# $H_2$ EDUCATE

## Student Guide


NEED

25th Anniversary 2005

Putting Energy into Education

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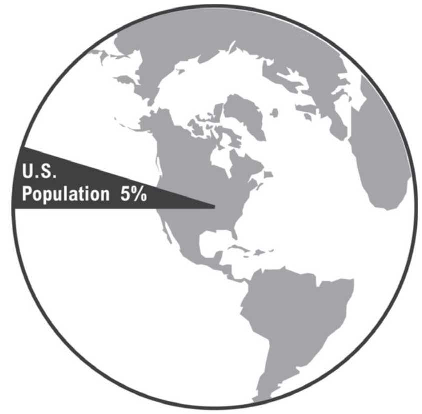
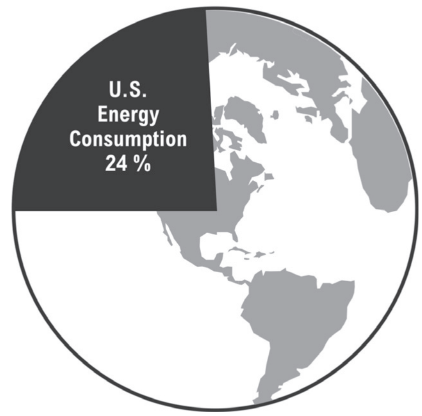
# Hydrogen: A Fuel‡for Today‡and Tomorrow‡

## The Energy Picture‡in‡the United States Today‡

The United States consumes a lot of energy, more energy than any other country in the world. We use almost a million dollars worth of energy each minute, 24 hours a day, every day of the year. With less than five percent of the world's population, we consume almost a quarter (24 percent) of the world's total energy production.




The average American uses six times more energy than the world's average per capita figure. We use energy to power our homes, businesses, and industrial plants, and to move people and goods from one place to another. However, the United States doesn't use this energy just to meet our own needs and wants, but also for the benefit of the world.  As a nation, the United States is responsible for 43 percent of the world's economic production, 40 percent of its high-technology production, and 50 percent of the research and development.

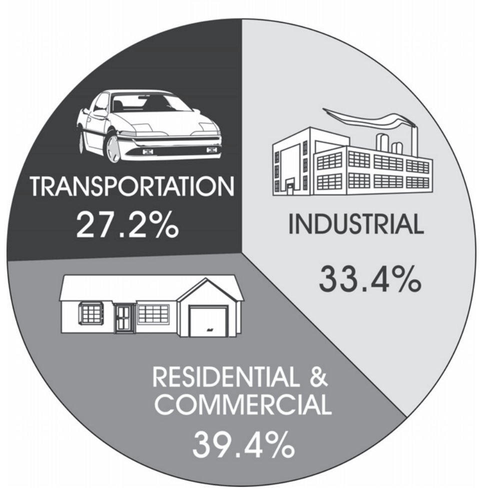
We rely on energy to make our lives productive, comfortable, and enjoyable. Sustaining this quality of life requires that we use our energy resources wisely and find new sources of energy for the future. If we was consumers make good decisions about the energy we use at home and in business and industry, we can accomplish even more with the same amount of energy.

Today, most of the energy we use—almost 94 percent—comes from **nonrenewable** energy sources such as coal, natural gas, petroleum, and uranium. Nearly 86 percent of the energy we use comes from **fossil fuels**, which can pollute the environment when they are burned.

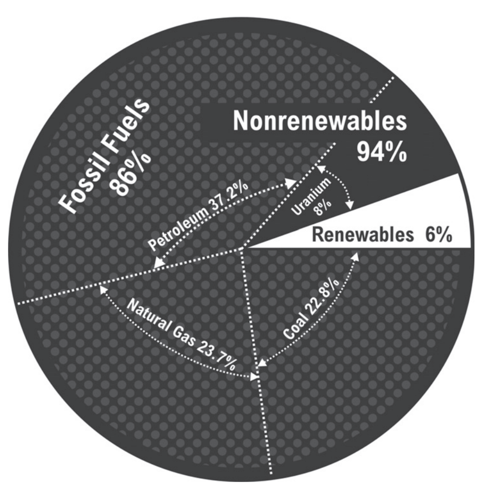
In addition, the world has limited reserves of nonrenewable energy sources; they take millions of years to form, so we can't make more to meet our future needs. It is estimated that the United States has about 250 years of coal reserves and 50 years of natural gas reserves at the present rate of consumption.

We can't produce enough petroleum to meet our needs; today we are importing almost two-thirds of our oil demand from foreign countries. Many experts predict that oil production will soon begin to decrease worldwide and demand will continue to increase, as countries like China and India become more industrialized. There will be increasing competition for the available petroleum. In ten years, three dollars a gallon for gasoline might seem a real bargain!

**U.S. Energy Consumption**




**U.S. Energy Consumption**



## Looking to the Future

To meet future energy challenges, the United States is expanding the use of **renewable** energy sources such as solar, wind, biomass, hydropower, and geothermal energy, and considering the increased use of nuclear power. The government and many private enterprises are also conducting research to use nonrenewable energy sources more cleanly and efficiently and to use alternative fuels such as hydrogen.

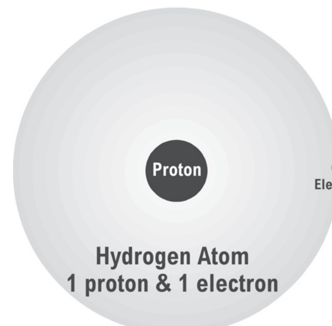
Many people think that hydrogen will be the most important fuel of the future because it meets so many requirements of a good energy system. Experts agree the ideal energy system should include the characteristics listed below.

