deployment of battery systems is accelerating rapidly, a number of storage technologies are currently in use.
- Energy storage can save operational costs in powering the grid, as well as save money for electricity consumers who install energy storage in their homes and businesses.
- Energy storage can reduce the cost to provide frequency regulation and spinning reserve services, as well as offset the costs to consumers by storing low-cost energy and using it later, during peak periods at higher electricity rates.

- Energy storage technologies encompass a variety of systems, which can be classified into
- five broad categories, **mechanical, electrochemical (or batteries), thermal, electrical, and hydrogen storage technologies.**
- Advanced energy storage technologies are capable of dispatching electricity within milliseconds or seconds and can provide power back-up ranging from a few minutes to many hours.
- The suitable duration (long or short) of storage, scale of systems (in MW and MWh) and response time are technology dependent making it important to choose the appropriate technology as per the application requirements and constraints.

Various forms of Energy Storage



Various forms of Energy Storage

Batteries

- There are various forms of batteries, including: **lithium-ion, flow, lead acid, sodium, and others designed to mee specific power and duration requirements**.
- Initially used for consumer products, **lithium-ion batteries** now have a wide range of applications including smalle residential systems and larger systems that can store multiple megawatt hours (MWh) and can support the entir electric grid.
- These systems typically house a large number of batteries together on a rack, combined with monitoring an management units.
- These systems have a small footprint for the amount of energy they store. For example, a system the size of a sma refrigerator could power an average home for several days. A utility-scale system of 100 MWh could fit on less than 0. acres.
- **Lithium-ion batteries** have received a lot of press for their rapidly declining costs, due to the growing popularity c electric vehicles.
- A different type of battery is a flow battery in which energy is stored and provided by two chemicals that are dissolve in liquids and stored in tanks. These are well suited for longer duration storage.

Various forms of Energy Storage

Thermal

- The principle of storage of energy in thermal energy storage systems is conceptually different from electrochemical or mechanical energy storage systems.
- Here, the energy by heating or cooling down appropriate materials using excess electrical energy.
- When required, the reverse process is used to recover the energy.
- This category of technologies **includes ice-based storage systems**, **hot and chilled water storage**, molten **salt storage and rock storage technologies**
- Thermal systems use heating and cooling methods to store and release energy. For example, **molten salt stores solar-generated heat for use when there is no sunlight.** Ice storage in buildings reduces the need to run compressors while still providing air conditioning over a period of several hours.
- Other systems use chilled water and dispatchable hot water heaters. In all cases, excess energy charges the storage system (heat the molten salts, freeze the water, etc.) and is later released as needed.

Mechanical Systems

- Flywheels store electrical energy as rotational energy in a heavy cylindrical rotating mass. Flywheel energy storage systems typically consist of a large rotating cylinder supported on a stator Stored electric energy increases with the square of the speed of the rotating mass, so materials that can withstand high velocities and centrifugal forces are essential for its construction. In general, flywheels are very suitable for high power applications due to their capacity to absorb and release energy in a very short duration of time.
- Flywheels store energy in a rapidly spinning mechanical rotor and are capable of absorbing and releasing high power for typically 15 minutes or less, although longer duration systems are being developed.
- These systems can balance fluctuations in electricity supply and demand where they respond to a control signal adjusted every few seconds.
- They also recapture braking energy from electric trains in some installations or provide short-term power until backup generation comes online during a grid outage, such as in a critical manufacturing process where product would be lost by a momentary electric interruption.

Various forms of Energy Storage

Pumped Hydro Power

- Pumped hydroelectric facilities are the most common form of energy storage on the grid and account for over 95% of the storage in use today. During off-peak hours, turbines pump water to an elevated reservoir using excess electricity. When electricity demand is high, the reservoir opens to allow the retained water to flow through turbines

Various forms of Energy Storage

- **Emerging Technologies**

Compressed air, superconducting magnets, underground pumped storage, and hydrogen storage are all forms of emerging energy storage that are in different stages of development.

Electrical Storage

Super capacitors and Superconducting Magnetic Energy Storage (SMES) systems store electricity in electric and electromagnetic fields with minimal loss of energy.

A few small SMES systems have become commercially available, mainly used for power quality control in manufacturing plants such as microchip fabrication facilities.

