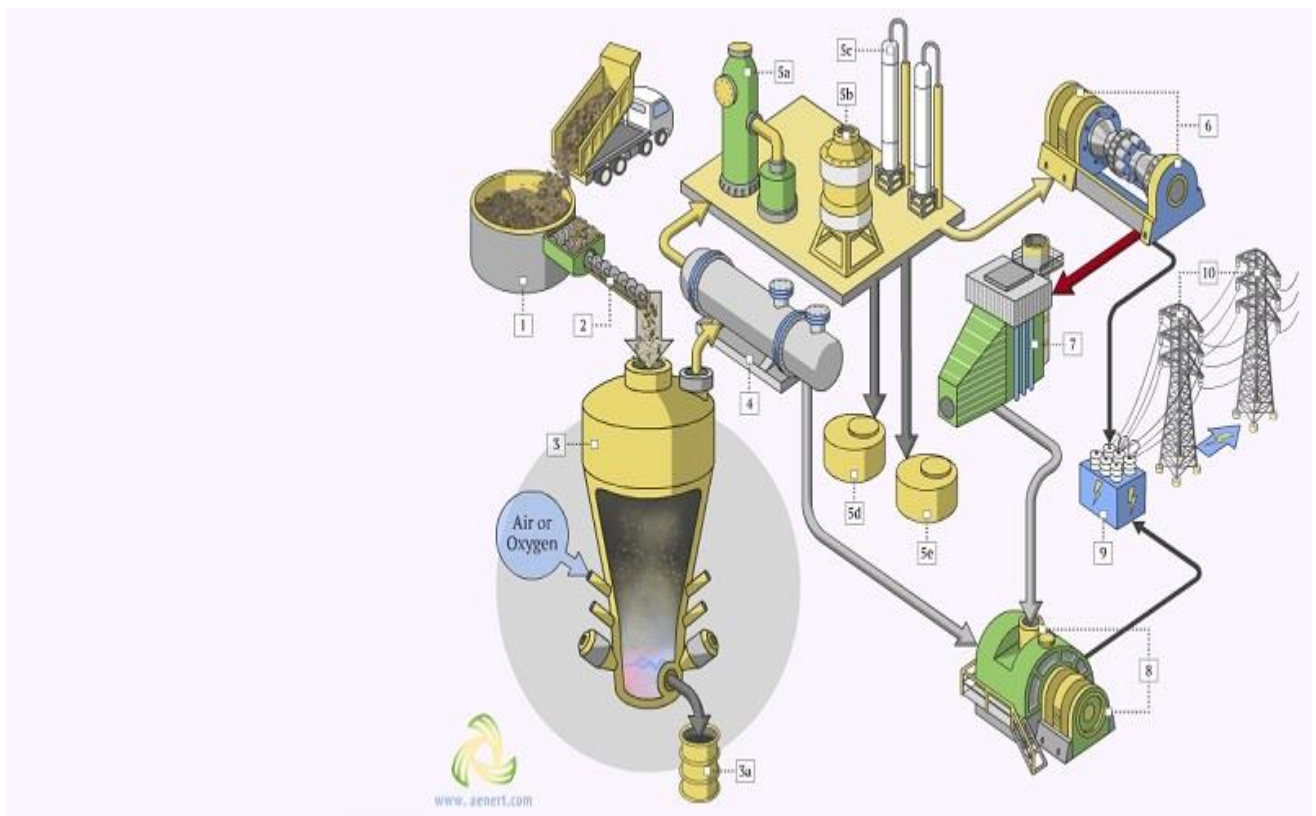# Advanced Energy Technologies

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Introduction

The generation, delivery, and utilization of electric power and energy remain one of the most challenging and exciting fields of electrical engineering. The astounding technological developments of our age are highly dependent upon a safe, reliable, and economic supply of electric power. The objective a contemporary overview of this far-reaching field as well as to be a useful guide and educational resource for its study. It is intended to define electric power engineering by bringing together the core of knowledge from all of the many topics encompassed by the field. The written primarily for the electric power engineering professional who is seeking factual information, and secondarily for the professional from other engineering disciplines who want an overview of the entire field or specific information on one aspect of it. The researches Each is organized into topical sections and chapters in an attempt to provide comprehensive coverage of the generation, transformation, transmission, distribution, and utilization of electric power and energy as well as the modeling, analysis, planning, design, monitoring, and control of electric power systems. The individual chapters are different from most technical publications.

They are intended to be tutorials or overviews providing ready access to needed information while at the same time providing sufficient references to more in-depth coverage of the topic. This work is a member of the Electrical Engineering been dedicated to the concept that when readers refer to a handbook on a particular topic they should be able to find what they need to know about the subject most of the time. This has indeed been the goal of this handbook. This volume of the handbook is devoted to the subjects of electric power generation by both conventional and nonconventional methods, transmission systems, distribution systems, power utilization, and power quality.

1 -Storage Systems

Energy storage technologies are of great interest to electric utilities, energy service companies, and automobile manufacturers (for electric vehicle application). The ability to store large amounts of energy would allow electric utilities to have greater flexibility in their operation because with this option the supply and demand do not have to be matched instantaneously. The availability of the proper battery at the right price will make the electric vehicle a reality, a goal that has eluded the automotive industry thus far. Four types of storage technologies (listed below) are discussed in this section, but most emphasis is placed on storage batteries because it is now closest to being commercially viable. The other storage technology widely used by the electric power industry, pumped-storage power plants, is not discussed as this has been in commercial operation for more than 60 years in various countries around the world. .

