Horizon
Fuel Cell Technologies

Renewable Energy
Science Education Manual

CREDITS

Contributors/Reviewers
Colleen Spiegel Ph.D.

Horizon Design and Production Staff
Stone Shen, Miro Zhang, Dane Urry

Horizon Fuel Cell Technologies
Block 19, No.2 Suide Rd.
Shanghai 200331, P.R. China
http://www.horizonfuelcell.com

Horizon
Fuel Cell Technologies

Renewable Energy
Science Education Manual

Contents

Chapter 1

The Environment and Climate Change

1.1 Introduction

1.2 World Energy Demand

1.3 Global Warming

1.4 Disadvantages of Current Energy Technologies

1.5 Innovative Green Technologies

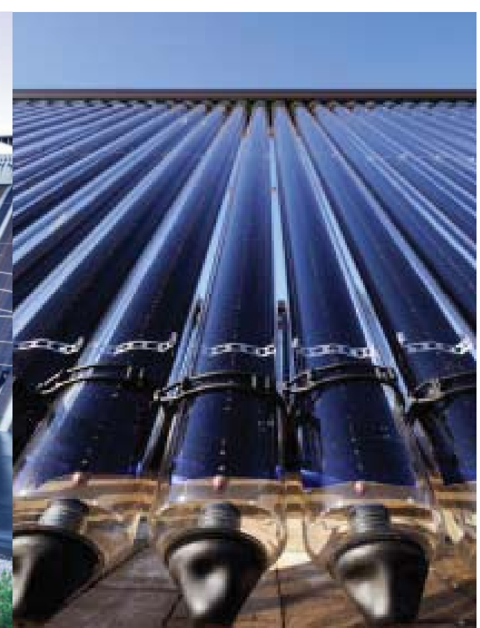
1.6 Vision of a Hydrogen Clean Energy Economy Based on Renewables in Combination

1.7 Conclusions

1.1 Introduction

Energy is a vital part of modern society – it enables life after dark, the movement of people and goods, and the continuous advancement of technology. Currently available energy sources, such as crude oil and natural gas, have been advantageous in serving the growth of the population for stationary and transportation purposes. However, the use of fossil fuels for power has resulted in many negative consequences; some of these include severe pollution, extensive mining of the world's resources, and political control and domination of countries that have extensive resources. In addition, the global demand for energy will increase rapidly due to the continuous growth in global population.

Fossil fuels are limited in supply, and are located in select regions throughout the world. This leads to regional conflicts and wars which threaten peace. The limited supply and large demand will cause the cost of fossil fuels to continue to increase. Therefore, the end of low-cost oil is rapidly approaching. Fossil fuels are currently needed in order to sustain our current living conditions. However, by using them, people, plants and animals are suffering from the side-effects of these fuels. Waste products from these fuels heat the earth's atmosphere and pollute the earth's air, water and ground. This results in decreased living conditions for all species of the earth. There are both economic and environmental reasons for developing alternative energy technologies.



A strong interest in alternative energy sources first occurred in the 1970's when crude oil was suddenly in short supply. Even though there still seemed to be plenty of fossils fuels left to mine -- it awakened the world to the fact that the supplies are limited and eventually will run out. During the past decade, there has been an increased interest in environmentally-friendly and more efficient power production. This interest has rapidly expanded research in alternative fuels and power sources. The reliance upon the combustion of fossil fuels has resulted in severe air pollution and extensive mining of the world's oil resources. In addition to being hazardous to our ecosystem, and the health of many species, the pollution is also changing the atmosphere of the world. This trend is called global warming, and will continue to become worse due to the increase in the combustion of fossil fuels for electricity due to the growing world population. The world needs a power source that has low pollutant emissions, is energy-efficient, and has an unlimited supply of fuel for a rising world population.

Many alternative energy technologies have been researched and developed. These include solar, wind, hydroelectric power, bioenergy, geothermal energy as well as many others. Solar cells use the sun to generate electricity, wind power is obtained from the kinetic energy of the wind and bioenergy is extracted from plants. There are also renewable energies that extract gas from biological waste and harness energy from ocean waves. Each of these alternative energy sources has its advantages and disadvantages and all are in varying stages of development. Figures 1-1 through 1-3 illustrate wind, solar and hydroelectric power.

It is advantageous for our earth and all of the species that inhabit it to be conscious of the energy that we are using. The Renewable Energy Kit explores all of the basic renewable energy technologies: wind, solar, electrolyzer, PEM fuel cell and a hydrogen storage system. This kit demonstrates how renewable energy can be transformed and utilized. These types of energy can be naturally replenished by our environment. By learning about this technology through experimentation, a student can learn exactly how these technologies work. We hope that by conducting experiments with the Renewable Energy Education Set that you will not only learn about the energy technologies in this kit – but will be inspired to explore alternative energy technologies even further. Some of the ways to examine these technologies is by watching the news, a science channel or by speaking with your friends. Maybe the energy technologies in this kit will motivate you to build larger prototypes – or help to improve these technologies one day as an engineer or scientist.

1.2 World Energy Demand

The use of fossil fuels increased rapidly during the twentieth century, and has quadrupled since the 1970s. The global population consumes petroleum products at a rate 100,000 times greater than the rate that they are formed [1, 2]. China is currently the third largest consumer of oil, however, if a Chinese citizen consumed oil at the same rate as an American citizen -- China would need 90 million barrels of oil per day to sustain its needs [1, 2]. According to [1], the typical amount of oil produced in one day is about 80 million barrels. Obviously there is something wrong with this equation!

Figure 1-4 shows the current and projected energy consumption from 1980–2030 [1]. International energy consumption is estimated to increase by 2.0 percent per year from 2003 to 2030. Total worldwide energy use grows from 421 quadrillion British thermal units (BTU) in 2003 to 563 quadrillion BTU in 2015 and 722 quadrillion BTU in 2030 [1].

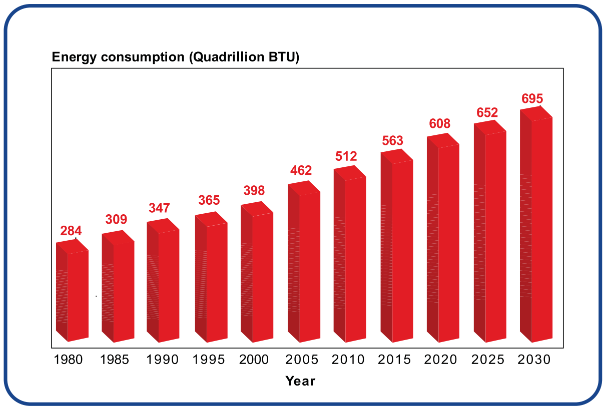


Figure 1-4. World energy consumption, 1980–2030

The British thermal unit (BTU):
A unit of energy used in power, steam generation and heating and air conditioning industries. The BTU has largely been replaced by the SI unit of energy, the joule (J), although it is still used in countries such as the United Kingdom, New Zealand, Canada and the United States.

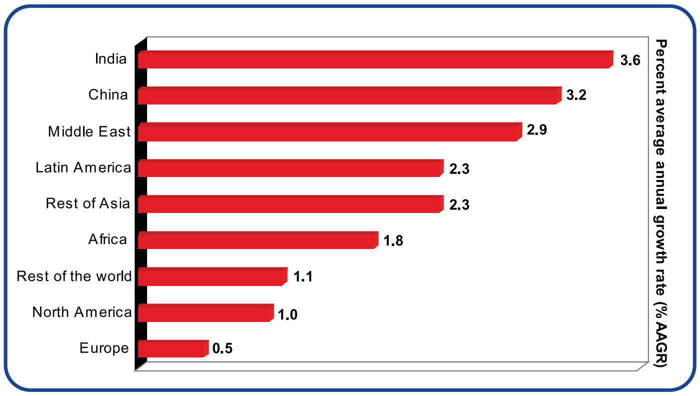


Figure 1-5.
Primary energy demand by region,
(% AAGR is for 1980–2030)

The most rapid growth in energy demand from 2003 to 2030 is projected for Asia, (including China and India), Central and South America, Africa, the Middle East, and Eurasia [1, 2]. The energy requirements for these nations are increasing by 5.0 percent per year on average. The energy demand by region is shown in Figure 1-5.

Average annual growth rate (% AAGR):
The average increase in growth over the period of one year. It is calculated by taking the arithmetic mean of the growth rate per year. For example, if the energy demand for a region is predicted to be 10% one year, and 20% the next, the AAGR for the two year period would be 15%.

In every country, there are groups that support fossil-fuel taxes in order to reduce the consumption of fossil fuels. There are also groups that are advocates of alternative energy technologies. Many experts are encouraging the reduction of fossil fuel use for industrialized countries, and are promoting the building of their infrastructure to adopt sustainable, renewable sources of power.

Approximately 43% of the global population use oil as their primary means of obtaining energy. Natural gas follows with 15%, waste and combustible renewables account for 13%, coal has 8%, and alternative sources of energy (including geothermal, hydro and solar) the remaining 3% as illustrated in Figure 1-6 [1, 2].

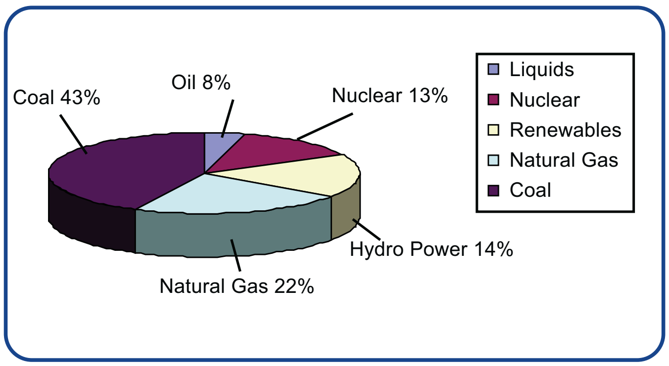


Figure 1-6. World electricity generation by fuel

During the 18th and 19th century, coal was the primary fuel used during the Industrial Revolution. After automobiles and household electricity became popular, oil became the primary fuel during the twentieth century. However, during the last few years, coal has become the fastest growing fossil fuel due to the increased consumption of fossil fuels in China. Although the renewable forms of energy currently have a small percentage of the total energy consumption, they have the highest average annual growth rate (AAGR) compared with all other energy forms as shown in Figure 1-7.

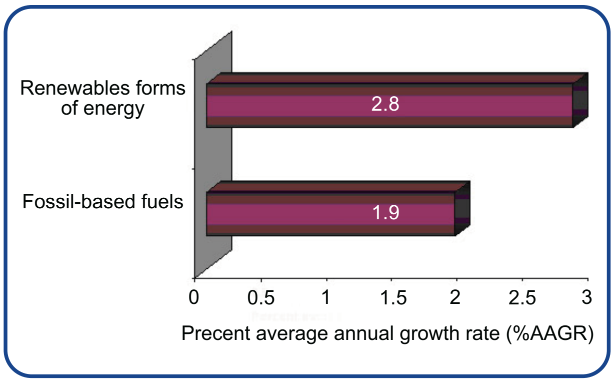


Figure 1-7.
Average annual growth rate for renewable and fossil-fuel based energies

1.3 Global Warming

Almost everyone has heard of the term "global warming", and knows that it means a "warming" of the planet. However, most of us do not know exactly what this means -- or how it is quantified.

Global warming:
A significant increase in the Earth's temperature over a short period of time due to the result of human activities.

Over the course of a century, an increase in temperature of 0.4° Celsius is significant, and an increase of 1° Celsius is considered global warming [3, 4].

Changes in climate typically take tens of thousands of years. Although 1° or 2° Celsius may not seem like a lot, small temperature changes can have significant effects. When you hear the term "ice age," you probably think of the world covered in snow and ice. Ice ages occur every 50,000 to 100,000 years, and the average global temperature was only 5 °C cooler than they currently are [3, 4].

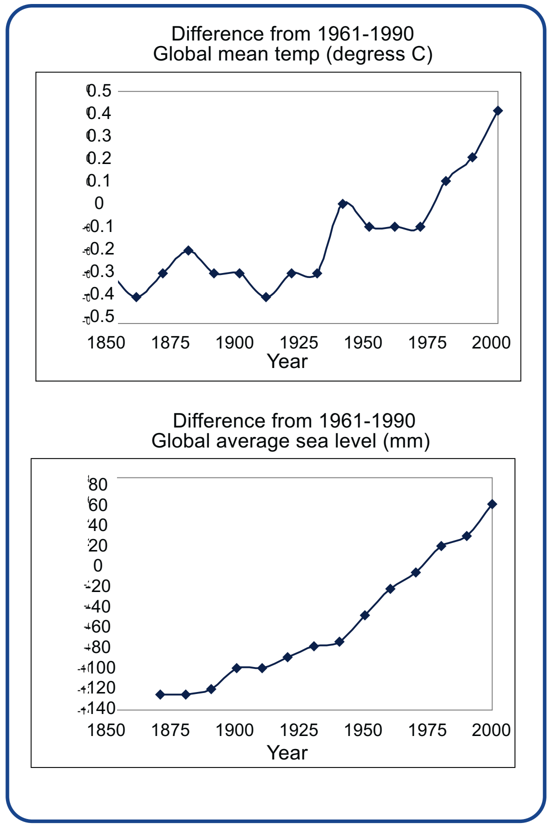


Figure 1-8. Intergovernmental Panel on Climate Change finding's on change in temperature and sea level (Adapted from [5])

The Intergovernmental Panel on Climate Change (IPCC) is a group of over 2,500 scientists from countries across the world. They met in 2007 to advance climate research. Figure 1-8 shows the intergovernmental panel on climate change's findings on change in the temperature and sea level. One of the conclusions of this meeting was that the last 15 years have been the warmest since 1850.

Other facts that were found during this conference include [3, 4, 5]:

- Glaciers and snow have decreased in the northern and southern hemispheres. Average arctic temperatures have increased by twice the global average during the last 100 years.
- Rain has increased in the Americas, northern Europe and parts of Asia. South Africa and the Mediterranean have been experiencing drying trends.
- Hot days have become more frequent, and cold days have become less frequent and severe.

Natural changes in climate such as heating due to volcanic activity, radiation from the sun, and changes in the chemistry of the atmosphere sometimes take thousands of years to change only 1 °C [3, 4, 5].

1.3.1 The Greenhouse Effect

Global warming is caused by an increase in the greenhouse effect. The greenhouse effect is generally a good phenomenon because it keeps the earth warm – which enables life to survive. When the sun's energy comes into the earth's atmosphere, about 70% of the energy stays on the planet, and the remaining 30% is reflected into space [5].

Global warming experiment The heat that stays on the planet gets absorbed by the land, oceans and plant life, and eventually it does get radiated out by the ocean's land masses. Clouds are responsible for reflecting heat back into space. Some of the heat gets absorbed into gases, (such as carbon dioxide, methane gas and water vapor), in the atmosphere and this trapped heat is what keeps the planet warm. Figure 1-9 shows the cycle of solar energy and the greenhouse effect. If the earth did not have a "greenhouse effect," it would probably look a lot like Mars. Some scientists have suggested that if we could put enough carbon dioxide and water vapor into Mars' atmosphere – the gases may become thick enough to retain heat and allow plants to live on the surface. These plants would eventually begin to produce oxygen. An image of Mars' current atmosphere is shown in Figure 1-10.

Figure 1-9. Solar energy and the greenhouse effect

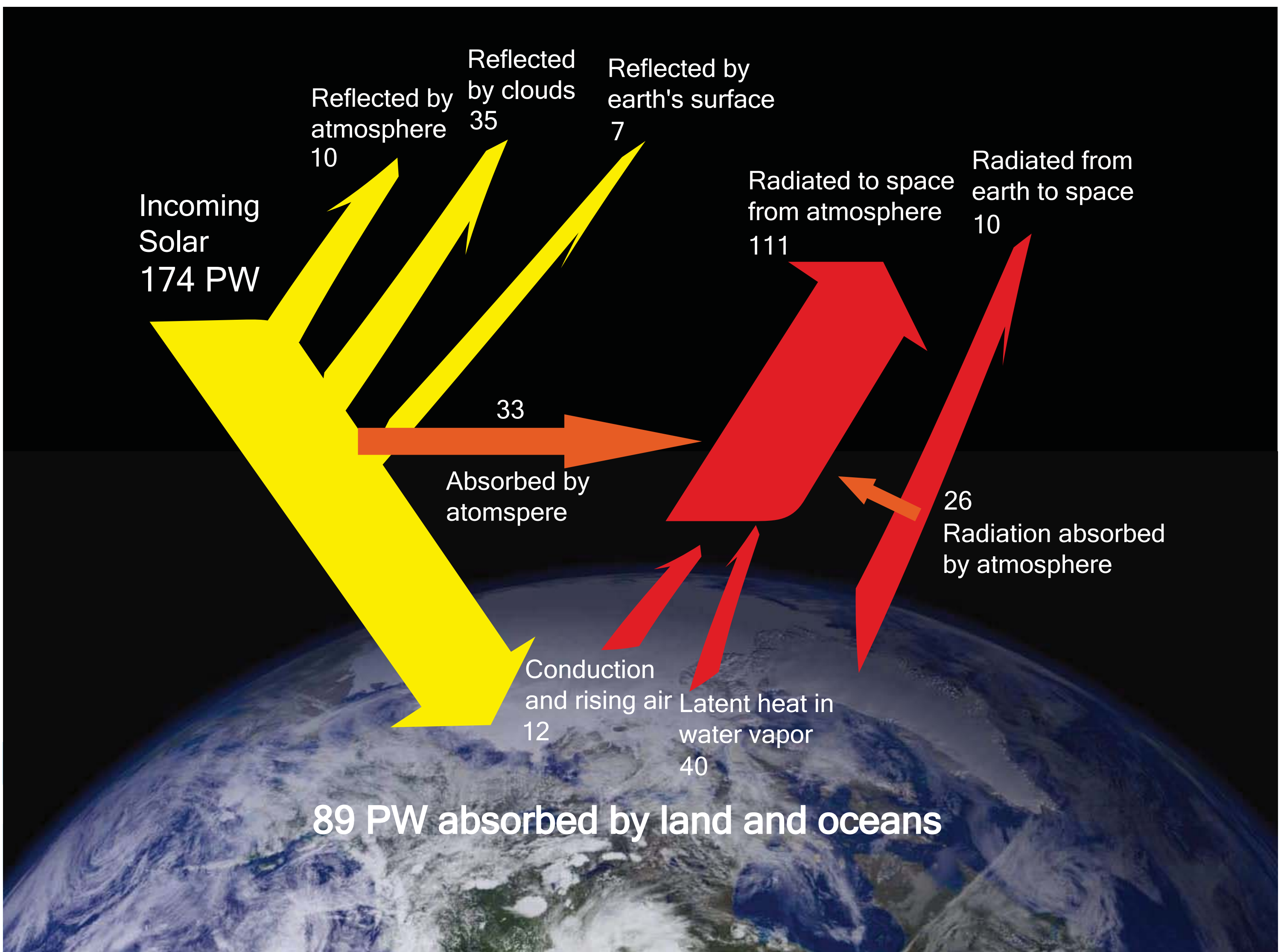
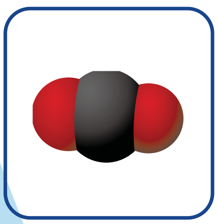
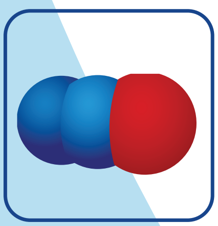


Figure 1-10.
This is a Viking image of the surface of Mars.

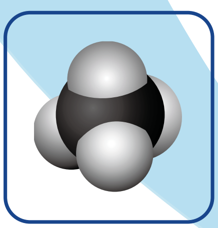
Since the Industrial Revolution, there have been an abundance of gases that have gone into the atmosphere that help to accelerate the greenhouse effect. Some of these gases include [5]:



1.Carbon dioxide (CO_2): This is a colorless gas that is one of the by-products of the combustion of fossil fuels. Most of the CO_2 currently in the atmosphere was put there from volcanic eruptions millions of years ago. We have been helping to increase carbon dioxide concentration for many years. Carbon dioxide is the primary contributor to global warming because it absorbs infrared radiation. Global CO_2 emissions have increased from 1 billion tons in 1900 to 8 billion tons in 2000 [5]. The IPCC estimates that the parts per million (ppm) of CO_2 in the atmosphere has increased from 280 in the early 1800's to 379 ppm in 2005 [5].



2.Nitrous oxide (NO_2): The nitrous oxide levels that have been released are less than the CO_2 levels, but the amount of energy that NO_2 absorbs is about 270 times as much [5]. NO_2 is also a byproduct of combustion, and occurs as a result of releasing nitrous oxide in great quantities.



3.Methane (CH_4): Methane is the main component of natural gas. It is created as a by-product of coal, the decomposition of garbage, and from large herds of feedstock. It absorbs about 20 times more energy than CO_2, and therefore, also heats up the earth [5].

4.Water Vapor: The greenhouse effect is also exacerbated by water vapor – but it is usually a result of climate change rather than man-made emissions. When the earth heats up, water vapor forms and rises, and the temperature of the lower air decreases. Eventually, the water vapor cools enough that it converts back into liquid water, and it falls again. As water vapor rises, more of it will condense into the clouds – which will help to reflect incoming solar radiation, therefore, allowing less energy to enter the earth's atmosphere. Figure 1-11 illustrates the water cycle of evaporation, condensation and precipitation. Scientists are uncertain of the exact effect of the increased amounts of water vapor on the earth, but they believe that the concentration of water vapor is correlated with increased amounts of carbon dioxide.

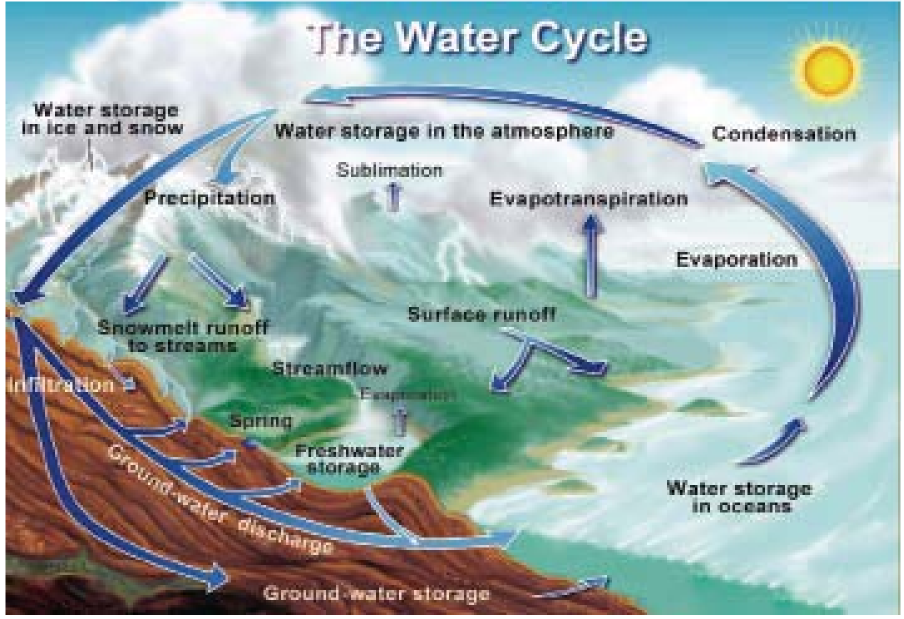


Figure 1-11.
The water cycle of evaporation, condensation and precipitation.

1.3.2 Sea Levels

Due to the global temperature increase, glaciers and ice shelves are melting as illustrated in Figure 1-12. The decrease of large ice masses could accelerate global warming due to the fact that less of the sun's energy will be reflected. Of course, melting of the ice masses will cause a rise in sea levels. The initial rise would only be an inch or two, however, even an inch or two can cause flooding for some low-lying coastal areas. If the West Antarctic Ice sheet melted and collapsed into the sea, the sea levels could rise about 10 meters (~ 32 feet) [2, 3, 5]. This would make many coastal areas disappear underneath the ocean.

The largest ice mass in the world is Antarctica with about 90 % of the world's ice. The ice thickness is approximately 2,133 meters (7,000 feet) thick [5]. If this ice melted, the oceans would rise approximately 61 meters (200 ft) [5]. The average temperature in Antarctica is -37 °C; therefore, it is difficult for the continent to get above freezing [3, 5].

The ice at the North Pole is not as thick as in Antarctica, and it floats on top of the water. If this ice melted, the sea levels would not be affected. Greenland also has a large ice covering, and would add about 7 meters (20 feet) to the sea level if it melted [5]. Since Greenland is closer to the equator, it can get above freezing, and therefore, it would be the most likely to melt first.

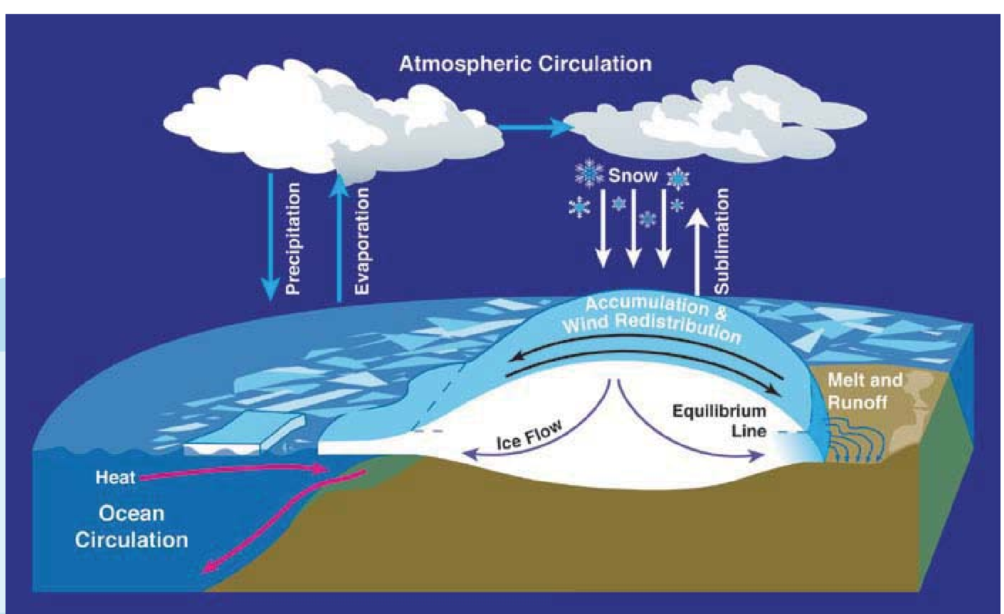


Figure 1-12 Water cycles between ocean,atmosphere,and glaciers.

1.3.3 Effects of Global Warming

It is hard to predict the effect of global warming on the ecosystem.

Many ecosystems are very delicate, and small changes can drastically alter them. Ecosystems are also interconnected; therefore, changes to one ecosystem will definitely affect other ecosystems. An increase in temperature or rain could affect crop growth. There is approximately $5 billion in crop losses per year due to global warming [7]. For every degree increase in temperature, there is a 3 – 5% decrease in crop yields [5, 6].

Ecosystem:
An area that consists of all of the living (plants, animals and micro-organisms) and non-living physical factors of the environment functioning in harmony with one another.

1.3.4 Can We Stop Global Warming?

Greenhouse gas emissions contribute directly to health problems, acid rain and formation of ozone. In many parts of China and India, air pollution remains a public health issue. Acid rain occurs when sulfur dioxide (SO_2), sulfur trioxide (SO_3) and nitrogen dioxide (NO_2) in the atmosphere undergo chemical reactions to form acidic compounds. These are absorbed by water droplets in the clouds, and then fall to the earth, increasing the acidity of the ecosystem. This can damage plant life, soil, and buildings. Most acidic compounds are deposited near the source of contamination, but they can also be carried in the atmosphere for hundreds or thousands of miles. This means pollution created in the U.S. can be carried to China and vice versa.

The current carbon dioxide concentration determined from the ice cores (180 to 300 ppm) is far greater than the natural range found over the last 650,000 years [3, 6]. If the CO_2 concentration rises to 400 – 440 ppm and stays there, the eventual rise in temperature would be around 2.4 – 2.8 °C [3, 4, 6].

Parts per million (ppm):
A measurement that describes very dilute concentrations of substances. Similar to 1 cent out of one hundred cents (United States cents), parts per milion, ppm, literally means the number of parts out of a milllion. One ppm is equal to one milligram per liter of water (mg/L), or 1 milligram per kilogram soil (mg/kg).

In order to stabilize the CO_2 level, it needs to peak, and then decline. The more quickly that this occurs, the lower the peak stabilization level. According to the IPCC, in order to stabilize the CO_2-equivalent concentrations around 445 to 490 ppm, CO_2 emissions would need to peak by 2015 (at the latest), and then fall to between 50 – 85% below the year 2000 levels by 2050 [3, 4]. A later peak and higher concentrations would lead to larger increases in temperature. Figure 1-13 shows the global mean temperature increase with CO_2 concentration according to year.

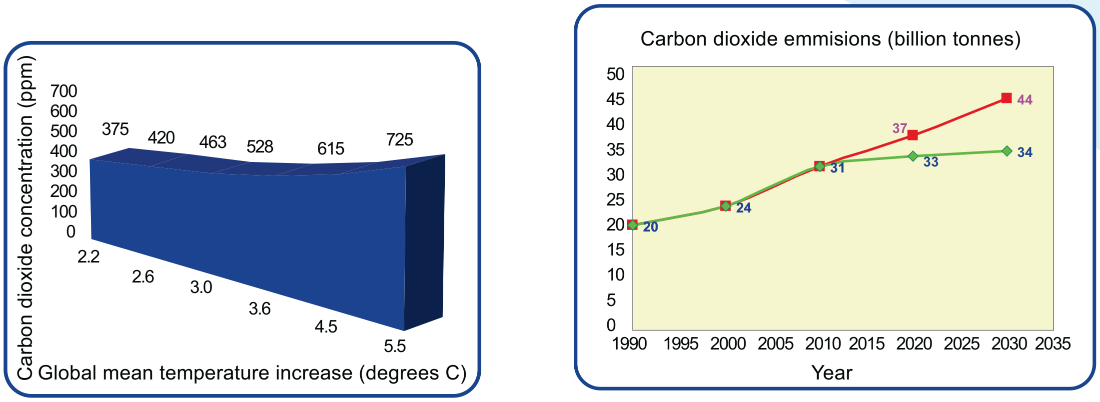


Figure 1-13. Carbon Dioxide Concentrations and Emissions

Global warming will continue for centuries with the greenhouse gases that have already been released into the atmosphere. Although it seems like a lot of damage has already been done, we can still reduce our emissions by doing several things:

- ***Improve energy efficiency:*** Energy efficiency is the ratio between the output of an energy device, and the input of energy.

$$\textbf{Energy efficiency} = \frac{\textbf{output of an energy device}}{\textbf{input of energy}}$$

All types of equipment can become more energy-efficient while performing the desired service. This results in less use of fossil fuels, which in turn, reduces greenhouse gas emissions. One way to improve energy efficiency is to make sure that the car that you use is properly tuned up; this will help it to generate fewer gases.

- ***Conserve energy:*** Conserving energy is using less of a service that requires energy, therefore, it lowers emissions. There are countless ways to conserve energy: turning the lights off, using a fan instead of the air conditioning, and using less hot water.

- ***Using less carbon intensive fossil fuels:*** If coal is processed without using Clean Coal Technologies, it emits 75% more carbon per unit of energy than natural gas, and a third more than oil [5]. Therefore, using natural gas instead of coal reduces the emissions' per unit of energy consumed.

- ***Using zero-carbon energy sources:*** Renewable energy sources such as wind, solar and nuclear power do not produce any CO_2. If hydrogen is obtained in a sustainable manner (like in the Renewable Energy Education set), fuel cells also do not produce CO_2. These power sources can be used to heat water, swimming pools or entire households and businesses.

- ***Capturing and storing CO_2 emissions:*** There are many technologies that exist to capture and store the CO_2 emitted when fossil fuels are burned. These technologies can be used either before or after combustion or both. Some of the places that can store CO_2 include depleted oil and gas fields, salt cavities, and unmineable coal beds.

The best method of substantially reducing our pollutant emissions is to develop non-fossil fuel sources. Alternative energy sources such as solar, wind and fuel cell power could create large reductions in greenhouse gases if they were widely used.

1.4 Disadvantages of Current Energy Technologies

Current energy technologies include fossil fuels such as coal, oil, gas, as well as the heat engine and batteries. Coal, oil and gas are foreseen to be in short supply in the near future, as the world population grows rapidly and the amount of fuel used increases.

The remaining estimates for fossil fuels vary widely. Assuming that the 2005 rate of usage remains constant, conventional oil will run out in about 40 years, and coal in about 150 years [4, 5]. Neither will actually run out since the prod uction will decline rapidly as the remaining reserves dwindle. The annual oil consumption was 0.18 ZJ in 2005 [8].

There is significant uncertainty surrounding these numbers. The 11 ZJ of future additions to the recoverable reserves could be optimistic [8]. Figure 1-14 shows an approximate oil breakdown of the remaining 57 ZJ on the planet [8].

Zettajoule (ZJ):

1 ZJ (zettajoule) = 1021 J (joule)

A joule (J) is a unit of energy in the International System of Units (SI). It can be defined as the work required to move an electric charge of one coulomb through an electrical potential difference of 1 volt. It can also be defined as the work done to produce one watt for one second.

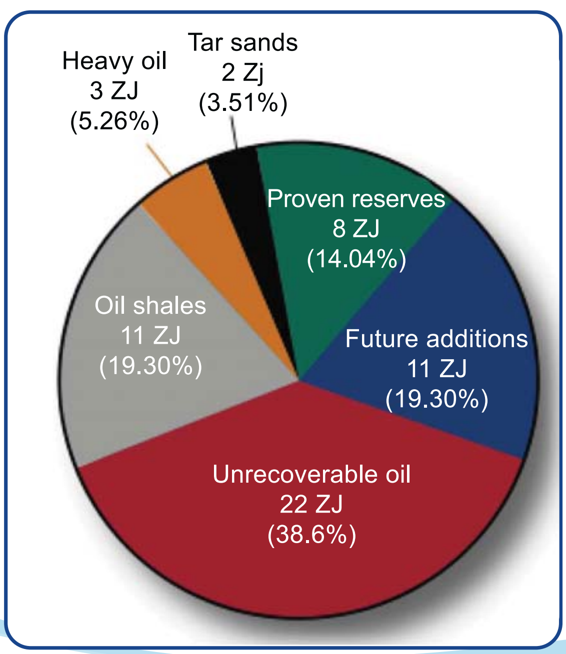


Figure 1-14.
Remaining Oil Breakdown of the remaining 57 ZJ oil on the planet.

We have already discussed the disadvantages of fossil fuels several times, but to reiterate, some of the disadvantages of fossil fuels include:

- Non-renewable: Fossil fuels are non-renewable resources that take millions of years to form. Therefore, once the reserves are depleted, there is no way to obtain more.
- Pollution: Carbon dioxide is emitted by fossils fuels – which are the main contributor to the greenhouse effect. Coal gives off both carbon dioxide and sulphur dioxide and sulphur trioxide, which creates acid rain. The acid rain can lead to the destruction of forests, and the erosion of rock and masonry structures. Crude oil has toxic chemicals that cause air pollution when combusted.
- Destruction of land: The mining of coal results in the destruction of land.
- Dangerous: The mining of coal is considered one of the most dangerous jobs in the world.
- Plant location: In order to burn enough fossil fuels to provide energy for the grid, trainloads of fuel are needed on a regular basis. Therefore, this means that the plants should be near fossil fuel reserves.
- Oil spills: Oil spills occur, and cause pollution and environmental hazards. They result in catastrophic effects on marine life for many years.
- Politics: Many of the countries that have oil reserves are politically unstable. Nations that do not have reserves and have an oil dependence may seek to influence politics of those countries for their own advantage.

Fuel cell and electric vehicles (EV) do not produce the pollution associated with internal combustion engines. In electric vehicles, fossil fuels are used to generate the electricity needed to recharge the batteries. In fuel cell vehicles, the hydrogen is also typically made from fossil fuels. So how do these types of vehicles benefit us?

(a)

(b)

(c)

Figure 1-15. (a) The Subaru R1e electric car can be charged overnight on an ordinary household current, (b) Honda's FCX Concept Vehicle. (c) Hydrogen powered Riversimple Urban Car using Horizon 6kW fuel cell.

If the electricity or hydrogen is produced from fossil fuels, carbon emissions are cut into half. If the electricity or hydrogen is generated from renewable resources such as solar panels and electrolysis – the carbon emissions can be reduced to less than 1%, therefore, the cars operated by EV batteries is still cleaner than gas-powered vehicles. In addition, the cost of the electricity required or the hydrogen generated can be only a fraction of the current cost of gasoline per gallon. Figure 1-15 illustrates an electric and a fuel cell vehicle.

