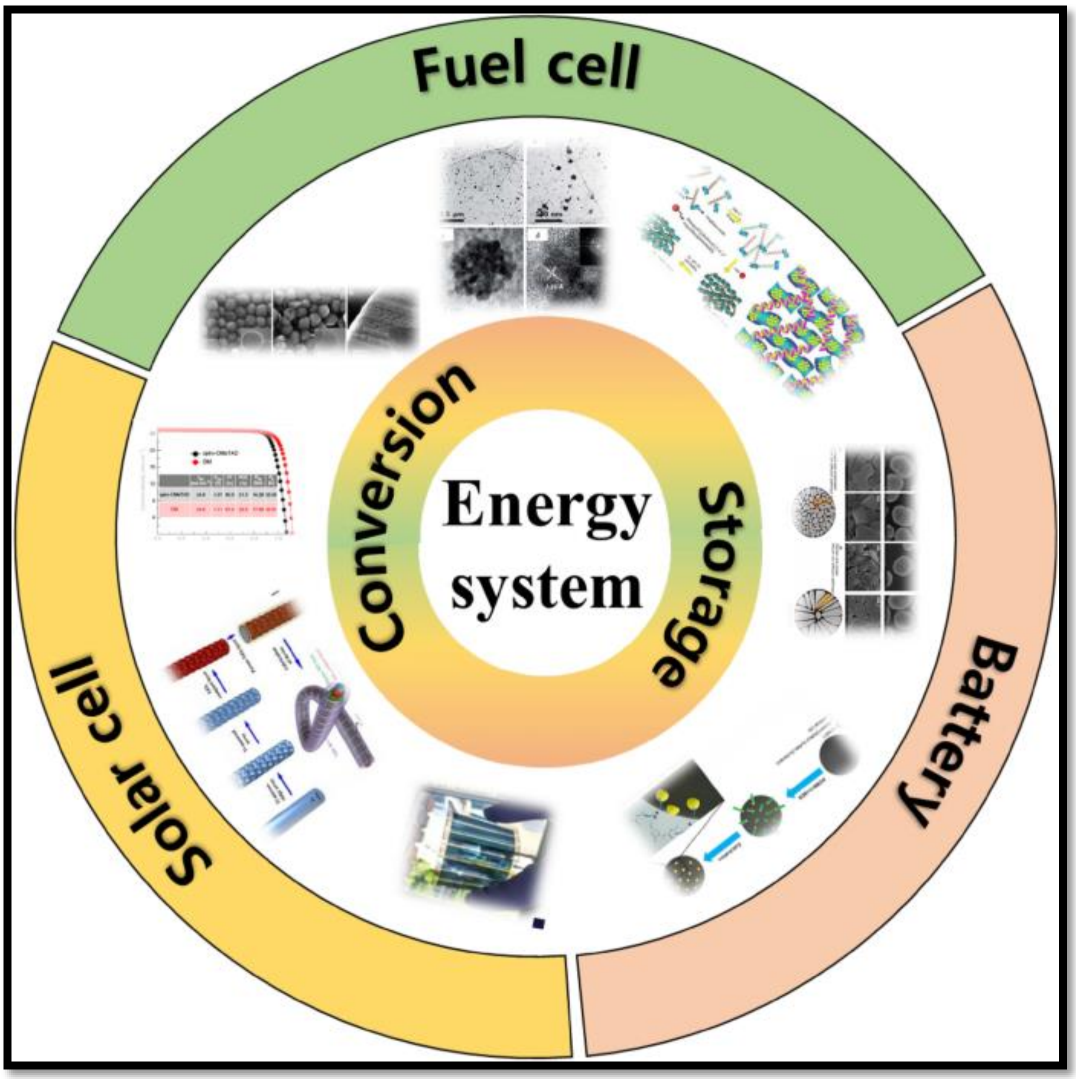
MODULE 2: Energy conversion and storage Batteries:

Module 2: *Energy conversion and storage (8hr) Batteries: Introduction, classification of batteries, components, construction, working and applications of modern batteries: Na-ion battery, solid state battery (Li-polymer battery) and flow battery (Vanadium redox flow battery). Fuel cells: Introduction, construction, working and applications of methanol–oxygen and polymer electrolyte fuel cell. Solar energy: Introduction, importance of solar PV cell, construction and working solar PV cell, advantages and disadvantages. Self-Study Components: Electrodes for electrostatic double layer capacitors, pseudo capacitors, and hybrid capacitor*



2.1 Introduction

Definition: *"Battery is a device consisting of two or more galvanic cells arranged in series or parallel or both, that can generate electrical energy".*

Following are the basic requirements:

1. It should be light, compact and portable.
2. It should give high sustained power output.
3. It should be capable of undergoing many recharging and discharging cycles.
4. It should be sealed and leak proof.