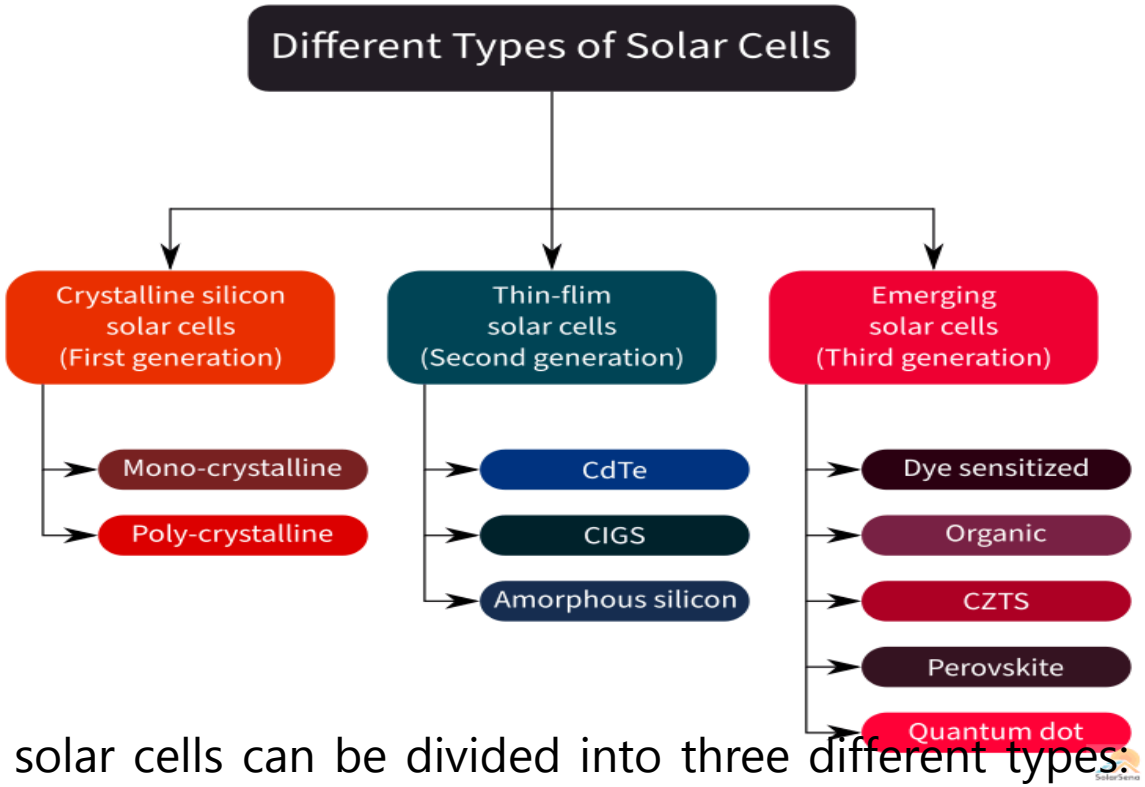
These technologies are ideal for storing and release high levels of energy over short bursts due to their lower price in $/kW (power).

Hydrogen Storage Technologies (Power-to-Gas)

The basic concept of hydrogen storage technologies is to use electricity to perform electrolysis of water to produce hydrogen and oxygen. The hydrogen produced is stored in high pressure containers and can be used as a fuel for direct combustion (cooking and heating applications) or for electricity generation via PEM Fuel Cells.

Solar cells, also known as photovoltaic (PV) cells, are photoelectric devices that convert incident light energy to electric energy. These devices are the basic component of any photovoltaic system. In the article, we will discuss different types of solar cells and their efficiency.

Scientists invented one of the earlier solar cells at Bell Laboratories in the 1950s. Since then, hundreds of solar cells have been developed. And the number continues to rise. As researchers keep developing photovoltaic cells, the world will have newer and better solar cells.



Most solar cells can be divided into three different types: crystalline silicon solar cells, thin-film solar cells, and third-generation solar cells. The crystalline silicon solar cell is first-generation technology and entered the world in 1954. Twenty-six years after crystalline silicon, the thin-film solar cell came into existence, which is second-generation technology. And the last, the third-generation solar cell, is still emerging technology and not fully commercialized.

Direct conversion of light into electricity.

Materials absorbing photons and being ionized such that electrons are released are known to have a photoelectric effect, often called solar cells. When the free electrons released are captured, electric current is the result.

Solar cells are made of semiconductor materials such as silicon (wafers) or non-silicon materials such as cadmium telluride, treated to form an electric field, positive on one side and negative on the other. Due to the semiconductor structure the electrons are forced in one direction creating the current. The current produced is directly dependent on how much light that strikes the module

N-Type Silicon (Negative)

N-type silicon has been chemically combined with phosphorus gas to make it conductive. A silicon atom has four electrons in its outer shell and bonds tightly with four surrounding silicon atoms creating a crystal matrix with eight electrons in the outer shells. Phosphorus has five electrons, and when combined, the fifth electron becomes a “free” electron that moves easily within the crystal when a voltage is applied. Since the charge carriers are electrons, n-type refers to a negative charge.