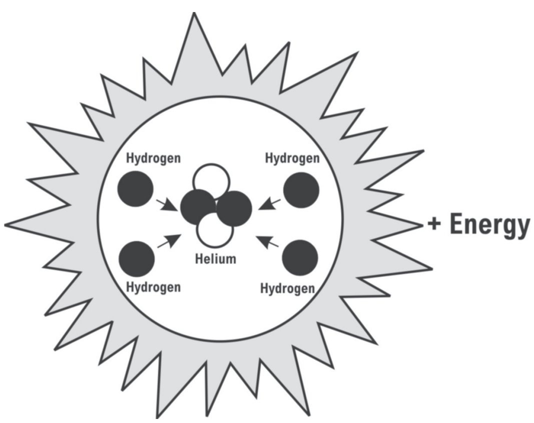
## The Ideal Energy System.....

- **should rely on domestic energy sources.**
- **should be able to utilize a variety of energy sources.**
- **should produce few harmful pollutants and greenhouse gas emissions.**
- **should be energy efficient (high energy output from the energy input).**
- **should be accessible (easy to find, produce or harness).**
- **should result in stable energy prices.**

## What Is Hydrogen?

Hydrogen is the simplest element known to exist. An atom of hydrogen has one proton and one electron. It is the lightest element and a gas at normal temperature and pressure. Hydrogen is also the most abundant gas in the universe and the source of all the energy we receive from the sun. Hydrogen has the highest energy content of any common fuel by weight, but the lowest energy content by volume.

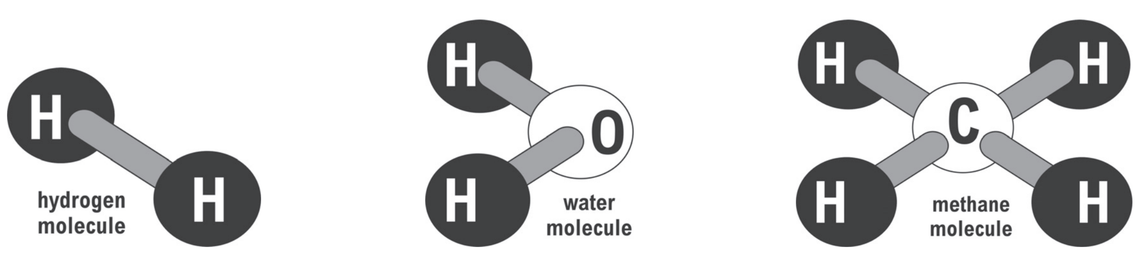


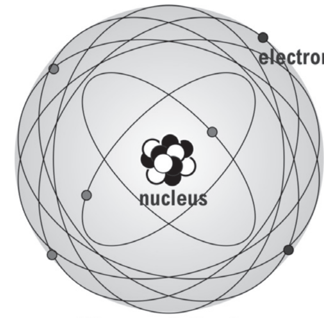

The sun is basically a giant ball of hydrogen and helium gases. In the sun's core, the process of **fusion** is continually taking place. During fusion, the protons of four hydrogen atoms combine to form one helium atom with two protons and two neutrons, releasing energy as radiation.

This **radiant energy** is our most important energy source. It gives us light and heat and makes plants grow. It causes the wind to blow and the rain to fall. It is stored as chemical energy in fossil fuels. Most of the energy we use originally came from the sun's radiant energy.

Hydrogen as a gas ($H_2$), however, doesn't exist naturally on earth. It is found only in **compound** form. Combined with oxygen, it is water ($H_2O$). Combined with carbon, it forms organic compounds such as methane ($CH_4$), coal, and petroleum. It is found in all growing things—biomass. Hydrogen is also an abundant element in the earth's crust.



## Atomic Structure‡




Atom of Carbon

Everything in the universe is made of atoms or particles of atoms—every star, every tree, every animal. The human body, water, and air are, too. Atoms are the building blocks of the universe. Atoms are so small that millions of them would fit on the head of a pin.

Atoms are made of even smaller particles. The center of an atom is called the **nucleus**. It is made of particles called **protons** and **neutrons**. The protons and neutrons are very small, but **electrons**, which move around the nucleus in **shells**, are much, much smaller. Atoms are mostly empty space.

If you could see an atom, it would look a little like a tiny center of balls surrounded by giant invisible clouds (or shells). Electrons are held in their shells by electrical force. The protons and electrons are attracted to each other. They both carry an electrical charge. An **electrical charge** is a force within the particle.

Protons have a **positive** charge (+) and electrons have a **negative** charge (–). The positive charge of the protons is equal to the negative charge of the electrons. Opposite charges attract each other. When an atom is in balance, it has an equal number of protons and electrons. The neutrons carry no charge and their number can vary. Neutrons act as glue to hold the nucleus together.

An **element** is a substance in which all of the atoms are identical. The number of protons in an atom determines the kind of atom or element it is. Every atom of hydrogen, for example, has one proton and one electron, with no neutrons. Every atom of carbon has six protons, six electrons, and six neutrons.

The electrons usually remain a constant distance from the nucleus in precise shells. The shell closest to the nucleus can hold two electrons. The outer shells can hold up to eight. The electrons in the shells closest to the nucleus have a strong force of attraction to the protons. Sometimes, the electrons in the outermost shells do not. The electrons farthest from the nucleus are called **valence electrons** and are the electrons involved in chemical reactions.

Atoms are more stable when their outer shells are full. Atoms with one, two, or three valence electrons can lose those electrons to become more stable. Atoms with five, six, or seven valence electrons can gain electrons to become more stable. Less stable atoms can also share electrons with other atoms to become more stable.