Basic Concepts: Basic electrochemical unit in a battery is a galvanic cell. Principal components of a battery are:

(a) **Anode or –ve electrode** – It liberates electrons to external circuit by undergoing oxidation.

(b) **Cathode or +ve electrode** – It accepts electrons from external circuit and undergoes reduction.

(c) **Electrolyte** – an ionic conductor. The electrolyte (active mass in anode and cathode compartments) is commonly a solution of an acid, alkali or salt having high ionic conductivity.

(d) **Separator** – It isolates anode and cathode in a battery to prevent internal short circuiting. Its main function is to transport ions from anode compartment to cathode compartment and vice a versa. Fibrous forms of regenerated cellulose, vinyl polymers, polyolefin, and cellophane membranes are commonly used as separators.

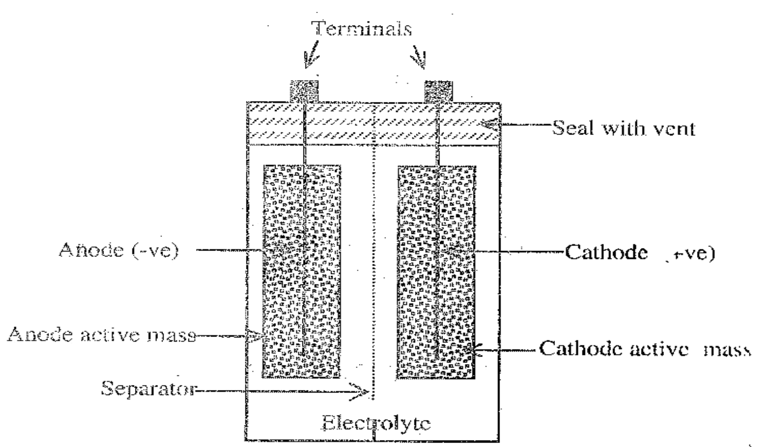


Figure: Principal components of a battery

2.2 Classification of Batteries

Batteries are classified under the following categories:

● **Primary battery:** In primary batteries, chemical energy stored in the battery is converted to electrical energy spontaneously as long as active materials are present. This battery cannot be recharged, because cell reaction is irreversible. *Example:* Zn-MnO_2 battery, Li-MnO_2 battery.

● **Secondary battery:** This battery can be recharged by passing electric current, because cell reactions are reversible. The redox reaction is reversed during recharing. Electrical energy is stored in the form of chemical energy in these batteries and used when needed. *Example:* Lead acid battery, Ni-MH battery, Li-ion battery. Primary cells act only as galvanic cell, whereas, a secondary cell can act both as galvanic cell and electrolytic cell. During discharging it acts as galvanic cell converting chemical energy to electrical energy and during charging process it acts as electrolytic cell converting electrical energy to chemical energy

● **Reserve battery:** In this battery, one of the key component is stored separately, and is incorporated into battery when required. When long storage is required, reserve batteries are often used, since the active component of the cell is separated until needed, thus reducing self-discharge. *Example:* Mg-AgCl battery. They are activated by adding sea water. These batteries have high reliability and long shelf life, hence they find applications in missiles and submarines. Another example is zinc-air batteries where the cell is sealed until use, the seal is removed to admit air and activate the cell when needed.