1-1 Flywheel storage.

1-2 Compressed air energy storage.

1-3 Super conducting magnetic energy storage.

1-4 Battery storage

1.1 Flywheel Storage

Flywheels store their energy in their rotating mass, which rotates at very high speeds (approaching 75,000 rotations per minute), and are made of composite materials instead of steel because of the composite's ability to withstand the rotating forces exerted on the flywheel. In order to store energy the flywheel is placed in a sealed container which is then placed in a vacuum to reduce air resistance. Magnets embedded in the flywheel pass near pickup coils. The magnet induces a current in the coil changing the rotational energy into electrical energy. Flywheels are still in research and development, and commercial products are several years away.
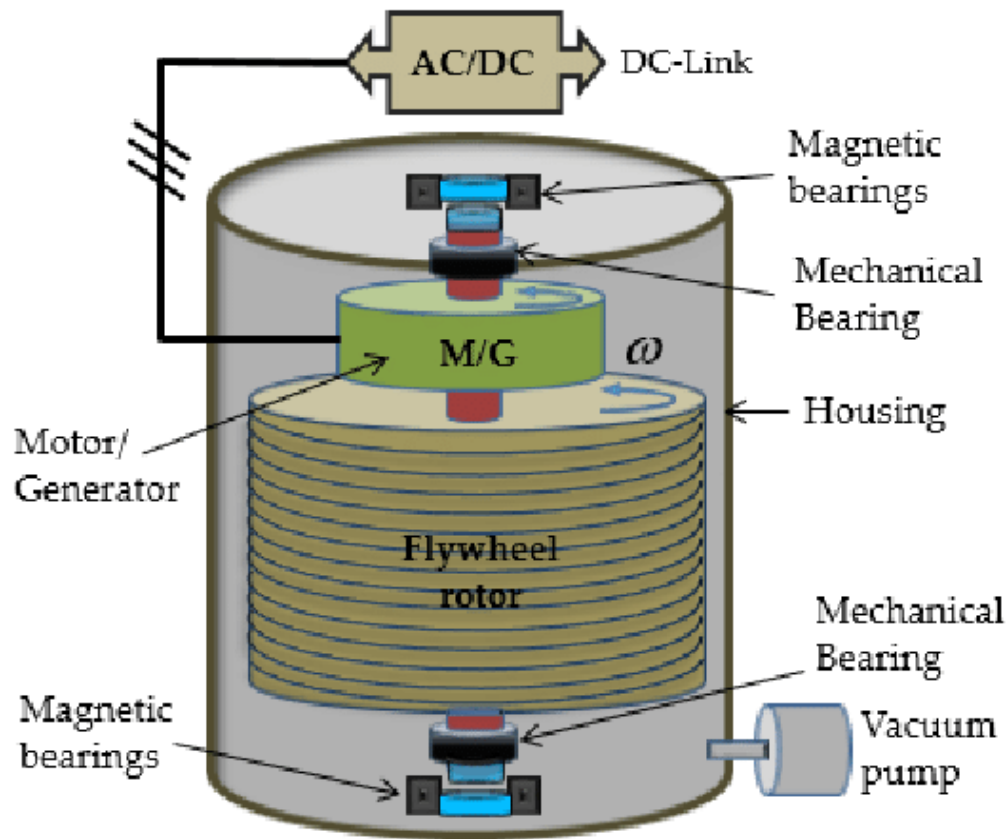
Fig 1 Flywheel Storage system

1.2 Compressed Air Energy Storage

As the name implies, the compressed air energy storage (CAES) plant uses electricity to compress air which is stored in underground reservoirs. When electricity is needed, this compressed air is withdrawn, heated with gas or oil, and run through an expansion turbine to drive a generator. The compressed air can be stored in several types of underground structures, including caverns in salt or rock formations, aquifers, and depleted natural gas fields. Typically the compressed air in a CAES plant uses about one third of the premium fuel needed to produce the same amount of electricity as in a conventional plant. A 290-MW CAES plant has