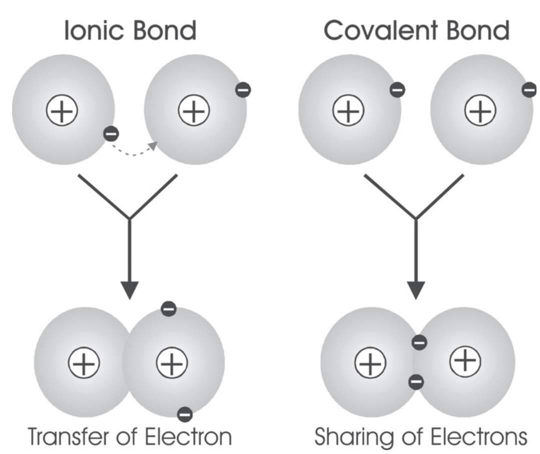
**Ions** are atoms or molecules that have gained or lost electrons and are electrically charged. An atom that has lost an electron has lost a negative charge and is a positive ion. An atom that has gained an electron has gained a negative charge and is a negative ion.

## Chemical Bonding‡

Chemical compounds are formed when two or more atoms join together in a chemical bond. In chemical bonds, atoms can either transfer or share their valence electrons. Stable compounds are formed when the total energy of the compound is less than that of the separate atoms.

**Ionic Bond—**An ionic bond is formed when valence electrons from one atom are removed and attached to another atom. The resulting ions have opposite charges and are attracted to each other to form a molecule. Ionic bonds are common between metals and nonmetals to form compounds such as salt––NaCl.

**Covalent Bond**—A covalent bond is formed when two atoms share electrons. Covalent bonds usually occur between two nonmetals. Water—$H_2O$—is an example of covalent bonding.



## The Periodic Table‡

In 1869, Dmitri Mendeleev, a Russian scientist, introduced the first periodic table. Mendeleev had arranged the elements according to their atomic mass—the average mass of one atom of the element. He then put the elements in rows according to their chemical and physical properties. Mendeleev's periodic table was not perfect, but it led to the periodic table used by scientists today.

The modern periodic table is arranged according to the atomic numbers of the elements, as well as according to patterns of properties of the elements. The properties of the elements repeat in each horizontal row or **period**. The elements in each vertical column or **group** have similar properties as well, although the similarities are stronger in some groups than in others.

Each element of the periodic table is represented by a rectangular box. The box includes information about that element. The information listed in the periodic table below are the element's atomic symbol, atomic number, atomic mass number and name.

The **atomic symbol** is a one or two-letter symbol that identifies the element. Many elements are named after the scientists that discovered them. The **atomic number** of an element is the number of protons in the nucleus of the atom. The **atomic mass number** is the average mass of one atom of the element.

# PERIODIC TABLE OF THE ELEMENTS

Key: Atomic Number / Symbol / Element / Atomic Mass

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H Hydrogen 1.008 | | | | | | | | | | | | | | | | | 2 He Helium 4.003 |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.012 | | | | | | | | | | | 5 B Boron 10.81 | 6 C Carbon 12.01 | 7 N Nitrogen 14.01 | 8 O Oxygen 16.00 | 9 F Fluorine 19.00 | 10 Ne Neon 20.18 |
| 11 Na Sodium 22.99 | 12 Mg Magnesium 24.31 | | | | | | | | | | | 13 Al Aluminum 26.98 | 14 Si Silicon 28.09 | 15 P Phosphorous 30.97 | 16 S Sulfur 32.07 | 17 Cl Chlorine 35.45 | 18 Ar Argon 39.95 |
| 19 K Potassium 39.10 | 20 Ca Calcium 40.08 | 21 Sc Scandium 44.96 | 22 Ti Titanium 47.88 | 23 V Vanadium 50.94 | 24 Cr Chromium 52.00 | 25 Mn Manganese 54.94 | 26 Fe Iron 55.85 | 27 Co Cobalt 58.93 | 28 Ni Nickel 58.69 | 29 Cu Copper 63.55 | 30 Zn Zinc 65.39 | 31 Ga Gallium 69.72 | 32 Ge Germanium 72.59 | 33 As Arsenic 74.92 | 34 Se Selenium 78.96 | 35 Br Bromine 79.90 | 36 Kr Krypton 83.80 |
| 37 Rb Rubidium 85.47 | 38 Sr Strontium 87.62 | 39 Y Yttrium 88.91 | 40 Zr Zirconium 91.22 | 41 Nb Niobium 92.91 | 42 Mo Molybdenum 95.94 | 43 Tc Technetium (98) | 44 Ru Rubenium 101.1 | 45 Rh Rhodium 102.9 | 46 Pd Palladium 106.4 | 47 Ag Silver 107.9 | 48 Cd Cadnium 112.4 | 49 In Indium 114.8 | 50 Sn Tin 118.7 | 51 Sb Antimony 121.8 | 52 Te Tellurium 127.6 | 53 I Iodine 126.9 | 54 Xe Xenon 131.3 |
| 55 Cs Cesium 132.9 | 56 Ba Barium 137.3 | * | 72 Hf Hafnium 178.5 | 73 Ta Tantalum 180.9 | 74 W Tungsten 183.9 | 75 Re Rhenium 186.2 | 76 Os Osmium 190.2 | 77 Ir Iridium 190.2 | 78 Pt Platinum 195.1 | 79 Au Gold 197.0 | 80 Hg Mercury 200.5 | 81 Tl Thallium 204.4 | 82 Pb Lead 207.2 | 83 Bi Bismuth 209.0 | 84 Po Polonium (210) | 85 At Astatine (210) | 86 Rn Radon (222) |
| 87 Fr Francium (223) | 88 Ra Radium (226) | ** | | | | | | | | | | | | | | | |
| | | * Lanthanide Series | 57 La Lanthanum 138.9 | 58 Ce Cerium 140.1 | 59 Pr Praseodymium 140.9 | 60 Nd Neodymium 144.2 | 61 Pm Promethium (147) | 62 Sm Samarium 150.4 | 63 Eu Europium 152.0 | 64 Gd Gadolinium 157.3 | 65 Tb Terbium 158.9 | 66 Dy Dysprosium 162.5 | 67 Ho Holmium 164.9 | 68 Er Erbium 167.3 | 69 Tm Thulium 168.9 | 70 Yb Ytterbium 173.0 | 71 Lu Lutetium 175.0 |
| | | ** Actinide Series | 89 Ac Actinium ~(227) | 90 Th Thorium 232.0 | 91 Pa Protactinium (231) | 92 U Uranium (238) | 93 Np Neptunium (237) | 94 Pu Plutonium (242) | 95 Am Americium (243) | 96 Cm Curium (247) | 97 Bk Berkelium (247) | 98 Cf Californium (249) | 99 Es Einsteinium (254) | 100 Fm Fermium (253) | 101 Md Mendelevium (256) | 102 No Nobelium (254) | 103 Lr Lawrencium (257) |