P-Type Silicon (Positive)

P-type silicon is combined with boron gas making it a conductive material that accepts electrons when voltage is applied. Boron has three electrons in its outer shell and can bond with only three of the four surrounding silicon atoms. This leaves one silicon atom with a vacant location in its outer shell, called a “hole” that accepts one electron. Since the

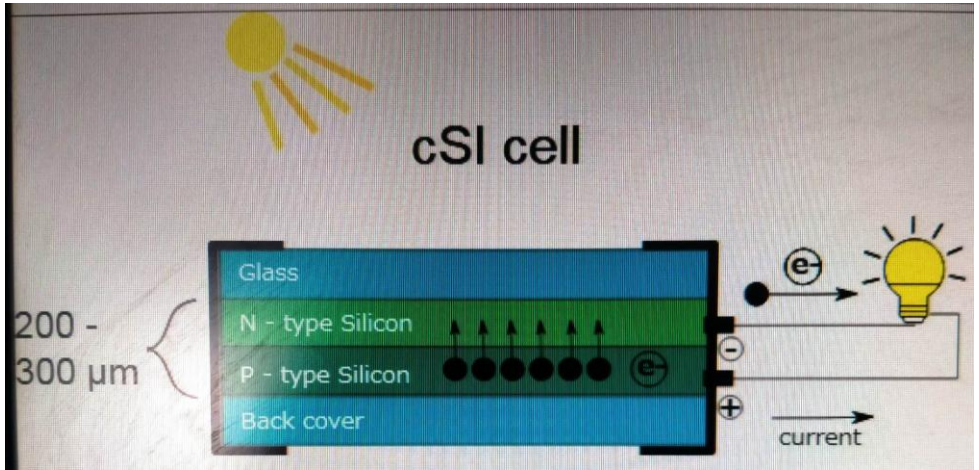
Efficiency of silicon based solar cells

The efficiency of solar cells is not 100% since some of the light spectrum is reflected, some is too weak to generate electricity (infrared) and some (ultraviolet) creates heat instead of electricity. Monocrystallin cells operate with an efficieny of 15%- 20 %. Multicrysatalline cells are less costly to manufacture but are a little less efficient, 12% -16%.

Thin film solar cells (Amorphous silicon (a-Si) Simplified amorphous silicon photovoltaic cell

Amorphous silicon (a-Si) is the non-crystalline form of silicon. The cell structure has a single sequence of p-i-n layers ("i" = intrinsic layer). A-SI type thin film solar cells are commonly found in calculators and other small electronic devices.

Thin film silicon solar cells operate with an efficiency of 6% – 10% but consume less material and have a high degree of flexibility in application compared to the traditional wafer based PV cells.

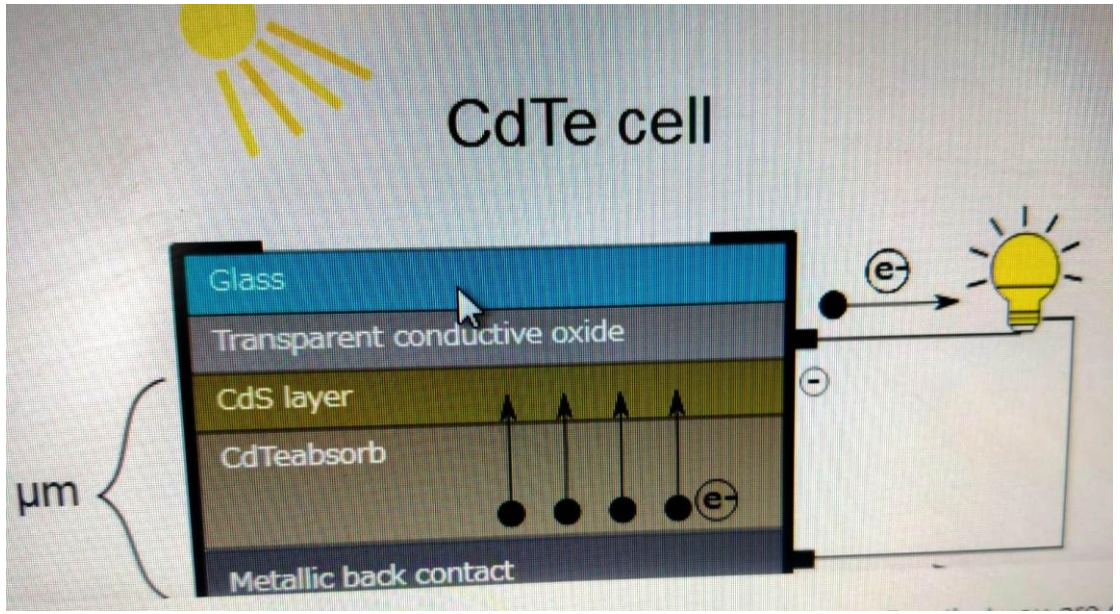


Cadmium Telluride (CdTe) solar cell Simplified cadmium telluride photovoltaic cell