Calculating the carbon emissions from various vehicle types can get complicated, however, there are a couple of easy relations that can be used to compare vehicles and the amount of carbon emissions are [9]:

$$PEF = Eg \times \frac{1}{0.15} \times AF \times DPF$$

where E_g is the gasoline-equivalent energy content of electricity factor, $\frac{1}{0.15}$ is the fuel content factor, *AF* is the petroleum-based accessory factor, and *DPF* is the driving pattern factor. This methodology was developed by the United States Department of Energy to compare the fuel economy of electric and hybrid vehicles with traditional gasoline vehicles.

A simple method of calculating vehicle emissions is based upon fuel type. The fuel emission factor is based upon the fuel's heat content, the fraction of carbon in the fuel that is oxidized and the carbon content. This can be calculated as follows [9]:

$$CO_2 \text{ emissions} = \text{fuel used} \times \text{heating value} \times \text{emission factor}$$

This equation is often used to obtain quick estimates for CO_2 emissions.

1.5 Innovative Green Technologies

As mentioned in Section 1.1, there are many types of renewable "green" technologies. In the Renewable Energy Education kit, the technologies that will be experimented with are fuel cells, solar cells, wind power and electrolysis. An introduction to these technologies is described in the next few sections.

1.5.1 Solar Cells

The heat and the light from the sun provide an endless amount of energy, and can be harnessed in many ways. There have been many technologies that have been used to take advantage of solar energy, including concentrating solar power systems, passive solar heating and day lighting, photovoltaic systems, solar hot water, and solar process heat and space heating and cooling.

Concentrating solar power systems (CSP): Systems that use lenses or mirrors and tracking systems to collect a wide array of sunlight into a small beam. The light beam can be used as a heat source for a traditional power plant. There are many types of concentrating technologies, such as the solar trough, solar power tower and the parabolic dish.

Solar power can be used for both large and small applications. Businesses and industry can diversify their energy sources, improve efficiency, and save money by choosing solar technologies. Home owners can use solar energy for heating and cooling, industrial processes, electricity, and water heating. Home owners can also use solar technologies for heating and cooling and water heating, and may even be able to produce enough electricity to operate "off-grid" or to sell the extra electricity to the utilities, depending on local programs. There are many solar design strategies that can help both homes and commercial buildings operate more efficiently and make them more pleasant and comfortable places in which to live and work.

Beyond these localized uses of solar power, utilities and power plants are also taking advantage of the sun's abundant energy resource and offering the benefits to their customers. Concentrating solar power systems allow power plants to produce electricity from the sun on a larger scale, which in turn allows consumers to take advantage of solar power without making the investment in personal solar technology systems.

1.5.2 Wind Power

Wind turbines use the wind to generate electricity. They are mounted on a tower to capture the most energy. At 100 feet (30 meters) or more above ground, they can take advantage of the faster and less turbulent wind. Turbines catch the wind's energy with their propeller-like blades. Usually, two or three blades are mounted on a shaft to form a rotor.

A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity.

Wind turbines can be used as stand-alone applications, or they can be connected to a utility power grid or even combined with a photovoltaic (solar cell) system. For utility-scale (megawatt-sized) sources of wind energy, a large number of wind turbines are usually built close together to form a wind farm. Several public electricity providers today use wind plants to supply power to their customers. Stand-alone wind turbines are typically used for water pumping or communications.

However, homeowners, farmers, and ranchers in windy areas can also use wind turbines as a way to cut their electric bills.

1.5.3 Electrolysis

Electrolysis involves the passage of an electric current through an ionic medium, which results in chemical reactions at the electrodes. Metal electrodes are typically used as the electrode in an electrolyzer because they are able to conduct electricity. There are solid and liquid ionic compounds, and free ions can conduct in both types.

Ion:
A particle that is electrically-charged (it can be a positive or negative charge), or an atom or molecule that had gained or lost electrons.

The electrolysis of water is the breaking of the water molecule using electricity into hydrogen and oxygen. The electrolysis of pure water is very difficult since it has a very low conductivity – approximately one millionth that of seawater. The electrical conductivity is sped up by adding an electrolyte such as an acid, salt and a base.

An electrical power source can be connected to two electrodes that are placed into water. Hydrogen will appear at the negatively charged electrode, and oxygen will occur at the positively charged anode. The amount of hydrogen and oxygen generated will be proportional to the electrical charge that was sent through the water. The electrolysis occurs because energy is required to keep the ions separated in order for them to gather at the respective electrodes.

1.5.4 Fuel Cells

Fuel cells convert chemical energy directly into electricity and heat with high efficiency. These devices can be used anywhere at anytime, for as long as necessary as long as hydrogen is supplied. Fuel cells are one of the few alternative energy devices that can be used for energy applications – it can power portable electrons, automobiles, houses, buildings, and even space ships (Figure 1-16 illustrates NASA fuel cells)! The basic technology behind a fuel cell is simple – it is made of many layers “sandwiched” together. A fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side.

Anode:
The negatively charged terminal of a fuel cell or battery that is supplying current.

Cathode:
The positively charged terminal of a fuel cell or battery that is supplying current.

Figure 1-16. NASA fuel cells

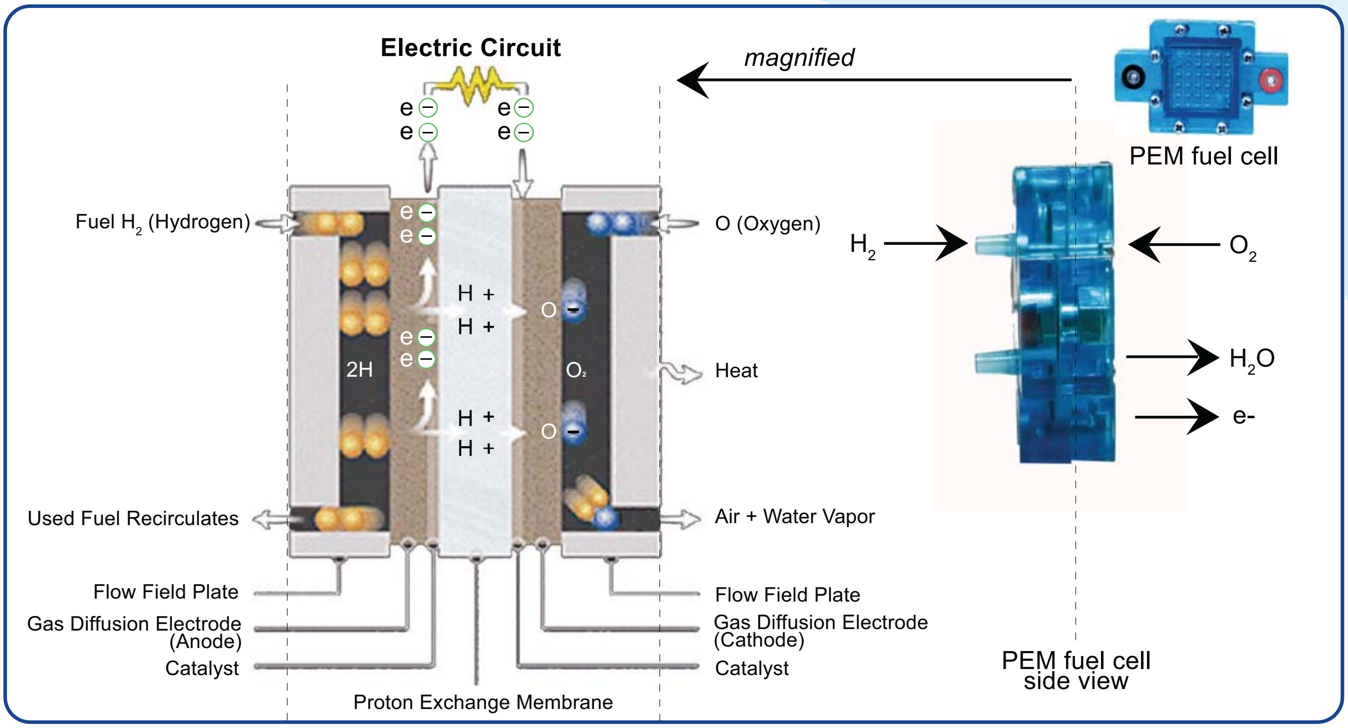


Figure 1-17. A single PEM fuel cell configuration

Hydrogen is broken into protons and electrons on the anode side, and oxygen is combined to produce water on the cathode side. Protons are transported from the anode to the cathode through the electrolyte, and the electrons are carried to the cathode over the external circuit. On the cathode, oxygen reacts with protons and electrons, forming water and producing heat [10]. Both the anode and cathode contain a catalyst to speed up the electrochemical processes.

Figure 1-17 shows an example of a typical proton exchange membrane (PEM) fuel cell with the following reactions:

Anode: $H_2\,(g) \rightarrow 2H^+\,(aq) + 2e^-$

Cathode: $\frac{1}{2}\,O_2\,(g) + 2H^+\,(aq) + 2e^- \rightarrow H_2O\,(l)$

Overall: $H_2\,(g) + \frac{1}{2}\,O_2\,(g) \rightarrow H_2O\,(l)$ + electric energy + waste heat

Reactants are transported by diffusion and/or convection to the catalyzed electrode surfaces where the electrochemical reactions take place. Though the half cell reactions will be different for other fuel cell types, the overall cell reaction should remain the same as the overall reaction listed previously. The water and waste heat generated by the fuel cell must be continuously removed, and may present critical issues for the operation of certain fuel cells [11].

Fuel cells can utilize a variety of fuels to generate power—from hydrogen, methanol, and fossil fuels to biomass-derived materials. Using fossil fuels to generate hydrogen is regarded as an intermediate method of producing hydrogen, methane, methanol, or ethanol for utilization in a fuel cell before the hydrogen infrastructure has been set up. Fuels can also be derived from many sources of biomass, including methane from municipal wastes, sewage sludge, forestry residues, landfill sites, and agricultural and animal waste.

1.6 Vision of a Hydrogen Clean Energy Economy Based on Renewables in Combination

Most of the current energy needs in the world are being met by fossil fuels. These fuels are easily obtained, stored, and transported because of the large amount of money that has been used to create, build, and maintain the system. Due to the current fuel distribution system, technology has advanced at a faster pace during the last two centuries than in all of recorded history. Despite all the advantages fossil fuels have provided for our society, it has also had negative effects on the environment, some of which likely has yet to be seen. Some of these harmful effects include air pollution due to acid rain emissions, water and soil pollution due to spills and leaks, and carbon dioxide accumulation in the atmosphere. These pollutants have the potential to warm the global atmosphere and kill many species.

For most countries around the world, if the supply of fossil fuels were cut off - -the entire economy would come to a stop. There would not be any way for people to drive to work or use the electricity in their homes or workplaces. However, cars burn gasoline and cause air pollution. In the process of burning the gasoline, carbon monoxide, nitrogen oxides and unburned hydrocarbons are released into the atmosphere. The catalytic converters reduce a large portion of the pollution, but they are not perfect. Many cities currently have dangerous levels of ozone in the air.

In addition to the negative environmental consequences of using these fuels, there is a finite supply of fossil fuels that will inevitably force the use of another form of energy. The demand for energy will also continuously increase due to the constant increase of the global population.

The future energy economy will consist of many renewable energy technologies used in combination. As far as fuels are concerned, hydrogen is one of the most powerful fuels. This is the most evident with NASA space ships – the primary fuel that is used is hydrogen. Hydrogen is the most abundant element in the universe; however, it does not exist in its pure form on earth. Therefore, it has to be extracted from common fuel types or water. The process that is used most frequently for extracting hydrogen is by steam reforming natural gas. It can also be extracted from coal, nuclear power, biofuels or even waste products.

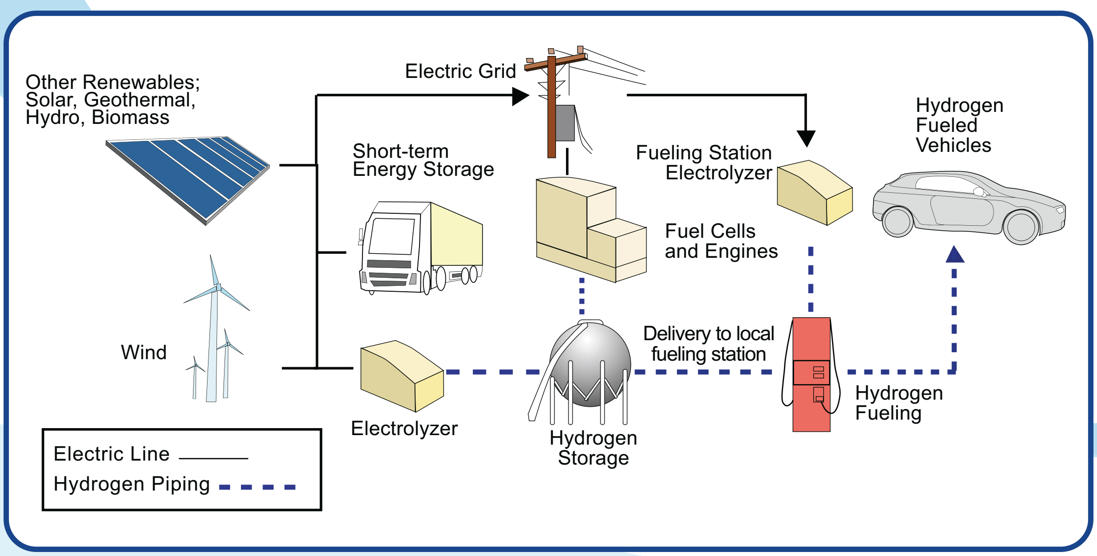


Figure 1-18. Hydrogen Linkages with the Energy System

Hydrogen can also be produced without fossil fuels through the process of electrolysis. Renewable forms of energy such as photovoltaic cells, wind, hydro and geothermal are increasingly being used to produce electricity. This electricity can be used for electrolysis, which splits water into hydrogen and oxygen. The hydrogen can be used, or stored to generate electricity. An example of hydrogen linkages to the energy system are shown in Figure 1-18.

In order to successfully have a society based upon renewable energy, there has to be a way to store energy because renewable energy is intermittent. Solar and wind energy are both excellent methods of obtaining energy from natural resources, however, the levels of sunshine, and the intensity of wind varies. When these sources are not available – electricity cannot be generated. When a large amount of energy is being produced, hydrogen can be created from water. The hydrogen can then be stored for later use.

Fuel cells have already been used for decades for stationary use – for business and residential use. Portable electronics such as laptops, cameras and cellular phones can last 10 – 20 times longer by using hydrogen. All of the major automakers have already invested heavily in hydrogen fuel cell technology vehicles. Although the cost of renewable energy systems is still very high, technological breakthroughs and larger quantities produced are dramatically reducing costs every year.

In addition, the costs of fossil fuels will continue to increase in the near future. Once the cost of renewable energy technologies becomes competitive with the rising oil costs, the fossil-fuel based economy will be replaced with the new renewable energy economy.

In the future energy economy, individual households will be able to produce their own energy. This will help to redistribute power because global oil companies will not control so much wealth and resources. Individual households can share their energy with the grid to help distribute energy to areas that may have less due to weather conditions.

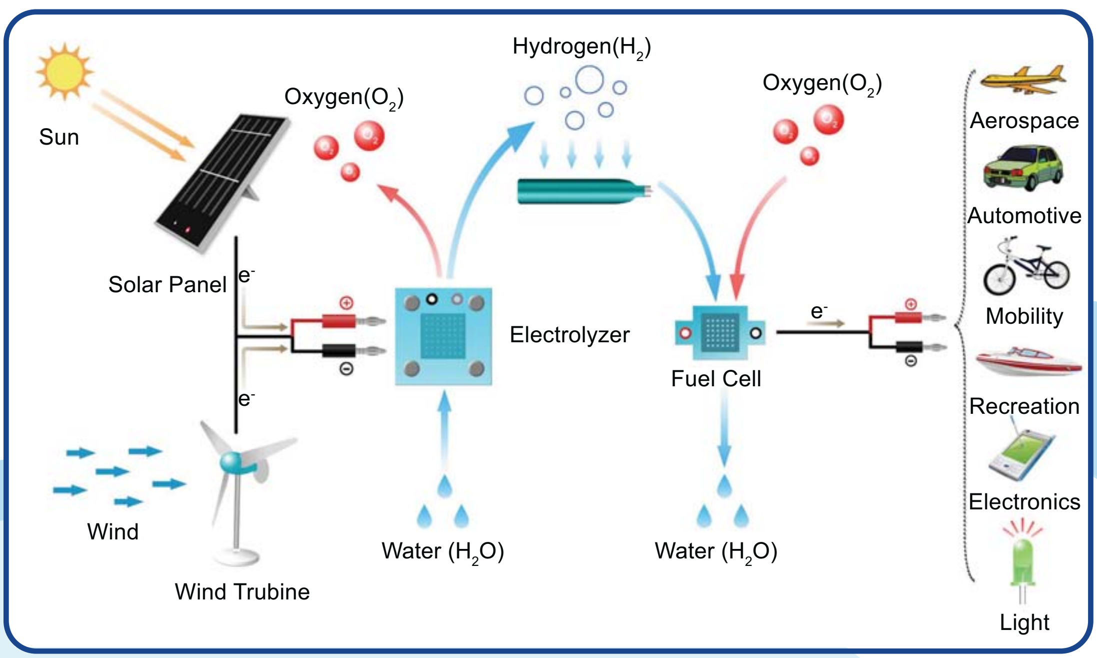


Figure 1-19. Diagram of Renwable Hydrogen Cycle from Renewables to Applications

In the future, automobiles will be plugged into an outlet in homes and offices to help generate electricity for both the vehicles and the houses. Houses only require an average of 10 kW to power everything. And since automobiles can generate 40 kW of power, a car can become a power plant for the house or office. Cars can also be plugged into a pole when individuals go to work to power the building. This transition to a hydrogen economy provides an important challenge, and great opportunity of the 21st century.

The transition to the hydrogen economy has already begun. We are a fossil fuel based economy today. We are currently working on reducing the costs associated with the hydrogen economy, and there are still improvements that need to be made -- but we are quickly learning....

1.7 Conclusions

Energy is needed to sustain our modern way of life. Fossil fuels have helped to grow and revolutionize our technology, transportation, and every other aspect of our modern lives. It has also resulted in several negative consequences, such as severe pollution, extensive mining of the world’s resources, and political domination of countries with fossil fuel resources. The demand for energy is also increasing due to the increase in global population. The estimates for the remaining amount of fossil fuels left vary, however, many experts agree that there is approximately 30 – 40 years left. Therefore, the end of low-cost oil is approaching. The pollution generated by fossil fuels affect the earth’s atmosphere and pollutes the air, water and ground. Therefore, there are both economic and environmental reasons for developing renewable energy technologies. There are many energy technologies have been researched and developed. These include solar, wind, hydroelectric power, bioenergy, geothermal energy as well as many others. Solar cells use the sun to generate electricity, wind power is obtained from the kinetic energy of the wind and bioenergy is extracted from plants. Each of these alternative energy sources has its advantages and disadvantages and all are in varying stages of development. The renewable energy kit demonstrates a hybrid renewable energy system which includes solar, wind, and fuel cell power combined with electrolysis. This education kit demonstrates on a small-scale the principals behind the future renewable energy economy. We are currently working on reducing the costs associated with the future energy economy, and there are still improvements that need to be made. We are quickly learning how to improve these technologies – because the future will soon be here.

Chapter 2

Solar Energy

2.1 Introduction

Most of us are already familiar with solar cells because we use or encounter them everyday – in calculators, street lamps, and many traffic road signs. As long as these devices have enough light – they seem to work forever. Solar (or photovoltaic) cells are made up of many individuals cell stacked together, and these are made of materials called semiconductors. Semiconducting materials are special materials that conduct electrons when light is absorbed. We will explain more about the science behind solar cells in Section 2.2, but first we will begin our study on solar cells with the history behind them.

Figure 2-1.
The Helios Prototype developed by AeroVironment and tested by NASA. A solar and fuel cell system-powered unmanned aerial vehicle

2.2 History

Solar cells were first discovered in 1839 when a 19 year old French physicist, Edmund Becquerel, was able to make voltage appear when he illuminated a metal electrode in a weak electrolyte solution [12, 13]. In 1876, Adams and Day were the first to study the photovoltaic effect in solids. They made solar cells of selenium that were 1 – 2% efficient [12, 13]. Charles Fritts furthered the photovoltaic (PV) technology by coating the selenium with an extremely thin layer of gold to form p-n junctions in 1883. Albert Einstein published a theoretical explanation of the photovoltaic effect in 1904, which won him the Nobel Prize in 1923 [12]. Around this time, a Polish scientist by the name of Jan Czochralski began to develop a method to grow perfect crystals of silicon. By the 1940s and 1950s, this process was used to grow silicon to make the first generation of single crystal silicon photovoltaics, and this technique is still currently used in the industry today [13, 14]. Russell Ohl patented the modern junction semiconductor solar cell in 1946 (U.S. Patent 2,402,662, "Light sensitive device"), which was discovered while working on the series of advances that would lead to the transistor [14]. A summary of the history of solar cells is illustrated in Figure 2-2.

1839	French Physicist Edmund Bacquerel, first made voltage appear when he illuminated a metal electrode in a weak electorlyte solution.
1876	Adams and Day were the first to study photovoltaic effect in solids. They made selenium cells that were 1-2% efficient.
1904	Albert Einstein published a theoretical explanation of the photovoltaic affect.
1916	Jan Czochralski began to develop a method to grow perfect crystals of silicon.
1940s	First generation of single crystal silicon photovoltaics.
1950s	First attempts to commercialize solar panels.
1958	First commercial solar panel used with NASA's Vanguard I satellite.
1980s	Solar panels are used for normal consumer applications.
1900's-Present	Cost for PV panels continue to decrease, and used in more normal consumer applications.

Figure 2-2. History of Solar Cells

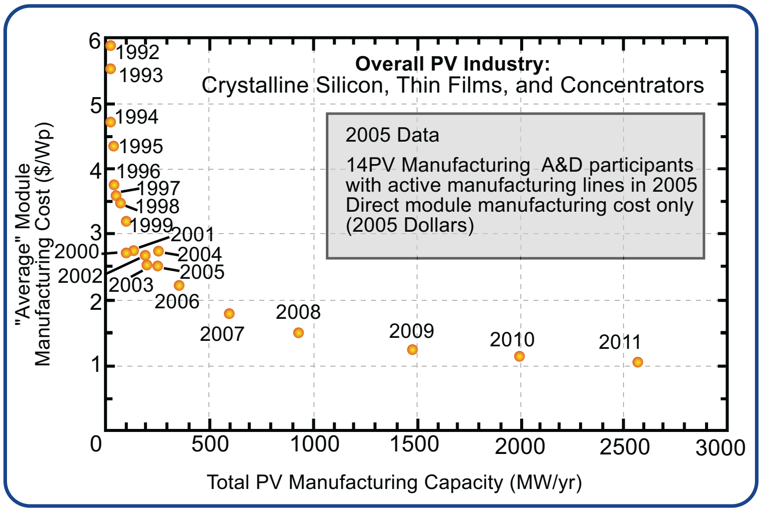


Figure 2-3. PV Industry Cost and Capacity.

There were several attempts to commercialize solar panels during the early 1950s, but their cost was prohibitive. Bell Laboratories began the modern age of solar technology in 1954 when they started experimenting with silicon doped with certain impurities that were very sensitive to light [14]. This resulted in the production of the first solar cells with a sunlight energy conversion efficiency of 6 percent. PV's first became a practical energy source for NASA when they were first used for the Vanguard I satellite in 1958 made by Hoffman Electronics [14]. It was easy to incorporate solar cells into space applications because cost is much less important than space and reliability. Solar cells have been used for satellites and other space crafts ever since. During the energy crisis of the 1970s, the research and development performed by NASA began to be used by commercial companies. By the late 1980s, the costs and the higher efficiencies began to be in the range for normal consumer applications, such as pocket calculators, highway lights and signs, emergency call boxes and small home systems. While the cost has decreased substantially during the 1990s, it is still more than double the required price needed to compete against existing technologies [12, 14]. Figure 2-3 demonstrates the manufacturing cost decreases for the overall PV industry since 1992.

2.3 Types of PV Systems

Two major types of PV systems are available in the marketplace today: flat plate and concentrators. Flat plate systems are the most common, and they consist of PV modules on a rigid and flat surface to capture sunlight. Concentrating photovoltaic systems use a specifically designed area of mirrors or lenses to focus the sunlight into a small area of cells. These systems reduce the amount of semiconducting material, and improve the performance of the system. If these systems have single or dual axis tracking, they area called Heliostat concentrator photovoltaics (HCPV). Although there are many advantages to this type of system, they have been limited due to the cost of focusing, tracking and cooling equipment [14].

When the two systems are compared, flat plate systems are typically less complicated but employ a larger number of cells, while the concentrator systems use smaller areas of cells but require more sophisticated and expensive tracking systems. Images of these systems are shown in Figure 2-4.

(a)

Figure 2-4.
Flat plate (a)
and
solar concentrator PV systems (b)

(b)

Chapter 2

2.4 Principals and Characteristics

Simple PV systems power many of the small calculators and wrist watches on the market today. Larger photovoltaic systems provide electricity for pumping water, powering communications equipment, and even lighting homes and running appliances. PV cells have become one of the major modern energy producers because of the recent improvements in conversion efficiencies, and the lowered costs of PV panels.

Solar cells are usually encapsulated and then connected together to form a module. PV panels have a glass layer over the solar cells to protect the semiconductor wafers while allowing light to pass through. Since a single solar cell only provides a voltage of about 1/2 V, it is unable to power most devices by itself [14]. Therefore, several cells are connected in series allowing the voltage to be added together. In order to create higher current, cells can be connected in parallel. Figure 2-5 illustrates laminated PV cells, a monocrystalline silicon wafer and polycrystalline PV cells.

The power output of a solar array is measured in watts or kilowatts. The electricity generated from a solar panel is fed into the electricity grid using inverters. In stand-alone systems, batteries can be used to store any energy that is not immediately used.

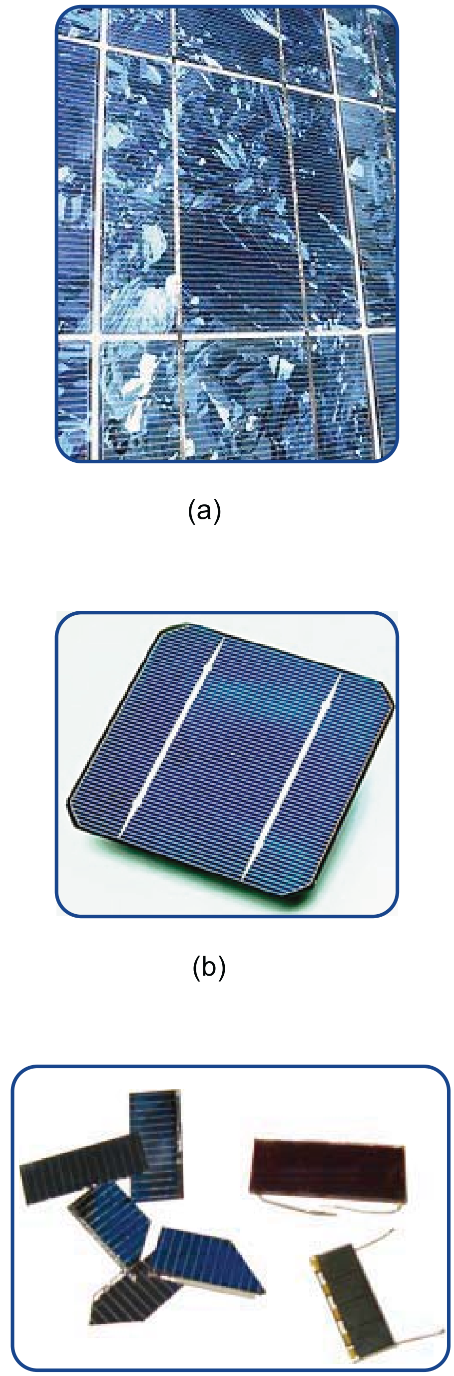


Figure 2-5. (a) Polycrystalline PV cells laminated to backing material in a PV module, (b) A monocrystalline silicon wafer and c) Polycrystalline PV cells

2.5 Solar Technology

When a PV cell is exposed to sunlight, the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. It is this movement of electrons and holes that generates electricity. The process of converting sunlight into electricity is known as the "photovoltaic effect".

Light is a form of energy, and electrons in the materials begin to move when light energy enters the material. **(See experiment for light and heat.)** The electrons freely flow through the materials, and are attracted to materials that conduct electrons or electricity. In order to collect these electrons, and use them for power, they are collected by electrically conductive materials such as copper. This current and the cell voltage (which is a result of electric fields) are the power that a solar cell produces.

To increase power output, many PV cells are connected together to form modules, which are then assembled into larger units called arrays. These different units of PV cells enable designers to build PV systems with various power output for different applications. A complete PV system consists not only of PV modules, but support structures, wiring, storage, and conversion devices.

The relationship between energy, work & power

Energy

Energy is a quantity that measures the amount of work that can be performed by a force. There are many forms of energy, including light, sound, heat, mechanical, chemical and electrical. All natural phenomena can be explained by breaking everything down into its different forms of energy. Energy can be transferred from one form to another, but the total amount of total energy always remains the same.

Work

Work is the amount of energy that is transferred from one system to another. The amount of energy transferred by a force is called mechanical work. The SI definition of work is the joule (J), which is the work done by a force of one Newton over a distance of one meter:
Work (J) = Force (Newtons) x Distance (meters)

Power

Power is the rate at which work is performed. Power can be obtained using the following relationship:
Power (watts) = Work (joules)/Time (sec)

2.5.1 Silicon Electron Transport

A silicon atom has 14 electrons arranged in three different shells. The first two shells are completely full, and the third shell is partially empty, having only four electrons as shown in Figure 2-6. In order for the atom to be in its ideal state, it actually needs eight electrons in its last shell. Therefore, in order to compensate for the empty spaces, it shares four electrons with its neighbor silicon atoms. This is what forms the crystalline structure. The material properties of silicon in this "pure" state allows it to be a pure conductor because its electrons are unable to move around (they are locked in this crystalline structure).

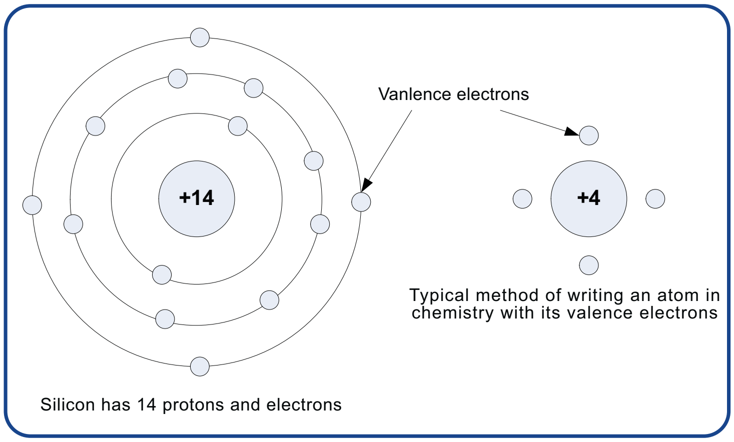


Figure 2-6.
Silicon has 14 protons and electrons, but all atoms are typically written with only their valence electrons.

Valence electron:
Electrons that are in the outermost, or valence electron shell of an atom. The electrons in the valence shell are important because they determine how an electron reacts chemically with other elements. If there are few valence electrons in the outer shell, then the atom will be more likely to react. If the valence shell is full, the atom is less likely to react with other atoms.

Therefore, the basic material properties need to be modified in order to allow the electrons to move around. This is accomplished by placing impurities into the silicon material. Other types of atoms are mixed into the material, which enables the electrons to move. For example, a phosphorous atom has five electrons in its outer shell, and if these are placed into the silicon material, it still bonds with the silicon atoms, but there is one free electron that is not bonded.

2.5.2 Photogeneration of charge carriers

When a photon hits a piece of silicon, it can either be absorbed by the silicon, can reflect off of the surface, or pass through the silicon.

This depends upon if the photon energy is higher or lower than the band gap.

Photon:
An elementary particle that is the basic unit of light, and other forms of electromagnetic radiation.

Band gap:
An energy range in a solid where no electron states exist. The amount of energy required to free an outer shell electron from its orbit to a free state.

If the photon is absorbed, its energy is given to an electron in the crystal lattice. The valence electron is normally bonded tightly due to neighboring atoms; however, the additional energy given to it by the photon excites it into the conduction band, where it can move around in the semiconductor. The electron moves to another location (hole), and leaves a "hole" where it once was. This is called mobile "electron-hole" pairs in the semiconductor.

2.5.3 The Electromagnetic Spectrum and Energy Loss

The electromagnetic spectrum is made up of many different wavelengths -- which means many different energy levels.

> ***Electromagnetic spectrum:***
> A term used to describe the entire range of light radiation, from gamma rays to radio waves.

We tend to think of optical radiation as "light," but the rainbow of colors that make up optical or "visible" light is just a tiny part of a much broader range of energy. Many of these other portions of the spectrum get totally or partially blocked by earth's atmosphere. The only way to observe these parts of the spectrum is to go into space! The names of the various sections of the electromagnetic spectrum are shown in the Figure 2-7.

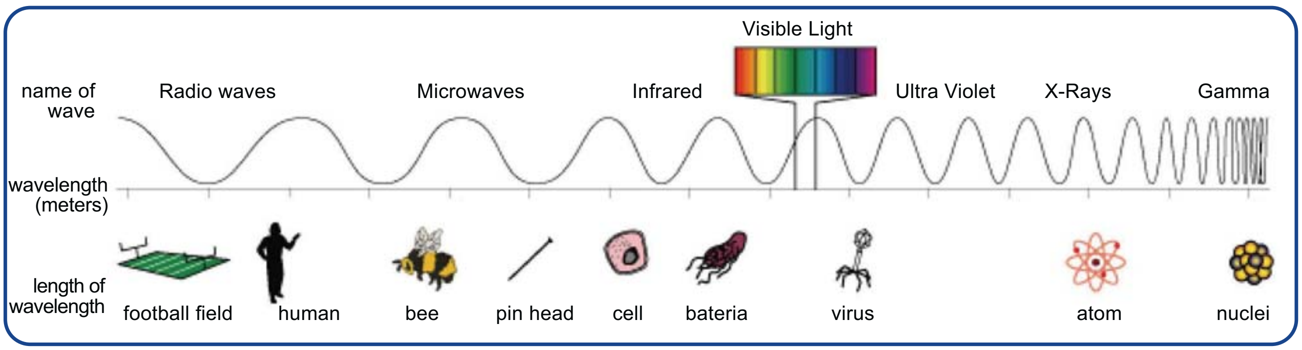


Figure 2-7. The electromagnetic spectrum.

When you witness a rainbow after a storm, you can witness the separation of light into its different wavelengths. Since PV materials only absorb a certain range of energies – some wavelengths of light will be unable to create free electrons. Depending upon the material type, a certain amount of energy (1.1 eV for crystalline silicon) will be required in order to make electrons move. This is called "the band gap energy" of the material.

> ***Electron volts (eV):***
> The electron volt (eV) is a unit of energy used in physics. It is equal to the amount of energy gained by an unbound electron as it accelerates through an electrostatic difference of one volt. 1 volt (1 joule/ 1 coulomb) multiplied by the electron charge (1.602 x 10-19 coulomb). The coulomb (C) is the SI unit of electric charge, and it is the amount of electric charge transported in one second by a current of 1 amphere (A).

So if we use materials with a really low band gap – can more photons be used? The band gap also determines the strength (voltage) of the electric field – and if it is too low – any extra photons that are absorbed do not create a high enough voltage to create the required power.

In order to balance these two effects – the optimal band gap is 1.4 eV for a cell material [12, 13]. There are other losses of energy as well. The electrons have to flow from one side of the cell to the other. The bottom and top is usually covered with metal, however, a large portion of it cannot be covered because photons need to flow through the material in order to generate the electric current. If the entire piece of material was covered with a contact, there would be no space left for the light to enter the material to make the electrons start to move. The silicon is a semiconductor, and the internal resistance is fairly high, which means it is difficult for electrons to travel through the material.

This translates to high losses. To reduce the losses, the cell is contacted by a metallic grid, which covers part of the surface. The grid also cannot be too small; otherwise, the contact resistance will be too high. This means that there will not be enough of the surface covered with contact material in order to collect the electrons properly.

2.5.4 Silicon and the P-N Junction

When energy is added to pure silicon, a few electrons break free from the lattice – which leaves a hole. These free electrons then try to become more stable by looking for another hole. These free electrons are termed “free carriers”. The silicon with the extra phosphorous electrons (doped) allows enough electrons to move to be able to conduct current. The process of adding electrons is called “doping”, and the silicon materials with the phosphorous atoms is termed “n-type silicon”.

Silicon material can also be doped with boron, which has only three electrons in its outer shell compared with the four that silicon has. This type of silicon is called “p-type,” and therefore, silicon has free “holes” instead of electrons. These “holes” move around like the electrons, and carry a positive charge.