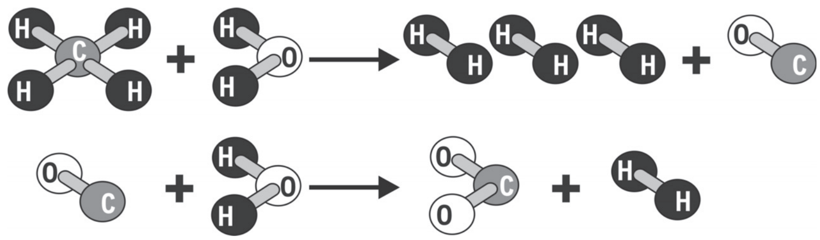
## How is Hydrogen Made?

Since hydrogen gas is not found naturally on earth, it must be manufactured. There are many ways to do this. The fact that hydrogen can be produced using so many different domestic resources is an important reason why it is a promising energy carrier. In a hydrogen economy, we will not need to rely on a single resource or technology to meet our energy needs.

**STEAM REFORMING** Industry produces hydrogen by steam reforming, a process in which high-temperature steam separates hydrogen atoms from carbon atoms in methane ($CH_4$), as shown below.

$$CH_4 + H_2O \text{ (steam)} \longrightarrow 3H_2 + CO$$

$$CO + H_2O \text{ (steam)} \longrightarrow CO_2 + H_2$$



Today, most of the hydrogen produced by steam reforming isn't used as fuel but in industrial processes. Steam reforming is the most cost-effective way to produce hydrogen today and accounts for about 95 percent of the hydrogen produced in the U.S. Because of its limited supply, however, we cannot rely on natural gas to provide hydrogen over the long term. Instead, we will need to produce hydrogen using other resources and technologies, such as those listed below.

**ELECTROLYSIS** One way to make hydrogen is by electrolysis—splitting water into its basic elements—hydrogen and oxygen. Electrolysis involves passing an electric current through water ($H_2O$) to separate the water molecules into hydrogen ($H_2$) and oxygen ($O_2$) gases.

The electricity needed for electrolysis can come from a power plant, windmill, photovoltaic cell or any other electricity generator. If the electricity is produced by renewable energy or nuclear power, there is no net increase in greenhouse gases added to the atmosphere. Hydrogen produced by electrolysis is extremely pure, but it is very expensive because of equipment costs and other factors. On the other hand, water is renewable and abundant in many areas.

Technological advances to improve efficiency and reduce costs will make electrolysis a more economical way to produce hydrogen in the future.

**PHOTOELECTROCHEMICAL PRODUCTION** Photoelectrolysis uses sunlight to split water into hydrogen and oxygen. A semiconductor absorbs energy from the sun and acts as an electrode to separate the water molecules.

**BIOMASS GASIFICATION** In biomass gasification, wood chips and agricultural wastes are super-heated until they turn into hydrogen and other gases. Biomass can also be used to provide the heat.

**PHOTOBIOLOGICAL PRODUCTION** Scientists have discovered that some algae and bacteria produce hydrogen under certain conditions, using sunlight as their energy source. Experiments are underway to find ways to induce these microbes to produce hydrogen efficiently.

**COAL GASIFICATION WITH CARBON SEQUESTRATION** In this process, coal is gasified (turned into a gas) with oxygen under high pressure and temperature to produce hydrogen and carbon monoxide (CO). Steam ($H_2O$) is added to the CO to produce hydrogen and carbon dioxide ($H_2$ and $CO_2$). The carbon dioxide is captured and **sequestered** (stored) to prevent its release into the atmosphere.

**NUCLEAR THERMOCHEMICAL** In this experimental process, the heat from a controlled nuclear reaction is used to decompose water into hydrogen and oxygen in a series of complex chemical reactions.

## HYDROGENÉASÉA FUELÉ

Many experts believe that hydrogen is the ideal fuel of the future. It is abundant, clean, flexible, and can be produced from many different domestic resources. The advantages of hydrogen include the following:

1. **Hydrogen resources are abundant in the United States and the world.**

    ♦ΨHydrogen is a component of many abundant compounds on Earth, including water, hydrocarbons, and carbohydrates.

    ♦ΨIt can be produced from a variety of resources (water, fossil fuels, biomass) and is a byproduct of other chemical processes.

    ♦ΨAll regions of the world have hydrogen-containing resources.

2. **Hydrogen is a domestic fuel.**

    ♦ΨThe United States has a wide variety of hydrogen resources, including plentiful water, biomass, natural gas, and coal. This diversity would help keep energy prices stable.

    ♦ΨEvery area of the country has the ability to produce hydrogen from regional resources.