CdTe solar cell is the most common photovoltaic (PV) technology next to crystalline silicon.

CdTe cells have a thin layer of cadmium telluride and are normally coated with cadmium chloride ($CdCl_2$) to increase the efficiency.

The CdTe thin-film solar cell is a cost efficient alternative to conventional silicon based cells. The manufacturing of the cells can be efficient and relatively inexpensive



Copper Indium Selenide (CIS) and Copper indium Gallium diSelenide CIGS Solar cell
Simplified copper indium selenide and copper indium gallium deselenide photovoltaic cell (not to scale)

CIS cells have a thin layer of $CuInSe_2$,on glass or metal backing.

A common variation of this cell is the copper indium gallium diselenide **CIGS** cell.

CIS cells have up to 14% efficiency and since they are thin film, they can be less costly than silicone based cells.

Crystalline Silicon Solar Cells

As mentioned earlier, crystalline silicon solar cells are first-generation photovoltaic cells. They comprise of the silicon crystal, crystalline silicon (c-Si). Crystalline silicon is the core material in semiconductors, including in the photovoltaic system.

These solar cells control more than 80% of the photovoltaic market as of 2016. And the **reason is the high efficiency of c-Si solar cells.**

There are two types of crystalline silicon: **monocrystalline silicon (mono c-Si) and polycrystalline silicon (poly c-Si)**.

Monocrystalline silicon solar cells

Monocrystalline silicon is **single** crystal silicon. In other words, it is a homogeneous material. All of its electric, **thermal, crystal properties remain the same throughout the cell.** There are no deflects in monocrystalline silicon.

This homogeneity of mono c-Si makes it a superior electrical material compared to poly c-Si. As a result, **mono c-Si solar cells have higher efficiency than poly c-Si solar cells.** At the lab-scale, the efficiency reported is around 25%, while at the **production-scale, the efficiency drops to 20–22%.**

One major disadvantage of monocrystalline silicon cells is they are relatively more **expensive than polycrystalline. The production of monocrystalline is less efficient and creates material wastage.**

A monocrystalline solar cell is a single-piece material. One can physically distinguish monocrystalline from polycrystalline. Monocrystalline solar cells give a more premium look. They typically have a black hue. Each corner of the cell is clipped, giving them an octagonal shape.

Polycrystalline silicon solar cells

polycrystalline silicon is composed of several small crystallites. It is a non-homogeneous material and shows a discontinuity in electrical, thermal, and crystal properties.

Because of defects in the crystal structure, poly c-Si solar cells are less efficient than mono c-Si cells. The highest lab-scale efficiency published **is 22%,** and in production, it falls to **18–20%.**

poly c-Si cells have less efficiency, they are cheaper than mono c-Si. Furthermore, the production process of poly c-Si cells is simpler and has a higher production rate than mono c-Si.

A polycrystalline solar cell is a non-uniform material. Each cell consists of several tiny crystallites.They show a different physical appearance than mono. Polycrystalline silicon cells give a bluish hue with a metallic shine.

People sometimes refer to polycrystalline silicon as multi-crystalline silicon (multi c-Si).

Thin-film solar cells

Thin-film solar cells are newer photovoltaic technology and consist of one or more thin films of photovoltaic materials on a substrate. Their primary advantage over traditional crystalline silicon cells is cost They are cheaper Another advantage is flexibility. The thickness of the film is in **nanometers.** That makes thin-film PV cells pliable.

Three common thin-film solar cells are **cadmium telluride (CdTe), copper indium gallium selenide** (CIGS), and **amorphous thin-film silicon (a-Si).**

Cadmium telluride solar cells

Cadmium telluride (CdTe) solar cells use Cadmium telluride to absorb solar energy They remain the most prominent thin-film cells because of a **lower manufacturing cost and lower carbon footprint**.