been in operation in Germany since the early 1980s with 90% availability and 99% starting reliability. In the U.S., the Alabama Electric Cooperative runs a CAES plant that stores compressed air in a 19-million cubic foot cavern mined from a salt dome. This 110-MW plant has a storage capacity of 26 h. The fixed-price turnkey cost for this first-of-a-kind plant is about $400=kW in constant 1988 dollars. The turbo machinery of the CAES plant is like a combustion turbine, but the compressor and the expander operate independently. In a combustion turbine, the air that is used to drive the turbine is compressed just prior to combustion and expansion and, as a result, the compressor and the expander must operate at the same time and must have the same air mass flow rate. In the case of a CAES plant, the compressor and the expander can be sized independently to provide the utility-selected ''optimal'' MW charge and discharge rate which determines the ratio of hours of compression required for each hour of turbine-generator operation. The MW ratings and time ratio are influenced by the utility's load curve, and the price of off-peak power. For example, the CAES plant in Germany requires 4 h of compression per hour of generation. On the other hand, the Alabama plant requires 1.7 h of compression for each hour of generation. At 110-MW net output, the power ratio is 0.818 kW output for each kilowatt input. The heat rate (LHV) is 4122 BTU=kWh with natural gas fuel and 4089 BTU=kWh with fuel oil. Due to the storage option, a partial-load operation of the CAES plant is also very flexible. For example, the heat rate of the expander increases only by 5%, and the airflow decreases nearly linearly when the plant output is turned down to 45% of full load. However, CAES plants have not reached commercial viability beyond some prototypes.
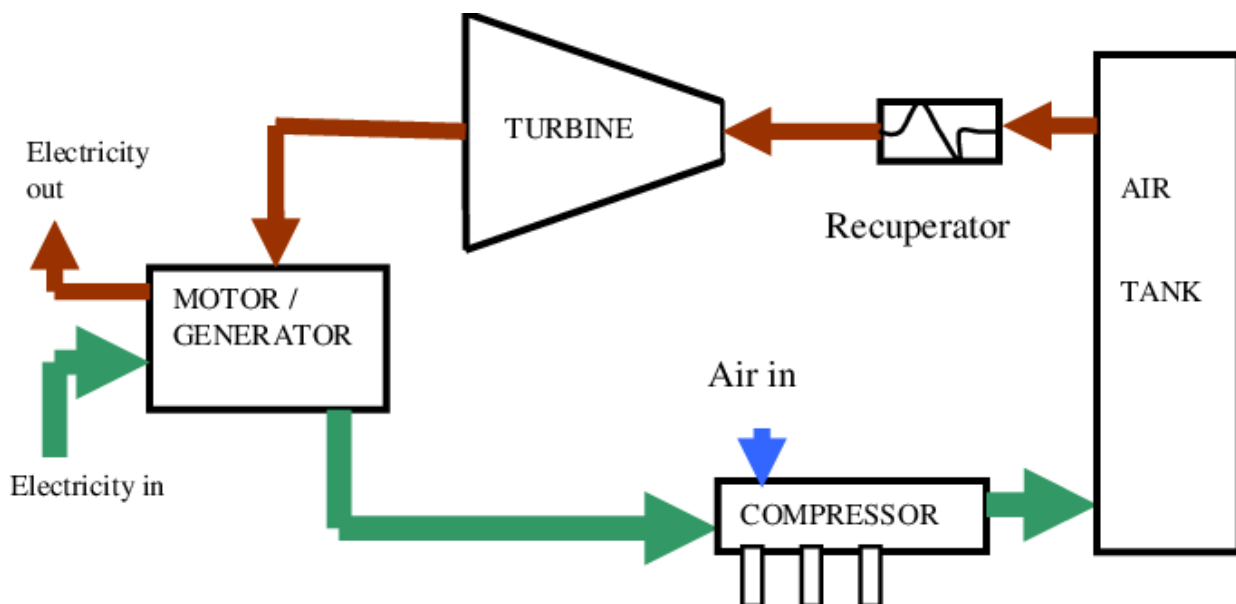
Fig 2 Compressed Air Energy Storage system

1.3 Superconducting Magnetic Energy Storage

A third type of advanced energy storage technology is superconducting magnetic energy storage (SMES), which may someday allow electric utilities to store electricity with unparalleled efficiency (90% or more). A simple description of SMES operation follows. The electricity storage medium is a doughnut-shaped electromagnetic coil of superconducting wire. This coil could be about 1000 m in diameter, installed in a trench, and kept at superconducting temperature by a refrigeration system. Off-peak electricity, converted to direct current (DC), would be fed into this coil and stored for retrieval at any moment. The coil would be kept at a low-temperature superconducting state using liquid helium. The time between charging and discharging could be as little as 20 ms with a round-trip AC–AC efficiency of over 90%. Developing a commercial-scale SMES plant presents both economic and technical challenges. Due to the high cost of liquid helium, only plants with 1000-MW, 5-h capacity are economically attractive. Even then the plant capital cost can exceed several thousand dollars per kilowatt. As ceramic superconductors, which become superconducting at higher temperatures (maintained by less expensive liquid nitrogen), become more widely available, it may be possible to develop smaller scale SMES plants at a lower price.
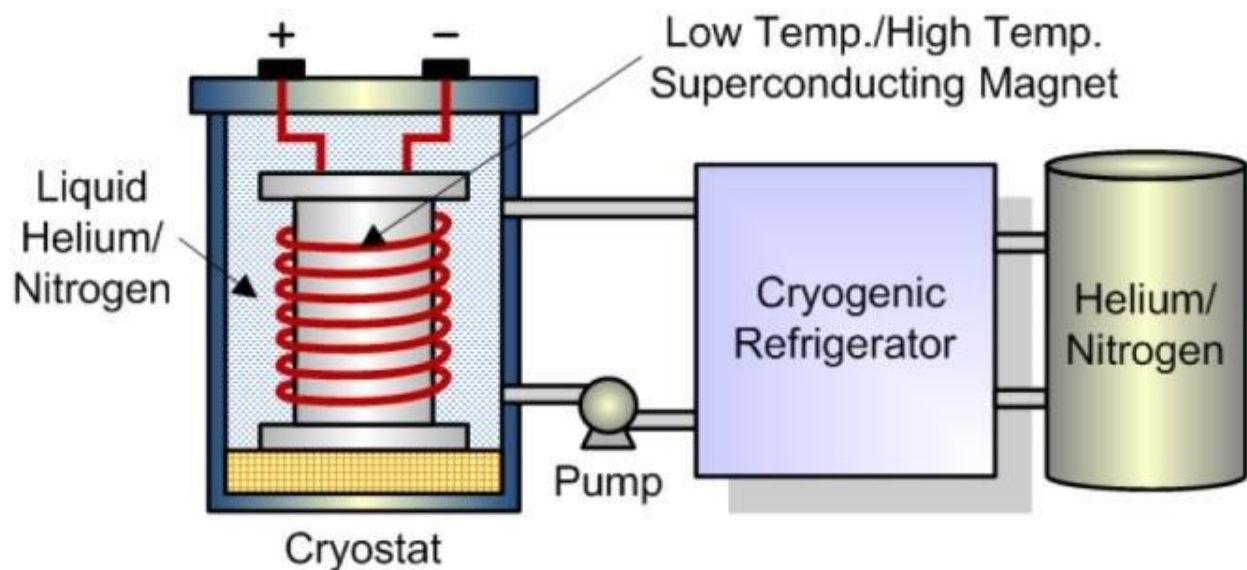