If a piece of p-type silicon is placed into contact with n-type silicon, then the electrons will diffuse from a region of high concentration (n-type side) to a region of low concentration (p-type side). The electrons in the n-type material are repelled by the negative electrode, and can drawn to the p-type electrode. The holes in the p-type material move the opposite way.

When the difference in voltage between the electrodes is high enough, the electrons in the depletion zone are boosted out of their holes, and begin moving freely again. The depletion zone disappears, and the charge moves across the diode. Figures 2-8 illustrates the P-N junction before and after the electrons begin to move.

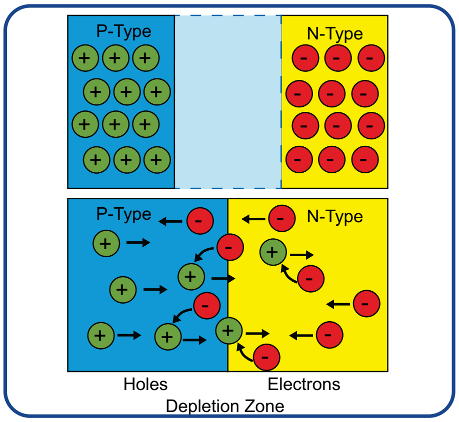


Figure 2-8. P-N Junctions

Metal contacts are placed onto the n-type and p-type sides of the solar cell and the electrodes are then connected to the device that needs to be powered. The electrons move from the n-type side, through the wire to power the load and continue through the wire until they reach the P-type semiconductor-metal contact. They then recombine with a hole that was created by an electron-hole pair on the P-type side or are swept across the junction from the N-type side after being created there. Figure 2-9 illustrates the concept as current flows across the junction.

2.5.5 Advanced Topic: Materials Engineering

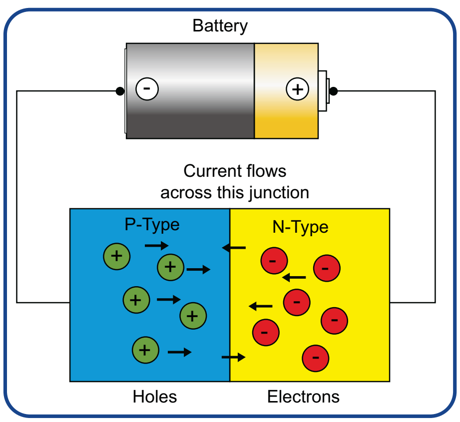


Figure 2-9. Connection to an external load.

Sections with purple text found within this book are for advanced level students and most suited to ages 14+.

An important aspect of building renewable energy systems is the study the type of materials that conduct electricity, and the reason why they conduct electricity. In renewable energy systems, there are many reasons why electricity is lost. Lost electrons are due to how closely each material is aligned (or bonded) with each other, how well that it conducts electrons, and how these electrons travel to the external device that it is powering.

The main types of charged particles in renewable energy systems are electrons and ions. Electron losses can occur when they are traveling through different types of materials, through materials that do not have a perfect crystalline structure, and through long lines or through different electronics or devices. Ionic losses are a result of more complex reasons. Ions sometimes can also be lost while traveling through materials or different mediums. In order to decrease these electron and ionic losses, materials should be made highly conductive with better electron and hole mobilities, and materials should be well-connected together to ensure that electrons are not lost when trying to move from one material to the next.

2.5.5.1 Voltage Loss Due to the Transport of Charges

Every material resists the flow of charge to a certain extent, and this resistance creates a loss of voltage. This phenomenon occurs in solar cells, fuel cells and electrolyzers. The components that contribute to transport losses in solar cells are the silicon material and contacts for solar cells. For fuel cells and electrolyzers, the charge losses are due to the electrolyte, catalyst, gas diffusion layers, bipolar plates, and contacts. The technical term for this type of loss is called "ohmic loss", which is calculated using Ohm's law (see Chapter 7 for more details about Ohm's law). This includes the electronic (R_{elec}) and ionic (R_{ronic}) contributions to fuel cell resistance [11]. This can be written as: $V_{onmic} = iR_{ohmic} = i (R_{elec} + R_{ionic})$

R_{ionic} accounts for the majority of the losses in Equation 2-1 because ionic transport is more difficult than electronic charge transport. R_{ionic} represents the ionic resistance of the electrolyte, and R_{elec} includes the total electrical resistance of all other conductive components, including the bipolar plates, cell interconnects, and contacts.

Conductivity:
The material's ability to support the flow of charge through the material.

The opposite of electrical resistance is often expressed in the literature as conductance (σ), which is the reciprocal of resistance:

$$\sigma = \frac{1}{R_{ohmic}}$$

Where the total cell resistance (R_{ohmic}) is the sum of the electronic and ionic resistance. Resistance is characteristic of the size, shape and properties of the material, as expressed by Equation 2-3:

$$R = \frac{L_{cond}}{\sigma A_{cond}}$$

Where L_{cond} is the length (cm) of the conductor, A_{cond} is the cross-sectional area (cm^2) of the conductor, and σ is the electrical conductivity (ohm^{-1} cm^{-1}).

Current density:
An amount of electric current or charge per unit area. It is a measure of the density of flow of a conserved charge. In SI units, the electric current density is in amperes per square meter (A/m2). In many renewable energy devices, the current density is measured in milliamperes per square centimeter (mA/cm2).

The current density, j, (A/cm2), can be defined as:

$$j = \frac{i}{A_{cell}}$$

Where A_{cell} is the active area of the fuel cell.

If the resistance to charge flow is decreased, then the performance will improve. The way that ions and electrons move through materials is different. In a metallic conductor, valence electrons associated with the atoms of the metal become detached and are free to move around in the metal. In a typical ionic conductor, the ions move from site to site, hopping to ionic charge sites in the material (like the silicon explained in Section). The number of charge carriers in an electronic conductor is much higher than an ionic conductor. Electron and ionic transport is shown in Figures 2-10 and 2-11.

Table 2-1 shows a summary and comparison of electronic and ionic conductors, and the renewable energy systems that use each type.

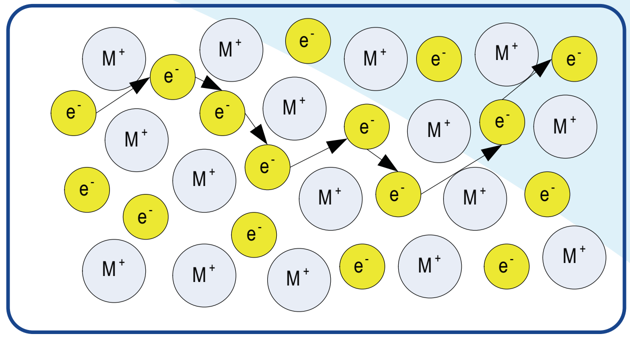


Figure 2-10. Electron Transport in a Metal [11]

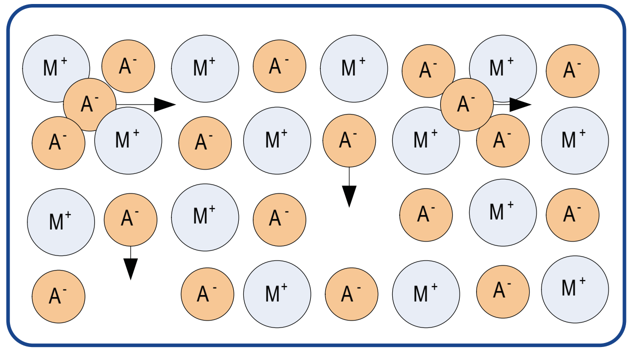


Figure 2-11.
Ionic Transport in a Crystalline Ionic Conductor [11]
Metal [11]

Materials	Conductivity	Components
Electronic Conductors		
Metals 1	10^3 to 10^7 F	Fuel cell and electrolyzer materials
Semiconductors	10^{-3} to 10^4	Solar cells
Ionic Conductors		
Solid/polymer electrolytes	10^{-1} to 10^3	PEMFC Nafion (c) electrolyte used for many fuel cells and electrolyzers
Liquid electrolytes	10^{-3} to 10^3	NaOH solution, phosphoric acid solution

Table 2-1.
Comparison of Electronic and Ionic Conduction in Renewable Energy Systems (Adapted from [11])

2.6 Other Materials for PV Cells

Although silicon is the most common type of material used for PV cells, there are other materials that are also commonly used. Polycrystalline silicon is sometimes used to reduce the manufacturing costs – although solar cells made of polycrystalline are not as efficient. Amorphous silicon can also be used to reduce production costs. Other common materials include:

1. gallium arsenide
2. copper indium diselenide
3. cadmium telluride

Each type of material has a different "band gap" which means that it absorbs different wavelengths of energy. One method of improved PV efficiency is to use two or more layers using different types of materials. These are called "multi-junction" cells, and can absorb different wavelengths of energy. The higher band gap is usually on the surface absorbing the high energy photons, and the lower band gap material is underneath. Figure 2-12 shows the potion of the periodic table that is relevant to photovoltaics [12].

I	II	III	IV	V	VI
		5 **B**	6 **C**	7 **N**	8 **O**
		13 **Al**	14 **Si**	15 **P**	16 **S**
29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**
47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**

Figure 2-12. Portion of the Periodic Table Important for Photovoltaics

2.6.1 Crystalline Silicon

The material that is most frequently used for PV panels is crystalline silicon, and has an average of 15% efficiency. It can be made from a silicon ingot, ribbon, or wafer. Monocrystalline silicon is usually made using the Czochralski process. These panels are expensive since they are made of pure cylindrical ingots.

Ingot:
Single crystal ingots are semiconductors that are grown using the Czochralski process, or Bridgeman technique. These processes are very expensive because they involve many manufacturing steps in extremely clean facilities. After the crystal ingots have been grown, they are sliced and polished, and then turned into semiconductor devices, solar cells and other devices.

It is difficult to use these for square solar cell modules without a substantial waste of refined silicon. Polysilicon or multicrystalline silicon is made from cast square ingots that have are large block of molten silicon that have been cooled and solidified.

2.6.2 Cadmium Telluride Solar Cell

Cadmium telluride (CdTe) is another efficient light-absorbing materials for solar cells. CdTe is easy to manufacture, and suitable for large-scale production. This is the only technology besides amorphous silicon that can be manufactured on a large scale.

However, there is a perception of toxicity with CdTe solar cells because they are based upon cadmium, which is a metal that can be a cumulative poison. Many studies have shown that the release of cadmium in the cadmium telluride solar cells is lower than in other cadmium-based solar cell technologies [14].

2.6.3 Copper-indium Selenide Solar Cell

Copper-Indium Selenide (CuInSe2) based solar cells have high light absorption properties. The optical and electrical characteristics can be manipulated to build customized devices. Some of the films have achieved greater than a 14% efficiency [14], however, the manufacturing costs are high in comparison with silicon solar cells.

2.6.4 Gallium Arsenide (GaAs) Multijunction Solar Cell

Gallium arsenide multijunction cells are high efficiency cells that were originally developed for special applications such as satellites and space exploration. These cells consist of several layers, such as GaAs, Ge, GaInP2, and these layers are deposited using metalorganic vapor phase epitaxy [12, 14].

Metalorganic vapor phase epitaxy:
A chemical vapor deposition method where a chemical reaction occurs in a gaseous phase at moderate pressures. This technique is used for the formation of devices with alloys. This technique is used for manufacturing solar cells, laser diodes and LEDs.

The semiconductors that are chosen to make up these multijunction cells are chosen to absorb nearly the entire solar spectrum, therefore, generating the maximum amount of energy. GaAs-based multijunction solar cells are the most efficient solar cells with an efficiency of 40.7% [14]. This technology is currently being utilized in the Mars rover missions.

2.6.5 Light-absorbing Dyes (DSSC)

Light absorbing dyes (DSSC) are currently being investigated for solar cell technology. An example is a ruthenium metallorganic dye that is deposited in a thin layer to absorb light. The dye sensitized solar cell depends upon a mesoporous layer of nanoparticulate titanium dioxide (TiO2) to maximize the surface area (200 – 300 m2/g TiO2, compared with 10 m2/g of the surface area of the crystal) [14]. When light hits this solar cell, the electrons are passed to the n-type TiO2, and the holes are passed to the electrolyte on the other side of the dye. This cell allows flexibility in the materials that are chosen, and can be manufactured by low-cost manufacturing methods such as screen printing. The dyes in these cells suffer from degradation under heat and UV light, and the casing can be difficult to seal due to the solvents used in the assembly.

2.6.6 Organic/Polymer Solar Cells

There are many organic and polymer solar cells that are fabricated from thin films (~ 100 nanometers) and are currently investigated for solar cells. Examples include polymers, thin films and specialty materials. Energy conversion efficiencies are currently much lower than other solar cells types with the highest efficiency reported at 6.5% [14]. This cell type would still be valuable where mechanical flexibility and disposability are important.

2.6.7 Silicon Thin Films

Solar thin films are mainly deposited by chemical vapor deposition from silane and hydrogen gas.

Chemical vapor deposition:
A chemical process that produces high-purity, high performance solid materials. This is used in the semiconductor industry to produce thin films.

Depending upon the deposition parameters, this will yield amorphous silicon, polycrystalline silicon or nanocrystalline silicon. The solar cells made from this process have lower energy conversion efficiency than bulk silicon, but are also less expensive to produce. One of the new types of thin film technology that is being developed is for building semitransparent solar cells that will be applied to the window as tinting while generating electricity.

2.7 Solar Power Applications

There are a limitless number of applications for solar power. We already see many of these applications everyday– in calculators, street lamps, and many traffic road signs. Solar power is also becoming more common in powering residences and business. It has even been used for solar powered cars! The next few sections take a detailed look into residential and automotive applications, and some of the current issues with each application.

2.7.1 Powering a House Using Solar Power

There are many details to think about when powering a house using solar power. Figure 2-13 shows an illustration of a typical home PV system. The first consideration (besides the cost) is to make sure that the roof has the correct angle or orientation to take advantage of the sun's energy.

The system should be inclined to an angle to absorb the maximum amount of energy year-round. It may be advantageous to change the angle for morning, noon and night and summer and winter. One must make sure that the PV panels are not shaded by trees and buildings because if one of the cells are shaded, the power production may be reduced substantially (more than by the proportional amount that is shaded).

The solar system that is required is based upon the system size that is needed, and the monthly production. The average monthly sunlight levels for different geographical areas. It should be designed for the months that use the most energy. The system voltage can be designed by deciding how many modules to wire in series (recall that each cell has 2 volts from Section 2.5.2).

2.7.2 Solving Solar-Power Issues

When there is no sunlight during the day, energy needs to be used from energy storage. Electricity can be stored using fuel cells or batteries, or the PV system can be connected to the house to the utility grid, and use energy from it when necessary – and sell energy back to the grid when it is produced in excess. Batteries are commonly being used with traditional solar panels, but depending upon the battery chemistry, the shelf life varies, and batteries will have to be replaced frequently. They also contain acidic electrolytes, so you need a well-ventilated, non-metallic enclosure for them. A replacement for the batteries that are typically used with the PV systems are hydrogen fuel cells. Fuel cells will not have to be replaced frequently, and have a long shelf life. They also do not require special enclosures.

One other important aspect of a PV system is that the energy generated by the system is in the form of direct current (DC). The electricity supplied by the utility and the type used by the appliances in your house is alternating current (AC). Therefore, a device is needed to convert DC to AC. This device is called an inverter. Some PV systems already have an inverter built into them. More about AC and DC converters can be found in Chapter 7. There are also companies that are starting to make DC appliances that can work directly with photovoltaic systems without the use of an inverter.

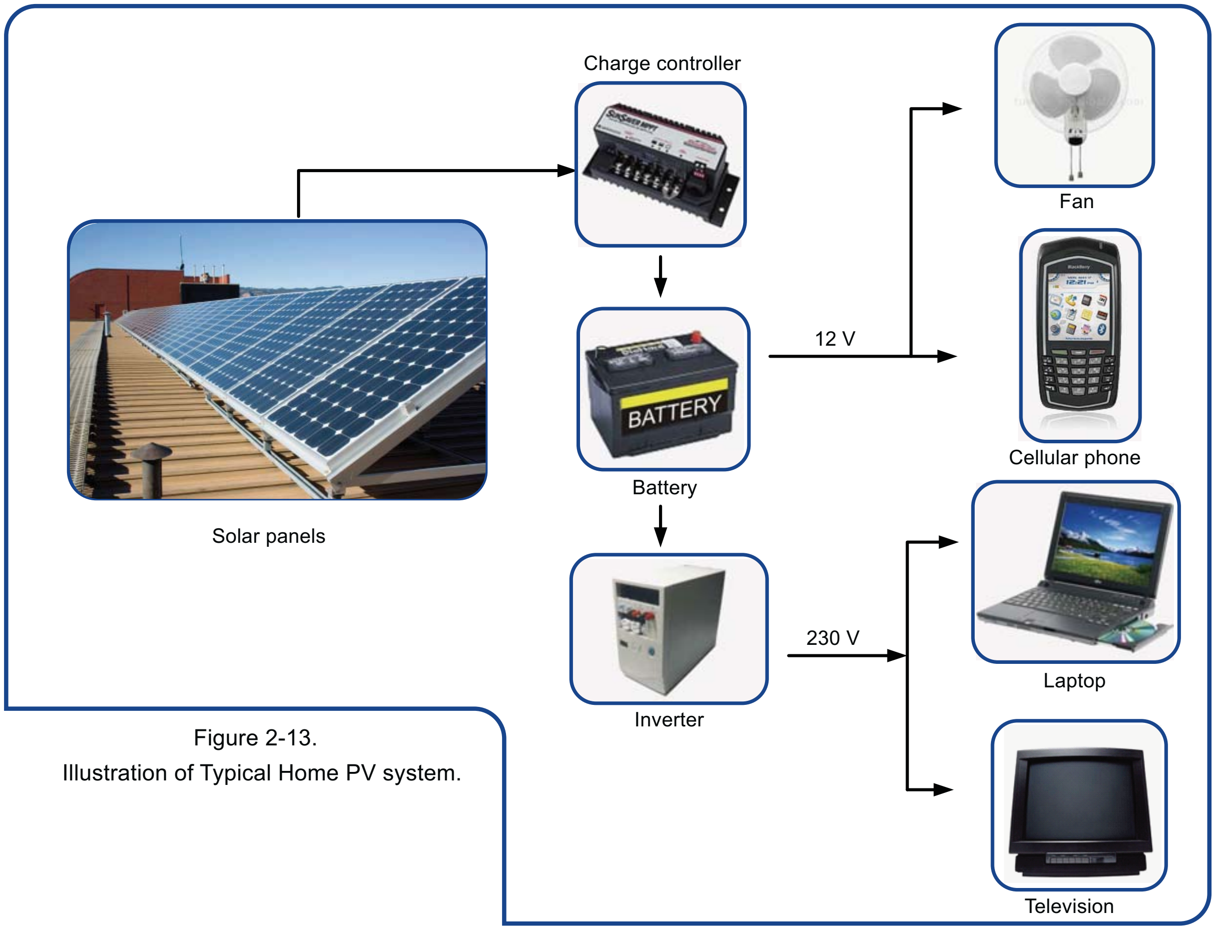


Figure 2-13.
Illustration of Typical Home PV system.

2.7.3 Solar Powered Cars

Wouldn't it be great if we could drive our cars without spending any money on fuel? There are solar powered cars that have successfully run for many miles. The electricity from the solar-powered car charges the battery. Some solar powered cars use the electricity to directly power the motor. There have been individuals that have been building their own models since the 1970s. A few major automotive makers (Ford and Mazda) have also done some research on solar powered cars. One interesting hybrid car model was displayed by the French car company, Venturi, at the 2006 Paris auto show. The Eclectic car combines solar, wind and battery power to provide electricity for a car made for city driving. This model was only engineered for city driving since it can only go up to 30 miles per hour (48 kph) [15]. The estimated price for the car is approximately $32,000 USD in 2007 [15]. Figures 2-14 and 2-15 illustrate the Venturi Eclectic car, and a solar-powered car at the Detroit Auto Show in the United States.

Solar cars that can travel 60 miles per hour (96 kph), and travel for hundreds of miles use very high quality solar cells. Achieving higher speeds is also dependent upon weight and aerodynamics of the solar race cars. These cars do not look beautiful – they are very flat, and can heat up very rapidly due to being covered in solar cells. When the sun is not out, the solar-powered car would require a battery or small gasoline engine as backup power.

Figure 2-15. A Solar Powered Car at the Detroit Auto Show.

Figure 2-14. The Venturi Eclectic.

2.8 Conclusions

This chapter briefly explained how solar power will be an essential part of the future renewable energy economy. The number of applications for solar power is endless. We already see many of these applications every day -- in calculators, street lamps, and many traffic road signs. It is beginning to become more common to power houses and businesses with solar energy. Solar panels are made up of many individual cells stacked together.

These cells are able to conduct electrons because they use semiconductor materials. Silicon is the most common type of semiconductor material used for PV cells. A few other common materials used are gallium arsenide, copper indium diselenide, and cadmium telluride. The two most popular types of PV systems on the market today are flat plate and concentrators. Flat plate systems consist of PV modules on a rigid and flat surface to capture sunlight, and concentrating PV systems use a specifically designed area of mirrors or lenses to focus the sunlight into a small area of cells. Solar systems will be essential part of the future hybrid energy system due to its proven ability to effectively use solar energy for power. Since solar energy can be intermittent, it would ideally be used with a system consisting of an electrolyzer, fuel cells, power electronics, and/or wind power. Chapters 3 – 7 cover these topics in more detail.

Chapter 3

Wind Energy

3.1 Introduction

3.2 History of Wind Power

3.3 Principles and Characteristics

3.4 Types of Wind Turbines

3.5 Parts of a Wind Turbine

3.6 Energy and Power in the Wind

3.7 Impact of Tower Height

3.8 Theoretical Potential of Wind Power

3.9 Simple Estimate of Wind Turbine Energy

3.10 Capacity Factor

3.11 Wind Farms

3.12 Conclusions

Figure 3-1. Wind power

3.1 Introduction

It is sometimes difficult to imagine that something that you cannot see can have enough movement to harness energy. Air is like any other fluid -- if it can be moved forcefully, the motion provides kinetic energy. In a wind-electric turbine, the turbine blades capture the kinetic energy of the wind. After the wind blade captures the wind energy, and starts moving, it spins a shaft which leads to a generator. In this way, rotational energy is turned into electrical energy. Wind power generates electricity by transferring energy from one medium to another. The typical wind power turbines are shown in Figure 3-1.

When air heats up, the hotter air quickly rises since a volume of hot air is lighter than an equal volume of cooler air. Hotter air particles exhibit a greater pressure than cooler particles; therefore, it takes fewer particles to maintain the same air pressure. When hot air rises, the cooler air flows into the spaces that the hot air leaves behind, and the air that rushes to fill the gap is called wind. Wind pushes on any object that is in its path, and in the process, transfers some of its own energy to the object. This is how a wind turbine captures energy from the wind. Figure 3-2 illustrates the air circulation due to temperature.

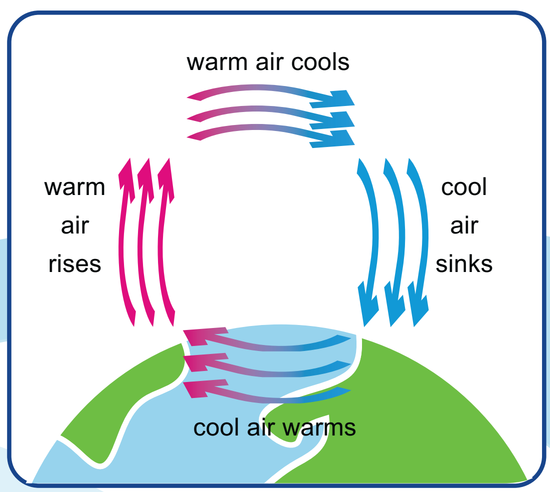


Figure 3-2. Air circulation due to temperature

3.2 History of Wind Power

Energy from wind has been used for power for at least 5,500 years for tasks such as pumping water, grinding grain, sailing ships, powering machinery and driving natural ventilation in buildings [17]. The Babylonian emperor, Hammurabi, planned to use wind power for his ambitious irrigation project in the 17th century BC.

In some smaller countries, such as Denmark, about 20 to 40 % (2007 figures) of the country's energy demand is met through the use of renewable wind energy [16]. This shows that wind is not just suited to power a rural house, but wind energy can power entire cities with the right design.

Hammurabi was the first king of the Babylonian empire. The Babylonian empire controlled all of Mesopotamia by winning a series of wars with neighboring kingdoms. Hammurabi is know for a set a laws called the Hammurabi Code. It was one of the first sets of written laws in recorded history. The laws were written in a stone tablet, which stood over six feet tall.

Evidence has been found that the ancient Sinhalese used the monsoon winds to power furnaces as early as 300 B.C. in cities such as Anuradhapura and Sri Lanka. Wind power was used to bring the furnace temperatures inside up to 1100 – 1200 °C [13, 16]. The first practical windmills were built in Sistan, Afghanistan in the 7th century. These were vertical axis windmills that had 6 – 12 sails covered in redd matting or cloth materials. Vertical axis windmills were used in the sugarcane and grist milling industries. Horizontal windmills were used in Northwestern Europe beginning in the 1180s, and many of these Dutch-style windmills still exist [13, 16]. Figure 3-3 shows an illustration of ancient windmills, and Figure 3-4 summarizes the important events related to the history of wind power.

Figure 3-3. Ancient Windmills

The development of the "water-pumping windmill" was a major factor in allowing the farming and ranching of vast areas of North America. A large part of North America did not have readily access to water during the 1800s. The water pumping windmill contributed to the expansion of rail transport systems throughout the world by pumping water to supply the needs of steam locomotives at the time.

An American named Charles F. Brush is credited as the first person to produce electricity using a wind-powered machine. He first used his wind turbine during the winter of 1887 [13, 16]. In 1891, a Scottish academic, Professor James Blyth, undertook similar experiments in the UK. His 33-foot (10 m) high, cloth-sailed wind turbine was installed in the garden of his holiday cottage in Scotland to power the lighting in the cottage. He also built a wind machine to supply emergency power to the local Lunatic Asylum, Infirmary, and Dispensary of Montrose – but the invention never really caught on because the technology was not considered to be economically viable [13, 16].

Dane Poul la Cour developed the first electrical output wind machine to incorporate aerodynamic design principles used in European tower mills in 1891. These mills were very practical for electricity generation, and had spread throughout Denmark. La Cour used the electricity generated by wind turbines to electrolyze water to produce hydrogen to power gas lights in the local schoolhouse. In this regard, we can say that he was 100 years ahead of his time because his vision included a system with solar and wind power system that made hydrogen by electrolysis to generate power. However, by the end of World War I, fossil fuel steam plants had put La Cour's mills out of business [14].

7th Century	First practical windmills were built in Sistan, Afganistan
1180s	Horizontal windmills were first used in North western Europe.
1887	Charles F. Brush was the first American to produce electricity using a wind turbine.
1891	Scottish professor, James Blyth, was the first person to produce electricity using a wind-powered machine. Dane Lacour also developed the first electrical output wind machine for European tower mills
Early 1900s	Hundreds of thousands of wind mills in Europe and the U.S.A. were used for rural areas not connected to the electricity grid.
1980s-Present	Wind turbine installations have been increasing worldwide,especially in Germany, Demark, Spain, the United States and India.

Figure 3-4. Brief history of wind turbine installations

By the early 1900s, hundreds of thousands of wind turbines were used in rural areas that were not connected to the electricity grid. The interest in wind systems declined as the utility grid expanded and became more reliable, and the price of the electricity declined. The oil shortages experienced in the 1970s increased awareness of the energy problems and created an increase in the awareness of wind power. During the next decade, wind turbines were installed worldwide, including many that were installed in California. The state of California initiated a tax credit which helped increase the popularity of wind power. But, by the mid-1980s, the tax credits were terminated, and this almost put an end to the wind power industry in the United States until the early 1990s.

The development of wind technology continued in Germany, Denmark and Spain. These countries were ready when sales began to increase again in the mid-1990s. Germany, Spain, the United States, Denmark, and India currently lead the world in generating electricity through wind power.

3.3 Principles and Characteristics

3.3.1 The Earth's Wind Systems

It is commonly known that the earth is tilted slightly along its axis, and that it travels around the sun. For this reason, different parts of the earth get different amounts of sun. The amount of wind a location receives varies from position to postion dependent upon its relative position to the sun. Due to the earth's tilt, different parts of the earth are warm and cold at various times throughout the year. This difference in heating results in a global atmospheric convection system, which stretches from the Earth's surface to the stratosphere. In the parts of the earth that are warm, the air is heated, and it rises toward the sky. Air moves because the earth is turning, and the earth's gravity keeps the warm air from flying into space. Most of the energy stored in the wind can be found at high altitudes where continuous wind speeds of over 160 km/h (100 mph) occur. The wind energy is eventually converted through friction into diffuse heat throughout the Earth's surface and atmosphere. Therefore, wind is actually stored up solar energy, and wind turbines capture this energy. An illustration of the global wind circulation is shown in Figure 3-5.

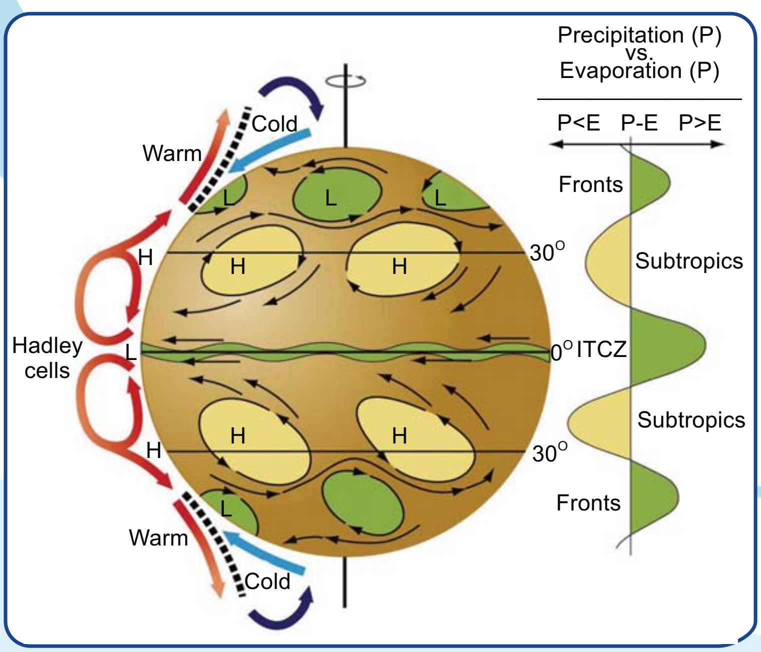


Figure 3-5.
Global Wind Circulation

Oceans, mountains and even buildings affect the wind patterns, but the major wind patterns develop and stay consistent because they are a result of temperature gradients. On weather maps, you will notice that there are regions of “high” and “low” pressure, and these regions are surrounded by contours. The contours represent lines of equal pressure as illustrated in Figure 3-6.

3.3.2 Aerodynamics of Wind Turbines

When a force is transferred from one object to another, the second object will move in the same direction as the first. However, when a solid object transfers force or energy to a liquid, the reaction is different. Two forces are created. They are drag and lift. “Drag” and “lift” forces act perpendicularly to each other. They depend upon the shape of the object, the directions of the movement, the density of the solid and fluid, and the velocities of each. In the case of wind turbines, the solid object is the blade, and the fluid is air [13, 16].

Drag force:
The force that occurs when an object is moving in-line with the fluid. This is the resistance of the object’s movement on the fluid. In order for an object to have less drag force, it needs to resist the fluid less, which means that it should allow the fluid to flow around it more easily. Airplane wing sections are designed to reduce the drag force as much as possible.

Lift force:
The force that propels an object upward, or at a right angle to the direction of the air stream.

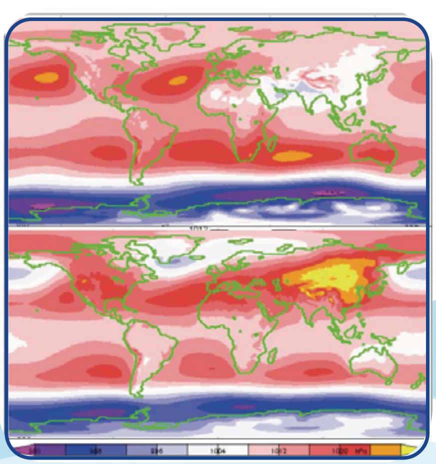


Figure 3-6. Weather map showing high and low pressures.

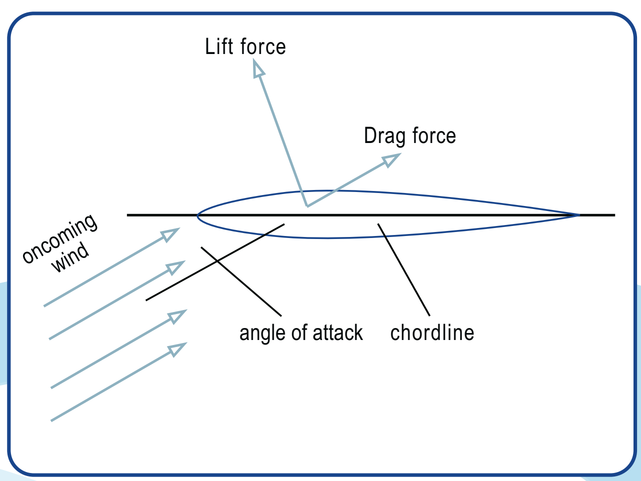


Figure 3-7 illustrates the concepts of lift and drag forces.

3.4 Types of Wind Turbines

Wind turbines are classified by the axis around which the turbines blades rotate. Most of the wind turbines are horizontal axis wind turbines (HAWT), but there are some blades that spin around a vertical axis (VAWT). Figure 3-8 illustrates the horizontal and vertical wind turbine configurations.

3.4.1 Horizontal Axis Wind Turbines

Horizontal wind turbines (HAWTs) consist of a main rotor shaft and electrical generator at the top of a tower. They typically have a gearbox, which turns a slower rotation into a faster one, which produces greater electricity. Turbine blades are usually very stiff to prevent the blades from being pushed into the tower, and are placed at a certain distance in front of the tower [13, 16, 17].

HAWTs can have any number of blades. The science behind modern wind turbines is based upon the understanding of aerodynamics, derived largely from aircraft wing and propeller design. HAWT's are, by far, the most common windmills used to generate electricity.

Figure 3-8. Horizontal and Vertical Wind Turbine Configurations

The optimal number of rotating blades varies on horizontal wind turbines. The multi-bladed, water-pumping windmill often seen on farms are for water pumping, and are designed differently than those designed for generating electricity. This windmill used for pumping water must provide high starting torque to overcome the weight and friction of the pumping rod that moves up and down in the well. They operate in low wind speeds to provide continuous water pumping. As the revolutions per minute (RPM) of the turbine increases, the turbulence from one blade affects the next one. Most Europ and cost of the turbine and three blades are also more difficult to hoist during construction or blade replacement [13, 16].

Figure 3-9. Types of HAWTs blades

Wind turbine blades are usually colored gray to blend in with the clouds, and can range in length from 20 to 40 meters. The steel wind towers range from 20 to 40 meters (200 to 300 feet). The blades typically rotate at 10 – 22 revolutions per minute [16, 17]. Some wind turbines operate at constant speed, but others can be collected by variable-speed turbines. All wind turbines have that automatically shut it down at very low or very high wind speeds.

3.4.2 Vertical Axis Wind Turbines

French engineer G. M. Darrieus first developed a vertical axis generator which had some commercial success in the 1920s. The shape of the blades make the vertical axis machine look like a vertical eggbeater. Sandia National Laboratories in the United States did considerable development of a 500 kW, 34 meter diameter machine vertical wind generator [13, 16].

Vertical axis wind turbines can harness winds from every direction without the need to reposition the rotor when the direction changes. The biggest advantage of the vertical axis turbine is that it did not need yaw control to keep it facing into the wind. Another advantage is that the many of the mechanical components are located near the ground where they can be serviced easily. In the vertical configuration, the tower does not need to be as strong as the HAWT because there is not heavy equipment perched on top of the tower. Vertical machines can also be lightweight because they do not have to handle the constant flexing associated with the blades on vertical axis machines. Using guy wires can further reduce the weight of the turbine.

The vertical configuration also has an advantage over the horizontal configuration because it allows the wind to control the yaw (left-right motion) so that it naturally orients itself correctly with respect to wind direction. When a blade swings behind a tower, it encounters a brief period of reduced wind which causes the blade to flex. The flexing reduces the power output; increases blade noise and can lead to blade failure due to fatigue [13, 16].

There are also several disadvantages of vertical axis turbines. One of the disadvantages is that the blades are closer to the ground, where the wind speed is lower. Winds closer to the ground are not only slower, but more turbulent – which increases stresses on VAWTs. Also, in low-speed winds, Darrieus rotors have very little starting torque, and the output power must be controlled to protect the generator.

3.5 Parts of a Wind Turbine

The principle behind wind turbines is very simple: the energy in the wind turns two or three blades around a rotor. The rotor is connected to the shaft, which spins a generator to create electricity.