A cadmium telluride (CdTe) solar cell is thin-film technology formed by depositing nano-layers on a substrate. CdTe shares 5% of the total photovoltaic market. These PV cells have an advantage of a low production cost compared to the convenient c-Si cell. But they are inefficient. The highest known lab efficiency is **22.1% by** First Solar This value falls to 16.1% on a commercial scale.

Copper indium gallium selenide solar cells

Copper indium gallium selenide (CIGS) is another common thin-film photovoltaic cell. The cell has shown high efficienc because of a high absorption coefficient of **copper indium gallium selenide**. Even though the lab efficiency exceeds **20% on a commercial-scale, it goes between 12 to 14%**

Amorphous silicon solar cells

Amorphous silicon (a-Si) solar cells use amorphous silicon as energy-absorbing material. We can deposit non-crystallin silicon on the glass to give rigidity or on the plastic to give flexibility.

Flexible amorphous silicon used in aerospace applications

There are several advantages of a-Si. It is abundant in the earth's crust and is non-toxic. Besides, silicon has semiconducto properties and can absorb solar energy in a broad spectrum.

One major shortcoming of amorphous silicon PV cells is very **low efficiency**. In labs, the maximum efficiency reached around **12%.** The value degrades largely on a commercial scale. It is **between 4 to 6%.**

To overcome the efficiency barrier, researchers have come up with some modifications to a-Si cells. For example, th pairing of a-Si with microcrystalline silicon increases efficiency.

Emerging solar cells

Emerging solar cells is third generation technology. Since they are in a developing state, we will find them mostly in research laboratories. This type has recently got a lot of attention. These cells are much cheaper and easy to produce by the roll-to-roll method. However, none of them has shown commercial efficiency similar to crystalline silicon cells.

The most popular of them are **dye-sensitized,** perovskite, and quantum dots.

Dye-sensitized solar cells

Dye-sensitized solar cells (DSSC) use organic dyes to absorb photons from solar energy. The main components of the cell include dye molecules, titanium dioxide nanoparticles, and an electrolyte solution.

Dye-sensitized solar cells

As of 2019, the lab efficiency of DSSC goes between 12 to 14%. And the efficiency trend shows it will increase in the coming years.

The major disadvantages of DSSCs are a **degradation on exposure to UV, temperature instability, and costly ruthenium dyes.** The electrolyte solution used is in the liquid state. So, it can expand or contract with temperature and cause damage to the cell.

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Perovskite solar cells

Perovskite solar cells consist of perovskite compounds. A perovskite is any compound whose crystal structure resembles that of calcium titanium oxide. The most common perovskite used in solar cells is methylammonium lead trihalide.

The major breakthrough in perovskite cells came in the last ten years. The efficiency of cells has increased from 3.8% in 2009 to 25.2% in 2020. That is an incredible jump. And it is the reason why scientists are giving more attention to this type.

A perovskite solar cell [Credit: NREL]Another advantage is the low cost of raw materials. The chemicals used in perovskite cells are relatively cheaper. However, perovskites have a major setback, i.e., the stability of the material. When exposed to heat, moisture, snow, perovskite cells degrade quickly.

Quantum dot solar cells

Quantum dot solar cells (QDSC) are quite an amazing concept. They use something called quantum dots as photovoltaic material to absorb light. In simple words, quantum dots are tiny particles in nanometers that have semiconductor properties.

A major advantage is the bandgap of quantum dot cells is tunable depending on the size of a quantum dot. It means we can design a cell that can absorb an entire spectrum of sunlight, including the far-infrared. That is impractical in convenient silicon cells. As of 2020, the highest known efficiency is 16.6%.

Electrical energy is stored in super capacitors via two storage principles, **static double-layer capacitance and electrochemical pseudo capacitance**; and the distribution of the two types of capacitance depends on the material and structure of the electrodes.

- Supercapacitors are electronic devices which are used to store extremely large amounts of electrical charge.
- They are also known as double-layer capacitors or ultra capacitors.
- Instead of using a conventional dielectric, supercapacitor use two mechanisms to store electrical energy: double-layer capacitance and pseudocapacitance.
- In case of **Double layer capacitance** is electrostatic in origin, while **pseudocapacitance is electrochemical**, which means that super capacitors combine the workings of normal capacitors with the workings of an ordinary battery.
- Capacitances achieved using this technology can be as high as 12000 F.
- In comparison, in case of ordinary electrostatic capacitor may have a high maximum operating voltage, the typical maximum charge voltage of a supercapacitor lies between 2.5 and 2.7 volts.
- Super capacitors are polar devices, meaning they have to be connected to the circuit the right way, just like electrolyte capacitors.
- The electrical properties of these devices, especially their fast **charge and discharge times,** are very interesting for some applications, where supercapacitor may completely replace batteries.