Fig 3 Superconducting Magnetic Energy Storage

1.4 Battery Storage

Even though battery storage is the oldest and most familiar energy storage device, significant advances have been made in this technology in recent years to deserve more attention. There has been renewed interest in this technology due to its potential application in non-polluting electric vehicles. Battery 2006 by Taylor & Francis Group, LLC. Systems are quiet and non-polluting, and can be installed near load centers and existing suburban substations. These have round-trip AC–AC efficiencies in the range of 85%, and can respond to load changes within 20 Ms. Several U.S., European, and Japanese utilities have demonstrated the application of lead–acid batteries for load-following applications. Some of them have been as large as 10 MW with 4 h of storage. The other player in battery development is the automotive industry for electric vehicle application. In 1991, General Motors, Ford, Chrysler, Electric Power Research Institute (EPRI), several utilities, and the U.S. Department of Energy (DOE) formed the U.S. Advanced Battery Consortium (USABC) to develop better batteries for electric vehicle (EV) applications. A brief introduction to some of the available battery technologies as well some that are under study is presented.

2.4.1 Battery Types

Chemical batteries are individual cells filled with a conducting medium-electrolyte that, when connected together, form a battery. Multiple batteries connected together form a battery bank. At present, there are two main types of batteries: primary batteries (non-rechargeable) and secondary batteries (rechargeable). Secondary batteries are further divided into two categories based on the operating temperature of the electrolyte. Ambient operating temperature batteries have either aqueous (flooded) or no aqueous electrolytes. High operating temperature batteries (molten electrodes) have either solid or molten electrolytes. Batteries in EVs are the secondary-rechargeable-type and are in either of the two subcategories. A battery for an EV must meet certain performance goals. These goals include quick discharge and recharge capability, long cycle life (the number of discharges before becoming unserviceable), low cost, recyclability, high specific energy (amount of usable energy, measured in watt-hours per pound [lb] or kilogram [kg]), high energy density (amount of energy stored per unit volume), specific power (determines the potential for acceleration), and the ability to work in extreme heat or cold. No battery currently available meets all these criteria.

<u>**Battery Types**</u>

1. Lead–Acid Batteries

2. Nickel Iron and Nickel Cadmium Batteries

3. Nickel Metal Hydride Batteries

4. Sodium Sulfur Batteries

5. Lithium Iron and Lithium Polymer Batteries

6. Zinc and Aluminum Air Batteries

2.4.2 Lead–Acid Batteries Lead–acid

Starting batteries (shallow-cycle lead–acid secondary batteries) are the most common battery used in vehicles today. This battery is an ambient temperature, aqueous electrolyte battery. A cousin to this battery is the deep-cycle lead–acid battery, now widely used in golf carts and forklifts. The first electric cars built also used this technology. Although the lead–acid battery is relatively inexpensive, it is very heavy, with a limited usable energy by weight (specific energy). The battery's low specific energy and poor energy density make for a very large and heavy battery pack, which cannot power a vehicle as far as an equivalent gas-powered vehicle. Lead–acid batteries should not be discharged by more than 80% of their rated capacity or depth of discharge (DOD). Exceeding the 80% DOD shortens the life of the battery. Lead–acid batteries are inexpensive, readily available, and are highly recyclable, using the elaborate recycling system already in place. Research continues to try to improve these batteries. A lead–acid no aqueous (gelled lead acid) battery uses an electrolyte paste instead of a liquid. These batteries do not have to be mounted in an upright position. There is no electrolyte to spill in an accident. No aqueous lead–acid batteries typically do not have as high a life cycle and are more expensive than flooded deep-cycle lead–acid batteries.
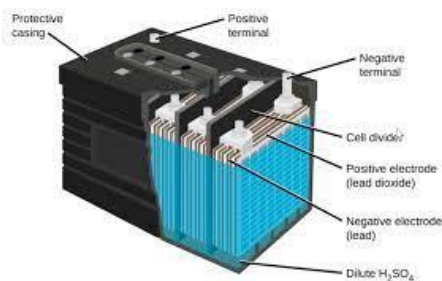