2.3.1 Na-ion battery: components, construction, working and applications of modern batteries

Introduction:

The sodium-ion battery (NIB or SIB) is a type of rechargeable battery analogous to the lithium-ion battery but using sodium ions (Na^+) as the charge carriers. Its working principle and cell construction are almost identical with those of commercially widespread lithium-ion battery types, but sodium compounds are used instead of lithium compounds. The largest advantage of sodium-ion batteries is the high natural abundance of sodium. This would make commercial production of sodium-ion batteries less costly than lithium-ion batteries. No electric vehicles use sodium ion batteries. Challenges to adoption include low energy density and a limited number of charge-discharge cycles. Sodium-ion batteries offer better performance and can operate at a wider temperature range. They work much more efficiently in cold environments, compared to lithium-ion batteries. Another advantage of sodium-ion batteries over lithium-ion batteries is they are nonflammable and there is no thermal runaway. Sodium ion batteries are lightweight compared to Li-ion batteries. Sodium falls short in terms of energy density, thus making it difficult to make small batteries for use in electric vehicles.

Construction:

Anode: Non-graphitic anodes, which consist largely of various carbonaceous materials (such as carbon black, pitch-based carbon-fibers, hard carbons etc)

Cathode: layer and tunnel type transition metal oxides, transition metal sulfides and fluorides etc

Electrolyte: The most common electrolyte formulations for SIBs are $NaClO_4$ or $NaPF_6$ salts in carbonate ester solvents (particularly propylene carbonate).

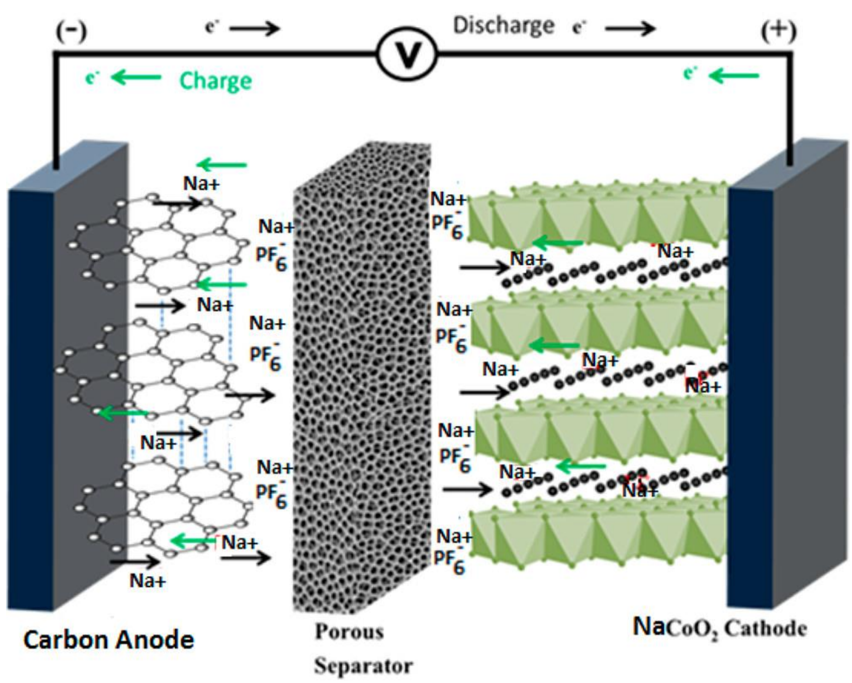


Figure. Na-ion Battery (SIB)

Working principles of SIBs

When the battery is being charged, Na atoms in the cathode release electrons to the external circuit and become ions which migrate through the electrolyte toward the anode, where they combine with electrons from the external circuit while reacting with the layered anode material. This process is reversed during discharge.

At anode: $$Na_xC_6 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} xNa^+ + xe^- + C_6$$

At cathode: $$Na_{1-x}MO_2 + xNa^+ + xe^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} NaMO_2 + C_6$$

Overall cell reaction: $$Na_xC_6 + Na_{1-x}MO_2 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} NaMO_2 + C_6$$

Applications: Sodium-ion batteries can be used for a broad range of battery applications, including renewable energy storage for homes and businesses, grid storage, and backup power for data and telecom companies.

2.3.2 Solid state battery (Li-polymer battery): components, construction, working and applications of modern batteries

Solid state battery: A solid-state battery is essentially battery technology that uses a solid electrolyte instead of liquid electrolytes**.** The solid-state battery uses solid electrolyte, not liquid electrolyte solution, and the solid electrolyte plays a role of a separator as well. A solid-state battery has higher energy density than a Li-ion battery that uses liquid electrolyte solution. It doesn't have a risk of explosion or fire, so there is no need to have components for safety, thus saving more space. Then we have more space to put more active materials which increase battery capacity in the battery.