Charge time

- Supercapacitor have charge and discharge times comparable to those of ordinary capacitors.
- It is possible to achieve high charge and discharge currents due to their low internal resistance. Batteries usually take up to several hours to reach a fully charged state –
- e.g. is a cell phone battery, while supercapacitor can be brought to the same charge state in less than two minutes.

Specific power

- The specific power of a battery or super capacitor is a measure used to compare different technologies in terms of maximum power output divided by total mass of the device.
- Super capacitors have a specific power 5 to 10 times greater than that of batteries.
- For example, while **Li-ion batteries have a specific power of 1 - 3 kW/kg** the specific power of a typical super capacitor is around 10 kW/kg.
- This property is especially important in applications that require quick bursts of energy to be released from the storage device. **Cycle life and safety**

Supercapacitor batteries are safer than ordinary batteries when mistreated. While batteries are known to explode due to excessive heating when short circuited, supercapacitors do not heat as much due to their low internal resistance. Shorting a fully charged supercapacitor will cause a quick release of the stored energy which can cause electrical arcing

- Supercapacitor batteries are safer than ordinary batteries when mistreated. While batteries are known to explode due to excessive heating when short circuited, supercapacitors do not heat as much due to their low internal resistance.
- Shorting a fully charged supercapacitor will cause a quick release of the stored energy which can cause electrical arcing, and might cause damage to the device,
- Supercapacitors can be charged and discharged millions of times and have a virtually unlimited cycle life, while batteries only have a cycle life of 500 times and higher.
- This makes supercapacitors very useful in applications where frequent storage and release of energy is required.

➢**Supercapacitors** come with some disadvantages as well. One disadvantage is a relatively **low specific energy**. The specific energy is a measure of total amount of energy stored in the device divided by its weight.

➢While Li-ion batteries commonly used in cell phones have a specific energy of 100-200 Wh/kg, supercapacitors may only store typically 5 Wh/kg. This means that a supercapacitor that has the same capacity (not capacitance) as a regular battery would weigh up to 40 times as much. The specific energy is not to be confused with the specific power, which is a measure of maximum output power of a device per weight.

➢Another **disadvantage** is a **linear discharge voltage**. For example, a battery rated at 2.7V, when at 50% charge would still output a voltage close to 2.7V, while a supercapacitor rated at 2.7V at 50% charge would output exactly half of its maximum charge voltage – 1.35V. This means that the output voltage would fall below the minimum operating voltage of the device running on a supercapacitor,

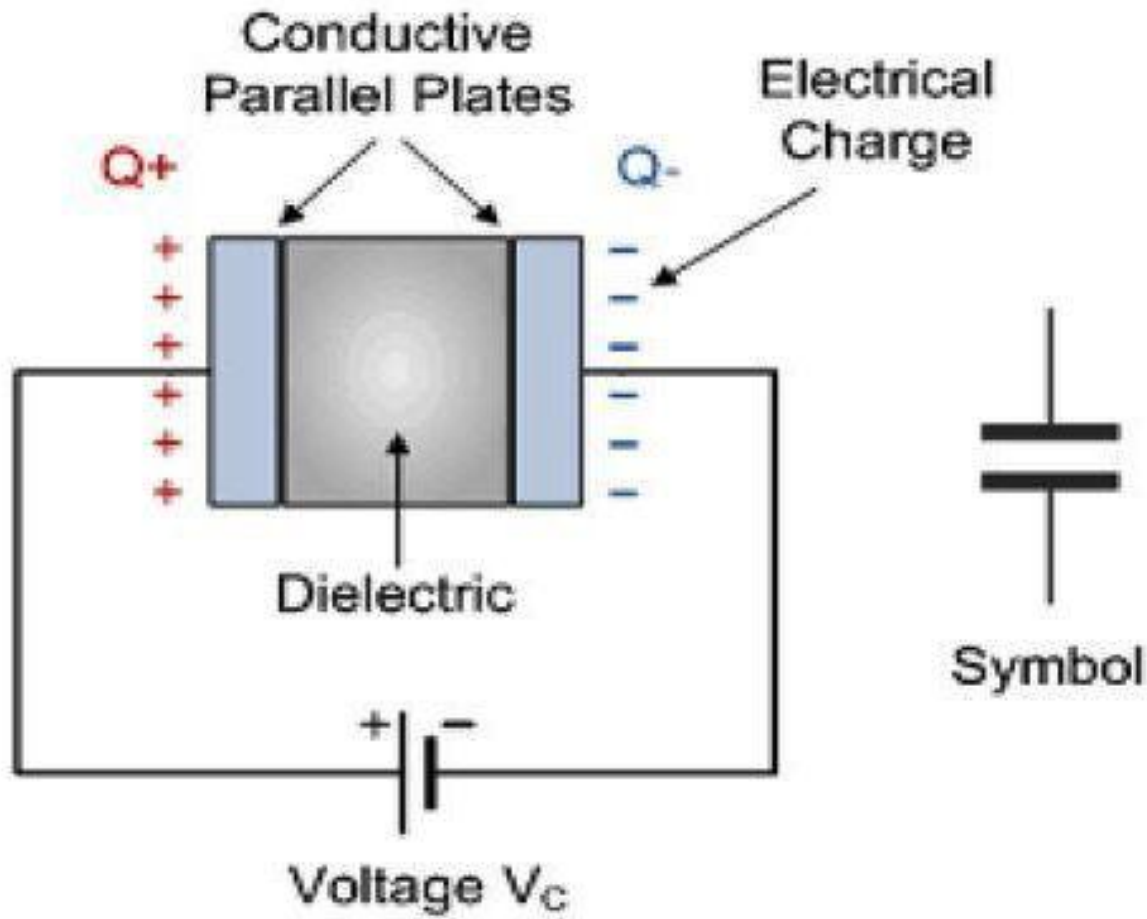
➢for example a cell phone, and the device would have to shut down before using all the charge in the capacitor. A solution to this problem is using DC-DC converters. This approach introduces new difficulties, such as efficiency and power noise..