Wind turbines are mounted on a tower to capture the energy from the wind. The higher the blades are, the more they can take advantage of faster and less turbulent wind. A simple wind turbine consists of three main parts, the blades, shaft and generator, as shown in Figure 3-10 and 3-11:

1) ***Blades***: The blade acts as barriers to the wind. When the wind forces the blade to move, some of the wind energy is transferred to the rotor.
2) ***Shaft:*** When the rotor spins, the shaft also spins, and transfers the mechanical energy into rotational energy.
3) ***Generator:*** A generator uses the difference in electrical charge (electromagnetic induction) to produce a change in voltage. Voltage is actually electrical pressure, the force that moves an electrical current. The voltage drives the electrical current (AC power) through power lines for distribution.

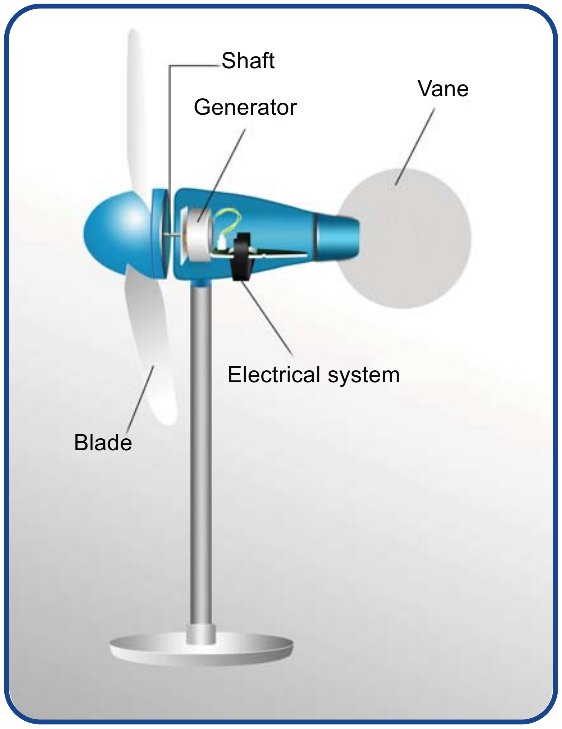


Figure 3-10. Basic parts of a wind turbine

Figure 3-11.
Typical components of a wind turbine
(the gearbox, rotor shaft and brake assembly).

The electricity generated from a wind farm is normally fed into an electric power transmission network. Individual turbines are interconnected to a power collections system and communications network. At a substation, the medium voltage electrical current produced from wind is increased in voltage with a transformer for connection to the high voltage transmission system. If there is any surplus power, it can often be sold back to the utility company to produce a credit for the customer to offset energy costs [13, 16].

3.6 Advanced Topic: Energy and Power in the Wind

If you have a particular mass, *m*, of air moving at speed, *V* , its kinetic energy (*KE*) can be expressed by a familiar relationship illustrated by Figure 3-12:

Kinetic energy = half of the mass x velocity squared

or

$$KE = \frac{1}{2} mV^2$$

where m is in kilograms, and V is in meters per second (m/s).

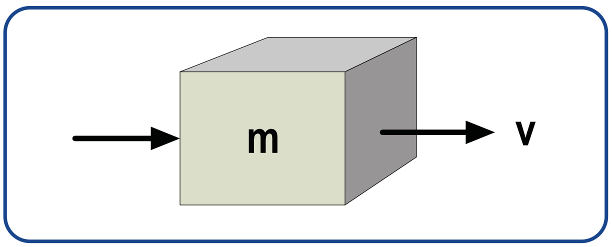


Figure 3-12. A mass of wind moving at a certain velocity.

By multiplying a volume of air by the density of air, ρ , (which is 1.2256 kg/m3), the mass of the air flowing through a volume per second can be expressed by [12]:

Mass of air per second (m) = air density x volume of air flowing per second

Figure 3-13 illustrates how power is the energy per unit time, and this can be represented by a mass of air moving at a velocity v through area A:

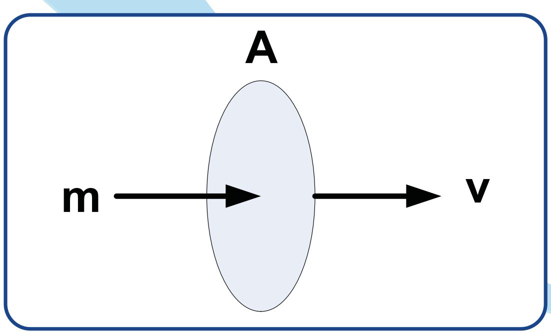


Figure 3-13.
Mass of air passing at a certain velocity through an enclosed area.

The mass flow rate, m , through area, A, is the product of air density, ρ, speed, *V*, and the cross-sectional area, A, can be expressed mathematically as [12]:

$$\frac{\text{Mass passing through A}}{\text{Time}} = m = \rho AV$$

Substituting for *m* in equation 3-3 above gives us an important relationship [13]:

$$P = \frac{1}{2} \rho AV^3$$

where P is the power in the wind (watts), ρ is the air density (kg/m3) (at 15 °C and 1 atm, ρ = 1.225 kg/m3); A is the cross-sectional area through which the wind passes (m^2); and v is the wind speed normal to A (m/s) (a useful conversion: 1 m/s = 2.237 miles per hour (mph)).

Wind power increases with the cube of wind speed – which means that doubling the wind increases the power by eightfold [13, 16]. Many wind turbines are automatically turned off in low-wind speeds. Equation 3-4 also indicates that wind power is proportional to the swept area of the turbine rotor and the blade diameter. Doubling the diameter increases the power available by a factor of four. The power obtained from a wind turbine is also related to the density of air. At higher elevations such as mountainous areas, the density is lower. The densities in cold climates are also 10 % higher than tropical regions. This helps to explain the economies of scale with larger wind turbines.

3.7 Impact of Tower Height

Since the power in the wind is proportional to the cube of the wind speed, even small increases in wind speed can be significant. One method of obtaining higher wind speed is to mount the turbine on a taller tower. In the first few hundred meters above the ground, the wind speed is affected by the friction that the air experiences as it moves across the earth's surface. Surfaces such as the sea offer much less resistance to the wind. In contrast, surface wind is slowed by buildings, forests and other structures.

3.8 Theoretical Potential of Wind Power

The potenial wind power available in the atmosphere is much greater than the current world energy consumption. The potential of wind power on land and near shore is about 72 terawatt (TW), which is equivalent to 54,000 million tons of oil equivalent per year, or five times the total world energy consumption [17]. This only takes into account locations with mean annual wind speeds ≥ 6.9 meters per second (m/s) at 80 meters [17]. It assumes that six 1.5 MW turbines per square kilometer is located on approximately 13% of the total global land area (this area would also have other uses such as farming) [16, 17].

3.8.1 Distribution of Wind Speed

The strength of the wind varies, and an average value for a location does not indicate alone how much wind can be produced there. To determine the wind speeds at a location, a probability distribution function is often fit to the observed data as shown in Figure 3-14. The wind speed distribution varies from location to location and time of the year.

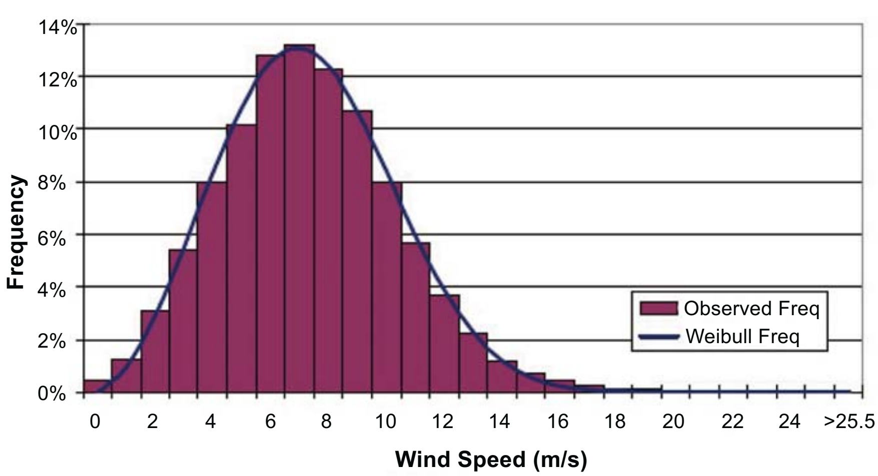


Figure 3-14 Wind speed probability distribution

Since power is generated by higher wind speed, energy may come in short bursts. Therefore, wind power does not have as a consistent an output as fuel-fired plants. Making wind power more consistent requires that existing technologies and methods be extended to link widely distributed wind farms together to take advantage of the resulting decrease in the average variability. Hybrid renewable energy systems (solar, fuel cell and electrolyzer systems) can also be designed to reduce periods of intermittant power.

If the mean annual wind speed at a site is known or can be estimated, a rough initial estimate of the vproduction can made from the following equation [12]:

Annual electricity production = KV^3 AT

Where K = 3.2, and is a factor based upon typical turbine performance characteristics, ***V*** is the site annual mean wind speed (m/s), ***A*** is the swept area of the turbine (m^2) and ***T*** is the number of turbines.

This formula should be used with caution because it is based upon the average characteristics of wind turbines available, and assumes an annual mean wind speed and frequency of wind speeds.

3.9 Simple Estimate of Wind Turbine Energy

The amount of energy in the wind that can be captured and turned into electricity depends upon many factors, such as, how the machine is built (rotor, generator, tower and controls), the terrain (topography, surface roughness and obstructions) and the wind regime (velocity, timing and predictability).

Predicing the potential output of a system depends upon whether one is comparing the production of various turbines to one another, or if the goal is to create an efficient wind farm. A few simple calculations can give a good energy estimate; however, more extensive wind turbine performance calculations are required to obtain a more precise estimates.

The power output of a wind turbine varies with wind speed, and every turbine has a wind speed power curve. An example wind speed power curve is shown in Figure 3-15.

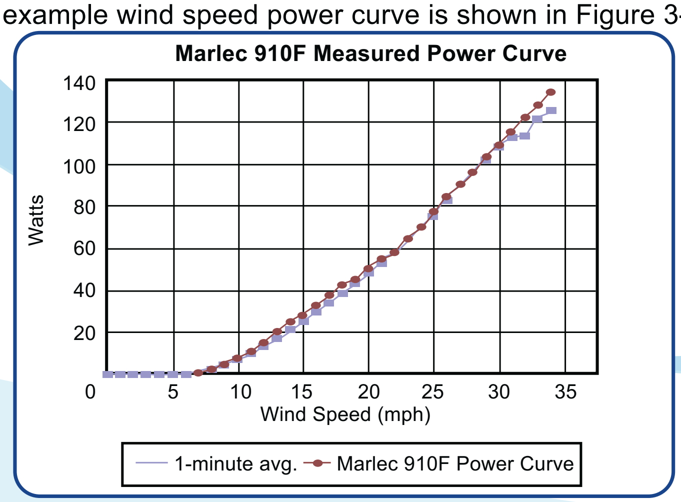


Figure 3-15. Typical wind speed power curve

3.10 Capacity Factor

It is not easy to estimate a wind farm's annual energy production, which is the sum of the wind turbine power ratings multiplied by the total hours in a year. The capacity factor is the ratio of the actual productivity in a year to the theoretical maximum, and is typically 20 - 40% [13, 16, 17]. The number of megawatt-hours (MWh) can be calculated from the following equation:

$$No.\ of\ MWh = CF \times No.\ hours \times No.\ days$$

For example, a 1 megawatt turbine with a capacity factor of 35% will not produce 8,760 megawatt-hours in a year (1x24x365), but only 0.35x24x365 = 3,066 MWh, averaging to 0.35 MW.

There is data available for specific global locations, and this data can be used to calculate annual output.

3.11 Wind Farms

In locations with high winds, multiple turbines can be installed in a wind farm, or wind park. The advantages of wind farms include reduced site development costs, centralized access, and easy connections to transmission lines. Figure 3-16 shows wind electrolysis being produced centrally or distributed at the point of use.

Wind turbines cannot be located too close together because they will interfere with the amount of wind received by those located downwind.

Downwind:
The wind is slowed as some of the energy is extracted by the rotor, which reduces the power available for wind machines downstream.

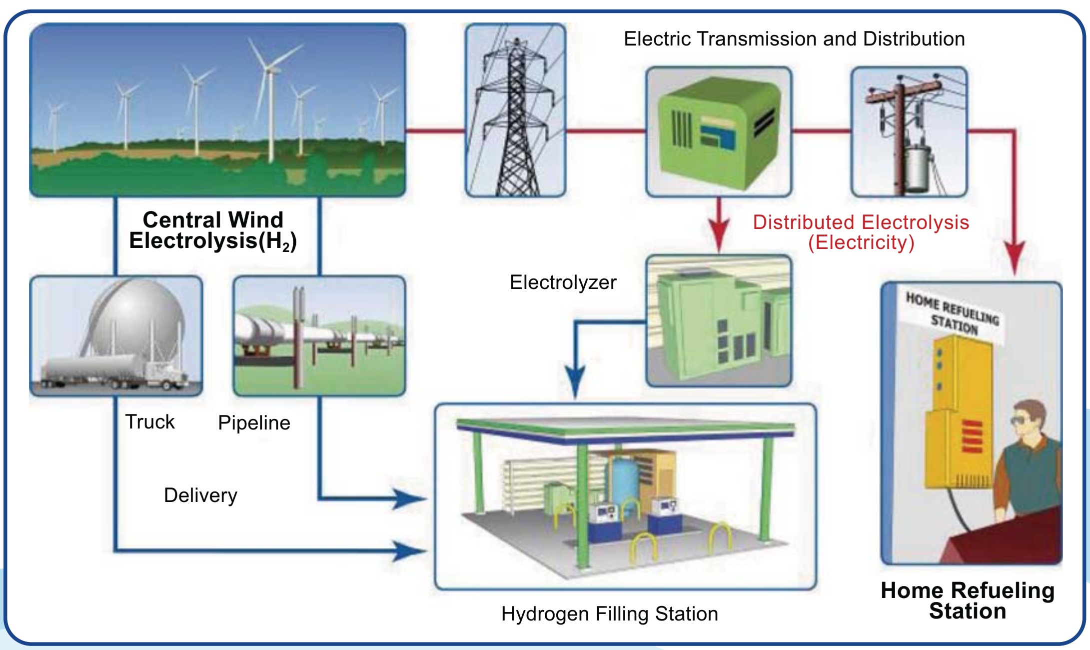


Figure 3-16. Examples of wind electrolysis being produced centrally or distributed

It is clear that wind energy is very advantageous for providing renewable energy, and it is targeted to be one of the largest contributors to providing energy in the future. Governments around the world have a strong interest in successfully developing wind energy as soon as possible.

3.12 Conclusions

This chapter briefly covered how wind power will be an essential part of the future renewable energy economy. Wind power harnesses the motion of the wind to provide kinetic energy. The three main parts of a wind turbine are the blades, shaft and generator. The kinetic energy of the wind is captured by the turbine blades when they start moving. The moving of the blades spins a shaft, which leads to a generator. The rotational energy is then turned into electrical energy. Wind turbines are classified by the axis around which the turbines blades rotate, and the two main types are horizontal axis (HAWT), and vertical axis (VAWT) wind turbines. Utility-scale (magewatt-sized) power can be obtained from vast wind farms, or by integrating a wind turbine with an electrolyzer and fuel cell as part of a hybrid energy system. Wind energy is very advantageous for providing renewable energy, and it is targeted to be one of the largest contributors to providing energy in the future.

Chapter 4

Electrolyzers

4.1 Introduction

Electrolyzers use electricity to break water into hydrogen and oxygen. The electrolysis of water is an electrochemical reaction that is a simple process that does not require moving parts. It is very reliable, and can produce ultra-pure hydrogen (> 99.999%) in a non-polluting manner when the electrical source is renewable energy. The hydrogen produced from an electrolyzer is perfect for use with hydrogen fuel cells (see Chapter 5 for more information about fuel cells). The reactions that take place in an electrolyzer are very similar to the reaction in fuel cells, except the reactions and the anode and cathode are reversed in a fuel cell, the anode is the place where the hydrogen gas is introduced, and in an electrolyzer, the hydrogen gas is created at the cathode. Hydrogen is the most abundant element in the universe, however, very little pure hydrogen exists naturally on earth. Hydrogen is the lightest element, and it is very useful because it is chemical energy with the potential to be transferred into electrical energy It can be obtained through many types of materials such as fossil fuels, biomass and water.

There are numerous processes currently used to create hydrogen; some of these include steam reforming, partial oxidation, coal gasification and the electrolysis of water. Most of these processes involve the use of fossil fuels, however many of these processes can also be used with fuels derived from plants and biomass.. Current technologies for producing hydrogen through electrolysisis about 75% energy efficient, and should be able to reach 90% in the future [11]. Approximately 39 kWh of electricity and 8.9 liters of water are required to produce 1 kg of hydrogen at 25 °C and 1 atm (atmospheres) [18].

Atmospheres:
An international reference pressure that is defined as 101,325 Pa. This unit of pressure has been replaced largely by the bar, which is equal to 100,000 Pa.

The biggest disadvantage of electrolysis of water as a source of hydrogen, is the requirement of electrical energy to complete the reaction. Electricity from the grid has to be transported through an expensive infrastructure of transmission and power distribution lines. Ideally, the electrical energy that is needed for the electrolysis reaction should come from renewable energy sources such as wind, solar and hydroelectric sources for it to be environmentally-friendly. In order to effectively achieve a hydrogen economy, one of the requirements is to produce hydrogen in a manner that does not generate carbon emission, and can be at a low enough cost to be competitive with other energy technologies. Many types of systems can be constructed with solar or wind power (or both) with the addition of power electronics. These systems usually contain an AC/DC or DC/DC power converter, power supply, system controller, radiator, control relays and DC disconnects if connected to a PV panel (see Chapter 7 for explanations of power electronics). There have been prototype hybrid systems that have been designed so that the capital costs of the system and the cost of the hydrogen produced are very low.

Electrolyzers would be very useful and ideal when incorporated into stationary, portable, and transportation power systems. Some examples of applications in which electrolyzers would be particularly advantageous are for soldiers, fuel cell–powered cars, boats, and portable electronics to generate a sufficient amounts of hydrogen before it is used. An electrolyzer can be a beneficial addition to a system that uses solar and wind power. Some energy obtained from the solar and wind turbines can be used to electrolyze water, and produce the hydrogen to be stored to power fuel cells when the solar and wind power is intermittent. Excess energy from solar power during the day can be used to produce hydrogen for nighttime use. Wind power is often produces the most energy in the middle of the night when winds are high, but when energy demand is relatively low. Excess wind power at night can be used to produce hydrogen to be used during the day when peak power requirements exist. There are currently many prototypes that generate electricity from the sunlight and hydrogen by electrolysis. There have been recent successes with this type of system, however, research and development needs to be continued to increase the efficiency and decrease the cost of these systems for integration into portable, transportation and stationary devices. Currently, the majority of electrolyzers are used to make hydrogen for applications other than fuel cells. Some of the advantages of using electrolyzers are [11]:

1. the hydrogen produced is very pure;
2. it can be produced directly at the location, and at the time at which it will be used and does not necessarily have to be stored;
3. it is a much cheaper method than gas supplied in high-pressure cylinders.

Figure 4-1 shows an illustration of an electrolyzer.

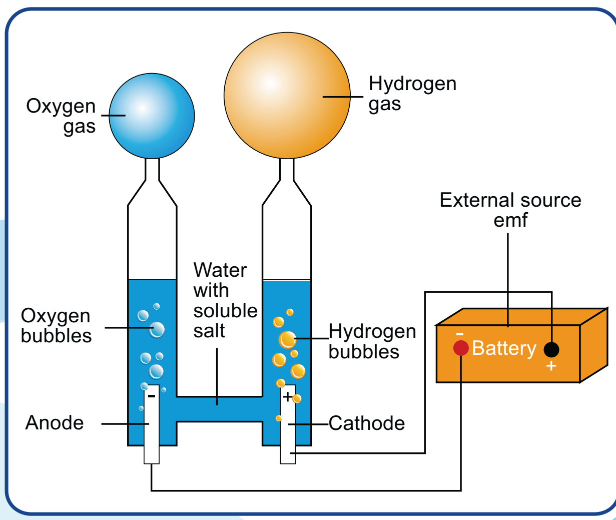


Figure 4-1. Illustration of an electrolyzer.

There are more than enough solar and wind natural resources globally to produce all the hydrogen needed for stationary, transportation and portable applications. Electrolysis has the potential to meet the cost requirements specified by many governments around the world. There are market opportunities today for utilities to start gaining experience in hydrogen production to position themselves as transportation fuel providers of the future. Several utilities are currently conducting research into the integration and optimization of these technologies with the electric power grid.

The Renewable Energy Education Set offers a model of solar/hydrogen and wind/hydrogen systems.

4.2 History of Electrolyzers

The history of electrolyzers and fuel cells are very similar because the basic principals and characteristics are the same. Electrolysis began its history in the 1800s, and continued to be researched throughout the 1900s and into the 21st century. More intense research on electrolyzers has occurred during the past twenty years. Chapter 5 gives further details on the history of the science behind both electrolysis and fuel cells. The most important scientists in the history of electrolysis are William Nicholson and Anthony Carlisle. They first described the process of using electricity to break water into hydrogen and oxygen in 1800 [11]. Nicholson and Carlisle used platinum electrodes and glass tubes to collect the gases at each electrode. The hydrogen bubbled from one electrode, and oxygen from the other in a ratio of two volumes of hydrogen for each volume of oxygen [18]. An illustration of the process of electrolysis first discovered by Nicholson and Carlisle is shown in Figure 4-2.

Nicholson and Carlisle:
First described the process of using electricity to break water into hydrogen and oxygen in 1800.

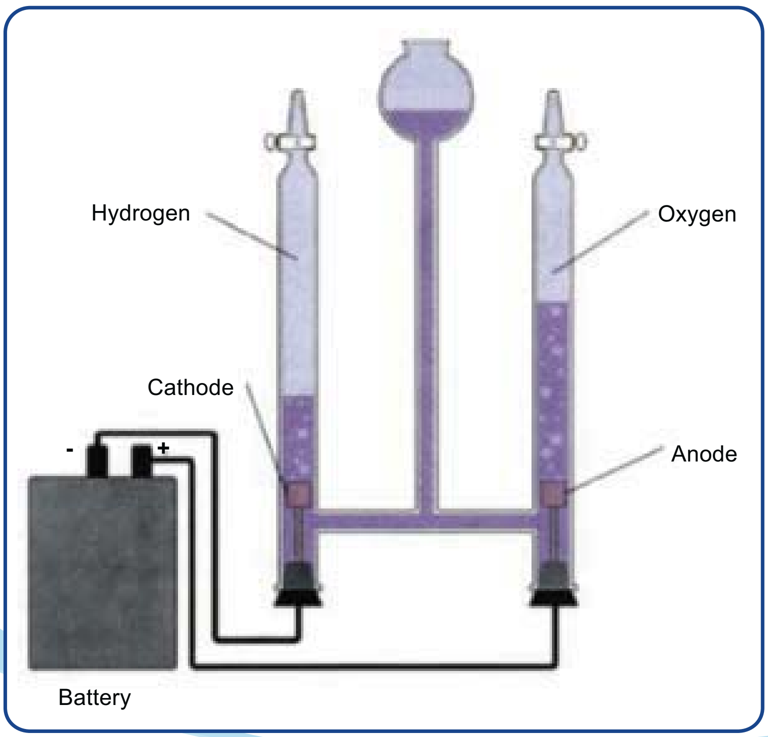


Figure 4-2. The process of electrolysis

William Nicholson

William Nicholson was an English chemist who was the first individual to produce a chemical reaction by electricity. Nicholson had many professions, including inventor, engineer, translator and scientific publicist. After he heard about an invention called the electric battery by Italian physicist, Alessandro Volta, he tried to replicate the experiment by placing battery leads in water. Bubbles began accumulating on the submerged ends of the wires, which ultimately lead to the discovery of electrolysis.

4.3 Types of Electrolyzer Designs

Electrolyzers can be divided into two main designs: unipolar and bipolar. The unipolar design typically uses liquid electrolyte, and the bipolar design uses a solid polymer electrolyte. More details about these electrolyzer designs are given in Sections 4.3.1 and 4.3.2.

4.3.1 Unipolar Design

The first electrolyzers used a unipolar design. An example of a simple unipolar design is illustrated in Figure 4-3. The electrodes, anodes and cathodes are suspended in a tank filled with a 20 – 30 % electrolyte solution. Each cell is connected in parallel, and operated at 1.9 – 2.5 V [18]. This design is easy to make and repair, but is not as efficient as more modern designs.

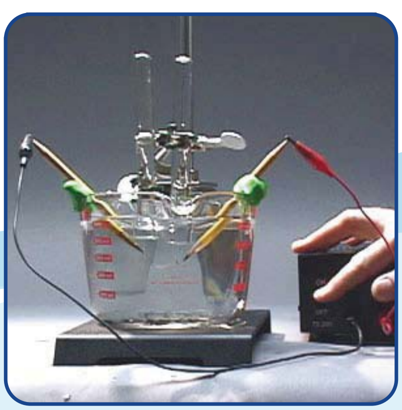


Figure 4-3.
An example of an unipolar electrolyzer

4.3.2 Bipolar Design

The bipolar design has many layers that are clamped together as shown in Figure 4-4. The cells are connected in series, which results in higher stack voltages. This stack can be small since the layers are very thin. Some advantages to the bipolar design are higher current densities, and the production of higher pressure hydrogen gas. Historically, an asbestos layer was used to separate the cells, but new polymer materials such as Ryton® has replaced this [18].

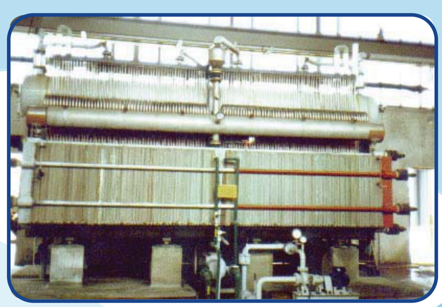


Figure 4-4.
Bipolar electrolyzer

4.4 Types of Electrolyzers

Electrolyzers can be divided into two main types: the alkaline and the polymer exchange membrane (PEM)-based electrolyzer. These electrolyzer types are based upon the electrolyte that each electrolyzer has. The alkaline type uses liquid electrolyte, and the PEM-based electrolyzer uses a solid polymer electrolyte. The construction of an electrolyzer is very similar to a battery or fuel cell. It consists of an anode, a cathode and an electrolyte. At the negative electrode, the protons are removed from the electrolyte, and electrons are provided by the external electrical supply. Sections 4.1.2 and 4.1.3 provide more detail on the alkaline and PEM-based electrolyzer types.

4.4.1 Alkaline Electrolyzer

Alkaline electrolyzers usually use an aqueous potassium hydroxide (KOH) solution as the electrolyte. Other frequently used electrolytes include sulfuric acid (H_2SO4), potassium hydroxide (KOH), sodium chloride (NaCl) and sodium hydroxide (NaOH) [11, 18]. The typical concentration for an electrolyzing solution is 20 – 30 **weigh**t % because the solution strength provides a balance between optimal **conductivity** and **corrosion resistance**.

Weight percent:
The mass of any solid particles in a solution (these may not be visible to the naked eye) divided by the mass of the solution (any solid particles plus the liquid). This ratio must then be multiplied by 100 to change it to a percent.

Conductivity:
A measure of a material's ability to conduct an electric current. If there is a difference in electrical charge in a material, the charges flow through the material to try to get the material back to a neutral state. This creates an electric current.

Corrosion resistance:
The ability of a material to resist the breaking down of its properties due to the chemical reactions with its surroundings.

Alkaline electrolyzers work well at operating temperatures between 25 – 100 °C and pressures of 1 – 30 bar respectively [18]. Commerical alkaline electrolyzers are run with current densities in the range of 100 - 400 mA/cm2 [18, 19]. The chemical reactions for the alkaline electrolyzer are:

Anode: $4H_2O + 4e- 2H_2 + 4OH-$

Cathode: $4OH- O_2 + 4e- + 2H_2O$

Overall: $2H_2O\ 2H_2 + O_2$

The overall construction of an alkaline electrolyzer is very simple. It typically has a unipolar design, which means that it consists of two metal electrodes suspended in an aqueous electrolyte solution. When electricity is supplied to the electrodes, hydrogen and oxygen gas will appear on each electrode. The electrolyzer must be designed so that each gas can be collected and removed from the electrolyzer efficiently. The designer must insure that the gases are unable to mix, because in the presence of a spark, a hydrogen and oxygen mixture is potentially flammable. Figure 4-2 and 4-3 illustrate examples of how an alkaline electrolyzer could be constructed.

4.4.2 (PEM) Based Electrolyzer

The polymer electrolyte membrane (PEM)-based electrolyzer is very popular, and many modern electrolyzers are built with PEM technology. The PEM electrolyzer uses the same type of electrolyte that is used for a PEM fuel cell. The electrolyte is a thin, solid ion-conducting membrane is used instead of the aqueous solution. These electrolyzers use a bipolar design, and can be made to operate at high differential pressures across the membrane. The reactions are as follows:

Anode: $4H^+ + 4e^- \rightarrow 2H_2$

Cathode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Overall: $2H_2O\ (l) + 4H^+ + 4e^- \rightarrow 2H_2\ O_2 + 4H^+ + 4e^-$

Equation 4-7 illustrates why the rate of production is twice that of oxygen during the electrolysis of water. The basic structure of a PEM-based electrolyzer is shown in Figure 4-5.

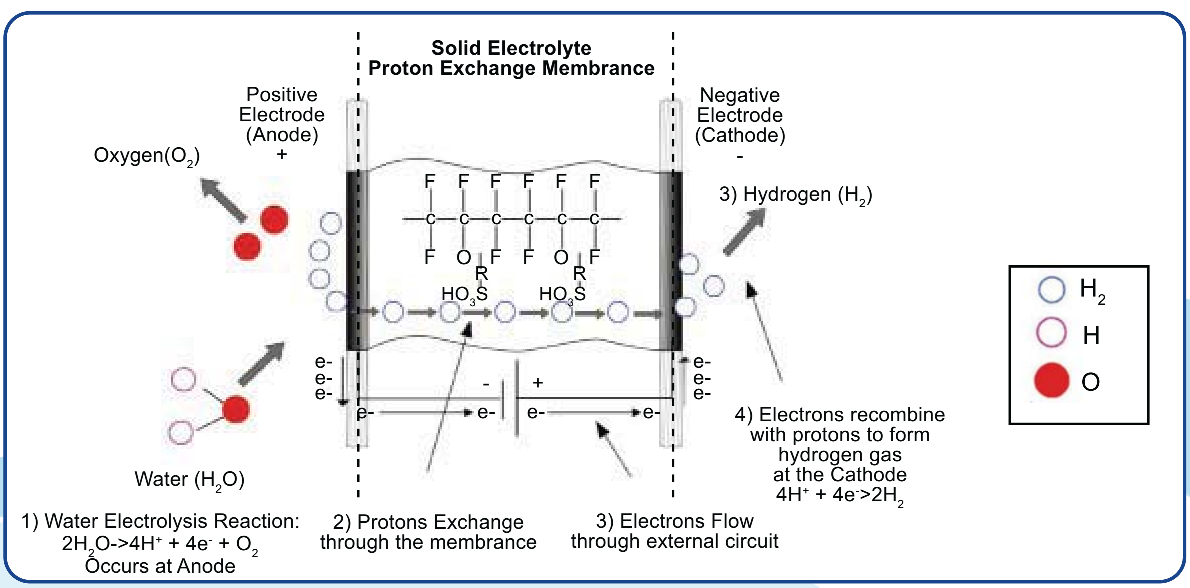


Figure 4-5. A simplified diagram of the PEM electrolyzer [11]

4.4.2.1 Electrolyte

In the PEM-based electrolyzer, the polymer membrane allows the H+ ion to transfer from the anode side of the membrane to the cathode side, and separates the hydrogen and oxygen gases. The hydrogen is produced at the anode, and oxygen is produced at the cathode. The most commonly used membrane material is Nafion® from DuPont. A platinum catalyst is applied to either side of the membrane to efficiently split the water molecule into hydrogen and oxygen.

4.4.2.2 Catalysts

In order to convert electrical energy into chemical energy, catalysts are needed to split the water into hydrogen and oxygen. Platinum (Pt) is the most commonly used catalyst for the reaction. An inexpensive catalyst would be ideal for the reaction, however, a less expensive one that works as well as Pt has not been found yet. If less effective catalysts are used for the cathode, then there will be greater voltage losses. The energy efficiency of water electrolysis is reported to be between 50 – 80 %, but these values only refer to the efficiency of converting electrical energy to chemical energy.

4.5 Electrolyzer Efficiency

There are many factors that influence the performance of electrolyzers. Some of these include the overall design, the materials used, and the operating temperature and pressure. Operating at higher temperatures will increase the efficiency, but will also increase the corrosion rate of the electrolyzer materials. High operating temperatures also mean that more expensive materials and equipment may be necessary. Higher pressures also increase the efficiency of the electrolyzer, but also mean additional equipment such as gas compressors.

Gas Compressor:
A mechanical device that increases the pressure of a gas by decreasing its volume.

The stack efficiency is calculated using the power losses due to the electricity needed for the pumps, valves, sensors and controller, and the amount of energy put into the stack. The system efficiency uses the higher heating value of hydrogen (HHV = 39 kWh/kg), the energy consumed by the stack (kWh), efficiency of the DC power 8.

Ancillary losses :
Power losses due to the electricity needed for pumps, valves, sensors, controllers and other mechanical and electrical devices that help distribute liquids and gases, and control the system.

The higher heating value (HHV) :
A property of a fuel that specifies the amount of heat released by a apecified quantity (initially at 25 °C) once it is combusted, and the products have returned to a temperature of 25 °C.

The stack efficiency (Equation 4-9) is determined by calculating the ideal cell potential at an operating temperature and pressure, multiplied by the number of cells in the stack, divided by the measured stack voltage [18].

$$\textit{System efficiency} = \frac{\textit{HHV}}{\dfrac{\left(\dfrac{\textit{Stack input energy}}{\textit{Power supply efficiency}}\right) + \textit{Ancillary losses}}{\textit{Hydrogen produced}}}$$

$$\textit{Stack efficiency} = \frac{\textit{Ideal stack potential}}{\textit{Actual stack potential}}$$

4.6 Advanced Topic: The Basics of Thermodynamics of Electrolyzer Design

Thermodynamics is the study of energy changing from one form to another. Thermodynamic equations allow predictions to be made to an electrolyzer or fuel cell system. Studying these concepts allows a scientist or engineer to predict states of the fuel cell system, such as voltage, temperature, pressure, and amounts of hydrogen, oxygen, water in an electrolyzer or fuel cell system.

Some concepts that need to be defined for the thermodynamic analysis of these systems are: absolute enthalpy, specific heat, entropy and Gibbs free energy. These can be defined as follows [19]:

Absolute enthalpy:

Absolute enthalpy includes both chemical and sensible thermal energy. Chemical energy or the enthalpy of formation (hf) is associated with the energy of the chemical bonds, and sensible thermal energy (Δhs) is the enthalpy difference between the given and reference state.

Specific heat:

Specific heat is a measure of the amount of heat energy required to increase the temperature of a substance by 1 ºC (or another temperature interval).

Entropy:

Entropy is another important concept, which is a measure of the quantity of heat that shows the possibility of conversion into work.

Gibbs free energy:

Gibbs free energy is the amount of useful work that can be obtained from an isothermal, isobaric system when the system changes from one set of steady-state conditions to another.

The maximum fuel cell performance is then examined through the ideal (reversible) voltage of the system, which is calculated using thermodynamics.

Net output voltage:
The reversible cell potential minus the irreversible potential at a certain current density. The irreversible potential is the actual voltage

The net output voltage can be expressed mathematically as: $V = V_{rev} - V_{irrev}$

Where $V_{rev} = E_r$ is the maximum (reversible) voltage of the fuel cell, and V_{irrev} is the irreversible voltage loss (overpotential) occurring at the cell. These losses in voltage will be explained in more detail in the next few paragraphs.

The actual voltage of a fuel cell is lower than the theoretical model due to reaction, charge and mass transfer losses. As shown in Figure 4-6, the performance of a electrolyzer or fuel cell can be illustrated using a polarization curve that can be broken into three sections: (1) activation losses, (2) ohmic losses, and (3) mass transport losses. Therefore, the operating voltage of the cell can be represented as the departure from ideal voltage caused by these three losses (polarizations) [10]:

$$V = E_r + V_{act} + V_{ohmic} + V_{conc}$$

Where V is the cell potential, E is the thermodynamic potential or Nernst voltage, V_{act} is the voltage loss due to activation polarization, V_{ohmic} is the voltage loss due to ohmic polarization and V_{conc} is the voltage losses due to concentration polarization. The explanation of the terms in Equation 4-11 and Figure 4-6 stems from the detailed study of different disciplines. The Nernst (ideal thermodynamic) voltage comes from the study of thermodynamics, activation losses are described by electrochemistry, charge transport examines ohmic losses and concentration losses can be explained by mass transport (which is usually studied in advanced college programs such as chemistry, physics or chemical engineering). Activation and concentration polarization occurs at both the anode and cathode, while the ohmic polarization represents resistive losses throughout the fuel cell. More advanced study of these concepts can be found in several fuel cell textbooks.