    ♦ΨUsing domestic energy resources increases national security.

3. **Hydrogen is a clean fuel.**

    ♦ΨUsing hydrogen as a transportation fuel can significantly reduce air pollution—hydrogen fuel cell vehicles produce no tailpipe emissions except heat and water.

    ♦ΨIf hydrogen is produced from fossil fuels at large centralized facilities, it is much easier to minimize emissions at these sites than it is to reduce emissions on individual petroleum-fueled vehicles.

    ♦ΨIf hydrogen is produced by electrolysis using renewable energy sources, there are no harmful emissions.

    ♦ΨUsing hydrogen as a fuel can reduce greenhouse gas emissions, especially if it is produced using renewable resources, nuclear energy, or fossil fuels such as coal coupled with **carbon sequestration** (capturing the carbon-based emissions and preventing them from entering the atmosphere).

4. **Hydrogen is a flexible fuel.**

    ♦ΨHydrogen can be produced from a variety of resources.

    ♦ΨHydrogen can be produced on–site in small quantities for local use (distributed generation) or in large quantities at production plants (centralized generation).

    ♦ΨHydrogen can be used in fuel cells to generate electricity, with only water and heat as by-products.

    ♦⌊ Hydrogen can be used as a transportation fuel for motor vehicles.

    ♦⌊ Hydrogen can be used to provide electricity and heat for buildings.

    ♦ΨHydrogen can be used in manufacturing processes in the industrial sector.

    ♦ΨHydrogen fuel cells can be used in remote places that can't be reached by power lines.

    ♦ΨHydrogen is an efficient energy carrier, although it is not a primary energy resource.

## Uses of Hydrogen

The U.S. hydrogen industry currently produces about nine million tons of hydrogen a year, enough to power more than 35 million cars or 5–8 million homes. Most of this hydrogen is used for industrial applications such as refining, treating metals, and food processing.

At the present time, hydrogen's main use as a fuel is in the NASA space program. Liquid hydrogen is the fuel that has propelled the space shuttle since the 1970s. Hydrogen fuel cells power the shuttle's electrical systems, producing pure water, which the crew uses as drinking water. Since hydrogen has the highest energy density of any fuel, it's the perfect fuel for space travel, in which keeping weight down is important.


Space shuttle fueled by hydrogen

A few hydrogen-powered vehicles are on the road today, but it could be more than a decade before you can walk into your local car dealer and drive away in one. There are only a small number of hydrogen fueling stations in existence today and few of those are open to the public.

Can you imagine how huge the task would be to quickly change the gasoline-powered transportation system we have today? Just think of the thousands of filling stations across the country and the production and distribution systems that serve them. Changing the nation's transportation system will take lots of time and money.

In the future, hydrogen will join electricity as an important energy carrier since it can be made safely from a variety of energy resources and is virtually non-polluting. It will also be used as a fuel for zero-emissions vehicles, to heat homes and offices, to produce electricity, and to fuel aircraft. With technological advances to increase efficiency and reduce cost, fuel cells will be able to power vehicles and other stationary applications anywhere.

As the production of electricity from renewable energy sources increases, so will the need for energy storage and transportation. Many of these sources—especially solar and wind—are located far from population centers and produce electricity only part of the time. Hydrogen, which can be produced by electrolyzing water using renewable energy, may be the perfect carrier for this energy. It can store the energy and distribute it to wherever it is needed.

## What's an Energy Carrier?

An **energy carrier** is a substance or system that moves energy in a usable form from one place to another. Electricity is the most well-known energy carrier. We use electricity to move the energy in coal, uranium, and other energy sources from power plants to homes and businesses. We use electricity to move the energy in flowing water from hydropower dams to consumers. It is much easier to use electricity than the energy sources themselves.

Some energy sources can also be energy carriers. Petroleum and natural gas, for example, are energy sources. They are also energy carriers because we transport them from place to place and they are in usable form. Uranium, on the other hand, can be transported from place to place, but we can't really use it at home to produce usable energy. It is an energy source, but not an energy carrier.

Hydrogen is an energy carrier, not an energy source. Like electricity, hydrogen must be produced from another substance, so it is not considered an energy source. Electricity is difficult to store. Once hydrogen has been produced, however, it has high energy content and can be stored and transported to where it is needed. Its potential for storing and transporting renewable energy is especially high.

## What is a Fuel Cell?

A fuel cell is a device that produces a chemical reaction between substances, generating an electric current in the process. It is an **electrochemical energy conversion device**. Everyone uses another electrochemical energy conversion device—a battery. A battery contains substances that produce an electric current as they react. When all of the substances have reacted, the battery is dead; it must be replaced or recharged.