➢Low specific energy, linear discharge voltage and high cost are the main reasons preventing supercapacitors from replacing batteries in most applications.

CAPACITOR

- A Capacitor (originally known as condenser) is a passive two terminal electrical component to store energy in an Electric field.

- When a Capacitor is attached across a battery, an electric field develops across a dielectric, causing positive charge +Q to develop on one plate and negative charge –Q to develop on the other plate.

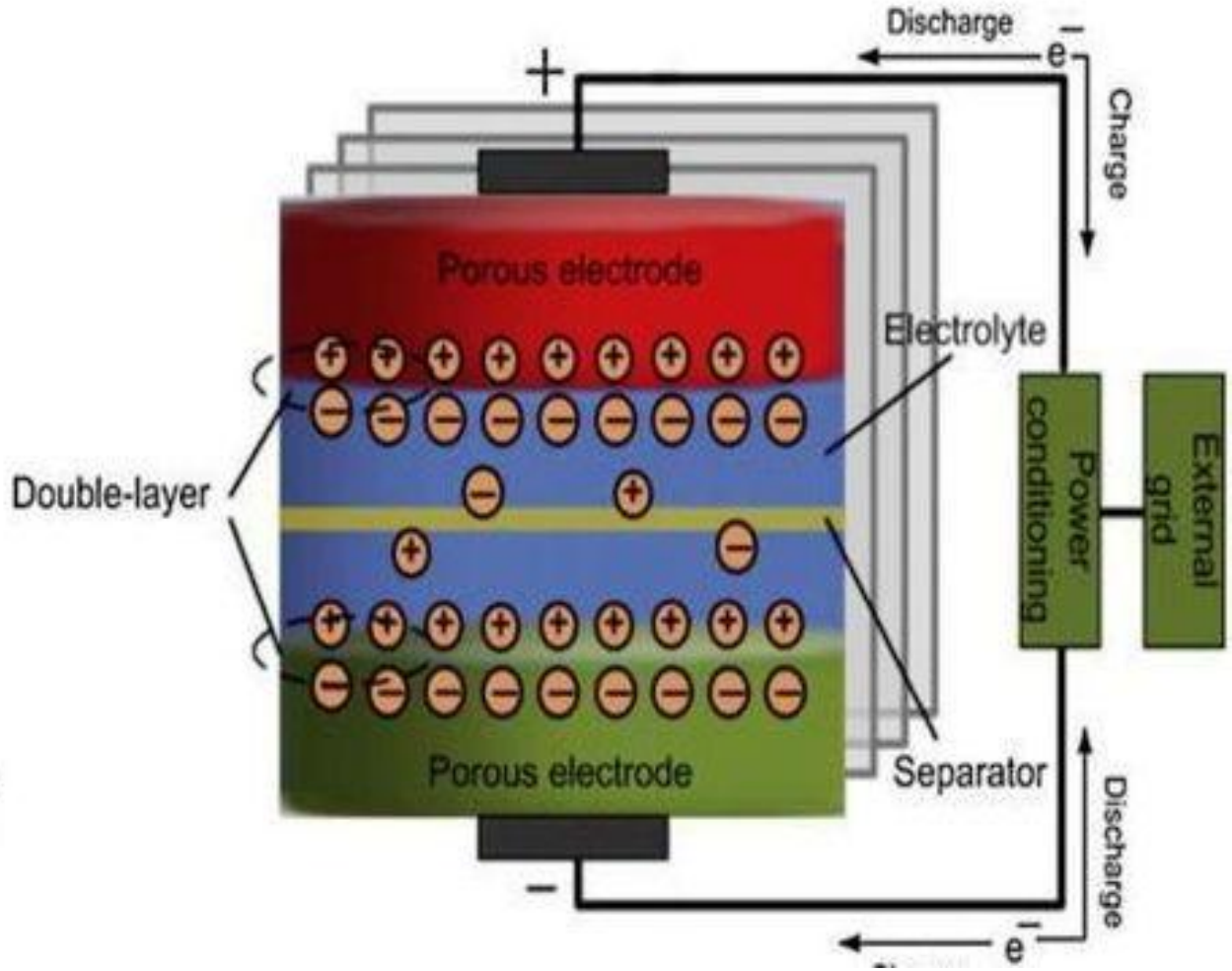


SUPERCAPACITOR

A Supercapacitor is an electrochemical capacitor that has a very high energy density as compared to common capacitors, about 100 times greater.

Supercapacitor is also known as an Electric Double layer Capacitor (EDLC) or an ultracapacitor.

The Capacitance range is from 100F to 5kF.



Electrochemical energy storage **covers all types of secondary batteries**. Batteries convert the chemical energy contained in its active materials into electric energy by an electrochemical oxidation-reduction reverse reaction. At present batteries are produced in many sizes for wide spectrum of applications.

Electrochemical energy storage covers all types of secondary batteries. Batteries convert the chemical energy contained in its active materials into electric energy by an electrochemical oxidation-reduction reverse reaction.

At present batteries are produced in many sizes for wide spectrum of applications. Supplied powers move from W to the hundreds of kW.

Common commercially accessible secondary batteries according to used electrochemical system can be divided to the following basic groups:

Standard batteries (lead acid, Ni-Cd) modern batteries (Ni-MH, Li–ion, Li-pol), special batteries (Ag-Zn, Ni-H2), flow batteries (Br2-Zn, vanadium redox) and high temperature batteries (Na-S, Na–metalchloride).

Electrochemical batteries convert chemical energy directly into electrical energy and provide DC current. A battery consists of electrochemical cells that convert stored chemical energy into electrical energy. When two dissimilar metals are immersed in an electrolyte (conductive liquid), the breakdown of chemicals into charged particles (ions) results in a flow