A solid-state battery can increase energy density per unit area since only a small number of batteries are needed. For that reason, a solid-state battery is perfect to make an EV battery system of module and pack, which needs high capacity.

Lithium polymer (LiPo) Batteries

LiPo batteries are composed of a lithium-based cathode and anode separated by a polymer electrolyte. LiPo batteries differ from other lithium-ion (Li-ion) batteries in that they have a solid polymer electrolyte component rather than a liquid electrolyte. Common polymer electrolytes may be dry, porous or a gel, and include poly(methyl methacrylate) (PMMA), poly(acrylonitrile) (PAN), poly(vinylidene fluoride) (PVdF), and poly(ethylene oxide) (PEO).

The science behind LiPo batteries is the same as in other Li-ion batteries: chemical energy is converted to electrical energy when electrons travel from the battery's anode to its cathode, creating an electrical current. The cathode contains a lithium metal oxide (such as lithium-cobalt oxide ($LiCoO_2$)), which provides lithium ions, whereas the anode contains a lithium carbon (such as graphite).

The anode and cathode are separated by an electrolyte that interacts with the anode to generate electrons, which creates a charge gradient in the cell. As the anode becomes negatively charged, the electrons travel along a conducting wire to the cathode. The whole system thus undergoes an electrochemical redox reaction (reduction/oxidation): the anode loses electrons and becomes oxidized while the cathode gains electrons and is reduced.

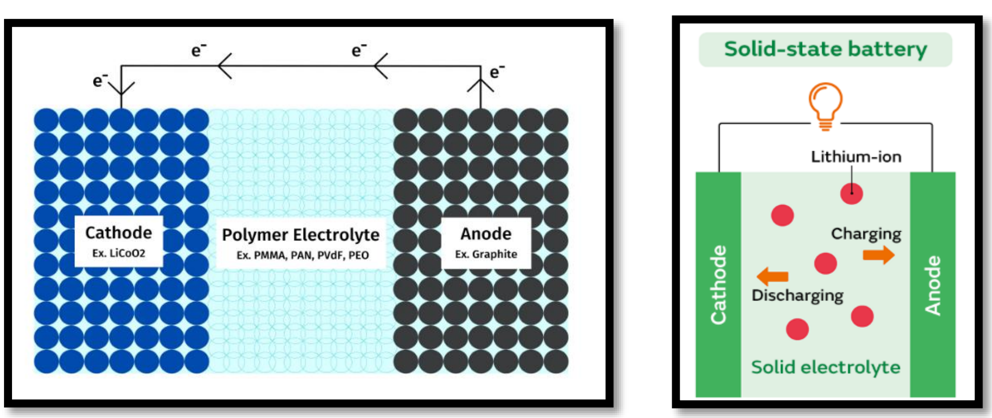


Figure: LiPo Battery

Anode: Lithium intercalated Carbon or graphite

Cathode: lithium transition metal oxides (such as lithium-cobalt oxide ($LiCoO_2$)),

Electrolyte & Separator: High conductivity semisolid (gel) polymers electrolyte polymer electrolytes and include poly(methyl methacrylate) (PMMA), poly(acrylonitrile) (PAN)

Working:

At anode: $$xLiC_6 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} xC_6 + xLi^+ + xe^-$$

At cathode: $$Li\,CoO_2 + xLi^+ + xe^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} Li_{x+1}\,CoO_2$$

Overall cell reaction: $$xLiC_6 + Li\,CoO_2 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} Li_{x+1}\,CoO_2 + xC_6$$

Applications: These batteries provide higher specific energy than other lithium battery types and are used in applications where weight is a critical feature, such as mobile devices, radio-controlled aircraft and some electric vehicles.

2.3.3 Flow battery (Vanadium redox flow battery): components, construction, working and applications of modern batteries

Flow battery: A flow battery, or redox flow battery, is a type of electrochemical cell where chemical energy is provided by two chemical components dissolved in liquids that are pumped through the system on separate sides of a membrane. Example: **Vanadium redox flow battery**

Vanadium redox flow battery: The vanadium redox battery (VRB), also known as the vanadium flow battery (VFB) or vanadium redox flow battery (VRFB), is a type of rechargeable flow battery. It employs vanadium ions as charge carriers.