Fig 4 Lead–Acid Batteries

2.4.3 Nickel Iron and Nickel Cadmium Batteries

Nickel iron (Edison cells) and nickel cadmium (NiCad) pocket and sintered plate batteries have been in use for many years. Both of these batteries have a specific energy of around 25 Wh=lb (55 Wh=kg), which is higher than advanced lead–acid batteries. These batteries also have a long cycle life. Both of these batteries are recyclable. Nickel iron batteries are non-toxic, while nicads are toxic. They can also be discharged to 100% batteries. The batteries should last at least 100,000 mi (160 DOD without damage. The biggest drawback to these batteries is their cost. Depending on the size of battery bank in the vehicle, it may cost between $20,000 and $60,000 for the,900km in normal service.

Fig 5 Nickel Iron and Nickel Cadmium Batteries
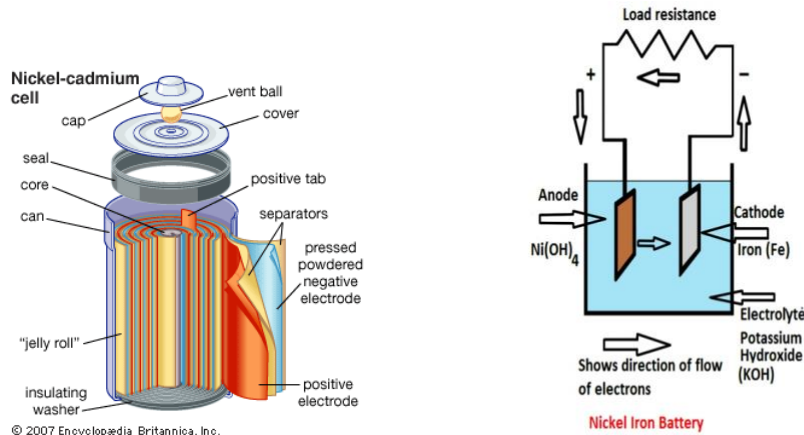
2.4.4. Nickel Metal Hydride Batteries

Nickel metal hydride batteries are offered as the best of the next generation of batteries. They have a high specific energy: around 40.8 Wh=lb (90 Wh=kg). According to a U.S. DOE report, the batteries are benign to the environment and are recyclable. They also are reported to have a very long cycle life. Nickel metal hydride batteries have a high self-discharge rate: they lose their charge when stored for long periods of time. They are already commercially available as ''AA'' and ''C'' cell batteries, for small consumer appliances and toys. Manufacturing of larger batteries for EV applications is only available to EV manufacturers. Honda is using these batteries in the EV Plus, which is available for lease in California
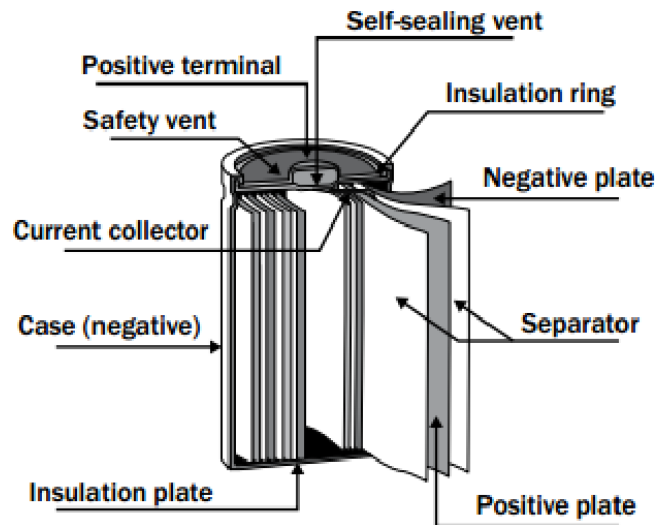
Fig **6 Nickel Metal Hydride Batteries**

2.4.5 Sodium Sulfur Batteries

This battery is a high-temperature battery, with the electrolyte operating at temperatures of 5728F (3008C). The sodium component of this battery explodes on contact with water, which raises certain safety concerns. The materials of the battery must be capable of withstanding the high internal temperatures they create, as well as freezing and thawing cycles. This battery has a very high specific energy: 50 WH=lb (110 WH=kg). The Ford Motor Company uses sodium sulfur batteries in their EchoStar, a converted delivery minivan that is currently sold in Europe. Sodium sulfur batteries are only available to EV manufacturers.
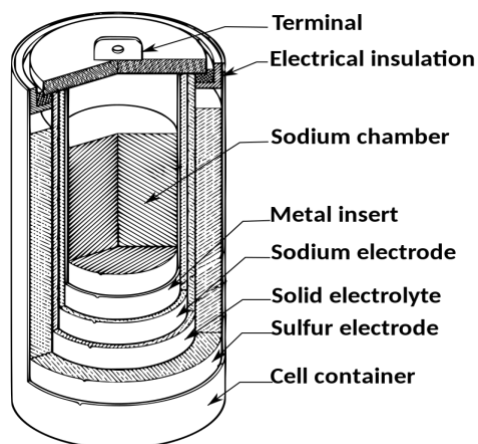