of electricity when the battery is connected to en external circuit. The electrochemical battery is powered by the redox reaction. Electrons are added at the cathode during charging, while electrons are removed at the anode. During discharge, the process is the reverse. The electrodes are electrically connected via the electrolyte. Different electrolytes might be used for each half-cell (+/-). In those cases the electrolytes are not mixed but ions are allowed to flow between the half-cells. The number of voltaic cells (pairs of half-cells) contained in a battery may very pending on the usage and desiered

Hydrogen can be produced using a number of different processes. Thermochemical processes use heat and chemical reactions to release hydrogen from organic materials, such as fossil fuels and biomass, or from materials like water. Water (H_2O) can also be split into hydrogen (H_2) and oxygen (O_2) using electrolysis or solar energy. Microorganisms such as bacteria and algae can produce hydrogen through biological processes.

Thermochemical Processes

Some thermal processes use the energy in various resources, such as natural gas, coal, or biomass, to release hydrogen from their molecular structure. In other processes, heat, in combination with closed-chemical cycles, produces hydrogen from feedstocks such as water. Learn more about the following thermochemical processes:

Natural gas reforming (also called steam methane reforming or SMR)
Biomass gasification
Biomass-derived liquid reforming
Solar thermochemical hydrogen (STCH).

Electrolytic Processes

Electrolyzers use electricity to split water into hydrogen and oxygen. This technology is well developed and available commercially, and systems that can efficiently use intermittent renewable power are being developed. Learn more about electrolysis.

Direct Solar Water Splitting Processes

Direct solar water splitting, or photolytic, processes use light energy to split water into hydrogen and oxygen. These processes are currently in various early stages of research but offer long-term potential for sustainable hydrogen production with low environmental impact. Learn more about the following solar water splitting processes:

Photoelectrochemical (PEC)