Construction: A vanadium redox battery consists of an assembly of power cells in which two electrolytes are separated by a proton exchange membrane.

Electrodes: The electrodes in a VRB cell are carbon based. The most common types are carbon felt, carbon paper, carbon cloth, and graphite felt. Recently, carbon nanotube-based electrodes have attracted interest from the scientific community.

Electrolytes: Both electrolytes are vanadium-based. The electrolyte in the positive half-cells contains VO_2^+ and VO^{2+} ions, while the electrolyte in the negative half-cells consists of V^{3+} and V^{2+} ions. The electrolytes can be prepared by several processes, including electrolytically dissolving vanadium pentoxide (V_2O_5) in sulfuric acid (H_2SO_4). The solution remains strongly acidic in use.

Membrane: The most common membrane material is perfluorinated sulfonic acid (PFSA) (Nafion). polytetrafluoroethylene (Teflon).

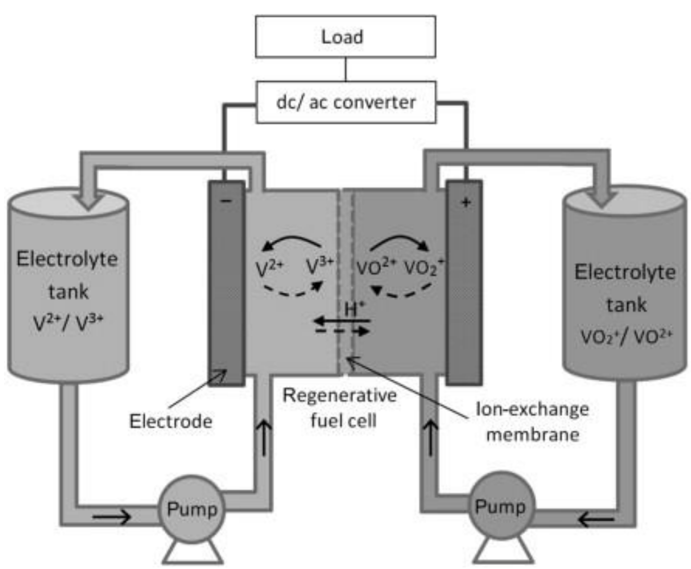


Figure. A diagram of a vanadium redox flow battery

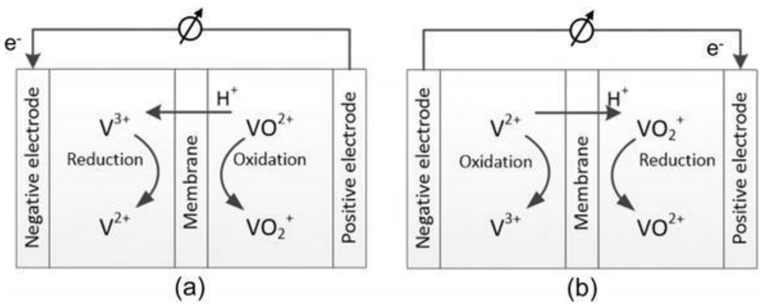


Figure. Vanadium redox flow battery: (a) charge reaction and (b) discharge reaction.

Working:

Negative electrode: $$V^{2+} \underset{\text{Charge}}{\overset{\text{Discharge}}{\longleftrightarrow}} V^{3+} + e^-$$

Positive electrode: $$VO_2^{+} + e^- + 2H^{+} \underset{\text{Charge}}{\overset{\text{Discharge}}{\longleftrightarrow}} VO^{2+} + H_2O$$

Overall reaction: $$VO_2^{+} + V^{2+} + 2H^{+} \underset{\text{Charge}}{\overset{\text{Discharge}}{\longleftrightarrow}} VO^{2+} + V^{3+} + H_2O \qquad (E^0 = 1.26\ V)$$

Application: Vanadium batteries are typically used for grid energy storage, i.e., attached to power plants/electrical grids.

2.4. Fuel cells:

Introduction

Definition: “Fuel cells are the galvanic cells which convert chemical energy of a fuel- oxidant system directly into electrical energy by oxidation of fuel at anode and reduction of oxidant at cathode”.