Resistive losses:
Losses due to electrons not transfering between materials and terminals.

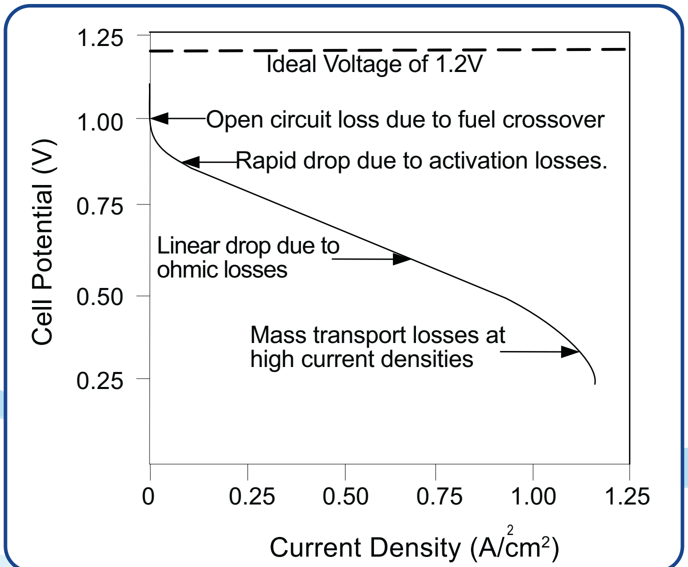


Figure 4-6.
Hydrogen–oxygen polarization curve at equilibrium [10]

Activation losses mainly occur when the electrochemical reactions are slow to produce current. As the PEM fuel cell produces more current, the activation losses increase at a slower rate than the ohmic losses.

Ohmic losses are due to the movement of charges from the electrode where they are produced, to the load where they are consumed. The two major types of charged particles are electrons and ions, and both electronic and ionic losses occur in the fuel cell. The electronic loss between the bipolar, cooling and contact plates are due to the degree of contact that the plates make with each other. The ionic charge losses occur in the fuel cell membrane when H+ ions travel through the electrolyte.

Concentration losses are due to reactants not being able to reach the electro-catalytic sites, which can significantly affect device performance. These mass transport losses can be minimized by making sure that the right amount of hydrogen, air and water travel through the flow field plates, gas diffusion layer and catalyst layers.

4.7 Current Hydrogen Production and Market

According to the U.S. Department of Energy, about 48% of hydrogen is currently produced from natural gas, 30% from oil, and 18% from coal worldwide. The remaining 4% is produced from water. In the United States, approximately 95% of the hydrogen produced is from natural gas [1]. Figure 4-7 shows the global hydrogen production by process.

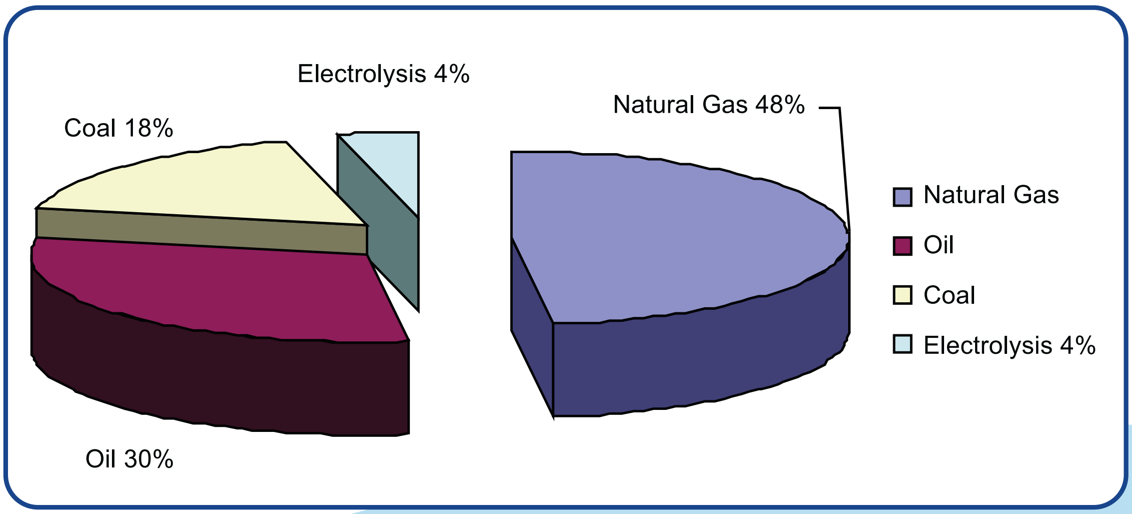


Figure 4-7. Global hydrogen production by process

Most of the hydrogen produced globally is made by steam methane reforming (SMR). The production of hydrogen by electrolysis is not as economically competitive with SMR, but it is currently positioned to become competitive with SMR because of the inevitable price increase of natural gas and the increased interest in environmental and political factors.

SMR, like the hydrogen production from fossil fuels, is limited in quantity, and also produces greenhouse gas emissions. The reforming process creates both CO_2 and carbon monoxide (CO). If millions of combustion engines are powered using hydrogen generated from SMR, a lot of greenhouse gas pollutants will still be emitted from the factories

About 4 % of the world's hydrogen is produced using electrolysis. Most of it is produced as a side product during the electrolysis of brine in the production of chlorine.

$$2\ NaCl + 2\ H_2O \rightarrow Cl_2 + H_2 + 2\ NaOH$$

In this reaction, hydrogen is produced at one electrode, and chlorine ions are produced at the other electrode. The hydrogen created from this process is either burned, used for specialty chemicals or other small-scale applications.

The current market for hydrogen is divided into two segments – users who use it at a location, and users that have it delivered to the location where it needs to be used. The market for hydrogen includes chemical producers, refineries, fat and oil hydrogenation and metal production. A smaller portion of the market includes electronics manufacturers, and public utilities. Table 4-1 lists the current applications for hydrogen [18].

Hydrogen Application	Uses
Chemicals	Ammonia and Fertilizer Manufacturing, Synthesis of Methanol
Fuels	Petroleum Refining, Rocket Fuel, Fuel Cells
Electronics	Polysilicon Production, Fiber Optics
Metals	Annealing, Heat Treating

Table 4-1. Current Hydrogen Applications

The future market for hydrogen is much larger. Electrolysis will become a viable option for competition in the hydrogen market as the price of natural gas increases. If hydrogen is going to be used as the preferred transportation fuel, the environmental gains by transitioning to a hydrogen economy can only be realized when renewable energy sources are used to produce an increasing amount of hydrogen gas. Electrolyte hydrogen production offers a more stable and secure energy future over oil.

4.8 Opportunities for Electrolysis

Integrating electrolyzers with a renewable energy system creates unique opportunities for providing power in the future. Renewable energy systems can connect to the utility grid through power electronics. The power electronics convert the alternating current (AC) from the grid to direct current (DC) power required by the electrolysis cell stack. Both PV and wind energy systems can be used as an electricity source. In many of the wind/electrolyzer systems used today for producing hydrogen, the electrolyzer uses the AC from the wind turbine directly.

There are many research and development projects that are being conducted globally that analyze and compare hydrogen production from solar and wind power and the electric grid. In these studies, the hydrogen is produced through electrolysis, and then compressed, and stored, to power an engine during periods with higher energy requirements. These projects will explore the coproduction of electricity and hydrogen to address the intermittent nature of solar and wind power, to create electricity when the energy demand is high. These studies also include the potential use of hydrogen for vehicle use. These research projects are studying multiple electrolyzer technologies; their abilities to be brought on- and off-line quickly; and the development of AC−DC and DC−DC converters to use the solar wind turbine to the electrolyzer to achieve efficiency gains. Figure 4-8 shows a diagram of one such project that is currently being conducted by the National Renewable Energy Laboratory (NREL) and Xcel Energy.

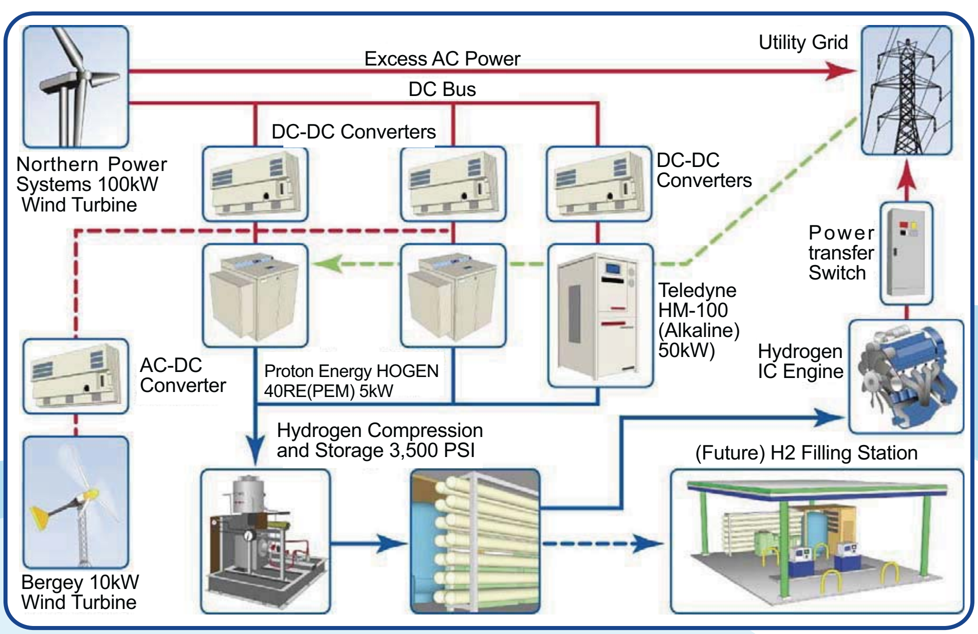


Figure 4-8. Xcel-NREL Wind2H_2 project diagram

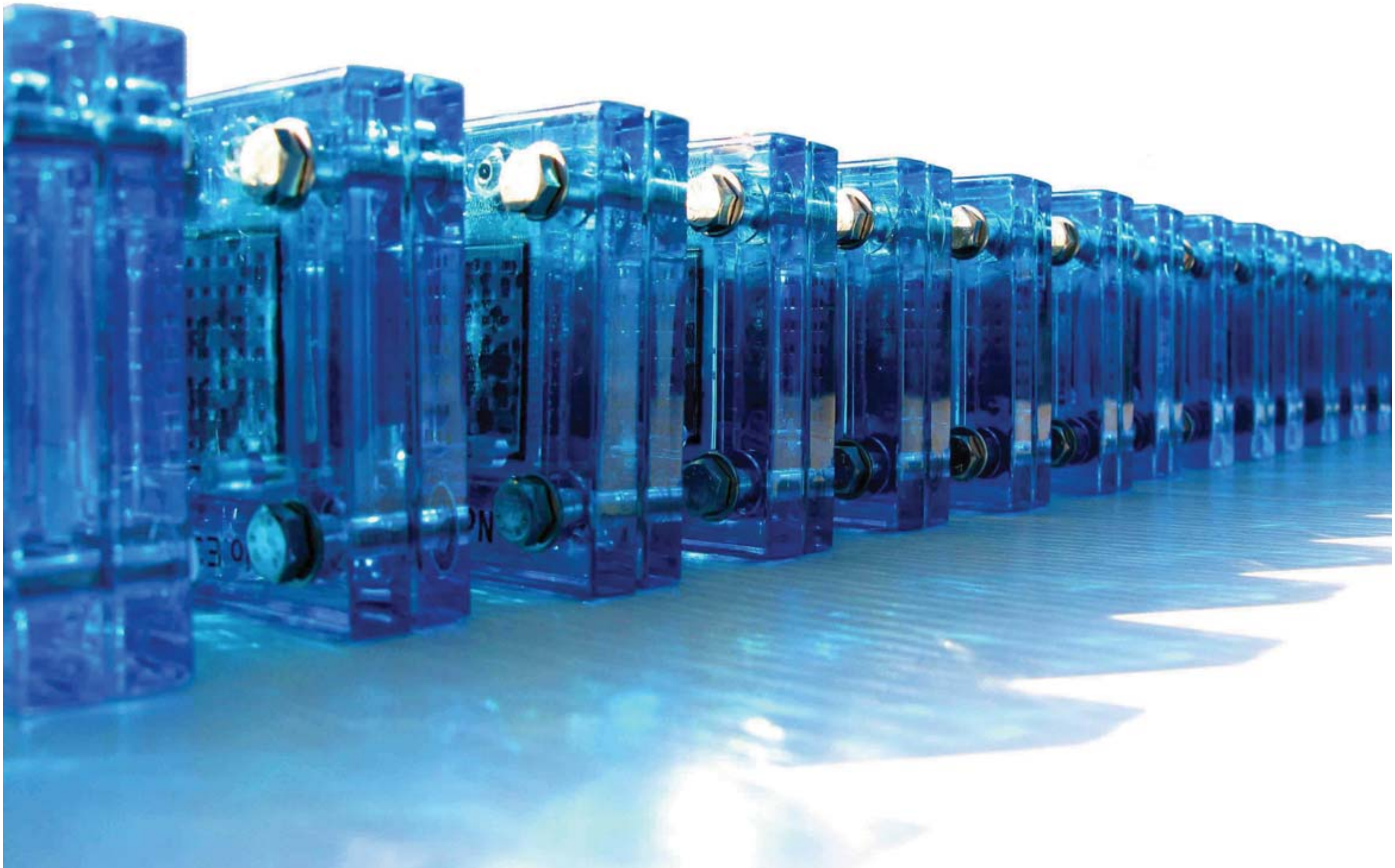
Chapter 4

Electrolysis can help to reduce the intermittent electricity production from renewable resources. Hydrogen systems can make hydrogen, and store it for later use – which can improve the capacity factor of renewable energy systems. This would help to make renewable energy constant, or this can be used for peak periods. By allowing the coproduction of hydrogen and electricity, the utility could optimize its production and storage system. Both solar and wind systems can benefit from producing electricity along with hydrogen. Some studies have shown that systems that are optimized for hydrogen and electricity generation have lower hydrogen prices – even when electricity is sold at a very low price.

Renewable energy systems that unitize electrolysis can be made cheaper by integrating the power electronics, or using the wind towers as storage tanks. Electric utilities can also use hydrogen on-site for generator cooling, which can be produced cheaply from their power plant. One of the main uses of hydrogen would be for transportation fuels. All transportation needs can be met with hydrogen produced from clean energy sources. This would help countries around the world to increase energy independence and reduce carbon and pollution levels. The current transportation market is much larger than the current electricity market. There are more than enough opportunities today to produce all of the hydrogen needed from wind and solar resources.

4.9 Conclusions

Electrolysis uses electricity to break water into hydrogen and oxygen. This process can produce ultra-pure hydrogen (> 99.999%) in a non-polluting manner when the electrical source is renewable energy. The hydrogen can also be produced directly at any location, at the time that it is needed, therefore, it does not necessarily have to be stored. This is the ideal method of producing hydrogen for hydrogen fuel cells. If this system is designed properly, it can be a much cheaper method than gas supplied in high-pressure cylinders. Electrolyzers would be very useful if they are integrated into a stationary, portable or transportation power systems to generate hydrogen. It would also be a useful addition to a system that uses solar and wind power because hydrogen can be used to power fuel cells when the solar and wind power is intermittent. In the future renewable energy economy, electrolysis can be used in conjunction with the hydrogen needed from wind and solar resources.



Chapter 5

Fuel Cells

5.1 Introduction

Fuel cells will be an integral part of the future hydrogen economy. Fuel cells have the ability to fulfill all of our global power needs while being highly efficient and a low-polluting technology. There are six main types of fuel cells. The type most commonly used for transportation and portable applications is the polymer electrolyte membrane (PEM) fuel cell. PEM fuel cells predominantly use hydrogen as the fuel, but also have the ability to use other types of fuel as well – including ethanol and biomass-derived materials. PEM fuel cells operate at temperatures between 20º and 80 ºC, which enable a startup time comparable to the internal combustion engine. PEM fuel cells are able to obtain net power densities of over 1 kW/liter, which makes them competitive with the internal combustion engine for transportation applications. There are numerous advantages and challenges for PEM fuel cells. Some advantages include:

- Fuel cells have the potential for a high operating efficiency.
- There are many types of fuel sources and methods of supplying fuel to a fuel cell.
- Fuel cells have a highly scalable design.
- Fuel cells produce no pollutants.
- Fuel cells are low maintenance because they have no moving parts.
- Fuel cells do not need to be recharged, and they provide power instantly when supplied with fuel.

Some limitations common to all fuel cell systems include the following:

- Fuel cells are costly due to the need for materials with very specific properties. There is an issue with finding low-cost replacements.
- Fuel reformation technology can be expensive, heavy and requires power in order to run.
- If another fuel besides hydrogen is fed into the fuel cell, the performance gradually decreases over time due to catalyst degradation and electrolyte poisoning.

This chapter covers the history of fuel cells, the principals and characteristics, types, and descriptions of fuel cell components in greater detail.

5.2 History of Fuel Cells

William Grove is credited with inventing the first fuel cell in 1839. Fuel cells were not researched greatly during the 1800s, and much of the 1900s. Extensive fuel cell research began during the 1960s at NASA. During the last decade, fuel cells have been extensively researched, and are finally nearing commercialization. Figure 5-1 summarizes the history of fuel cells.

1800	W. Nicholson & A. Carlisle described the process of using electricity to break water.
1836	Willam Grove fuel cell demonstration.
1889	Separate teams: L. Mond & C. Wright & C. Thompson/ L. Cailleteon & L. Colardeau performed various fuel cell expeiments.
1893	F.ostwald describes roles of fuel cell components.
1896	W. Jaccques constructed a carbon battery.
Early 1900's	E. Baur and students conducted experiments on high temperature devices.
1960s	T. Grubb & L. Niedrach invented PEMFC technology at GE.
1990s-Present	Worldwide extensive fuel cell research on all fuel cell types.

Figure 5-1. The history of fuel cells

William Grove

Known as the Father of Fuel Cells, Grove developed the first cell which furthered fuel cell technology by reversing the electrolysis process in Oxford, England in 1839.

William Nicholson and Anthony Carlisle first described electrolysis in 1800.

The process of using electricity to break water into hydrogen and oxygen (electrolysis) was first described in 1800 by William Nicholson and Anthony Carlisle. William Grove invented the first fuel cell in 1839, but using the idea from Nicholson and Carlisle to "recompose water."He accomplished this by combining electrodes in a series circuit with separate platinum electrodes in oxygen and hydrogen submerged in a dilute sulfuric acid electrolyte solution. The gas battery, or "Grove cell" generated 12 amps of current at about 1.8 volts [10]. Figure 5-2 shows an illustration of Grove's fuel cell.

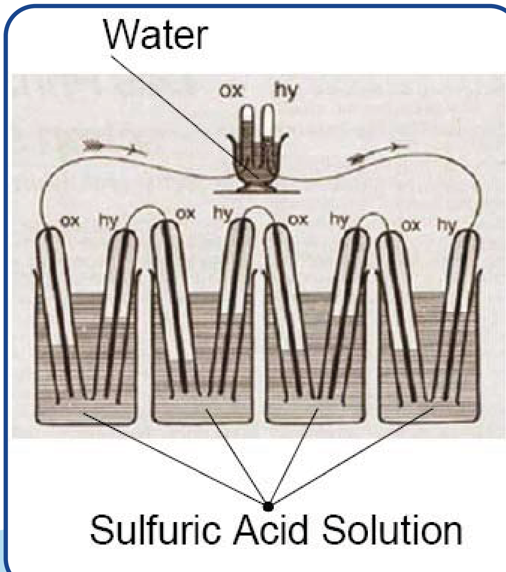


Figure 5-2. Grove's Fuel Cell

One of the founders of physical chemistry, Friedrich Wilhelm Ostwald (1853–1932), provided a large portion of the theoretical understanding of how fuel cells operate. In 1893, Ostwald experimentally determined the roles of many fuel cell components. Ludwig Mond (1839–1909) was a chemist who spent most of his career developing soda manufacturing and nickel refining. In 1889, Mond and his assistant Carl Langer performed numerous experiments using a coal-derived gas. They used electrodes made of thin, perforated platinum, and had many difficulties with liquid electrolytes. The maximum power they achieved was 6 amps per square foot (the area of the electrode) at 0.73 volts.

Charles R. Alder Wright (1844–1894) and C. Thompson developed a similar fuel cell around the same time as Mond and Langer. They had difficulties in preventing gases from leaking from one chamber to another. This and other causes prevented the fuel cell from reaching voltages as high as 1 volt. They felt that if they had received more funding, they would have been able to create a better, robust cell that could provide adequate electricity for many applications.

Louis Paul Cailleteton (1832–1913) and Louis Joseph Colardeau (France) came to a similar conclusion as Wright and Thompson, but thought the process was not practical due to needing "precious metals." In addition, many papers were published during this time saying that coal was so inexpensive that a new system with a higher efficiency would not decrease the prices of electricity drastically.

William W. Jacques (1855–1932) constructed a "carbon battery" in 1896. Air was injected into an alkali electrolyte to react with a carbon electrode. He thought he was achieving an efficiency of 82 percent, but actually obtained only 8-percent efficiency.

Emil Baur and students (1873–1944) (Switzerland) conducted many experiments on different types of fuel cells during the early 1900s. His work included high-temperature devices, and a unit that used a solid electrolyte of clay and metal oxides.

Thomas Grubb and Leonard Niedrach invented PEM fuel cell technology at General Electric in the early 1960s. GE developed a small fuel cell for the U.S. Navy's Bureau of Ships (Electronics Division) and the U.S. Army Signal Corps. The fuel cell was fueled by hydrogen generated by mixing water and lithium hydride. It was compact, but the platinum catalysts were expensive.

Based upon the research, development, and advances made during the last century, technical barriers are being resolved by a world network of scientists. Fuel cells have been used for over 20 years in the space program, and the commercialization of fuel cell technology is rapidly approaching.

5.3 Fuel Cell Applications

Fuel cells would be a beneficial addition to our energy mix because they provide electric power in applications that are currently energy-limited. For example, one of the most annoying things about a laptop computer is that the battery gives out after a couple of hours! Current small fuel cell technology has the potential topover laptops for up to 8 hours at which time a quick recharge of chemicals would allow the user to continue working. Each market needs fuel cells for varying reasons as described in the next few sections.

5.3.1 Stationary Sector

Large stationary fuel cells can produce enough electricity to power a house or business. These fuel cells may also make enough power to sell back to the grid. Stationary fuel cells are especially advantageous for businesses and residences where no electricity is currently available. In addition, stationary fuel cells can be integrated with solar and wind power devices to create an energy-efficient hybrid power system.

5.3.2 Transportation Market

The transportation market will benefit from fuel cells because fossil fuels will continue to become scarce, and because of this, there will be inevitable price increases. Legislation around the world is also becoming more diligent about enacting legislation with will control environmental emissions. Many countries are passing laws to reduce emissions, and to sell a minimum number of zero emission vehicles annually. Fuel cell vehicles can offer higher efficiencies than conventional vehicles that are powered by other fuels.

5.3.3 Portable Sector

One of the primary markets for fuel cells in the future will be in the portable sector. The military also has a need for high-power, long-term devices for troop equipment. There are numerous commercial portable devices that will use fuel cells in order to power the device for longer amounts of time. Some of these devices include laptops, cell phones, video recorders, and iPods. Fuel cells will power a device as long as there is fuel supplied to it. The current trend in electronics is the convergence of devices, and the limiting factor of many new devices is the amount of power that it requires. Therefore, power sources, such as fuel cells, that can supply greater power for a longer period of time will allow the development of new, multifunctional devices.

Figure 5-2. Horizon MiniPak Portable Electronics Charging Unit

Special Topic: Fuel Cells for Automobiles

Most automobile manufacturers have been developing fuel cell vehicles for at least a decade, and have demonstrated at least one prototype vehicle. The major reasons for developing automotive fuel cell technology are their efficiency, low or zero emissions, and fuel that could be reproduced from local sources rather than imported. Automotive fuel cells can have one or all of the following characteristics [10]:

- A fuel cell is sized to provide all of the power to a vehicle.
- A battery may be present for startup.
- A fuel cell typically supplies a constant amount of power, so for vehicle acceleration and other power spikes, additional devices are typically switched on such as batteries, ultra or supercapacitors, and so on.
- Sometimes a fuel cell is used as the secondary power source. A system is set up where batteries power the vehicle, and the fuel cell just recharges the batteries when needed.
- A fuel cell can run part or all of the vehicle's electrical system.

The operating temperature of the fuel cell stack for an automobile ranges from 60 to 80 ºC. Operating temperatures above 100 ºC would improve the heat transfer and simplify stack cooling, but most automotive fuel cells use PEMFCs (proton exchange membrane fuel cells) or DMFCs (direct methanol fuel cells) which are limited the operation to temperatures below 100 ºC due to water management issues in the device [10]. The main components of a fuel cell system are shown in Figure 5-3.

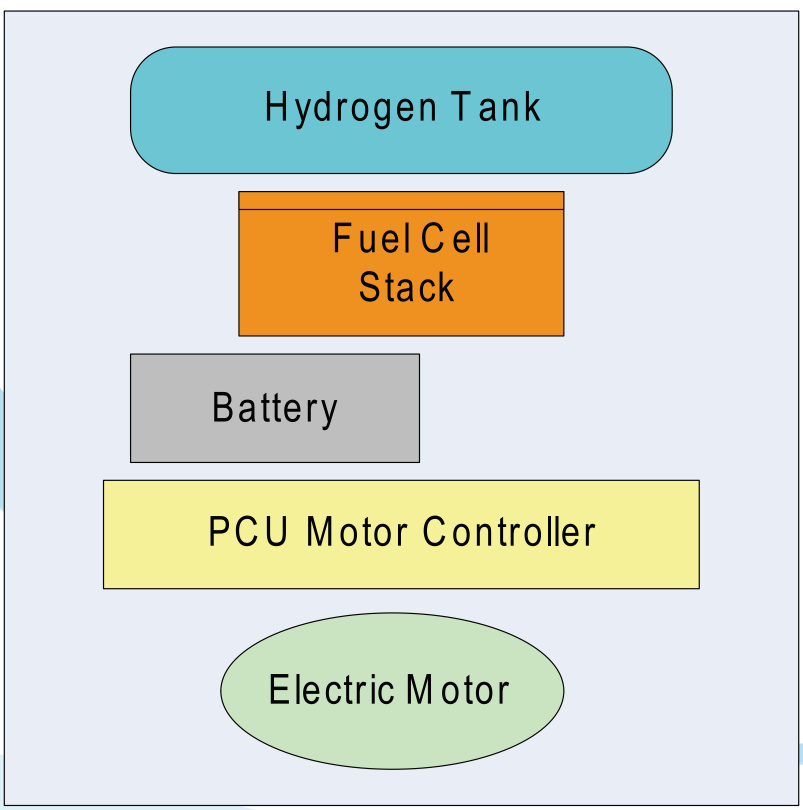


Figure 5-3. Hydrogen Fueled Fuel Cell Vehicle [10]

The design of a fuel cell as a power source in transportation applications involves a number of parameters. These include the same power requirement as with any conventional power source, weight and size of the fuel cell, electic motor and power electronics, the type of fueling system, and the distance between fueling and the time it takes to refuel. The fuel cell allows automotive engineers to employ completely non-traditional concepts in vehicle design. One such design is the General Motors Fuel Cell Car with the skateboard design. Fueling options include on-board production of hydrogen from conventional fuels, and on-board hydrogen hydrogen storage with home or standard refueling stations. The US Department of Energy has opted to only support on-board hydrogen storage. Home refueling stations may employ reformation of hydro-carbon fuels or electrolysis of water.

When designing a fuel cell for automobile (or any other vehicle type), there are many forces that affect a vehicle and the fuel system. The vehicle engine needs to provide enough power to overcome these forces to move the vehicle. A free body diagram is created to understand the forces acting on an object. The forces must be balanced if an object remains at rest. If the forces are not balanced, then the object will move.

The effect of the forces on an object is dependent upon the forces acting on the object, and its surroundings. Common forces include weight, resisting force, friction, air resistance or drag and driving force. The weight of an object is the force created by gravity acting on the object's mass. The resisting force is a force that equals the weight of an object in the opposite direction. Friction occurs when two objects contact one another, and slide against each other. Air resistance or drag is a result of the air flow on an object. The air flow will be different if the shape, velocity and object roughness varies. The driving force is the force that moves an object. This force must overcome other forces that are holding it in place. These forces are mathematically explained by Newton's law of motion, which includes the concepts of mass, force and acceleration. The first law states that an object in motion stays in motion, and an object at rest stays at rest unless a force causes it to move. The second law relates mass to force:

$$F = ma$$

where F is the force acting on an object, m is the mass of the object and a is the acceleration of the object due to the force acting on an object. If the acceleration acting on an object is due to gravity, a "g" is substituted for the "a" in the equation to get:

$$F = mg = W$$

where g is the gravitational acceleration. When the acceleration is due to gravity the force, F, now becomes the weight of an object.

Newton's third law states, for every action, there is an equal and opposite reaction.

A free body diagram of a vehicle is shown in Figure 5-4.

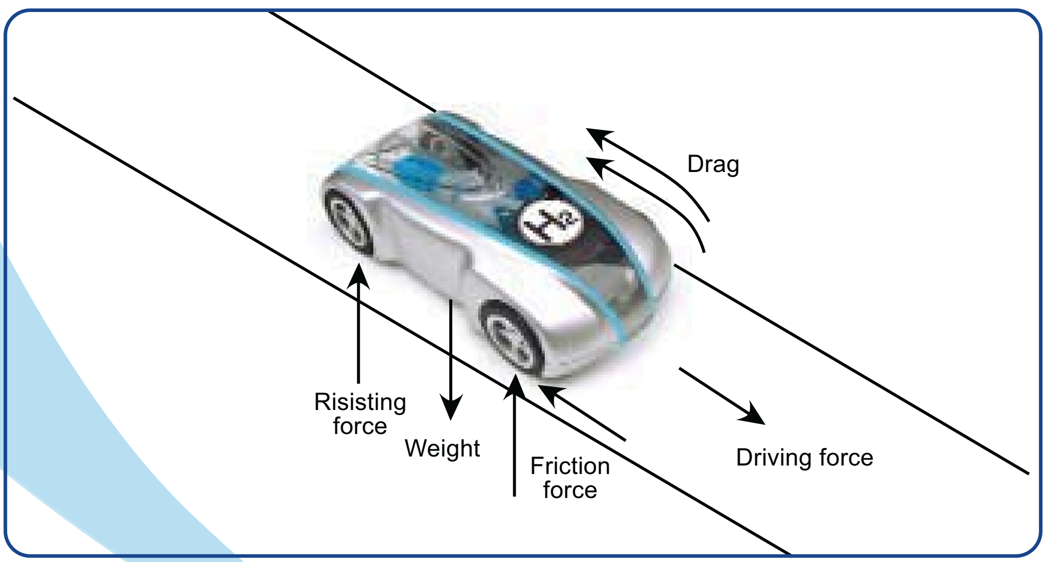


Figure 5-4: Free-body diagram of an automobile

These forces must have a sum of zero if the vehicle is to maintain a constant velocity. If the vehicle needs to accelerate, the net forward acceleration times the mass can provide a quick estimate. The various power demands can be summarized for a total mechanical power demanded by the motion of the vehicle.

5.4 Types of Fuel Cells

Many types of fuel cells are currently being researched. The six primary types of fuel cells are differentiated from one another on the basis of the electrolytes and/or fuel used with that particular type of fuel cell. The operating temperature and size of fuel cells are often the determining factor is which fuel cell will be used for specific applications. Fuel cell types include the following:

- Polymer electrolyte membrane fuel cells (PEMFCs)
- Alkaline fuel cells (AFCs)
- Phosphoric acid fuel cells (PAFCs)
- Solid oxide fuel cells (SOFCs)
- Molten carbonate fuel cells (MCFCs)
- Direct methanol fuel cells (DMFCs)

Details of each fuel cell type described in the next few sections.

5.4.1 Polymer Exchange Membrane Fuel Cell (PEMFC)

The polymer electrolyte membrane (also called proton exchange membrane or PEM) fuel cell delivers high-power density while providing low weight, cost, and volume. A PEM fuel cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte membrane, as shown in Figure 5-5. It is a very similar configuration to the bipolar-type electrolyzers in Chapter 4. Hydrogen is used on the anode side, and oxygen is utilized on the cathode. Protons are transported from the anode to the cathode through the electrolyte membrane and the electrons are carried over an external circuit load. A typical PEM fuel cell has the following reactions:

Anode: $H_2\ (g) \rightarrow 2H^+\ (aq) + 2e^-$

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

Overall: $H_2\ (g) + \frac{1}{2}\ O_2\ (g) \rightarrow H_2O\ (l)$ + electric energy + waste heat

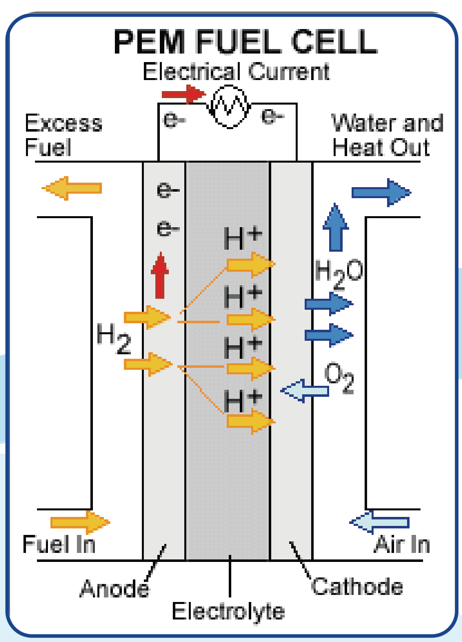


Figure 5-5. PEM Fuel cell

5.4.2 Alkaline Fuel Cells (AFCs)

Alkaline fuel cells (AFCs) have been used by NASA on space missions and can achieve power-generating efficiencies of up to 70 percent. The operating temperature of these cells range between 150 to 200 °C (about 300 to 400 °F) [10]. An aqueous solution of alkaline potassium hydroxide soaked in a matrix act as the electrolyte. This is advantageous because the cathode reaction is fast in the alkaline electrolyte, which means higher performance. Several companies are examining ways to reduce costs and improve operating flexibility. Alkaline fuel cells typically have a cell output from 300 watts to 5 kW [10]. An illustration of an alkaline fuel cell is shown in Figure 5-6. The chemical reactions that occur in this cell are:

Anode:

$2H_2\ (g) + 4(OH)^-\ (aq) \rightarrow 4H_2O\ (l) + 4e^-$

Cathode:

$O_2\ (g) + 2H_2O\ (l) + 4e^- \rightarrow 4(OH)^-\ (aq)$

Overall:

$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (l)$

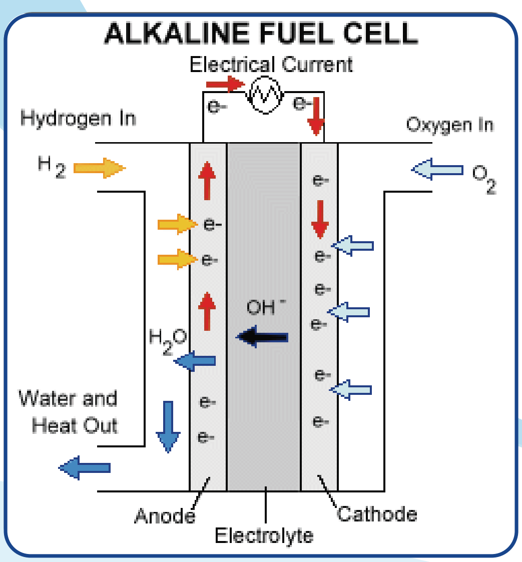


Figure 5-6. An alkaline fuel cell (AFC)

5.4.3 Phosphoric Acid Fuel Cell (PAFC)

The phosphoric acid fuel cell (PAFC) is one of the few commercially available fuel cells. Several hundred fuel cell systems have been installed all over the world. Most of the PAFC plants that have been built are in the 50 to 200 kW capacity range, but large plants of 1 MW and 5 MW have been built [10]. The largest plant operated to date achieved 11 MW of grid-quality alternating current (AC) power. A PAFC is shown in Figure 5-7.

PAFCs are very efficient fuel cells, generating electricity at more than 40 percent efficiency. Operating temperatures are in the range of 300 to 400 °F (150 to 200 °C) [10]. The PAFC is a poor ionic conductor at lower temperatures, and carbon monoxide (CO) poisoning of the platinum catalyst in the anode can become severe.