Fig 7 Sodium Sulfur Batteries

2.4.6 Lithium Iron and Lithium Polymer Batteries

The USABC considers lithium iron batteries to be the long-term battery solution for EVs. The batteries have a very high specific energy: 68 WH=lb (150 Wh=kg). They have a molten-salt electrolyte and share many features of a sealed bipolar battery. Lithium iron batteries are also reported to have a very long cycle life. These are widely used in laptop computers. These batteries will allow a vehicle to travel distances and accelerate at a rate comparable to conventional gasoline-powered vehicles. Lithium polymer batteries eliminate liquid electrolytes. They are thin and flexible, and can be molded into a variety of shapes and sizes. Neither type will be ready for EV commercial applications until early in the 21st century.
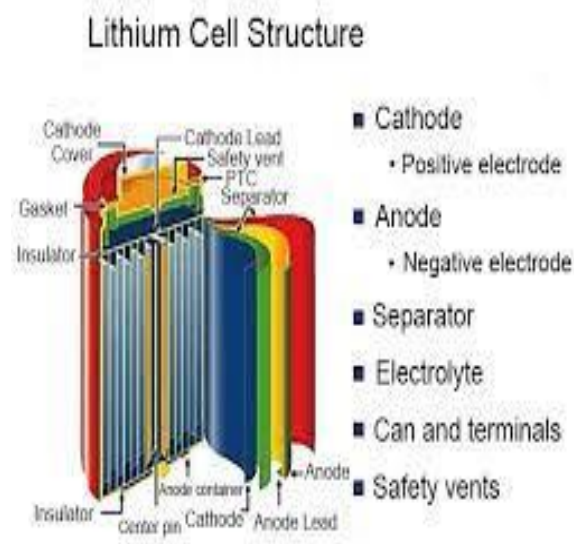

Fig 8 Lithium Iron and Lithium Polymer Batteries

2.4.7 Zinc and Aluminum Air Batteries

Zinc air batteries are currently being tested in postal trucks in Germany. These batteries use either aluminum or zinc as a sacrificial anode. As the battery produces electricity, the anode dissolves into the electrolyte. When the anode is completely dissolved, a new anode is placed in the vehicle. The aluminum or zinc and the electrolyte are removed and sent to a recycling facility. These batteries have a specific energy of over 97 Wh=lb (200 Wh=kg). The German postal vans currently carry 80 kWh of energy in their battery, giving them about the same range as 13 gallons (49.2 liters) of gasoline. In their tests, the vans have achieved a range of 615 mi (990 km) at 25 miles per hour (40 km=h).
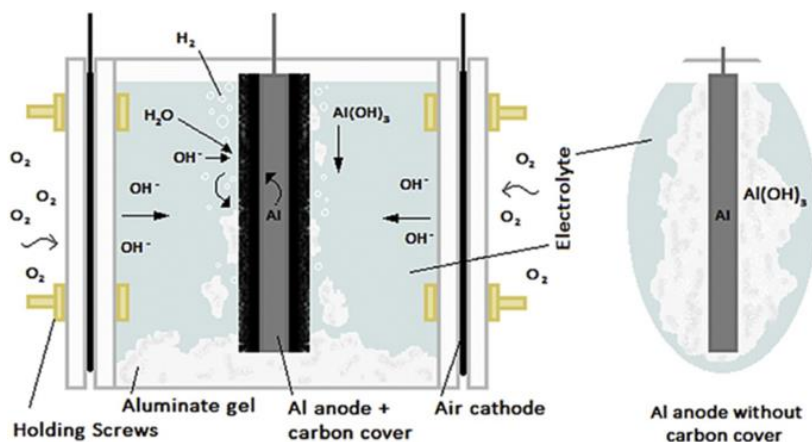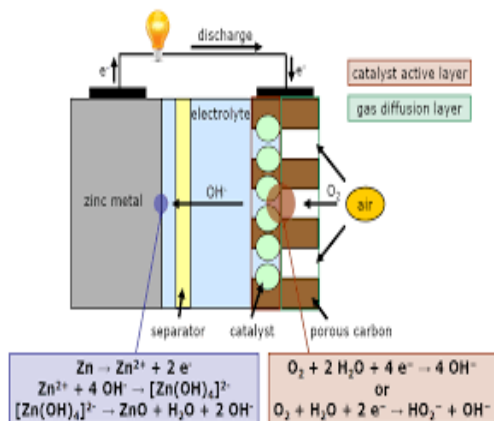
Fig 9 Zinc and Aluminum Air Batteries

3. Fuel Cells

 In 1839, a British Jurist and an amateur physicist named William Grove first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electricity and water which was then used to split water in a different container to produce hydrogen and oxygen. However, it took another 120 years until NASA demonstrated its use to provide electricity and water for some early space flights. Today the fuel cell is the primary source of electricity on the space shuttle. As a result of these successes, industry slowly began to appreciate the commercial value of fuel cells. In addition to stationary power generation applications, there is now a strong push to develop fuel cells for automotive use. Even though fuel cells provide high performance characteristics, reliability, durability, and environmental benefits, a very high investment cost is still the major barrier against large-scale deployments.