Or

A fuel cell is a device that converts the chemical energy of a fuel (hydrogen, natural gas, methanol, gasoline, etc.) and an oxidant (air or oxygen) into electricity.

A fuel cell also has two electrodes and an electrolyte. In the fuel cell device, fuel and oxidizing agents are continuously and separately fed into their respective electrodes, at which they undergo redox reactions generating energy. The feature is that the fuel cell produce electrical energy with continuous replenishment of fuel at the electrode. These cells are capable of supplying current as long as they are supplied with reactant. A fuel cell may be represented as:

electrode/fuel/ electrolyte / oxidant/ electrode

Advantages:

1. High efficiency and no harmful pollutants (eco friendly).
2. Charging is not required for fuel cells.
3. Silent operation.
4. They can produce direct currents for long periods at a low cost.
5. They offer high energy conversions (75%).

Limitations:

1. Cost of power is high as electrodes are costly.
2. Fuels in form of gases and oxygen need to be stored in tanks under pressure.
3. Power output is moderate.

2.4.1 Construction, working and applications of methanol–oxygen fuel cell.

It is good example for liquid fuel cell. They use either acidic or alkaline medium. The preferred electrolyte is the acidic. Methanol is an efficient active organic fuel at low temperature.

Construction: Methanol – oxygen fuel cell consist of

1. Anode – It is a porous Nickel (Ni) electrode impregnated with Pt/Pd catalyst.
2. Cathode - It is a porous Nickel (Ni) electrode coated with silver (Ag) catalyst.
3. Electrolyte – Aqueous sulphuric acid (H_2SO_4), 3.7 M.
4. Active components: (a) Fuel – Methanol mixed with sulphuric acid supplied at anode. (b) Oxidant – Pure oxygen is supplied at cathode.

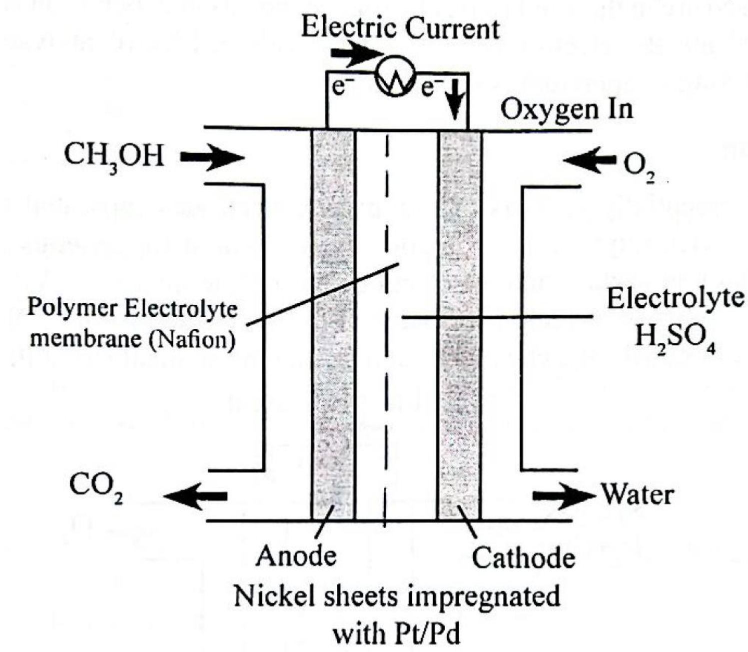


Figure: Methanol – oxygen fuel cell

Working:

Cell reaction;

Anode Reaction: $CH_3OH + H_2O \longrightarrow CO_2 + 6H^+ + 6e^-$

Cathode Reaction**:** $3/2\ O_2 + 6\ H^+ + 6e^- \longrightarrow 3\ H_2O$

Overall Cell Reaction: $CH_3OH + 3/2\ O_2 \longrightarrow CO_2 + 2\ H_2O$

H_2O and CO_2 are formed as by-products but they do not harm the cell functioning because they are removed as and when they are formed.

Cell Potential : 1.2 V

Applications:

1. used in automobiles, military applications.
2. Power backup and portable instruments.
3. In large scale power production.