The chemical reactions for PAFCs are as follows:

Anode: $H_2\ (g) \rightarrow 2H+\ (aq) + 2e^-$

Cathode: $\frac{1}{2}O_2\ (g) + 2H^+\ (aq) + 2e^- \rightarrow H_2O\ (l)$

Overall: $H_2\ (g) + \frac{1}{2}O_2\ (g) + CO_2 \rightarrow H_2O\ (l) + CO_2$

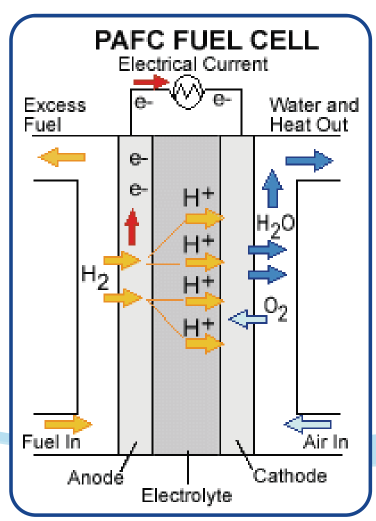


Figure 5-7. A phosphoric acid fuel cell (PAFC)

5.4.4 Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells (SOFCs) seem promising for large, high-power applications such as industrial and large-scale central electricity generating stations. A solid oxide system is usually constructed of a hard ceramic material consisting of solid zirconium oxide and a small amount of Ytrria, instead of a liquid electrolyte.

See Figure 5-8 for an illustration of a solid oxide fuel cell. The operating temperatures can reach 1,800 ºF or 1000 ºC [10]. Power-generating efficiencies could reach 60 to 85 percent with cogeneration and when cell output is up to 100 kW [10]. The anode, cathode, and overall cell reactions are:

Anode: H_2 (g) + O_2– → H_2O (g) + $2e^-$

Cathode: ½O_2 (g) + 2e– → O_2^-

Overall:H_2 (g) + ½O_2 (g) → H_2O (g)

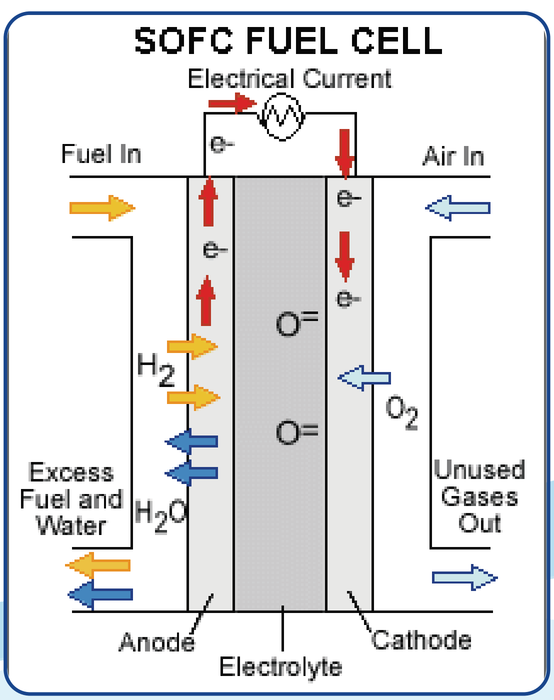


Figure 5-8. A solid oxide fuel cell (SOFC)

5.4.5 Molten-Carbonate Fuel Cells (MCFCs)

Molten carbonate fuel cells are another fuel cell technology that has been successfully demonstrated in several locations throughout the world. The high operating temperature offers a significant advantage because it enables a higher efficiency and the flexibility to use more types of fuels and inexpensive catalysts. A disadvantage of MCFCs is that high temperatures enhance corrosion and the breakdown of cell components. The electrolyte in the molten-carbonate fuel cell is a liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix. MCFCs have high fuel-to-electricity efficiencies ranging from 60 to 85 percent with cogeneration, and operate at about 1,200 ºF or 650 ºC [10].

Cogeneration:
A process that uses waste energy to produce heat or electricity.

This high operating temperature is needed to achieve sufficient conductivity of the electrolyte. These high temperatures also allow cheaper catalysts for the cell's electrochemical oxidation and reduction processes. Figure 5-9 shows an example of a MCFC.

Molten carbonate fuel cells can use hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and coal gasification products. MCFCs producing10-kW to 2-MW MCFCs has been tested on a variety of fuels and is primarily targeted to electric utility applications. The reactions at the anode, cathode, and the overall reaction for the MCFC are:

Anode:

$H_2\ (g) + CO_{32}– \rightarrow H_2O\ (g) + CO_2\ (g) + 2e^-$

Cathode:

$½O_2\ (g) + CO_2\ (g) + 2e^- \rightarrow CO3^{2-}$

Overall:

$H_2\ (g) + ½O_2\ (g) + CO_2\ (g) \rightarrow H_2O\ (g) + CO_2\ (g)$

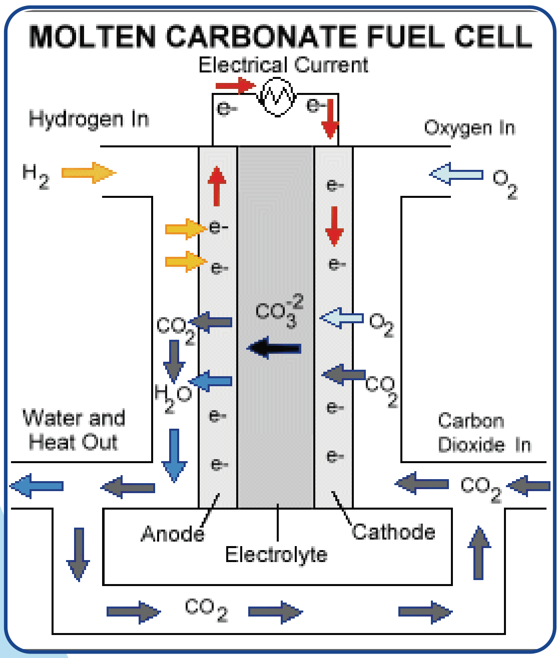


Figure 5-9. A molten carbonate fuel cell (MCFC)

5.4.6 Direct Methanol Fuel Cells (DMFCs)

The large potential market for fuel cell portable applications has generated a strong interest in a fuel cell that can run directly on methanol. The direct methanol fuel cell (DMFC) uses the same polymer electrolyte membrane as the PEM fuel cell. The fuel for the DMFC, however, is methanol instead of hydrogen. Methanol flows through the anode as fuel and is broken down into protons, electrons, water, and carbon dioxide. Advantages of methanol include its wide availability and its ability to be easily reformed from gasoline or biomass. Although it only has a fifth the energy density of hydrogen by weight, since it is liquid it offers more than four times the energy per volume when compared to hydrogen at 250 atmospheres. The chemical reactions for this fuel cell are as follows:

Anode:

$CH_3OH(l) + H_2O(l) \rightarrow CO_2 + 6H^+ + 6e^-$

Cathode:

$6\ H+ + 3/2\ O_2 + 6e^- \rightarrow 3\ H_2O(l)$

Overall:

$CH_3OH(l) + 3/2\ O_2\ (g) \rightarrow CO_2\ (g) + 2\ H_2O(l)$

5.5 How Do Fuel Cells Work?

A single fuel cell operates at a voltage ranging from 0.6 – 0.8 V, and produces a current per active area (current density) of 0.2 to 1 A/cm2. A fuel cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte. Hydrogen is oxidized on the anode and oxygen is reduced on the cathode. Protons are transported from the anode to the cathode through the electrolyte, and the electrons are carried to the cathode over an external circuit. Electrons are transported through conductive materials and travel to the load when needed. Both, the anode and cathode, contain a catalyst to create electricity from the electrochemical process as shown in Figure 5-10.

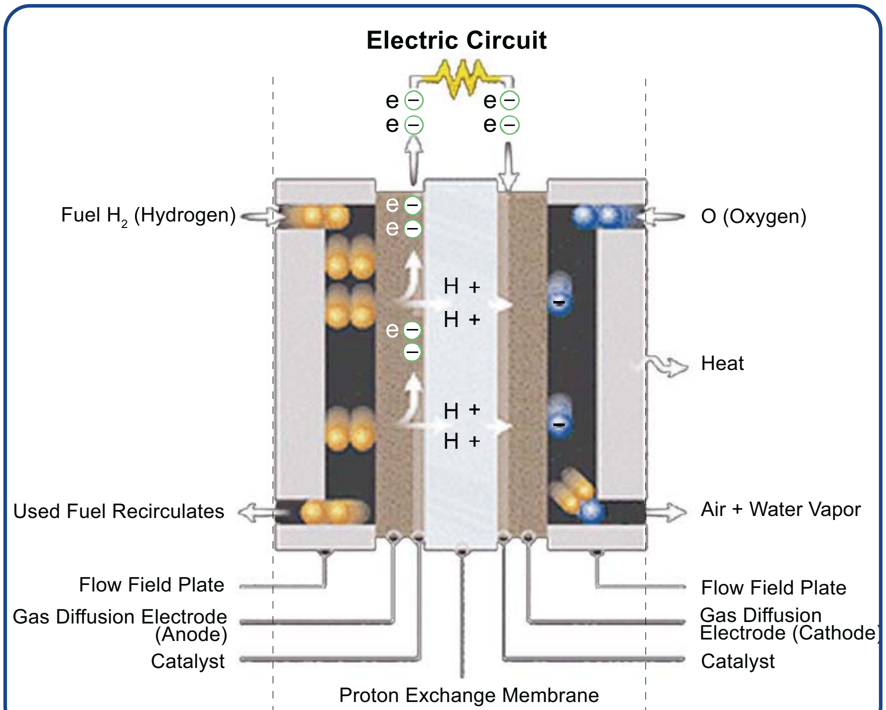


Figure 5-10. A Single PEM Fuel Cell .

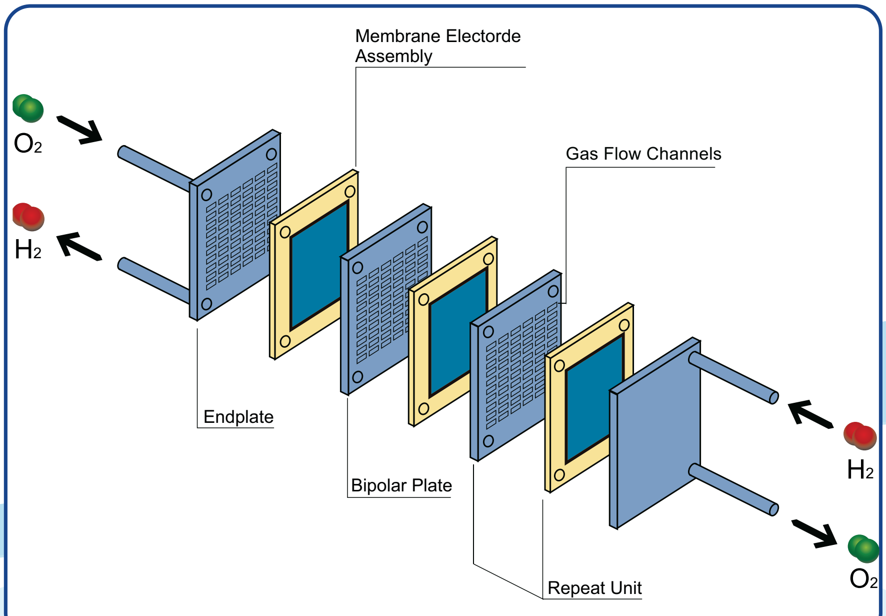


Figure 5-11. An Exploded View of a Polymer Electrolyte Membrane Fuel Cell Stack.

The conversion of the chemical energy of the reactants to electrical energy, heat, and liquid water occurs in the catalyst layers. The fuel and oxidant travel to the catalyst layers where the electrochemical reactions take place. The water and waste heat generated by the fuel cell must be continuously removed, and may present critical issues for fuel cells.

Because most applications have voltage or power requirements that cannot be satisfied by a single cell, a number of cells are connected in series to make a fuel cell stack. These repeating cells are separated by flow field plates. Increasing the number of cells in the stack increases the voltage, while increasing the surface area of the cells increases the current. A PEM fuel cell stack is made up of bipolar plates, membrane electrode assemblies (MEA), and end plates as shown in Figure 5-11.

The bipolar plates are constructed of graphite or metal, and they simultaneously distribute gases through flow channels to the fuel cell layers (MEA) while transporting electrons to the load. Gas flow channels allow the anode and cathode reactants to enter the MEA, where the electrochemical reactions occur. In a PEM fuel cell, the MEA typically has a thickness of 500 – 600 μm, and consists of five layers: the proton exchange membrane, two anode and cathode catalyst layers and two anode and cathode gas diffusion layers. These fuel cell layers are described in more detail in the next few sections.

5.5.1 Electrolyte Layer

The electrolyte layer is the heart of a fuel cell. It enables the fuel cell to conduct its electrons properly by attracting the protons, and enabling them to travel through the layer while maintaining their proton state. The electrons travel to the external circuit to power the load, and the hydrogen protons travel through the electrolyte until they reach the cathode to combine with oxygen to form water. The electrolyte must be able to conduct ions well; it must present a good enough barrier to not allow other reactants to enter it; it must not conduct electrons; and it has to be easy to integrate into the fuel cell stack.

5.5.2 Gas Diffusion Layer

The gas diffusion layers (GDL) have two main functions: they must allow gases to pass through them, and be conductive enough to allow electrons to travel through them. These layers also provide a layer to bond the catalyst to, and its structure promotes the removal of water that may get in the way of the reaction. This layer is very thin, with a thickness of 0.25 – 0.40 mm, and a pore size ranging between 4 – 50 microns [11].

5.5.3 Catalyst Layer

The fuel cell reactions occur in the catalyst layer. The anode catalyst layer breaks the hydrogen fuel into protons and electrons, and at the cathode catalyst layer, oxygen combines with the protons to form water. These catalyst layers are often the thinnest layer in the fuel cell (5 to 30 μm), but are often the most complex because they incorporate several types of gases and water and electrochemical reactions. The catalyst layers are usually made of a porous mixture of carbon supported platinum or platinum/ruthenium.

The reactions in the catalyst layers are exothermic; therefore, heat must be transported out of the cell. The heat can be removed through the convection in the flow channels and conduction in the solid portion of the catalyst layers, gas diffusion media. and bipolar plates. Since liquid water is produced by the PEM fuel cell, the condensation and evaporation of water affects the heat transfer in a PEM fuel cell. Therefore, the water and heat management in the fuel cell are closely linked.

5.5.4 Bipolar Plates

Bipolar plates evenly distribute fuel and oxidant to the cells, and collect the current to power the desired devices. In a fuel cell with a single cell, there are no bipolar plates (only single-sided flow field plates). Yet, in fuel cells with more than one cell, there is usually at least one bipolar plate (flow fields exist on both sides of the plate). Bipolar plates perform many roles in fuel cells. They distribute fuel and oxidant within the cell, separate the individual cells in the stack, collect the current, carry water away from each cell, humidify gases, and keep the cells cool. Bipolar plates also have reactant flow channels on both sides, forming the anode and cathode compartments of the unit cells on the opposing sides of the bipolar plate. Commonly used designs can include straight, serpentine, parallel, interdigitated or pin-type flow fields as shown in Figure 5-12. Materials are chosen based upon chemical compatibility, resistance to corrosion, cost, density, electronic conductivity, gas diffusivity/impermeability, manufacturability, stack volume/kW, material strength, and thermal conductivity.

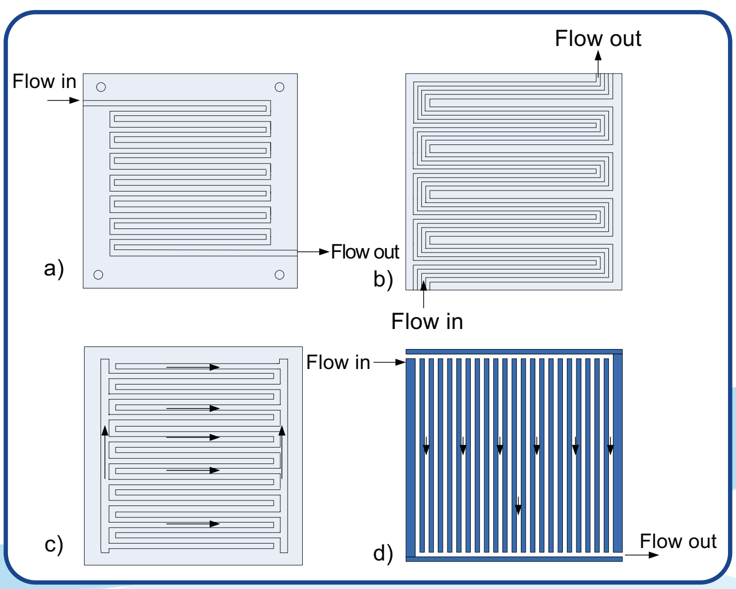


Figure 5-12. (a) Serpentine Flow Field Design,
(b)Multiple Serpentine Flow Channel Design,
(c) A Parallel Flow Field Design,
(d) Interdigitated Flow Channel Design [10]

5.6 Stack Design and Configuration

In the traditional bipolar stack design, the fuel cell stack has many cells in series, and the cathode of one cell is connected to the anode of the next cell. The MEAs, gaskets, bipolar plates and end plates are the typical layers of the fuel cell. The cells are usually clamped together. The most common fuel cell configuration is shown in Figure 5-13. Each cell (MEA) is separated by a plate with flow fields to distribute the fuel and oxidant. The majority of fuel cell stacks are of this configuration regardless of fuel cell size, type or fuel used.

Fuel cell performance is dependent upon the flow rate of the reactants. Uneven flow distribution can result in uneven performance between cells. Reactant gases need to be supplied to all cells in the same stack through common manifolds.

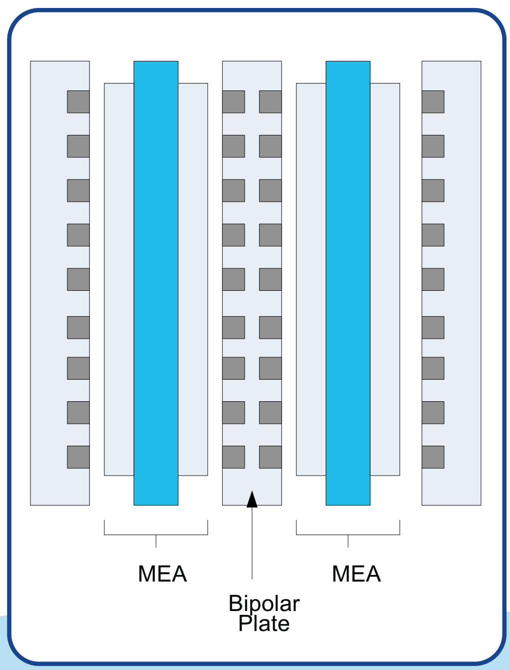


Figure 5-13.
Typical Fuel Cell Stack Configuration
(a two-cell stack) [11]

5.7 Operating Conditions

One of the advantages of fuel cell technology is that it has a wide range of operating conditions. This means that many fuel cells can operate at room temperature for certain applications, and others can run at higher temperatures in systems where it is advantageous. Fuel cell performance is determined by the pressure, temperature, and humidity during operation of the application, Performance can often be improved (depending upon fuel cell type) by increasing the temperature, pressure, humidity and optimizing other important fuel cell variables. The ability to increase these variables is application-dependent, because system issues, weight and cost play important factors when optimizing certain parameters.

5.7.1 Polarization Curves

The traditional measure of characterizing a fuel cell is through a polarization curve – which is a plot of cell potential versus current density. This curve was first introduced in Chapter 4. An I-V curve is the most common method for characterizing and comparing fuel cell efficiency to other published data. The polarization curve illustrates the voltage-current relationship based upon operating conditions such as temperature, humidity, applied load, and fuel/oxidant flow rates. Figure 5-14 shows a typical polarization curve for a single PEM fuel cell, and the regions of importance.

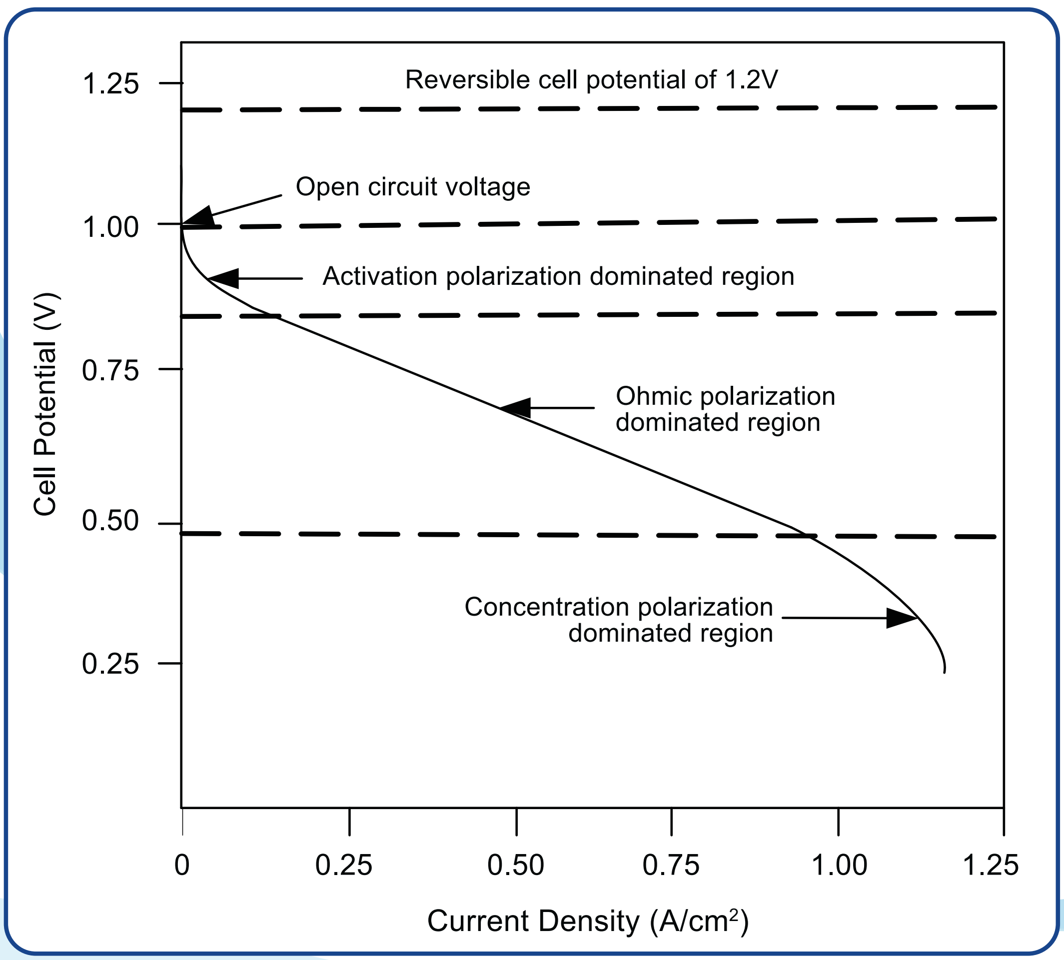


Figure 5-14. Example of a PEMFC Polarization Curve [11].

As shown in Figure 5-14, the polarization curve can be divided into three regions: (1) the activation overpotential region, (2) the ohmic overpotential region, and (3) the concentration overpotential region (these losses were first described in Chapter 4). In the activation overpotential region, voltage losses occur when the electrochemical reactions are slow to produce current. The oxygen electrochemical reaction on the cathode is responsible for most of the activation overpotential. As the PEM fuel cell produces more current, the activation losses increase at a slower rate than the ohmic losses. The ohmic overpotential is due to the resistance of the transport of charged species in the polymer electrolyte membrane, catalyst and gas diffusion layers and bipolar plates.

The concentration overpotential is due to mass transport limitations; the rates of the electrochemical reactions within the catalyst layers are hindered by a lack of reactants. The mass transport limitations are due to both diffusional limitations in the electrode backing layer and water flooding in the cathode catalyst layer. At high current densities, the amount of liquid water produced in the cathode catalyst layer becomes greater than the amount of water that can be removed from the flow in the gas channels. For further details on these voltage losses, please see Chapter 4.

5.8 Conclusions

This chapter covered how fuels cells will be an essential part of the future renewable energy economy. They have the ability to fulfill all of our power needs in the stationary, transportation and portable power industry. There are six main types of fuel cells: PEMFCs, AFCs, PAFCs, SOFCs, MCFCs, and DMFCs. The type most commonly used for transportation and portable applications is the polymer electrolyte membrane (PEM) fuel cell. PEM fuel cells typically use hydrogen as the fuel, but also have the ability to use other types of fuel as well – including ethanol and biomass-derived materials. Fuel cells are made up five main layers: two gas diffusion layers, two catalyst layers and an electrolyte. The two gas diffusion layers are made of a conductive carbon cloth that is porous. The catalyst layers are a mixture of porous platinum and carbon. The fuel cell electrolyte determines many other parameters in the fuel cell system, such as: reaction chemistry, operating temperatures, cell materials, and cell and stack designs. The differences lead to important characteristics, advantages, and disadvantages of each fuel cell type. Any of the fuel cell types can be used in conjunction with a hybrid energy system. Solar, wind, electrolysis and power electronics can be part of an ideal hybrid energy system as discussed in chapters 2 – 4 and 6 – 7.

Chapter 6

Hydrogen Storage & Transportation

6.1 Introduction

Hydrogen has many unusual characteristics compared to other elements. It is the lightest and most abundant element, and it can burn with oxygen to release large amounts of energy. Hydrogen has high energy content by weight, and has a low energy density by volume at standard temperature and atmospheric pressure. Table 6-1 compares the relevant properties of hydrogen compared to methane, methanol, ethanol, propane, and gasoline. Hydrogen does not exist in its natural form on earth; therefore, it must be manufactured through electrolysis, steam reforming of natural gas, the gasification of coal, or the reforming/oxidation of other hydrocarbons or biomass.

Property	Hydrogen	Methane	Methanol	Ethanol	Propane	Gasoline
Molecular Weight (g/mol)	2.016	16.043	32.04	46.0634	44.10	~107.0
Density (kg/m^3) 20 °C and 1 atm	0.08375	0.6682	791	789	1.865	751
Normal Boiling point (°C)	-252.8	-161.5	64.5	78.5	-42.1	27-225
Flash Point (°C)	<-253	-188	11	13	-104	-43
Flammability Limits in Air (Volume %)	4.0-75.0	5.0-153.0	6.7-36.0	3.3-19	2.1-10.1	1.0-7.6
CO_2 Production per Energy Unit	0	1.00	1.50	1.60	1.70	1.80
Autoignition Temperature in Air (°C)	585	540	385	423	490	230-480
Higher Heating Value (MJ/kg)	142.0	55.5	22.9	29.8	50.2	47.3
Lower Heating Value (MJ/kg)	120.0	50.0	20.1	27.0	46.3	44.0

Table 6-1. Hydrogen Compared with Other Fuels [11]

Hydrogen is a good choice for a future energy source for many reasons. Some of these reasons are [11]:

- Hydrogen can be made from various sources. It is completely renewable. The most abundant and cleanest precursor for hydrogen is water.
- Hydrogen can be stored as a gas, a liquid or a solid. It also can be stored in various chemicals and substances such as methanol, ethanol, and metal hydrides.
- It can be produced from, and converted to, electricity with high efficiencies.
- It can be transported and stored as safely as other fuels used today.

Hydrogen can provide energy for all parts of the economy: industry, residences, transportation, and mobile applications. It can replace oil-based fuels used for automobiles, and can provide an attractive solution for electricity for communities. One of the main attractions for hydrogen is its environmental advantage over fossil fuels. Hydrogen can be produced without pollutants if it is produced by one of three methods:

- Through electrolysis using electricity derived solely from nuclear power or renewable energy sources (as in the Renewable Energy Education Set).
- Through steam reforming of fossil fuels combined with new carbon capture and storage technologies.
- Through thermochemical or biological techniques based on renewable biomass.

As discussed throughout this text, a major disadvantage of processing hydrocarbons is the pollution and carbon dioxide. The best low-pollution alternative for creating hydrogen is a process involving electrolysis of water by electricity. This method creates no carbon dioxide, or nitrous or sulfurous oxides.

6.2 Safety Aspects of Hydrogen as a Fuel

One critical roadblocks to the adoption of hydrogen as a consumer fuel is the public's perception of the safety of hydrogen. Contrary to popular belief, hydrogen is less flammable than gasoline and other fossil fuels. Like any other fuel, hydrogen has risks if not properly stored or transported. These hazards of hydrogen can be controlled through the use of proper handling and controls.

The ***Hindenburg disaster*** occurred on May 6, 1937. The German airship, Hindenburg, was destroyed within one minute while attempting to dock in Manchester Township, New Jersey. Thrity-five people died of the 97 individuals on board. The disaster was the subject of extensive news and radio covereage. The cause of the fire has been heavily speculated, and a wide variety of theories on the cause of ignition and the initial fuel for growing the fire. The one that has been most scientifically accepted is that the paint on the fabric of the Hindenburg in addition to static electricity caused the airship to ignite.

The reputation of hydrogen as unsafe has been unfairly tainted by the Hindenberg incident and the hydrogen bomb. Hydrogen by itself cannot start a fire – it has to be mixed with oxygen in the presence of an ignition source. Therefore, there had to be another cause of ignition that caused the fire on the Hindenberg.

Since hydrogen is a small molecule, it has a tendency to escape through small openings more easily than other gaseous or liquid fuels. Since natural gas has an energy density three times greater than hydrogen, a natural gas leak results in a greater energy release than a hydrogen leak. If a hydrogen leak occurs, hydrogen disperses much more quickly than other fuels. Hydrogen is lighter and more diffusive than gasoline, propane, or natural gas. If an explosion occurrs, hydrogen has the lowest explosive energy per unit of stored fuel [11].

The potential dangers of hydrogen aboard a vehicle are explosion and toxicity. A hydrogen fire can occur as a result of a problem with a fuel storage system or a fuel cell itself. In a fuel cell, small amounts of hydrogen and oxygen exist, which are separated by a thin polymer membrane (see Chapter 5). If the membrane were to rupture, the fuel cell would immediately lose its potential, and a control system could disconnect the supply lines. There are many control system features that make using hydrogen systems very safe [11]:

- Leak prevention through thorough testing of tanks and equipment.
- Installing more than one valve.
- Designing equipment for shocks, vibrations, and wide temperature ranges.
- Adding hydrogen sensors or leak detectors.
- Ignition prevention by illuminating all sources of electrical sparks.
- Designing fuel cell supply lines that are physically separated from other equipment.

In order for hydrogen to become widely accepted, international regulations codes and standards need to be developed for construction, maintenance, and operation of hydrogen facilities and equipment. The uniformity of safety requirements will increase customer confidence in using hydrogen.

6.3 Hydrogen Production, Distribution, and Storage

In order to store, transport, and dispense hydrogen, it must be compressed and stored in pressurized containers, or converted to the liquid form and stored in a cryogenic liquid hydrogen tank. Hydrogen can be transported by pipeline, but only over short distances. There are a few hydrogen-pipeline systems that are being used today in the United States and Europe, but it is easier to transport hydrogen by rail or trucks, for long distances.

6.3.1 Technologies for Hydrogen Production

Currently, hydrogen is produced from various fossil fuels such as oil, natural gas, and coal. Some of the technologies to produce hydrogen include steam reforming of natural gas, partial oxidation of hydrocarbons, and coal gasification. However, these technologies will not help to decrease the dependence on fossil fuels.

The electrolysis of water is a mature technology that was developed for hydrogen production (see Chapter 4). It is efficient, but requires large amounts of electricity. This can be solved, however, by using solar or wind energy to produce the electricity required to release the hydrogen. This technology is mature enough to be used on a large scale for electricity and hydrogen generation. Other options for generating hydrogen include hydropower, nuclear plants, especially during off-peak hours, direct thermal decomposition, thermolysis, thermochemical cycles, and photolysis. These technologies are at various stages of development, and a few have been abandoned. The most common methods of producing hydrogen are steam reforming, partial oxidation, coal gasification, biomass and water electrolysis [11].

6.3.1.1 Steam Reforming

The cheapest method of producing hydrogen on a large scale today is through steam reforming of fossil fuels as shown in Figure 6-1. The current methods use a nickel catalyst. Methane first reacts with steam to produce carbon monoxide and hydrogen. The carbon monoxide passes over the catalyst, then reacts with the steam to produce carbon dioxide and hydrogen. Natural gas is the cheapest feedstock for producing hydrogen from steam reforming, but this cost is not yet competitive because it is still two to three times higher than producing gasoline from crude oil.

Figure 6-1. Steam reforming plant

6.3.1.2 Partial Oxidation

Another method used to produce hydrogen is partial oxidation. This process involves reacting the methane and other hydrocarbons in natural gas with a small amount of oxygen (usually from air), to turn the hydrocarbon to carbon dioxide and water. If there is less oxygen available for the reaction than what is required, the products of the reaction will be hydrogen and carbon monoxide, a small amount of carbon dioxide and possibly small amounts of other compounds (depending upon whether the oxygen is taken from air) [11].

Partial oxidation is an exothermic reaction.

Exothermic reaction:
A chemical reaction that releases energy in the form of heat, light or sound.

The opposite of an exothermic reaction is an endothermic reaction.

Endothermic reaction:
A chemical reaction that needs to absorb energy in order to proceed.

This process is much faster than steam reforming, and requires a smaller reaction vessel. However, the process initially produces less hydrogen per unit of the input fuel than is obtained by steam reforming the same fuel.

6.3.1.3 Coal Gasification

The gasification of coal is one of the oldest methods for producing hydrogen. It was used to produce "town gas" before natural gas became available. The coal is heated to a gaseous state, then mixed with steam in the presence of a catalyst to produce synthesis gas. This gas can be processed to extract hydrogen and other chemicals, or burned to produce electricity. There has been a lot of research conducted by various governments that has focused on the lowering of pollutants, such as nitrogen and sulfur oxides, mercury, and carbon monoxide. Figure 6-2 illustrates a syngas plant in Germany.

Figure 6-2. Syngas plant in Germany.

6.3.1.4 Biomass

Hydrogen can be produced from many types of biomass such as agricultural and animal residues using pyrolysis and gasification processes.

Pyrolysis:
A process of using high temperatures to decompose a substance into solids, liquids and gases. The new substances can be used as fuel, or other chemicals required for the chemical or material industries. Common materials that are used in pyrolysis processes are coal, biomass, garbage, plastics and rubber.

Gasification:
A chemical or heat process that converts a substance into gas. A gasification process is often used to convert coal or biomass into a liquid fuel.

Using biomass instead of fossil fuels to produce a gaseous fuel emits no carbon dioxide emissions. Unfortunately, biomass hydrogen production costs are much higher than hydrogen production costs from fossil fuels. Biological processes for producing hydrogen from biomass includes fermentation, anaerobic digestion, and metabolic processing techniques, but these are far from being competitive with traditional hydrogen-producing techniques [11]. Figure 6-3 shows a simple use of biomass.

6.3.1.5 Water Electrolysis

Hydrogen production using water electrolysis is used when extremely pure hydrogen is needed (see Chapter 4 for more details). The environmental benefits of using electrolysis depend on what method is used to produce the electricity to break the water. If the electricity were produced from renewable energy sources such as wind, solar, and biomass, it would produce pollutant-free hydrogen. If electrolysis is performed with electricity from the grid or nuclear power, a large reduction in the cost of producing hydrogen is required.

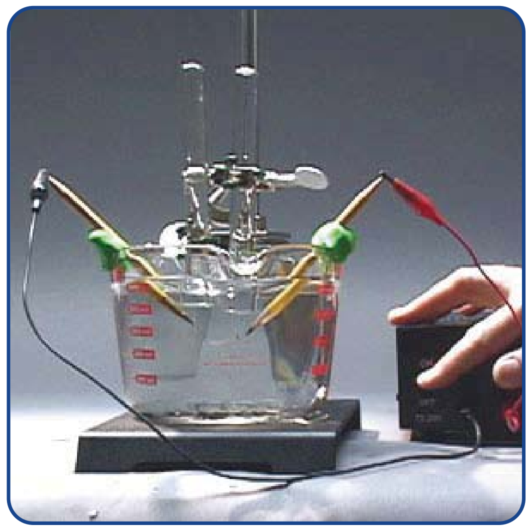


Figure 6-4. The electrolysis of water.

Figure 6-3.
Simple use of biomass.

6.4 Technologies for Hydrogen Storage

Many commercially available technologies exist for storing hydrogen. The most common storage method used today is the pressurized storage tank, which is available in many sizes and pressure ranges. Other storage methods that may be considered for various applications in the future are described in this section.

6.4.1 Large Underground Storage

Hydrogen can be stored underground in caverns, aquifers, and depleted petroleum and gas fields. These large underground storage systems will be similar to systems currently employed for natural gas, but systems for hydrogen can be approximately three times more expensive. Figure 6-5 shows a wellhead above a hydrogen cavern and integrated cavern support equipment. Underground hydrogen storage systems pose minimal technical difficulties. In fact, there are already several instances of hydrogen and other gasses being stored underground. The city of Kiel, Germany, stores town gas underground. Gaz de France, the French gas company, stores natural gas. Imperial Chemical Industries of Great Britain stores hydrogen in salt mines in Teeside, United Kingdom [11].