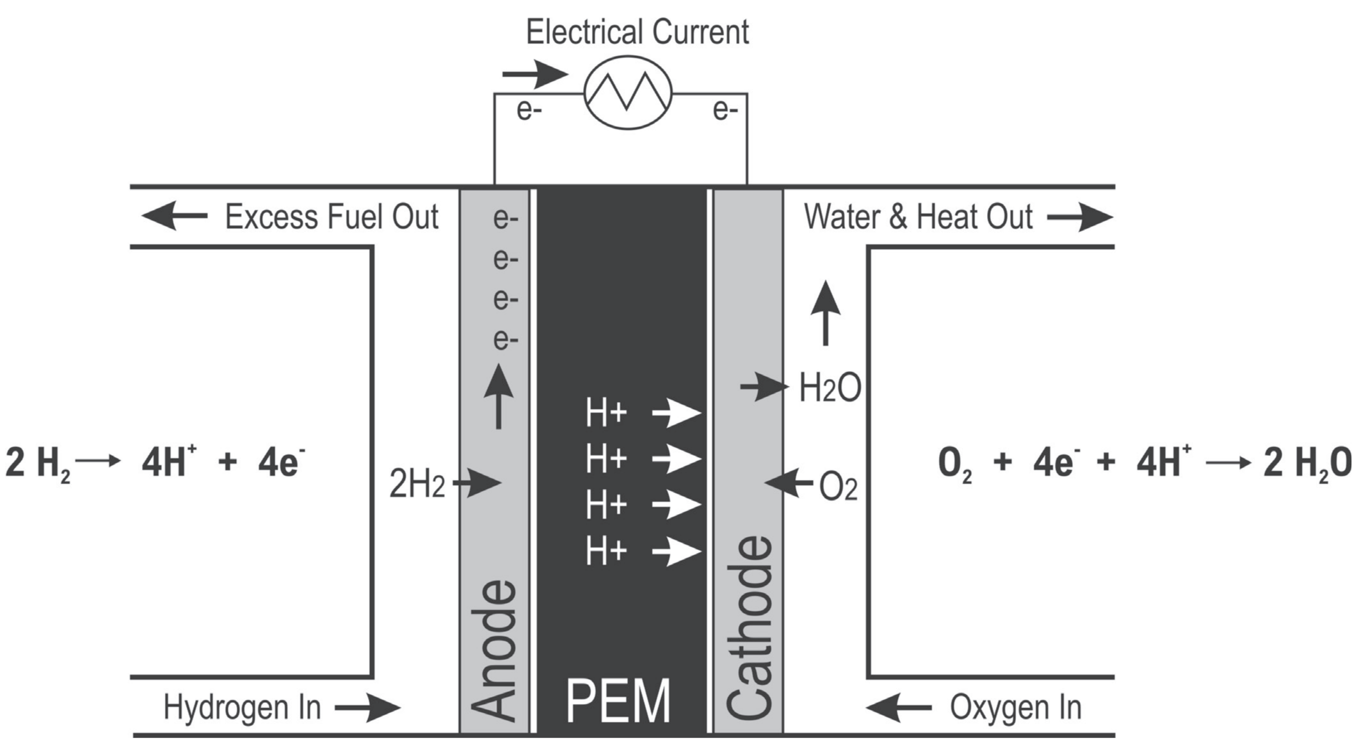
With a fuel cell, the substances (in this case, hydrogen and oxygen) are stored outside of the device. As long as there is a supply of hydrogen and oxygen, the fuel cell can continue to generate an electric current, which can be used to power motors, lights, and other electrical appliances. There are many types of fuel cells, but the most important technology for transportation applications is the polymer electrolyte (or proton exchange) membrane or PEM cell. A PEM fuel cell converts hydrogen and oxygen into water, producing an electric current during the process.

The **anode** is the negative side of the fuel cell. The anode has channels to disperse the hydrogen gas over the surface of the catalyst. Hydrogen gas under pressure enters the fuel cell on the anode side and reacts with the catalyst.

The **catalyst** is a special material—usually made of platinum—that facilitates the reaction of hydrogen and oxygen. The catalyst splits the hydrogen gas into two hydrogen ions ($2H^+$) and two electrons ($2e^-$). The electrons flow through the anode to an external circuit, through a load where they perform work, to the cathode side of the cell.

The **polymer electrolyte membrane (PEM)** is a specially treated material that conducts positive ions (protons), but blocks electrons from flowing through the membrane. Electrons flow through a separate circuit (that can be used to do work) as they travel to the cathode.

The **cathode** is the positive side of the fuel cell. It has channels to distribute oxygen gas to the surface of the catalyst. The oxygen reacts with the catalyst and splits into two oxygen atoms. Each oxygen atom picks up two electrons from the external circuit to form an oxygen ion ($O^{--}$) that combines with two hydrogen ions ($2H^+$) to form a water molecule ($H_2O$).



## The Challenges‡ of Hydrogen‡

Before hydrogen can make a significant contribution to the U.S. energy picture, many new systems must be designed and built. There must be sufficient production and storage facilities and a distribution system to support widespread use. And consumers must have the technology and confidence in its safety to use it.

## Hydrogen Storage‡

Hydrogen can be stored in many ways, but all have advantages and disadvantages. Safety, cost, efficiency, and ease of use are important considerations.

- ♦Ψ Hydrogen can be stored as a gas at standard temperature and pressure. Hydrogen can be stored safely this way, but it is not efficient; a small amount of hydrogen energy takes up a very large amount of space.
- ♦Ψ Hydrogen gas can be compressed and stored in high-pressure tanks. Hydrogen gas takes up less space when it is compressed, but it still has much lower energy content than the same volume of gasoline. A compressed hydrogen tank would have to be many times larger than a gasoline tank to hold an equivalent amount of energy. It also takes energy to compress the gas, and the storage tanks to hold the hydrogen must meet strict safety standards since any compressed gas can be dangerous.
- ♦Ψ Hydrogen gas can be liquefied (turned into a liquid) by compressing it and cooling it to a very low temperature (–253$^{o}$C). The storage tanks must be reinforced and insulated. Because it requires a lot of energy to compress and cool the gas, as well as keep it cold, liquid hydrogen is not cost-efficient or energy-efficient at this time. Liquid hydrogen is safe if the tanks are well made and the temperature of the hydrogen is maintained.
- ♦Ψ Hydrogen can also be stored using materials-based technologies—within the structure or on the surface of certain materials, as well as in chemical compounds that undergo chemical reactions to release the hydrogen. With these technologies, hydrogen is tightly bound with other elements in a compound (or storage material), which may make it possible to store larger quantities of hydrogen in smaller volumes at low pressure at near room temperature. Hydrogen can be stored in materials through ***absorption***, in which hydrogen is absorbed directly into the storage material; ***adsorption***, in which hydrogen is stored on the surface of the storage material; or in ***compound form***, in which hydrogen is contained within a chemical compound and released in a chemical reaction.