2.4.2 Construction, working and applications of polymer electrolyte fuel cell.

Polymer electrolyte fuel cells (PEFC) are electrochemical devices, converting the chemical energy of fuel directly into electrical energy. They are also known as Polymer electrolyte membrane (PEM) fuel cells or proton exchange membrane fuel cells. They deliver high power density and offer the advantages of low weight and volume compared with other fuel cells.

Construction: A PEFC comprising a proton-conductive solid polymer electrolyte membrane of thickness 50–180 μm and porous carbon electrodes containing a platinum or platinum alloy catalyst (Figure). The most typical polymer electrolyte membrane is the perfluorosulfonic-acid-type ion exchange membrane such as Nafion®, which has a molecular structure based on a main polytetrafluoroethylene chain with side chains containing sulfonic acid. Pure hydrogen or hydrogen reformed from methanol or natural gas is used as fuel.

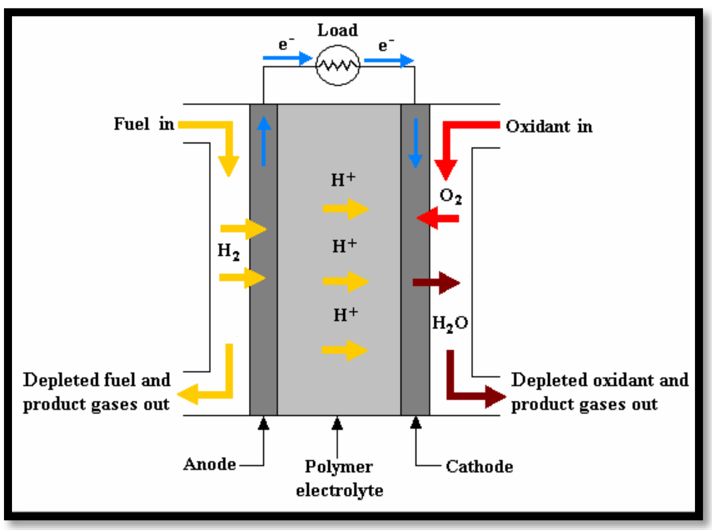


Figure: Polymer electrolyte fuel cell

<u>Working:</u>

Hydrogen supplied to the anode side is oxidized, and produced H^+ moves through the membrane to the cathode side. This H^+ is used in the reaction in which water is formed by the reduction of oxygen supplied to the cathode side. As the electrons generated at the anode flow through the external circuit to arrive at the cathode, an electric current can be retrieved. The reactions at the anode and cathode, and the overall reaction, are given as follows.

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Overall reaction: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

Applications: Polymer electrolyte fuel cells (PEFCs) are of interest as power sources in vehicles and portable applications because of their high energy efficiency and environmentally friendly qualities.

Additional Information: *PEM fuel cells operate at relatively low temperatures, around 80°C (176°F). Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to carbon monoxide poisoning, making it necessary to employ an additional reactor to reduce carbon monoxide in the fuel gas if the hydrogen is derived from a hydrocarbon fuel. This reactor also adds cost.*

2.5 Solar energy: Introduction, importance of solar PV cell, construction and working solar PV cell, advantages and disadvantages.

Introduction: Radiations from the sun constitute solar energy. Solar energy is freely available and is an inexhaustive energy on which our entire planet is surviving. Solar energy is the radiant energy. It can be converted into various forms of energy such as thermal and electrical energies. A wide range of power technologies exist which can make use of the solar energy and converting them into different useful forms of energy.

The solar cells or the photovoltaic cells are the electrical devices that convert the energy of sunlight into the electricity by the photovoltaic effect which is the ability of matter to emit the electrons when a light is shone on it. The photovoltaic solar cells are thin silicon disks that convert the sunlight into the electricity, and these disks act as energy sources for a wide variety of uses.

Importance of Solar PV cells

PV cells or panels convert sunlight, which is the most abundant energy source on earth, directly into electricity. They have many advantages including completely silent operation, adaptability into various weather and installation environments, and no moving parts. They also require minimal maintenance and have a long life. Maybe the most important advantage is that they generate electricity without producing emissions of greenhouse or any other gases. Photovoltaic Applications: The importance of PV cell can be realized based on their vast applications such as Solar Farms, remote Locations Stand-Alone Power (parking meters, temporary traffic signs, emergency phones, radio transmitters, water irrigation pumps, stream-flow gauges, remote guard posts, lighting for roadways etc), Power in Space, Building-Related Needs, Transportation.