Figure 6-5.
Wellhead above hydrogen cavern
and
integrated cavern support equipment.

6.4.2 Vehicular Pressurized Hydrogen Tanks

A pressurized hydrogen tank is used for most hydrogen storage. There is a limited number of suitable materials for storing hydrogen because hydrogen embrittles many of the materials commonly being used for gas storage The best tank materials are ultra-light composite materials that allow pressures in excess of 20 bars. They are used in prototype automobiles and buses. Some tanks are used for long-term, continuous storage, and others are designed to be exchangable for refueling at a hydrogen station. There are four types of hydrogen tanks [20]:

1. Type I is a metal tank made of steel or aluminum, and can hold a maximum pressure of 175 bar for aluminum, or 200 bar for steel [20].
2. Type II is a aluminum tank with glass fiber/aramid or carbon fiber windings around a

metal cylinder. The maximum pressure that the Type II cylinders can hold is 263 bar for aluminum/glass and steel/carbon and 299 bar for glass/aramide [20].

3. Type III cylinders are made from composite material, glass fiber/aramid or carbon fiber with a metal liner. The maximum pressure is 305 bars for aluminum/glass, and 438 bars for aluminum/aramide [20].

4. Type IV cylinders are tyically carbon fiber with a polymer liner, and they are able to withstand pressures of 661 bar and up. The first fuel cell vehicles on the road to use Type IV tanks were the Mercedes-Benz F-Cell, the Toyota FCHV and the HydroGen4 [20].

Figure 6-6 shows the technology behind the hydrogen storage tanks, and an image of typical hydrogen storage tanks.

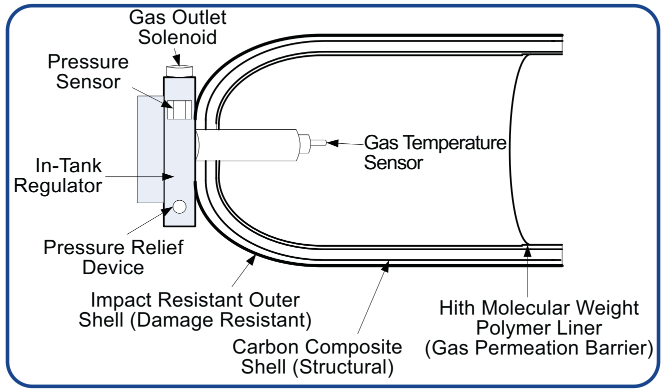


Figure 6-6. Compressed Hydrogen Storage

6.4.3 Liquid Hydrogen Storage

Liquid hydrogen storage can be beneficial for transportation and portable applications. The process of producing liquid hydrogen fuel requires a lot of energy. Hydrogen must be pressurized and cooled to a very low temperature (20.28 K, −423.17 °F/−252.87°C). The biggest advantage of using liquid hydrogen instead of pressurized gaseous hydrogen is that storing it in a liquid form takes less space than storing it as a gas. Once hydrogen gas is converted into its liquid sate, it can be maintained in this state by storing it in pressurized and thermally insulated containers. Figure 6-7 shows a liquid hydrogen storage tank.

Figure 6-7.
Prototype liquid hydrogen storage tank.

Liquid hydrogen is used as "rocket fuel" for rocket applications. Rockets use both liquid hydroge for hydrogen-based combustion engines, and for fuel cells. It cools the nozzle and other parts before it is mixed with oxidizer (liquid oxygen). It is burned in the rocket engine to produce energy, water, and traces of ozone and hydrogen peroxide.

6.4.4 Metal Hydride Storage

Metal hydride hydrogen storage has been the focus of intense research during the last 25 years. Many types of metal hydrides have been developed that readily absorb and deabsorb hydrogen at room temperature and atmospheric pressure (20 °C and 1 atm). The group of lighter metals in the periodic table, such as Li, Be, Na, Mg, B and Al form a large variety of metal hydride compounds. These compounds are very interesting because they are lightweight and have a high ratio of hydrogen atoms per metal atom, which is usually around a ratio of H/M = 2.

Metal hydride storage can occur under moderate temperatures and pressures, which creates a safety advantage over pressurized gaseous storage and liquid hydrogen storage. Metal hydrides have a higher hydrogen storage density than hydrogen gas or liquid hydrogen (6.5 H atoms/ cm3 versus 0.99 H atoms/cm3 and 4.2 H atoms per cm3). Therefore, metal hydride storage is a good candidate for storing hydrogen for vehicular applications. Metal hydride storage is illustrated in Figure 6-8.

Figure 6-8.Metal hydride hydrogen storage.

Most metal hydrides are either too stable or unstable at room temperature and atmospheric pressure, but there are a few that work well in these conditions. One unique example is palladium, which absorbs about 900 times its own volume of hydrogen at room temperature. The resultant compound is palladium hydride. The hydrogen gas is released proportionally to the temperature and pressure applied. Using palladium was one of the original ways that hydrogen was supposed to be stored for automotive fuel cells. However, the cost of palladium detered futher research and production. Commercial batteries are made from one popular type of metal hydride, nickel metal hydride, which has largely replaced Ni-Cd rechargeable batteries. Metal hydrides have also found applications in sorption cryocoolers, nickel-hydride batteries, and heat pumps. For transportation applications, metal hydrides should be easily charged/discharged at low temperatures (25 – 100 °C), and able to be charged and discharged numerous times.

Hydrogen is able to react with many metals and alloys which create a range of metal hydride choices for hydrogen storage. The formation of a metal hydride involves the hydrogen gas chemically adhering to the metal surface, and then the H atom diffusing into the metal. The hydrogen is then stored interstitially in the lattice of heavy atoms. This formation of metal hydrides produces a lot of heat (exothermic reaction), and the removal of hydrogen from the metal occurs under a certain temperature and pressure – depending upon the metal hydride system. These metal hydrides are suitable for many applications; however, most are still limited because they are capable of storing only 2 percent weight of hydrogen.

Metal hydrides must meet all of the following properties in order to be effective at releasing hydrogen:

1) Must be able to store a significant amount of hydrogen per unit mass and volume. This determines the amount of available energy
2) Must be able release hydrogen easily, and require a low amount of energy to release the hydrogen.
3) Must not release a large amount of heat during the formation of the metal hydride, and during the charge and discharge of hydrogen.
4) Must be very stable against oxygen and moisture for long periods of time.
5) Must be low-cost and be very safe during charging and discharging times.

A couple of the interesting metal hydrides that are currently being researched are alanate and lithium amide materials. Alanate (AlH4) materials, which can release more hydrogen than conventional metal hydride materials. About 3.7 wt. % hydrogen is released at temperatures above 33°C, and another 1.8 wt % hydrogen is released above 110°C.

Lithium amide complex hydride systems are another interesting metal hydride system that is currently being investigated. This reaction allows 6.5 wt.% hydrogen to be stored with the potential for 10 wt.%. This reaction, however, occurs at high temperatures, but can be lowered to 220 °C with higher pressures and magnesium substitution.

6.4.5 Carbon Nanofibers

There are many novel hydrogen methods are currently being investigated that offer the potential for higher energy density than conventional methods. These include hydrogen storage in carbon nanotubes. Carbon nanotubes are unique structures with amazing electronic and mechanical properties. A carbon nanotube is a hexagonal network of carbon atoms that have often been rolled up into a cylinder. The sizes of these structures are often a nanometer across, and tens of microns long.

Carbon nanotube:
Large molecules of pure carbon that are long and thin like tubes. They are 100 times stronger than steel, and 1/6 the of the weight. They can be used as electrical and heat conductors, hydrogen storage, as well as many other applications.

Carbon nanotubes are potentially useful for many applications due to their unique properties. Some of these include nanotechnology, electronics, optics and materials science. Carbon nanotubes have useful electrical properties, can conduct heat and exhibit high strength. The structure becomes apparent when examined under an electron microscope.

Electron microscope:
A type of microscope that has very high magnifications, and uses electrons to illuminate a specimen to create an enlarged image. These microscopes can magnify objects up to 2 million times. Light microscopes are commonly used to magnify specimens, but the highest magnification is only 2000 times.

Under an electron microscope, the nanotube material looks like a mat of carbon ropes. These ropes are 10 to 20 nm across, and up to 100 microns long. Each rope consists of a bundle of single-wall nanotubes aligned in a single direction.

Carbon nanotubes can be categorized as single-walled nanotubes (SWNTs), and multi-walled nanotubes (MWNTs). Single-walled nanotubes are important because they exhibit good electrical properties. Single-walled nanotubes are the most likely candidate for miniaturizing electronics. The SWNTs can replace electric wires on the micro electromechanical scale. The main hindrance is that they are still expensive to produce, and cheaper methods of synthesis need to be discovered.

Multi-walled nanotubes (MWNT) consist of multiple layers of carbon nanotubes to form a cylindrical shape. These structures typical look like rolls of cylinders, or like newspaper pages rolled up in into a cylinder.

6.4.5.1 Strength of Carbon Nanotubes

Carbon nanotubes are some of the strongest and stiffest materials discovered. This high-strength may make them potentially useful for improving the strength of other non-social structures and materials. A recent study published in the journal, Nature, determined that carbon nanostructures are probably present in high-strength steel. This was probably one of the factors that accounted for the legendary strength of ancient swords.

Because of carbon nanotubes high-strength and superior mechanical properties, nanotubes can produce materials, or be incorporated into materials to promote high strength, and unmatchable toughness. One possibility that could bring all types of new engineering designs and technologies into development is putting carbon nanotube molecules into a polymer matrix to form a super high-strength composite material. This would enable extremely high-pressure hydrogen storage for fuel cells, super-bullet-proof vests and clothing, many rocket ship applications, and many other types of new technologies.

6.4.5.2 Hydrogen Storage and Other Applications

Carbon nanotubes have found many potential uses for energy applications. Hydrogen storage, solar cells, and many possibilities within fuel cells are just some of the areas where carbon nanotubes can store hydrogen, enable electrons to flow, or increase catalyst activity. Carbon nanotubes can store small amounts of hydrogen at ambient temperatures and pressures. The main types of carbon nanotubes that are being investigated for hydrogen storage are single-walled carbon nanotubes (SWNTs), and multiwalled carbon nanotubes (MWNTs). There has not been consensus yet among scientists regarding how much hydrogen SWNTs and MWNTs can hold. Figure 6-9 shows a schematic of types of single-walled and multiwalled carbon nanotubes.

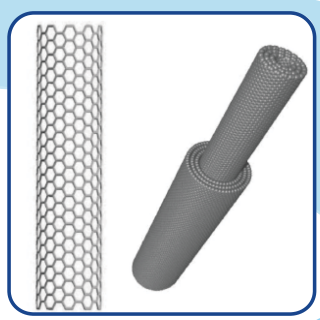


Figure 6-9. Schematic Representation of Carbon Nanotubes (a) Single-Walled Nanotube (SWNT), (b) Multi-Walled Nanotube (MWNT) [11]

New solar cells have been developed use a mixture of carbon nanotubes and carbon Buckyballs. Buckyballs have the ability to trap electrons (see Chapter 2), but they cannot make electrons flow. Since nanotubes act like copper wires, they are able to make the electrons flow to the load.

Carbon nanotubes have been used in several areas of fuel cell research. Carbon nanotubes have been added to the platinum/carbon catalyst mixture in order to improve the efficiency of the catalyst reactions in the fuel cell. Another area of carbon nanotube research that may improve fuel cells is the possibility of nitrogen-doped carbon nanotubes to reduce oxygen in fuel cells. If rows of these nanotubes are vertically aligned, they have the ability to reduce oxygen in alkaline solution more effectively than platinum.

6.5 Worldwide Hydrogen Refueling Stations

The number of hydrogen refueling stations around the world is shown in Figure 6-10. There has been a slow buildup of refueling stations in the countries listed since the 1990s. Certain countries, such as Germany, will begin rapidly introducing hydrogen refueling stations during the next five years. This increase in introduction is the result of a number of factors.

- Many fuel cell vehicle manufacturers will not begin production for a niche market.
- Both the automotive industry and fuel suppliers need to mass produce a certain number of units in order to reduce cost.
- Consumers will not accept a fuel that is not “widely available.”
- There is an alternative fuel and vehicle market in countries in Brazil and Argentina. Brazil uses ethanol, and Argentina uses natural gas. Lessons learned from studying the introduction of alternative fuel vehicles and fuel stations implies that a rapid introduction is a better way to gain customers and acceptance of the new technology.

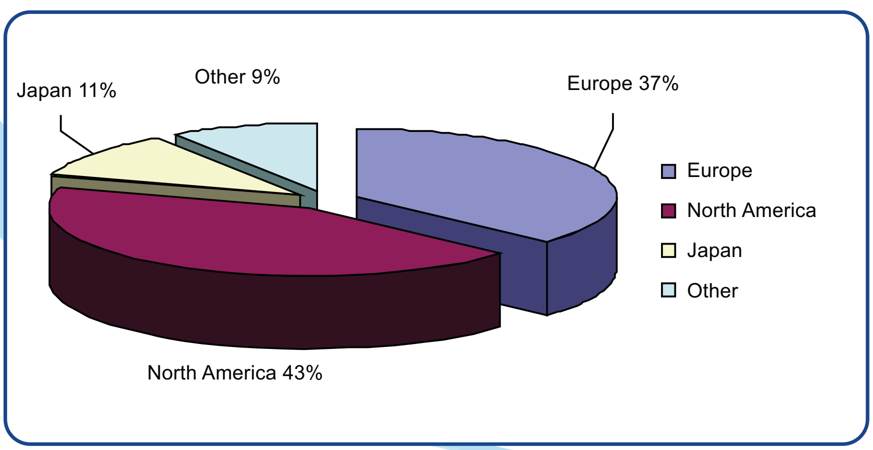


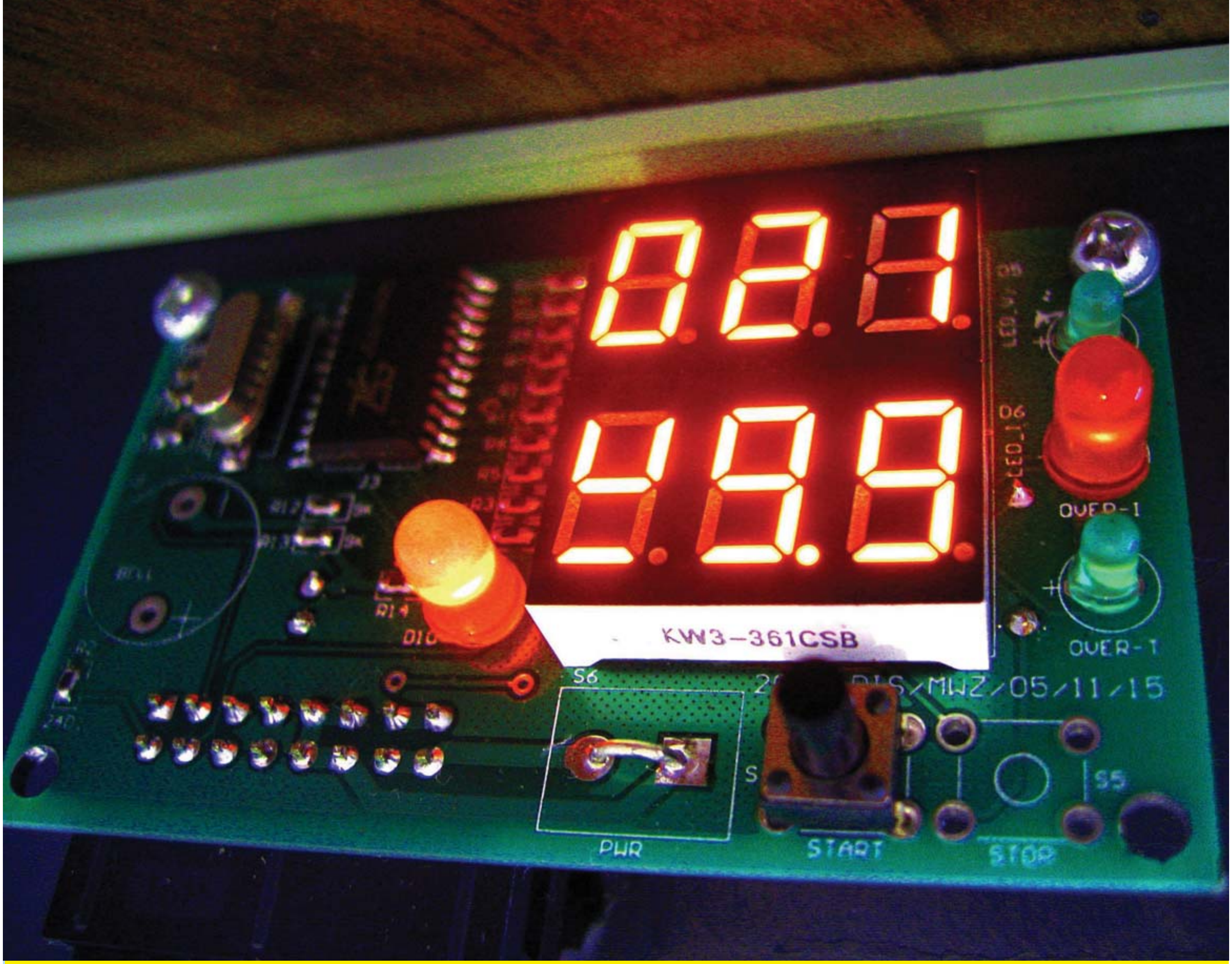
Figure 6-10. Worldwide Fueling Stations

The United States has the most hydrogen refueling stations. The majority of stations in the United States are located in California. Germany has the next highest number of refueling stations, followed by Japan. This correlates with the countries that have the highest funding for fuel cell and hydrogen infrastructure research. Figure 6-11 shows a hydrogen gas station in British Columbia, Canada.

Figure 6-11.
Hydrogen Gas Station
in British Columbia, Canada

6.6 Conclusions

Hydrogen has many unique properties that make it suitable for use as a fuel for stationary, transportation and portable applications. There are many ways that hydrogen can be used and stored, including compressed gas, liquid, metal hydrides, and carbon nanotubes. Several types of fuel processing systems can also be used to obtain hydrogen. Some common methods of processing hydrogen include steam reforming, internal reforming, partial oxidation, and methanol reforming, as well as many other types. Other methods of producing hydrogen include using electricity to electrolyze water, and producing hydrogen through the use of biological methods. The ultimate goal of fuel cell technology is to use pure hydrogen extracted using renewable sources of energy rather than fossil fuels.



Chapter 7

Basic Power Electronics

7.1 Introduction

Power electronics are a necessary part of the devices that many of us use on a daily basis. Driving a car, using a computer, and speaking on the telephone all depend upon power electronics. In order to begin to understand power electronics, a good understanding of basic electronics is necessary. Some of the essentials to understand include:

- Electrons, protons and neutrons
- Electricity
- Open circuit, short circuit and grounding
- Testing basics
- Circuits

The basis of electricity is electrons, and the majority of the studies which led to our understanding of how electrons control machines and process information was performed during the 20th century. Power electronics are very important for renewable energy devices because they convert the power from the energy source into a form of useful power for the load. Power electronics control the flow of electrical power through special devices that are described in more detail in the advanced topics in this chapter. Some common applications for power electronics in devices are voltage regulators, audio systems, electronic motor controllers and electronic ignitions. The power electronics may transform the direct current (DC) into alternating current (AC), help to increase the voltage of an energy system, regulate the power that a system provides, or create the proper waveforms and timing that a motor requires.

7.2 The Basics of Electronics

Electricity is made up of atoms. The three main types of atoms are protons, electrons and neutrons. Everything that you see is made up of atoms. The structure of an atom is similar to the earth revolving around the sun. The electrons are like the earth, and the "sun" of the atom is the nucleus. The nucleus is made up of neutrons and protons. Electrons have a negative charge, protons have a positive charge, and neutrons are neutral. [Figure 7-1] shows an illustration of the electrons and nucleus of an atom.

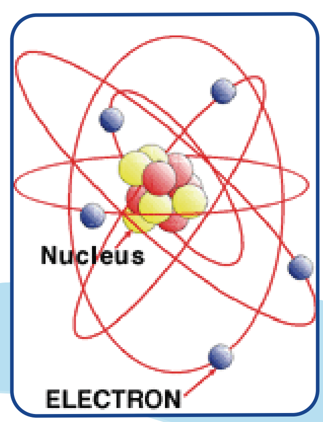


Figure 7-1. Illustration of an atom.

There are 118 types of atoms, as can be seen in a periodic table. Combinations of atoms make up every single element. The difference between the types of atoms in the periodic table are due to the arrangement of electrons, protons and neutrons in each atom. No matter how many particles an atom has -- the number of protons and electrons are the same for each element. This explains why the periodic table is numbered from 1 to 118; each element is specified by its the number of protons and electrons. As long as the number of protons and electrons are the same, the atom is balanced and stable.

If an atom loses an electron, it has more protons than electrons, and this atom would be called “positively-charged”. An atom that gains electrons is more “negatively charged”. Depending upon the type of material, electrons can be made to move between the atoms – and this creates a current of electricity. When one electron is attached to an atom, another electron is lost, which then moves to the next atom.

In order to create electricity, scientists have found ways to create large numbers of positively and negatively charged atoms. These groups have strong attractions to each other. The movement of electrons creates a current of electricity. When an electron is removed from an atom, it becomes positively-charged. Atoms in nature do not like to be positively or negatively-charged because they are unstable in this state. They need to obtain a stable or neutrally-charged state. In order to return to the balanced state, the atom wants to obtain a “free” electron. The positively charged atom wants a negatively-charged electron to return to a neutral state.

Electricity conducts better in certain materials. If the atoms in a material hold the electrons in their orbit very tightly, that particular piece of material will not conduct electrons well. The materials that do not conduct electrons well are called insulators. Some types of insulators include plastics, cloth, and glass. Materials that allow electrons to be easily moved from their orbits are called conductors. Some examples of conductors are called copper, aluminum, and steel. The measurement of how well something conducts electricity is called resistance. Resistance depends not only on the material, but how long the materials are. This determines the distance that the electrons need to travel.

Periodic Table of the Elements

Non Metal	Alkaline Earth	Alkali Metals
Transition Metal	Rare Earth	Basic Metal
Semi Metal	Noble Gas	Halogen

1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
1 H 1.00794																	2 He 4.002602
3 Li 6.941	4 Be 9.012182											5 B 10.811	6 C 12.0107	7 N 14.0067	8 O 15.9994	9 F 18.9984032	10 Ne 20.1797
11 Na 22.989769	12 Mg 24.3050											13 Al 26.9815386	14 Si 28.0855	15 P 30.973762	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.955912	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938045	26 Fe 55.845	27 Co 58.933195	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.798
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.96	43 Tc [98]	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.90447	54 Xe 131.293
55 Cs 132.9054519	56 Ba 137.327	57-71 Lanthanides	72 Hf 178.49	73 Ta 180.94788	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.084	79 Au 196.966569	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98040	84 Po [209]	85 At [210]	86 Rn [222]
87 Fr [223]	88 Ra [226]	89-103 Actinides	104 Rf [267]	105 Db [268]	106 Sg [271]	107 Bh [272]	108 Hs [270]	109 Mt [276]	110 Ds [281]	111 Rg [280]	112 Uub [285]	113 Uut [284]	114 Uuq [289]	115 Uup [288]	116 Uuh [293]	117 Uus [294]	118 Uuo [294]

Lanthanides	57 La 138.90547	58 Ce 140.116	59 Pr 140.90765	60 Nd 144.242	61 Pm [145]	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92535	66 Dy 162.500	67 Ho 164.93032	68 Er 167.259	69 Tm 168.93421	70 Yb 173.054	71 Lu 174.9668
Actinides	89 Ac [227]	90 Th 232.03806	91 Pa 231.03588	92 U 238.02891	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]	103 Lr [262]

7.2.1 Circuits

In electronics, electrons are "collected" into one place, and then moved using electronically-conductive materials. Electrons do not automatically "jump" into the air by themselves! They are bonded to molecules due to many types of forces. Circuits provide an environment to collect and move electrons from place to place, and from component to component. When a circuit is turned on, the switch is like a "bridge" that allows electricity to move through the circuit. Figure 7-2 shows a diagram of a simple circuit.

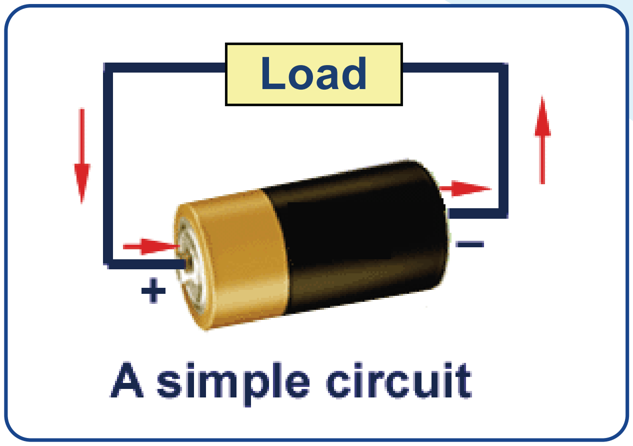


Figure 7-2. A simple circuit

In circuits, the number of electrons that move through the circuits can be manipulated and limited. This can be accomplished in several ways – using different types of materials, components and devices. When electrons are moving through material, they can collide with atoms along the way, which can slow them down, or even reverse their direction. When this occurs, the energy dissipates as heat.

The circuits inside electronic equipment are packed with components, which perform different jobs and are linked to each other by cables or metal connections. The job that a circuit performs is determined by a combination of standard components. These components can be assembled in a number of ways to do an infinite number of jobs.

Circuit boards are made of an insulator with the conductive materials embedded throughout the board which enables electricity to travel. Originally circuit boards used wires to connect the individual components on the board, but in the 1980s, surface mount technology began to be used. This technology allows very tiny components to be mounted mechanically onto a cool solder mixture. These components are connected using lines of copper. These copper lines are either put into the board mechanically, or they are placed into the board by coating the entire board in copper, and then striping away the excess. Some common parts of a circuit are illustrated in Figure 7-3:

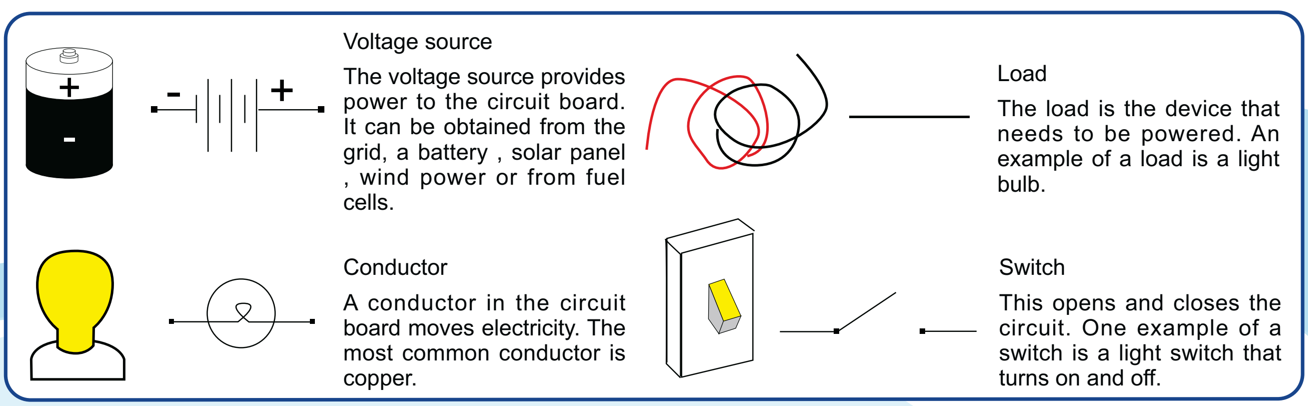


Figure 7-3. Common parts of a circuit board

7.2.2 Common Terms Used in Electronics Testing

Common terns that are used in electronics testing are open circuit voltage (OCV), grounding and short circuit. A useful measure of a power device is the open circuit voltage (OCV).

Open circuit voltage (OCV):
This is the difference in voltage between two terminals of a device when there is no load connected.

This means that there is no external electric current between terminals – although there may be currents within the device. The open-circuit voltages of fuel cells, solar cells and batteries are often given under certain temperatures or other conditions.

Grounding:
Grounding is a common reference point in an electrical circuit where other voltages are compared and measured. It is a common return path for electric current, which is back to the earth.

There are many reasons why electrical circuits are connected to the ground. In many types of power equipment, metal parts that are exposed are connected to the ground to prevent contact with a dangerous voltage if the electrical insulation fails. A ground connection limits voltage buildup between the power circuits and the earth. Ground connections also limit the buildup of static electricity when handling flammable products or repairing electronic devices.

Short circuit:
A short circuit occurs in a circuit when the current travels in another direction other than what was intended.

It is common to use the term "short circuit" to describe any electrical malfunction. Short circuits could potentially cause circuit damage, overheating, fire and/or explosion.

7.2.3 Testing Basics

One of the most useful and basic pieces of electronics testing equipment is the multimeter.

> ***Multimeter:***
> A multimeter is a device that measures current, resistance, and voltage, or amps, ohms, and volts.

To use a multimeter, the meter must first be turned on, and then the probes must be inserted into the correct positive and negative terminals. Depending upon what you are testing, the correct measurement type and range should be selected. A slightly higher voltage range should be used to ensure that the meter will not be overloaded.

7.2.3.1 Testing Voltage

To test voltage, switch the multimeter to an appropriate voltage range so that the meter will not be overloaded and damaged. The test leads are plugged into the correct sockets. Multimeters usually have two leads: one black (negative) and one red (positive). The black one is connected to the negative socket, and the red one should be connected to the positive socket.

The positive lead should be connected to the terminal on the device that has a positive charge. If the leads are connected the wrong way, a negative voltage will result. Power should be applied to the circuit after the multimeter has been connected.

7.2.3.2 Testing Current

To measure current with a multimeter, the meter should be turned on, and the probes should be inserted into the correct connections. The correct type, current and range should be selected for the current that you need to read. It is useful to optimize the range to ensure the leading digits will read something other than zero, which will allow the greatest number of significant digits to be read.

7.2.3.3 Testing Resistance

To measure resistance with a multimeter, insert the probes into the correct connections, and turn on the multimeter. In order to obtain the most accurate readings, each component should be measured when they are not connected in a circuit. If the measurement of a single component is made in a circuit, the other components around it will affect the readings and make them inaccurate to a certain degree. Also, the circuit that is being tested should not be powered on. Any current flowing in a circuit will invalidate the readings, and if the voltage is high enough – it can damage the meter. Be aware of your fingers on the component when you are making measurements. Your fingers can also change the readings, and under certain conditions, this can be noticeable.

7.3 Analog and Digital Electronics

There are two methods of storing information in electronics: analog and digital. These methods are analagous to many basic concepts in electronics – such as alternating and direct current, which are explained throughout this chapter. Analog methods of storing information use waves to capture and interpret data. Electronic equipment works on information in either analog or digital format. In an old-fashioned radio, the signals that are flowing through the air – radio waves -- are picked up by the antenna. The radio transmitter keeps the signals in analog form as it receives them, and transforms the up and down patterns of the wave form into sounds that you can hear. Another example of analog technology is a traditional film camera, which captures the light through the shutter as a pattern of light and dark areas on the chemically-treated plastic. In a digital format, the signals travel as coded numbers. Most modern equipment uses digital electronics. If a digital camera is used to take the photograph, the light and dark areas are converted into numbers, and store the numbers instead. These numbers are then translated in the device to a full color picture. Figure 7-4 shows an example of a modern digital camera with an analog camera.

Figure 7-4.
(a) An example of a modern digital camera,
and (b) an analog camera

7.4 Ohm's Law

The basic laws for electronics and elementary circuits were developed in the early 1800s by German physicist, Georg Simon Ohm and are known as Ohm's law. Ohm's law is a mathematical equation explaining the relationship between voltage, current, and resistance within electrical circuits. It can be expressed as follows:

$$V = I \times R$$

where V is the voltage, which is measured in volts, I is the current measured in amps, and R is the resistance, which is measured in ohms. Voltage is a measure of free electron activity and the driving force through the resistor (it pushes the electrons along the circuit); the current is the amount of charge passing through the resistor in a given time. The electrons in a circuit are always trying to reach a state of equilibrium.

Another measure of free electron activity in a circuit is power. Power is a measure of how much work can be performed in a given amount of time. The heavier the weight, or the higher it is lifted, the more work needs to be done. Power is a measure of the rate at which a certain amount of work is done, and it is expressed by the following equation:

$$P = I^2 \times R = \frac{V^2}{R} = I \times V$$

where P is the power (Watts), I is the current (Amps) and R is the resistance (ohms). The unit of measurement for power is Watts, and it is a combination of both current and resistance.

7.5 History of Electronics

In the early 1900s, the invention of the two-element electron tube (1904) by John Ambrose Flemming, and the three-element tube (1906) by Lee De Forest began the electronics industry [22]. These inventions led to the development of the commercial radio in the 1920s. Two corporations brought radio technology into public use: Radio Corporation of America (RCA), a joint venture between GE, Westinghouse and AT&T) and Telefunken (a joint venture between Siemens and AEG) [23]. By the end of the 1920s, radio sales were $300 million [22]. During World War II Telefunken began focusing in other areas which allowed, RCA to be solely responsible for commercializing television worldwide. When John Bardeen, Walter Brattain, and William Shockley invented the transistor in 1947, the electronics industry made another important advance. Since transistors were smaller and lighter than the vacuum tubes that were being used in radios, a period of miniaturization of electronic devices was able to develop. The invention of integrated circuits in the 1950s allowed the integration of several circuits onto one circuit, and the introduction of the analog devices in the 1960s increased the amount of information that could be stored on a single chip [22].

A single enterprise singlehandedly led the computer industry: IBM. IBM has dominated the computer industry in terms of revenues and product lines. In the 1970s, the Japanese industry became competitive by making and marketing IBM –like compatible computers. In the 1980s, the most successful producers of computers imitated IBM computers. IBM was the dominant data-processing enterprise well before the electric computer came around. From its inception in 1914, IBM created an integrated learning base to commercialize new data processing punch-card technology. In the 1920s, IBM was manufacturing its electrically-driven data processing equipment. A competitor, Remington Rand, was the first to move to typewriters for data processing, but by the 1930s, it had never gained more than 15 percent of the market. After WWII, Remington Rand acquired two of the four projects in developing high speed analytical devices for military purposes. It introduced the UNIVAC -- the first commercial computer. IBM also immediately came out with its own 700 MHz computer.

The first power semiconductor devices appeared in 1952 with the power diode developed by R. N. Hall. The power diode was made of Germanium, and operated at 200 volts and a current rating of 35 amperes. The thyristor was created in 1957, and it was able to withstand very high reverse breakdown voltage and high current. The first bipolar transistors were introduced in the 1960s, and these overcame some limitations of the thyristors because they were turned on or off with a signal.

Power MOSFETS (metal–oxide–semiconductor field-effect transistor) became available in the 1970s using the improved Metal Oxide Semiconductor technology that was originally developed for integrated circuits. These devices allowed higher frequency than bipolar transistors, but could only be used for low-voltage applications. Electronics are devices that allow electrons to be directed around circuits to process signals, or store and process information. Electronics is the study of the flow of electrons as they are directed around circuits to process signals or store and process information.

7.6 Power Electronics for Renewable Energy Systems

Hybrid renewable energy power systems are positioned to become the long-term power solution for portable, transportation and stationary system applications. Hybrid power systems are virtually limitless in possible setups and configurations that will produce the desired voltage for a particular system. A hybrid system can consist of solar panels, wind power, fuel cells, electrolyzers, batteries, capacitors, and other types of power devices.

Hybrid systems can be setup with power electronics to handle low, high, and variable power requirements. For example, solar panels can be used to convert solar energy into electrical energy to the system when sunlight is directly hitting the PV panels for maximum efficiency, and power from wind turbines can be used when wind speed and direction is ideal. The energy from these devices can be stored in batteries and used for electrolysis to produce hydrogen. The hydrogen will then be fed to fuel cells to provide power for long periods of time, or for portable devices or transportation applications. Power electronics provide a key element in stabilizing, and boosting voltage and power, and providing other features such as saving or providing more power when necessary.

The electrical output of a power system may not be the correct input needed for powering certain devices. Many applications, such as grid power or residential power require AC power. Some devices such as cell phones require DC power. The output of all fuel cells, however, is DC voltage, the intensity of which varies depending on the number of cells stacked in series. An inverter can be used to change the output from DC to AC power when needed. Also, many renewable energy systems are slow to respond to higher power needs, and may have slow startup times. Therefore, systems usually have to be designed to compensate for high power needs, or intermittent power. Power converters can be used to regulate the amount of power flowing through a circuit. Figure 7-5 shows a general schematic with a fuel cell that illustrates the power electronics component as a key element in the fuel cell system.