## Hydrogen Distribution‡

Today, most hydrogen is transported short distances, mainly by pipeline. There are about 600 miles of hydrogen pipelines in the United States. Longer distance distribution is usually by tanker trucks carrying hydrogen in liquefied form. There is no nationwide hydrogen distribution system.

If hydrogen is to become a major energy carrier used widely by consumers, a national distribution system must be developed. The cost of building a new nationwide system of pipelines for hydrogen would be very costly. Researchers are looking into ways to use the existing natural gas pipeline system, but there are problems to be solved. Hydrogen can permeate the pipes and fittings, causing them to become brittle and rupture. And the present pipelines cannot transport as much energy moving hydrogen as natural gas. The costs would also be higher.


*Hydrogen storage tank and truck*

For many applications, **distributed generation** (producing hydrogen where it will be used) may be a solution. Buildings and fueling stations can use small reformers to produce the hydrogen fuel they need. Wind machines, solar panels, and other renewables can power **electrolyzers** (systems that split water into hydrogen and oxygen by electrolysis) to produce hydrogen close to where it will be used.

## Hydrogen Safety‡

Like any fuel we use today, hydrogen is an energy-rich substance that must be handled properly to ensure safety. Several properties of hydrogen make it attractive compared to other volatile fuels when it comes to safety. Important hydrogen properties relating to safety are described below.

*Hydrogen flame*

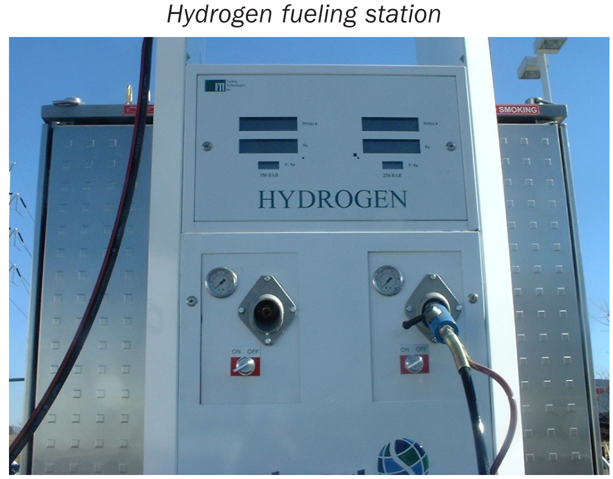
- ♦Ψ Hydrogen is much lighter than air and rises at a speed of almost 20 meters per second—two times faster than helium and six times faster than natural gas. When released, hydrogen quickly rises and dilutes into a non-flammable concentration.
- ♦Ψ An explosion cannot occur in a tank or any contained location that contains only hydrogen; oxygen would be needed.
- ♦Ψ Hydrogen burns very quickly, sometimes making a loud noise that can be mistaken for an explosion.
- ♦Ψ The energy required to initiate hydrogen combustion is significantly lower than that required for other common fuels such as natural gas or gasoline.
- ♦Ψ Hydrogen is odorless, colorless, and tasteless—so it is undetectable by human senses. Industries that produce and use hydrogen have sensors to detect hydrogen leaks. Natural gas is also odorless, colorless, and tasteless; industry adds an odorant called mercaptan to natural gas so people can detect it. Odorants cannot be used with hydrogen, however, because they contaminate fuel cells.
- ♦Ψ A hydrogen flame produces a relatively small amount of radiant heat compared to a hydrocarbon flame. Although the flame itself is just as hot, the risk of sparking secondary fires is reduced with a hydrogen flame.
- ♦Ψ Any gas except oxygen can cause asphyxiation (oxygen deprivation) in high enough concentrations. Since hydrogen is buoyant and diffuses rapidly, it is unlikely that a situation could occur in which people were exposed to high enough concentrations of hydrogen to become asphyxiated.
- ♦Ψ Hydrogen is non-toxic and non-poisonous. It will not contaminate groundwater and a release of hydrogen is not known to contribute to air or water pollution.

## Reaching‡a Hydrogen Economy‡

Hydrogen offers the promise of a clean and secure energy future, but a hydrogen economy will require major changes in the way we produce, deliver, store, and use energy. The United States and countries all over the world are investing millions of dollars in research and development to overcome several important technical challenges that must be solved before we will see hydrogen at local fueling stations and fuel cell vehicles in auto dealer showrooms.

**Reducing the cost of hydrogen:** The cost of hydrogen, including the cost of producing and delivering it, must be similar to or less than the cost of fuels we use today. Researchers are working to lower the cost of production equipment and to find ways to make production processes more efficient, which will lower the cost of hydrogen for consumers.

*Hydrogen fueling station*




**Reducing fuel cell cost and improving durability:** Fuel cells are currently more expensive than conventional power systems such as the engines used in cars today. Researchers are working to develop technologies that will lower the cost of fuel cells and ensure that fuel cell systems can operate reliably for long periods of time in a wide range of weather and temperature conditions.

**Improving hydrogen storage technology:** Most people expect to be able to drive their cars more than 300 miles before having to refuel. Even in a highly-efficient fuel cell vehicle, today's hydrogen storage technology does not allow drivers to travel more than 300 miles between fill-ups. Scientists are researching ways to improve storage technology and to identify new ways to store hydrogen on board a vehicle to achieve a 300+ mile driving range.

In addition to research, hydrogen education is also necessary to support a hydrogen economy. Consumers must be familiar with hydrogen in order to feel as comfortable driving and refueling a hydrogen fuel cell vehicle as they do driving and refueling a gasoline vehicle. Government, industry, and the education system also need knowledgeable students with an interest in hydrogen to become the future researchers, engineers, scientists, and technicians.