3.1. Basic Principles

The fuel cell works by processing a hydrogen-rich fuel—usually natural gas or methanol—into hydrogen, which, when combined with oxygen, produces electricity and water. This is the reverse electrolysis process. Rather than burning the fuel, however, the fuel cell converts the fuel to electricity using a highly efficient electrochemical process. A fuel cell has few moving parts, and produces very little waste heat or gas.

A fuel cell power plant is basically made up of three subsystems or sections. In the fuel-processing section, the natural gas or other hydrocarbon fuel is converted to a hydrogen-rich fuel. This is normally accomplished through what is called a steam catalytic reforming process. The fuel is then fed to the power section, where it reacts with oxygen from the air in a large number of individual fuel cells to produce direct current (DC) electricity, and by-product heat in the form of usable steam or hot water. For a power plant, the number of fuel cells can vary from several hundred (for a 40-kW plant) to several thousand (for a multi-megawatt plant). In the final or third stage, the DC electricity is converted in the power conditioning subsystem to electric utility-grade alternating current (AC).

In the power section of the fuel cell, which contains the electrodes and the electrolyte, two separate electrochemical reactions take place: an oxidation half-reaction occurring at the anode and a reduction half-reaction occurring at the cathode. The anode and the cathode are separated from each other by the electrolyte. In the oxidation half-reaction at the anode, gaseous hydrogen produces hydrogen ions, which travel through the ionic ally conducting membrane to the cathode. At the same time, electrons travel through an external circuit to the

Thus, the final products of the overall reaction are electricity, water, and excess heat. cathode. In the reduction half-reaction at the cathode, oxygen supplied from air combines with the hydrogen ions and electrons to form water and excess heat.

3.2 Types of Fuel Cells

The electrolyte defines the key properties, particularly the operating temperature, of the fuel cell. Consequently, fuel cells are classified based on the types of electrolyte used as described below.

1. Polymer Electrolyte Membrane (PEM)

2. Alkaline Fuel Cell (AFC)

3. Phosphoric Acid Fuel Cell (PAFC)

4. Molten Carbonate Fuel Cell (MCFC)

5. Solid Oxide Fuel Cell (SOFC)

These fuel cells operate at different temperatures and each is best suited to particular applications.

3.3. Fuel Cell Operation

Basic operational characteristics of the four most common types of fuel cells are discussed in the following.

3.3.1 Polymer Electrolyte Membrane (PEM)

The PEM cell is one in a family of fuel cells that are in various stages of development. It is being considered as an alternative power source for automotive application for electric vehicles. The electrolyte in a PEM cell is a type of polymer and is usually referred to as a membrane, hence the name. Polymer electrolyte membranes are somewhat unusual electrolytes in that, in the presence of water, which the membrane readily absorbs, the negative ions are rigidly held within their structure. Only the positive (H) ions contained within the membrane are mobile and are free to carry positive charges through the membrane in one direction only, from anode to cathode. At the same time, the organic nature of the polymer electrolyte membrane structure makes it an electron insulator, forcing it to Travel through the outside circuit providing electric power to the load. Each of the two electrodes consists of porous Carbon to which very small platinum (Pt) particles are bonded. The electrodes are somewhat porous so that the gases can diffuse through them to reach the catalyst. Moreover, as both platinum and carbon conduct electrons well, they are able to move freely through the electrodes. Chemical reactions that take place inside a PEM fuel cell are presented in the following

Anode $2H_2 \rightarrow 4H_+ + 4e-$ cathode $O_2 + 4H_+ + 4e \rightarrow 2H_2O$ Net reaction $2H_2 + O_2 = 2H_2O$
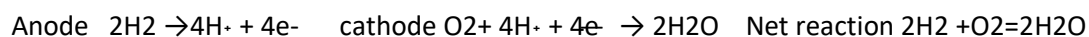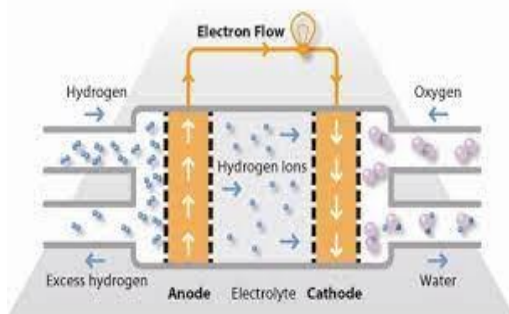
Hydrogen gas diffuses through the polymer electrolyte until it encounters a Pt particle in the anode. The Pt catalyzes the dissociation of the hydrogen molecule into two hydrogen atoms (H) bonded to two neighboring Pt atoms. Only then can each H atom release an electron to form a hydrogen ion (H+) which travels to the cathode through the electrolyte. At the same time, the free electron travels from the anode to the cathode through the outer circuit. At the cathode the oxygen molecule interacts with the hydrogen ion and the electron from the outside circuit to form water. The performance of the PEM fuel cell is limited primarily by the slow rate of the oxygen reduction half-reaction at the cathode, which is 100 times slower than the hydrogen oxidation half-reaction at the anode.