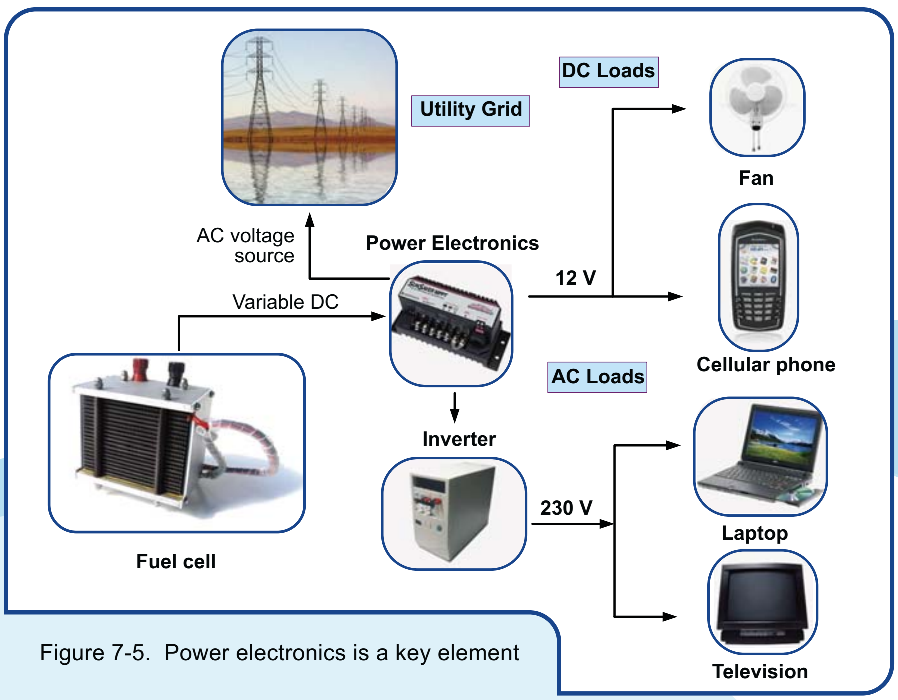


Figure 7-5. Power electronics is a key element

Chapter 7

Most renewable energy technologies only give a certain voltage and current density (depending upon the load) to the power converter. The power converter must then adjust to whatever voltage is available from the fuel cell to a voltage high enough to operate the load. As shown in Figure 7-6, a DC-DC boost converter is required to boost the voltage level for the inverter. This boost converter, in addition to boosting the fuel cell voltage, also regulates the inverter input voltage and isolates the low and high voltage circuits [11].

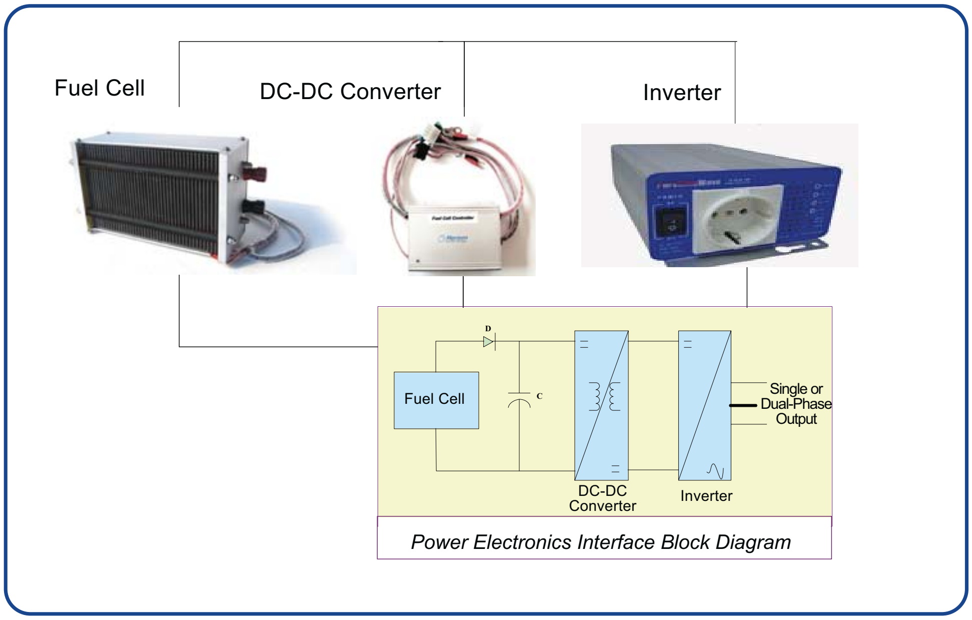


Figure 7-6.
A typical fuel cell power electronics interface block diagram

An example of a hybrid power system is shown in Figure 7-7. This fuel cell/lithium-ion battery charger system includes the following major components: the fuel cell, the lithium-ion battery, a constant voltage regulation system, and a smart battery charger [11].

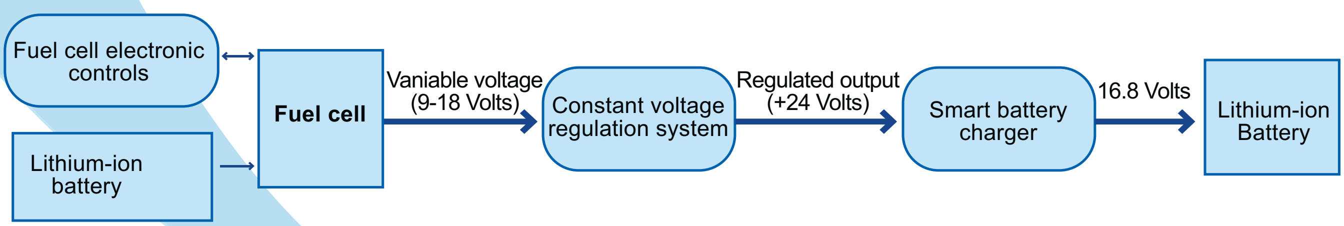


Figure 7-7. A diagram of the overall fuel cell/Li-ion charger system [11]

A rechargeable lithium-ion battery can be located inside the fuel cell unit to maintain the microcontroller in a low-power standby or programmed-timer sleep state for several days. The battery will also allow the system immediate startup and save the system during shutdown. The battery will be automatically charged whenever the fuel cell is running. The internal battery charging circuit will stop charging the Li-ion battery once it has reached a certain voltage or has been charged for a specific amount of time [11].

7.7 Types of Semiconductor Power Devices

Typical types of power devices used in hybrid systems are the power diode, thyristor, power MOSFET and IGBT. Simple changes are made in power electronics to accommodate higher current density, power dissipation, and higher reverse breakdown voltage. Power devices are divided into two main categories [21]:

1. Two terminal devices, where the state is dependent upon the external power circuit that they are connected to. An example of the diode.
2. Three terminal devices depend upon the external power circuit and upon the signal hat is driving the terminal. Examples are transistors and thyristors.

The other classification of power devices are majority and minority carrier devices. Majority carrier devices are Schottky diode and MOSFET. Examples of minority carrier devices are the thyristor, bipolar transistor and the IGBT. The majority devices use only one type of charge carrier (for background, see Chapter 2) and are faster, and the minority devices use both electrons and holes for better on-state performance. The groups of power devices are shown in Figure 7-8.

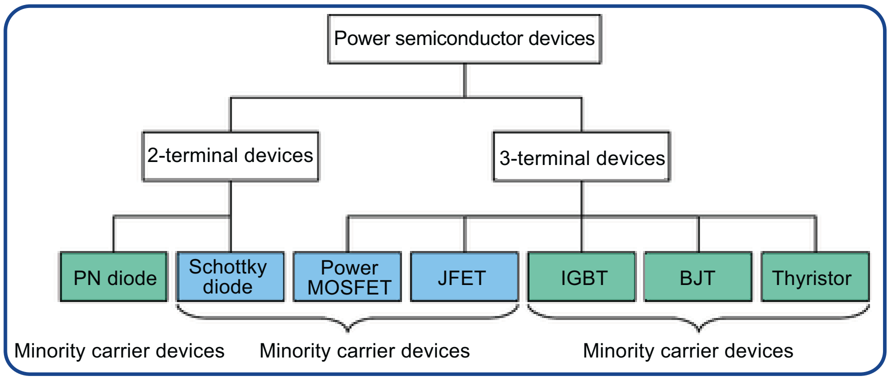


Figure 7-8.
Types of semiconductor power devices

The current generated by solar panels, wind turbines, and fuel cells is direct current (DC), which is advantageous for many smaller fuel cell systems. Larger renewable energy systems that connect to the power grid must be converted to alternating current (AC) using inverters. The basics of power semiconductor devices can be classified as [11]:

- Diodes
- Thyristors or silicon controlled rectifiers (SCRs)
- Power MOSFET
- Insulated gate bipolar transistor (IGBT)
- Integrated gate-commutated thyristor (IGCT)

These devices are described briefly in Sections 7.7.1 through 7.7.8.

7.7.1 Power Diodes

Power diodes are used in DC-DC, DC-AC, and AC-DC power conversion. Figure 7-6 shows the diode symbol, and images of various types of diodes.

> ***Diode:***
> A diode is a simple circuit element that only allows the current to flow in one direction, but not in the reverse direction. This process is also called rectification.

Due to the fact that diodes only allow current to flow in a certain direction, they are widely used in the conversion of alternating current (AC) to direct current (DC). Small signal diodes can be used as rectifiers in low-power, low current applications, but if larger currents and higher voltages are used, power diodes have to be used to prevent the PN-junction of a signal diode from melting (see Chapter 2 for more information about PN-junctions).

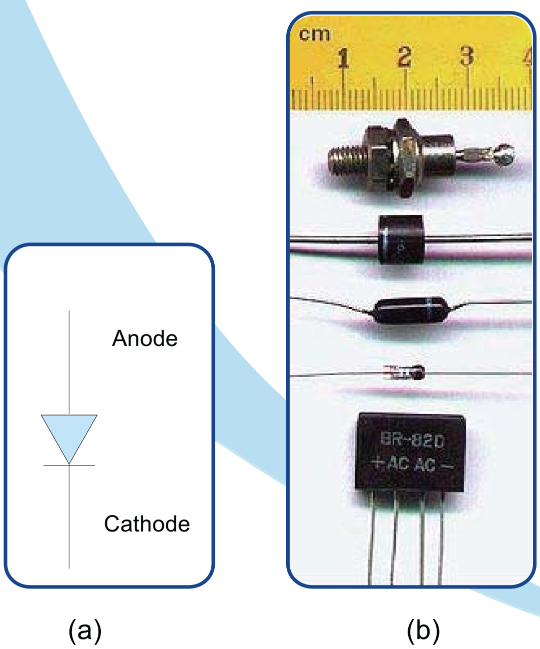


Figure 7-9. (a) Diode symbol and (b) various types of diodes

7.7.2 Switching Devices

Fuel cells, solar panels and wind turbines give a very unregulated voltage, and since most electronic and electrical equipment require a steady voltage, the voltage output must be regulated. The voltage can be regulated by dropping the voltage down to a fixed value under the operating voltage, or boosting the voltage to a fixed voltage [11]. Typically, the voltage is boosted to a higher voltage. The voltage adjustments can be achieved by switching or chopping circuits. The basic electronic switches that will be discussed are the MOSFET, IGBT, and the thyristor.

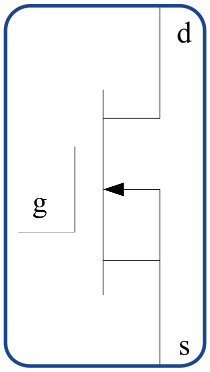
7.7.2.1 Power MOSFET

The metal oxide semiconductor field effect transistor (MOSFET) is a voltage-controlled device that is turned on by applying a voltage to the gate.

> ***MOSFET:***
> MOSFET is a type of transistor that carries electrons that flow along channels. How well the device conducts is dependent upon the width of the channels, which are controlled by a gate.

> ***GATE:***
> A gate is an electrode that is separated from a channel by a thin layer of oxide insulation. The insulation can keep current from flowing between the gate and channel.

When the device is "on," the resistance between the drain (d) and source (s) is very low. Figure 7-10 shows an example MOSFET device. MOSFETs are typically used in systems that have a power of less than 1 kW [11]. Common MOSFET applications are switch mode power supplies and battery charging.



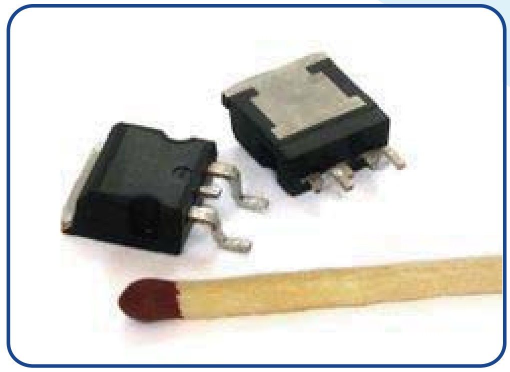


Figure 7-10.
(a) Example of a MOSFET device,
and (b) surface mount power MOSFETs

(a) (b)

7.7.2.2 Insulated Gate Bipolar Transistor (IGBT)

The IGBT (insulated gate bipolar transistor) is a device that combines a MOSFET and a conventional bipolar transistor. In case you were wondering.

Bipolar transistor:
A semiconductor device that is used for amplification. It can amplify both analog and digital signals. It usually amplifies current, but can be connected in circuits to amplify voltage or power.

IGBT:
A device that combines a MOSFET and a conventional bipolar transistor.

The IGBT requires a fairly low voltage with minimal current at the gate to turn on. The main current flow is from the collector to the emitter, and the voltage does not rise much above 0.6 V with any current within the device. Figure 7-11 shows an example The IGBT is the preferred choice in systems from 1 kW to several hundred kilowatts [11]. One of the reasons is because the IGBT can reach voltages of 1700 volts with a maximum current of 600 amps, with switching times of 1 to 4 microseconds. Common IGBT applications are DC-AC inverters for motor control, backup power systems, and low power lighting.

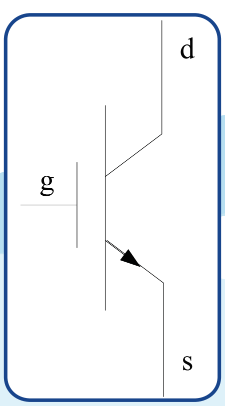


Figure 7-11.
(a) Example of an IGBT device,
(b) image of a IGBT device

(a) (b)

Chapter 7

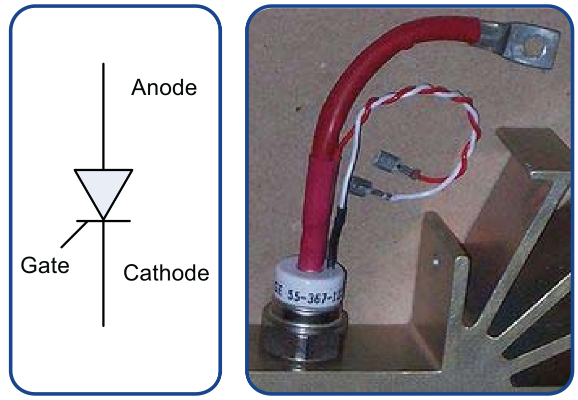
7.7.2.3 Thyristors or Silicon Controlled Rectifiers (SCRs)

One of the most common electronic switches is the thyristor, which can only be used as an electronic switch.

Thyristor:
A semiconductor component that only allows current flow in one direction, but it is switched like a transistor. Once it is turned on, current flows until it falls below a certain threshold.

These devices block the voltage in both the forward and reverse directions. A pulse of current into the gate triggers the transition from the blocking to the conducting state. The device continues to conduct until the current falls to zero. Figure 7-12 shows an example of a thyristor device.

The energy required to effect the switching is greater in the thyristor than in the MOSFET or IGBET. The main advantage of the thyristor for DC switching is that higher currents and voltages can be switched, even though the switching times are much longer. Commercial thyristors are available with very large current and voltage ratings [11]. Thyristors have applications in high-power static bypass switches and in backup power systems.



(a) (b)

Figure 7-12.
(a)An example of a thyristor device, and (b) an SCR rated about 100 amperes, 1200 volts mounted on a heat sink - the two small wires are the gate trigger leads

Figure 7-13. Image of IGCT devices

7.7.2.4 Integrated Gate-Commutated Thyristor (IGCT)

The integrated gate-commutated thyristor (IGCT) is a high-voltage, high-power device, that was just introduced in 1997 [11].

IGCT:
An advanced semiconductor device for high frequency, high power applications. The IGCT are like a thyristor, and can be turned on and off with a gate signal.

This device is an asymmetric-blocking gate turn-off thyristor (GTO) that requires a negative turnoff current. This IGCT is commonly used in power distribution systems installations such as medium voltage static transfer switches and industrial drive systems. Figure 7-13 shows images of IGBT devices.

7.8 Converters for Power Systems

The two basic power electronics areas that need to be addressed in renewable energy applications are power regulation and inverters. The electrical power output of a solar cells, wind turbines and fuel cells are not constant. The fuel cell voltage is typically controlled by voltage regulators, DC/DC converters, and other circuits at a constant value that can be higher or lower than the fuel cell operating voltage.

Multilevel converters are of interest in the distributed energy resources area because several batteries, fuel cells, solar cells, and wind turbines can be connected through a multilevel converter to feed a load or grid without voltage-balancing problems. The general function of the multilevel inverter is to create a desired AC voltage from several levels of DC voltages. For this reason, multilevel inverters are ideal for connecting an AC grid either in series or in parallel with renewable energy sources such as photovoltaics or fuel cells, or with energy storage devices such as capacitors or batteries. Multilevel converters also have lower switching frequencies than traditional converters, which results in reduced switching losses and increased efficiency [11].

Advances in fuel cell technology require similar advances in power converter technology. By considering power conversion design parameters early in the system design, a small, inexpensive converter can be built to accompany a reasonably sized solar panel, wind turbine or fuel cells for high system power and energy density.

7.8.1 DC-to-DC Converters

A DC-to-DC converter is used to regulate the voltage because the output of a renewable energy system varies with the load current. Many fuel cell and solar cell systems are designed for a lower voltage; therefore, a DC-DC boost converter is often used to increase the voltage to higher levels. A converter is required for these renewable energy systems because the voltage varies with the power that is required. It may drop from 1.23 V DC (no-load) to below 0.5 V DC at full load [11]. Consequently, a converter will have to work with a wide range of input voltages.

DC-to-DC converters are important in portable electronic devices such as cellular phones and laptop computers where batteries are used. These types of electronic devices often contain several sub-circuits, that each has its own voltage level requirement that is different than supplied by the battery or an external supply. As the battery's stored power is drained, a DC-to-DC converter offers a method to increase voltage from a partially-lowered battery voltage which saves space instead of using multiple batteries to accomplish the same task. Figure 7-14 shows images of DC-to-DC converter devices.

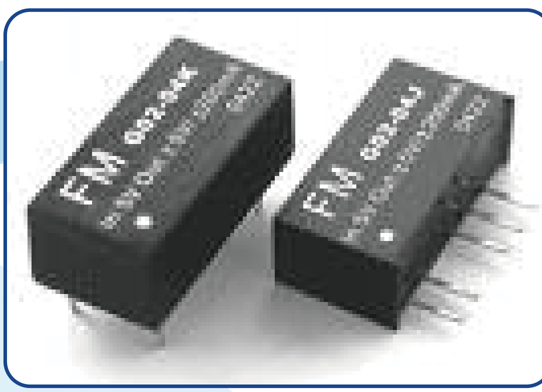


Figure 7-14. DC to DC converters

7.8.2 Inverters

Renewable energy can be used in both homes and businesses as the main power source. These energy systems will have to connect to the AC grid. The renewable energy system output will also need to be converted to AC in some grid-independent systems. An inverter can be use to accomplish this.

Inverter:
An electrical device that converts direct current (DC) into alternating current (AC).

The resulting AC current can be at the required voltage and frequency for use with the appropriate transformers and control circuits. Inverters are used in many applications from switching power supplies in computers to high voltage direct current applications that supply bulk power. Inverters are commonly used to apply AC power from DC sources such as fuel cells, solar panels and batteries. Figure 7-15 shows an image of an inverter.

Figure 7-15. An image of an inverter.

7.9 Conclusions

This chapter described how electronics are an important part of devices that we use every day, and how they are a critical part of hybrid energy systems. Since the study of power electronics is an advanced topic in electronics, a good understanding of basics electronics is essential. Some important basic concepts to know are electrons, protons, neutrons, circuits, open circuit, short circuit, and grounding. Power electronics are required for every energy system because they insure that the power generated by the system is able to be used to power the load. It does this using special electronic components such as diodes, thyristors or silicon controlled rectifiers (SCRs), power MOSFETs, insulated gate bipolar transistors (IGBT), and integrated gate-commutated thyristors (IGCT). These components help to transform direct current (DC) into alternating current (AC), help to increase the voltage of an energy system, regulate the power that a system provides, and/or creates the proper waveforms and timing that a motor requires. Without integrating these electronics into the system, the voltage and power produced by an energy system would not be very useful. Therefore, power electronics is an essential part of any hybrid energy system.

Summary

Energy is vital for the continued development of our modern civilization. Fossil fuels have been critical for technology development, and modernization of our society. It has also resulted in many negative consequences, such as severe pollution, extensive mining of the world's resources, and domination and control of countries that have fossil fuel resources. The demand for energy is increasing due to the growing global population, and the increasing amount of energy used per person. In addition, the amount of fossil fuels left for mining is diminishing, with experts estimating that there is approximately 30 – 40 years left. Therefore, the end of low-cost oil is approaching.

Although the use of fossil fuels for energy has helped create today's modern civilization, the pollution generated by fossil fuels has affected the earth's atmosphere. Fossil fuels have accelerated the natural "greenhouse effect". The greenhouse effect is generally a good phenomenon because it keeps the earth warm, and enables life to survive. Changes in climate usually take tens of thousands of years. Although 1° or 2° Celsius may not seem significant, small temperature changes can have large effects. During natural ice ages, the average global temperature was only 5 °C cooler than they currently are.

Greenhouse gas emissions contribute directly to health problems, acid rain and formation of ozone. In many parts of China and India, air pollution remains a public health issue. Acid rain occurs when sulfur dioxide (SO_2), sulfur trioxide (SO_3) and nitrogen dioxide (NO_2) in the atmosphere undergo chemical reactions to form acidic compounds. These are absorbed by water droplets in the clouds, and then fall to the earth, increasing the acidity of the ecosystem. This can damage plant life, soil, and buildings. Most acidic compounds are deposited near the source of contamination, but they can also be carried in the atmosphere for hundreds or thousands of miles. In order to stabilize the CO_2 level, it needs to peak, and then decline. The more quickly that this occurs, the lower the peak stabilization level.

There are many energy technologies that can be used to replace fossil fuels. These include solar, wind, hydroelectric power, bioenergy, geothermal energy as well as many others. Solar cells use the sun to generate electricity, wind power is obtained from the kinetic energy of the wind, and bioenergy is extracted from plants. Each of these renewable energy sources has its advantages and disadvantages, and all are in varying stages of development. The most promising and developed of these technologies is solar, wind, and fuel cell power. A hybrid system containing all of these technologies used in conjunction with electrolysis would be ideal.

Solar power can be used for both large and small applications. The heat and the light from the sun provide an endless amount of energy, and can be harnessed in many ways. There are many technologies that can be used to take advantage of solar energy, including concentrating solar power systems, passive solar heating and day lighting, solar hot water, and solar space heating and cooling. Businesses and industry can diversify their energy sources, improve efficiency, and save money by choosing solar technologies. Homeowners can use solar energy for heating and cooling, industrial processes, electricity, and water heating.

Wind power harnesses the motion of the wind to provide kinetic energy. The kinetic energy of the wind is captured by the turbine blades when they start moving. The moving of the blades spins a shaft, which leads to a generator. The rotational energy is then turned into electrical energy. At high elevations, they can take advantage of the faster and less turbulent wind. Wind turbines can be used as stand-alone applications, or they can be connected to a utility power grid or combined with a photovoltaic or hybrid energy system. For utility-scale (megawatt-sized) sources of wind energy, a large number of wind turbines are usually built close together to form a wind farm. Several public electricity providers today use wind plants to supply power to their customers. Wind turbines are mounted on a tower to capture the most energy.

Electrolysis uses electricity to break water into hydrogen and oxygen. This process can produce ultra-pure hydrogen produced directly at any location, at the time that it is needed; therefore, it does not necessarily have to be stored. This is the ideal method of producing hydrogen for hydrogen fuel cells. If this system is designed properly, it is a much cheaper method than gas supplied in high-pressure cylinders. Electrolyzers would be very useful if they are integrated into stationary, portable, and transportation power systems to generate hydrogen. It would also be a useful addition to a system that uses solar and wind power because hydrogen can be used to power fuel cells when the solar and wind power is intermittent.

Fuel cells convert chemical energy directly into electricity and heat with high-efficiency. These devices can be used anywhere at anytime, for as long as necessary as long as hydrogen is supplied. Fuel cells are one of the few alternative energy devices that can be used for any energy application – it can power portable electrons, automobiles, houses, buildings, and even space ships. Fuel cells have the ability to fulfill all of our power needs in the stationary, transportation and portable power industry. The type most commonly used for transportation and portable applications is the polymer electrolyte membrane (PEM) fuel cell. PEM fuel cells typically use hydrogen as the fuel, but also have the ability to use other types of fuel as well. Hydrogen has many unique properties that make it suitable for use as a fuel for any application. There are many ways that hydrogen can be used and stored, including gaseous, liquid and solid forms. Hydrogen can be produced by many processes: steam reforming, internal reforming, partial oxidation, methanol reforming, and ideally – by electrolysis. The ultimate goal of fuel cell technology is to use pure hydrogen extracted from renewable sources of energy rather than fossil fuels.

Without electronics, we would not have any of the modern devices that we take for granted. Power electronics are unique electronic devices that are a critical part of hybrid energy systems. Power electronics are required for every energy system because they insure that the power generated by the system is able to be used to power the load. It helps to transform direct current (DC) into alternating current (AC), help to increase the voltage of an energy system, regulate the power that a system provides, or create the proper waveforms and timing that a motor requires. Without integrating these electronics into the system, the voltage and power produced by an energy system may not be able to be used at all.

The future energy economy will consist of many renewable energy technologies used in combination. In order to successfully have a society based upon renewable energy, there has to be a way to store energy because renewable energy is intermittent. Solar and wind energy are both excellent methods of obtaining energy from natural resources, however, the levels of sunshine, and the intensity of wind varies. When these sources are not available – electricity cannot be generated. When a large amount of energy is being produced, hydrogen can be created from water. The hydrogen can then be stored for use with hydrogen fuel cells. Once the cost of renewable energy technologies becomes competitive with the rising oil costs, the fossil-fuel based economy will be replaced with the new renewable energy economy.

An ideal hybrid renewable energy system includes solar, wind, and fuel cell power combined with electrolysis. These technologies are demonstrated by the Renewable Energy Education Kit. This education kit demonstrates the principals behind the future renewable energy economy. We are a fossil fuel-based economy today; however, the transition to the renewable energy economy has already begun. We hope that the energy technologies in this kit will motivate you to seek further information about renewable energy, experiment and build prototypes, and possibly help to improve these technologies one day as an engineer or scientist. We are currently working on reducing the costs associated with the future energy economy, because the future renewable energy economy will soon be here.

Sources

[1] Energy Information Administration. (2008). International Energy Outlook 2008, Washington DC, November 2008 (No. DOE/EIA-0484(2008)). Retrieved January 25, 2009 from http://www.eia.doe.gov/oiaf/ieo/index.html

[2] International Energy Agency, Organization for Economic Co-operation and Development. (2008). World Energy Outlook 2008. Retrieved from http://www.sourceoecd.com/

[3] IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved February 4, 2009 from http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_SPM.pdf

[4] Hegerl, G.C., F. W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved February 4, 2009 from http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch09.pdf

[5] Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp. Retrieved February 8, 2009 from http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf

[6] Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved February 8, 2009 from http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch01.pdf

[7] Carnegie Institution (2007, March 16). Crops Feel The Heat As The World Warms. ScienceDaily. Retrieved February 25, 2009, from http://www.sciencedaily.com-/releases/2007/03/070316072609.htm

[8] World energy resources and consumption. (2009, February 2). In Wikipedia, The Free

Encyclopedia. Retrieved 05:28, February 2, 2009, from http://en.wikipedia.org/w/index.php?title=World_energy_resources_and_consumption&oldid=272714347

[9] Gray, D., White, C. & Tomlinson, G., National Energy Technology Laboratory. (2007). Increasing Security and Reducing Carbon Emissions of the U.S. Transportation Sector: A Transformational Role for Coal with Biomass, Washington DC, August 2007 (No. DOE/NETL–2007/1298). Retrieved January 28, 2009 from
http://www.netl.doe.gov/energy-analyses/pubs/NETL-AF%20CBTL%20Study%20Final%202007%20Aug%2024.pdf

[10] Spiegel, C.S. (2008). PEM Fuel Cell Modeling and Simulation Using MATLAB, 1st Ed. New York: Elsevier Science.

[11] Spiegel, C.S. (2007). Designing and Building Fuel Cells, 1st ed. New York: McGraw-Hill.

[12] Masters, G.M. (2004). Renewable and Efficient Electric Power Systems, 1st ed. Hoboken, NJ: John Wiley & Sons, Inc.

[13] Boyle, G. (2004). Renewable Energy: Power for a Sustainable Future, 2nd ed. Oxford: Oxford University Press.

[14] Solar cell. (2009, February 4). In Wikipedia, The Free Encyclopedia. Retrieved 05:56, February 4, 2009, from http://en.wikipedia.org/w/index.php?title=Solar_cell&oldid=273042670

[15] Kurczewski, N. (June 27, 2008). "How Eclectic!" AutoWeek. June 18, 2007. Retrieved from http://www.autoweek.com/apps/pbcs.dll/article?AID=/20070612/FREE/70608014

[16] Gipe, P. (2004). Wind Power: Renewable Energy for Home, Farm and Business, 1st ed. White River, VT: Chelsea Green Pub.

[17] Wind power. (2009, February 15). In Wikipedia, The Free Encyclopedia. Retrieved 06:16, February 15, 2009, from http://en.wikipedia.org/w/index.php?title=Wind_power&oldid=272831096

[18] Rajeshwar, K, McConnell, R., Licht, S. (2008). Solar Hydrogen Generation: Toward a Renewable Energy Future, 1st ed. New York: Springer.

[19] Li, X. (2005). Principles of Fuel Cells. New York: Taylor & Francis.

[19] Electrolysis of water. (2009, February 20). In Wikipedia, The Free Encyclopedia. Retrieved 06:30, February 20, 2009, from http://en.wikipedia.org/w/index.php?title=Electrolysis_of_water&oldid=273108169

[20] Hydrogen tank. (2009, January 2). In Wikipedia, The Free Encyclopedia. Retrieved 06:43, February 2, 2009, from http://en.wikipedia.org/w/index.php?title=Hydrogen_tank&oldid=261554690

[21] Power semiconductor device. (2009, January 28). In Wikipedia, The Free Encyclopedia. Retrieved 06:47, February 22, 2009, from http://en.wikipedia.org/w/index.php?title=Power_semiconductor_device&oldid=266985889

Image Sources

P1/P2/P8/P9/P21/P23/P38/P44/P46/P53/P87	http://www.istockphoto.com/
P7	http://space.lamost.org/
P23	http://www.altenergystocks.com/archives/solar/
P42	http://www.sonoma.edu/users/f/freidel/global/207lec2images.htm
P45	http://greenterrafirma.com/wind%20turbines.html
P104	http://en.wikipedia.org/wiki/File:S9000.jpg

Figure 1-8	http://www.ipcc.ch/index.html
Figure 1-10	http://en.wikipedia.org/wiki/File:Viking2lander1.jpg
Figure 1-11	http://en.wikipedia.org/wiki/File:Water_cycle.png
Figure 1-12	http://en.wikipedia.org/wiki/Sea_level
Figure 1-14	http://en.wikipedia.org/wiki/Energy_demand
Figure 1-15	http://en.wikipedia.org/wiki/Subaru_R1e http://en.wikipedia.org/wiki/File:FCX_Clarity.jpg
Figure 1-16	http://www.nasa.gov/centers/glenn/technology/fuel_cells.html
Figure 2-1	http://www.solarpanelsplus.com/solar-panel-pictures/
Figure 2-3	http://www.nrel.gov/pv/pv_manufacturing/cost_capacity.html
Figure 2-5	http://en.wikipedia.org/wiki/Solar_cell
Figure 2-6	http://science.hq.nasa.gov/kids/imagers/ems/index.html
Figure 2-8	http://electronics.howstuffworks.com/led1.htm
Figure 2-9	Solar panels: http://free-stock-photos.com/science/solar-panel-1.html Battery & inverter http://www.fuellessusa.com/5000WATT.html Fan: http://www.isplc2006.org/b2b/paraffin/1/wall_fan_8.html Cell phone: http://www.topcellphonereviews.org/ Laptop: http://blog.loaz.com/timwang/index.php/2007/04/03/mini_laptops TV: http://www.fotosearch.com/PDS051/ls016154/ Charge controller: http://greenhome.huddler.com/products/morningstar-sunsaver-mppt-controller
Figure 2-14	http://www.time.com/time/specials/2007/article/0,28804,1677329_1677971_1677977,00.html
Figure 2-15	http://flickr.com/photos/joeross/2224566267/
Figure 3-1	http://www.greenlivingtips.com/articles/65/1/How-wind-turbines-work.html
Figure 3-8	http://www.greentown.ca/Images/vertical%20wind%20turbine.jpg
Figure 3-15	http://www.wind-works.org/articles/marlec910f.html
Figure 4-1	http://www.sparknotes.com/chemistry/electrochemistry/electrolytic/section1.html
Figure 4-2	http://chem.ch.huji.ac.il/history/nicholson.html
Figure 4-3	http://www.sespi.it/sezione.php?language=1&cod=2&s=18
Figure 4-4	http://www.encyclopedia.com/topic/electrolysis.aspx
Figure 5-1	http://www.princeton.edu/~chm333/2002/spring/FuelCells/fuel_cells-history.shtml
Figure 5-2	http://commons.wikimedia.org/wiki/File:1839_William_Grove_Fuel_Cell.jpg
Figure 6-1	http://www.nrel.gov/data/pix/Jpegs/05048.jpg

Figure 6-2	http://www.linde-le.com/process_plants/hydrogen_syngas_plants/gas_products/syngas.php
Figure 6-3	http://en.wikipedia.org/wiki/Biomass
Figure 6-4	http://www.encyclopedia.com/topic/electrolysis.aspx
Figure 6-5	http://www.praxair.com/praxair.nsf/0/3A0AB529A089B473852571F0006398A3/$file/027847_PRAX_RefinSpec_4_low_res.pdf
Figure 6-6	http://en.wikipedia.org/wiki/Gas_cylinder
Figure 6-7	http://www.networlddirectory.com/blogs/permalinks/6-2008/prototype-hydrogen-storage-tank.html
Figure 7-1	http://www.energyquest.ca.gov/story/chapter02.html
Figure 7-2	http://www.energyquest.ca.gov/story/chapter04.html
Figure 7-3	http://scifiles.larc.nasa.gov/text/kids/Problem_Board/problems/electricity/circuits2.html
Figure 7-8	http://en.wikipedia.org/wiki/Power_semiconductor_device
Figure 7-9	http://en.wikipedia.org/wiki/Diode
Figure 7-11	http://theelectrostore.com/shopsite_sc/store/html/media/transistors-igbts/skm145gal123d-semikron-igbt-skm-145-gal-123d-123-d-new.jpg
Figure 7-12	http://en.wikipedia.org/wiki/Thyristors
Figure 7-13	http://fmccgroup.ru/images/semiconductors/igbt/IGCT_img_0.jpg
Figure 7-15	http://en.wikipedia.org/wiki/Inverter_(electrical)

About the Author: Dr. Colleen Spiegel

Dr. Colleen Spiegel has been a chemical engineer, R&D manager and consultant for ten years, and also founded Clean Fuel Cell Energy in 2006. She is the author of "Designing and Building Fuel Cells" (McGraw-Hill, 2007), and "PEM Fuel Cell Modeling and Simulation Using MATLAB" (Elsevier Science, 2008).

Dr. Spiegel has been involved with designing and building PEM fuel cell stacks, ranging from micro to macro designs using standard and alternative materials and configurations. She has also been involved with the development of hybrid power systems, crystal growth, thin films and polymers. In addition, she has extensively used MATLAB for modeling fuel cells and other types of technologies. She has created detailed mathematical models of each fuel cell layers to calculate heat and mass transfer and pressure drop to predict heat and water management in a fuel cell stack.

Dr. Spiegel has a BSChE and MSChE in chemical engineering, and a PhD in electrical engineering from the University of South Florida. Colleen has a passion for designing and promoting fuel cells, and helping to educate young people in science, math and technology. For more information about Colleen, visit www.colleenspiegel.com.