Photovoltaic Cells:

Photovoltaic cells or solar cells are semiconductor device that converts sunlight into direct current (DC) electricity. As long as light is shining on the solar cell, it generates electrical power. When light stops, electricity stops.

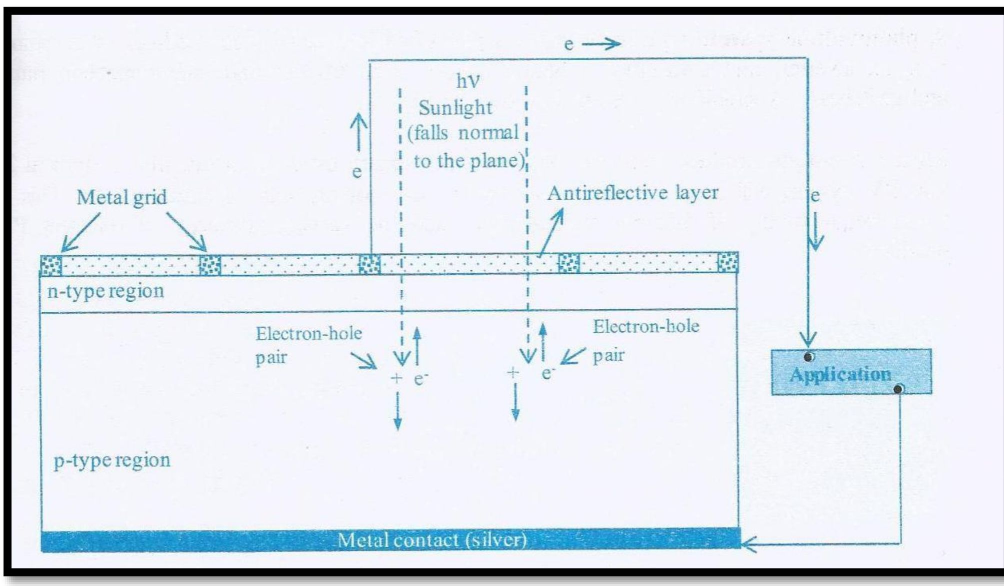


Figure Photovoltaic cells

Construction & Working of PhotoVoltaic Cells

Construction:

- PhotoVoltaic Cells consist of a semiconductor diode (p-n junction) made of a silicon.
- Silicon wafer or very thin silicon slices are made by silicon blocks and they are doped by p-type and n-type dopents to make p-n junction.
- It has two electrical contact, on one of its sides, a mettalic grid is used and on the other side a layer of noble metal (such as Ag) is used.
- The metal grid permits the light to fall on the diode between the grid lines.

- The part between the metallic grid is coated with antireflective compound. eg TiO_2

Working:

- Electromagnetic radiation consists of particle called photon (hv). They carry a certain amount of energy given by the Plank quantum equation.

$$\mathbf{E = hc/\lambda}$$

Where, h = Planck's constant, c = velocity of light, λ = wavelength of the radiation

- The electromagnetic radiation (sunlight) falls normal to the plane of the solar cell, the photons which possess energy sufficient to overcome the barrier potential are absorbed, electrons are ejected and electron-hole pairs are formed.
- The electrons move towards the n-region (as it is positively charged). The electrons are driven into the external circuit and used for various applications or appliances.

Advantage of PhotoVoltaic cells -

1. It is unlimited, inexhaustible and renewable source of energy.
2. The solar cell operates reliably for a long period of time with no maintenance.
3. A photovoltaic system can be constructed to any size based on energy requirement.
4. Easy to operate
5. Quick installation.
6. Can be integrated into new or existing building structure.
7. Completely pollution free during its use.

Disadvantage of PhotoVoltaic cells –

1. High installation cost.
2. Energy can be produced only during the day-time.
3. The efficiency of solar cells depends on the seasonal variations, latitude and climate.
4. Space required to generate unit power output is relatively more.
5. Solar cell generates DC current. It needs to be converted to AC for use.