3.3.2. Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid technology has moved from the laboratory research and development to the first stages of commercial application. Turnkey 200-kW plants are now available and have been installed at more than 70 sites in the U.S., Japan, and Europe. Operating at about 2008C, the PAFC plant also produces heat for domestic hot water and space heating, and its electrical efficiency approaches 40%. The principal obstacle against widespread commercial acceptance is cost. Capital costs of about $2500 to $4000=kW must be reduced to $1000 to $1500=kW if the technology is to be accepted in the electric power markets. The chemical reactions occurring at two electrodes are written as follows:

 At anode: $2H_2 \rightarrow 4 H_+ + 4e_-$

At cathode $O_2+ 4H_+ + \rightarrow 4e_- \rightarrow 2H_2O$

# 3.3.3 Molten Carbonate Fuel Cell (MCFC)

 Molten carbonate technology is attractive because it offers several potential advantages over PAFC. Carbon monoxide, which poisons the PAFC, is indirectly used as a fuel in the MCFC. The higher operating temperature of approximately 6508C makes the MCFC a better candidate for combined cycle applications whereby the fuel cell exhaust can be used as input to the intake of a gas turbine or the boiler of a steam turbine. The total thermal efficiency can approach 85%. This technology is at the stage of prototype commercial demonstrations and is estimated to

Enter the commercial market by 2003 using natural gas and by 2010 with gas made from coal. Capital costs are expected to be lower than PAFC. MCFCs are now being tested in full-scale demonstration plants. The following equations illustrate the chemical reactions that take place inside the cell.

At anode: $2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$

And $2CO_2 + 2CO_3^{2-} \rightarrow 4CO_2 + 4e^-$ at cathode: $O_2 = 2CO_2 + 4e \rightarrow 2O_3^{2-}$
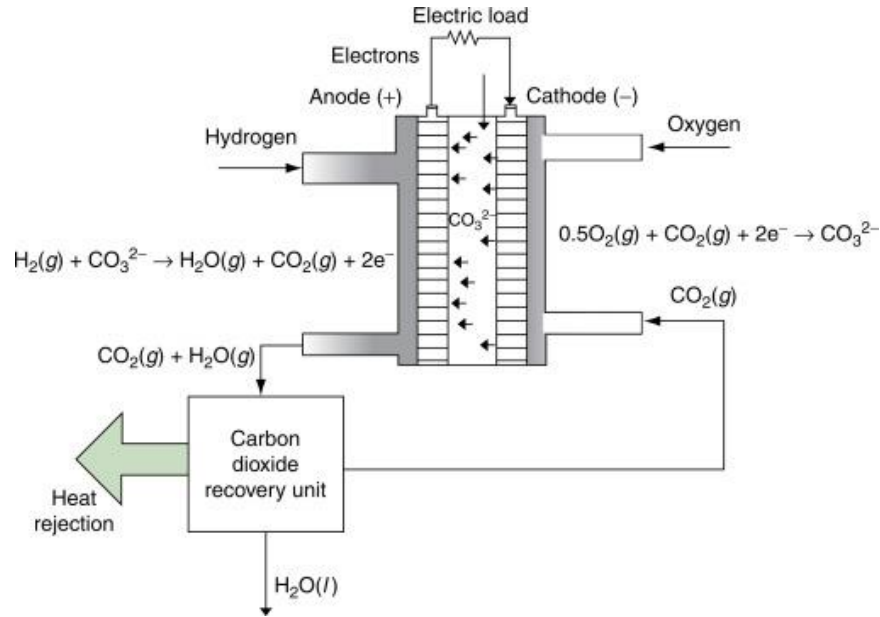
3.3.4 Solid Oxide Fuel Cell (SOFC)

A solid oxide fuel cell is currently being demonstrated at a 100-kW plant. Solid oxide technology requires very significant changes in the structure of the cell. As the name implies, the SOFC uses a solid electrolyte, a ceramic material, so the electrolyte does not need to be replenished during the operational life of the cell. This simplifies design, operation, and maintenance, as well as having the potential to reduce costs. This offers the stability and reliability of all solid-state construction and allows higher temperature operation. The ceramic make-up of the cell lends itself to cost-effective fabrication techniques. The tolerance to impure fuel streams make SOFC systems especially attractive for utilizing H2 and CO from natural gas steam-reforming and coal gasification plants. The chemical reactions inside the cell may be written as follows:

At anode: $2H_2 + 2O_2^- \rightarrow 2H_2O + 4e^-$

And $2CO + 2O_2^{2-} \rightarrow CO_2 + 4e^-$ at cathode: $O_2 + 4e \rightarrow 2O_2^-$

3.3.5 Summary

Fuel cells can convert a remarkably high proportion of the chemical energy in a fuel to electricity. With the efficiencies approaching 60%, even without co-generation, fuel cell power plants are nearly twice as efficient as conventional power plants. Unlike large steam plants, the efficiency is not a function of the plant size for fuel cell power plants. Small-scale fuel cell plants are just as efficient as the large ones, whether they operate at full load or not. Fuel cells contribute significantly to the cleaner environment; they produce dramatically fewer emissions, and there by-products are primarily hot water and carbon dioxide in small amounts. Because of their modular nature, fuel cells can be placed at or near load centers, resulting in savings of transmission network expansion.

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