*Hydrogen demonstration vehicles*

## Into‡the Hydrogen Future‡

The goal of the Department of Energy Hydrogen Program is to develop new technologies for hydrogen production, delivery, storage, and fuel cells. These technologies will allow automotive and energy companies to make fuel cell vehicles and hydrogen fuel infrastructure available in the 2020 timeframe. Hydrogen from a variety of domestic resources will then be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles and stationary and portable power applications.

Development of hydrogen energy will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the nation's prosperity throughout the 21st century.

## Hydrogen Information Web Links‡

Ames Laboratory: www.ameslab.gov

Argonne National Laboratory: www.anl.gov

Brookhaven National Laboratory: www.bnl.gov

Department of Energy: www.hydrogen.energy.gov

Energy Information Administration: www.eia.doe.gov

Federal Interagency Hydrogen Task Force: www.hydrogen.gov

International Partnership for the Hydrogen Economy: www.iphe.net

Lawrence Berkeley National Laboratory: www.lbl.gov

Lawrence Livermore National Laboratory: www.llnl.gov

Los Alamos National Laboratory: www.lanl.gov

National Energy Education Development Project: www.need.org/hydrogen

National Energy Technology Laboratory: www.netl.doe.gov

National Renewable Energy Laboratory: www.nrel.gov/hydrogen/projects.html

National Hydrogen Association: www.hydrogenassociation.org/general/index.asp

Oak Ridge National Laboratory: www.ornl.gov

Pacific Northwest National Laboratory: www.pnl.gov

Sandia National Laboratory: www.sandia.gov

Savannah River National Laboratory: www.srs.gov

Sentech, Inc: www.sentech.org

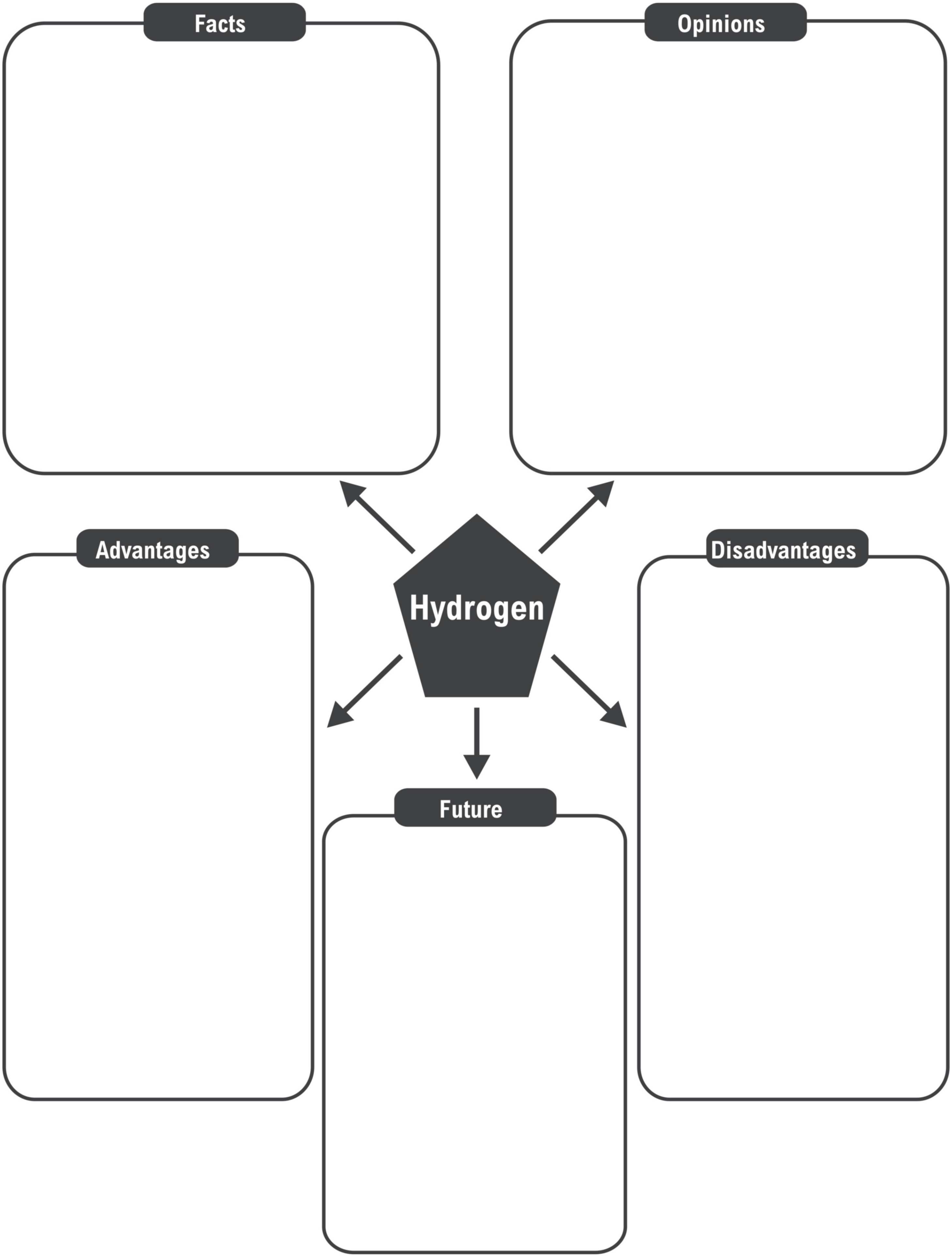
U.S. Fuel Cell Council: www.usfcc.com

Role Group:

| Question 1 | Question 2 | Question 3 | Question 4 |
|---|---|---|---|
| | | | |

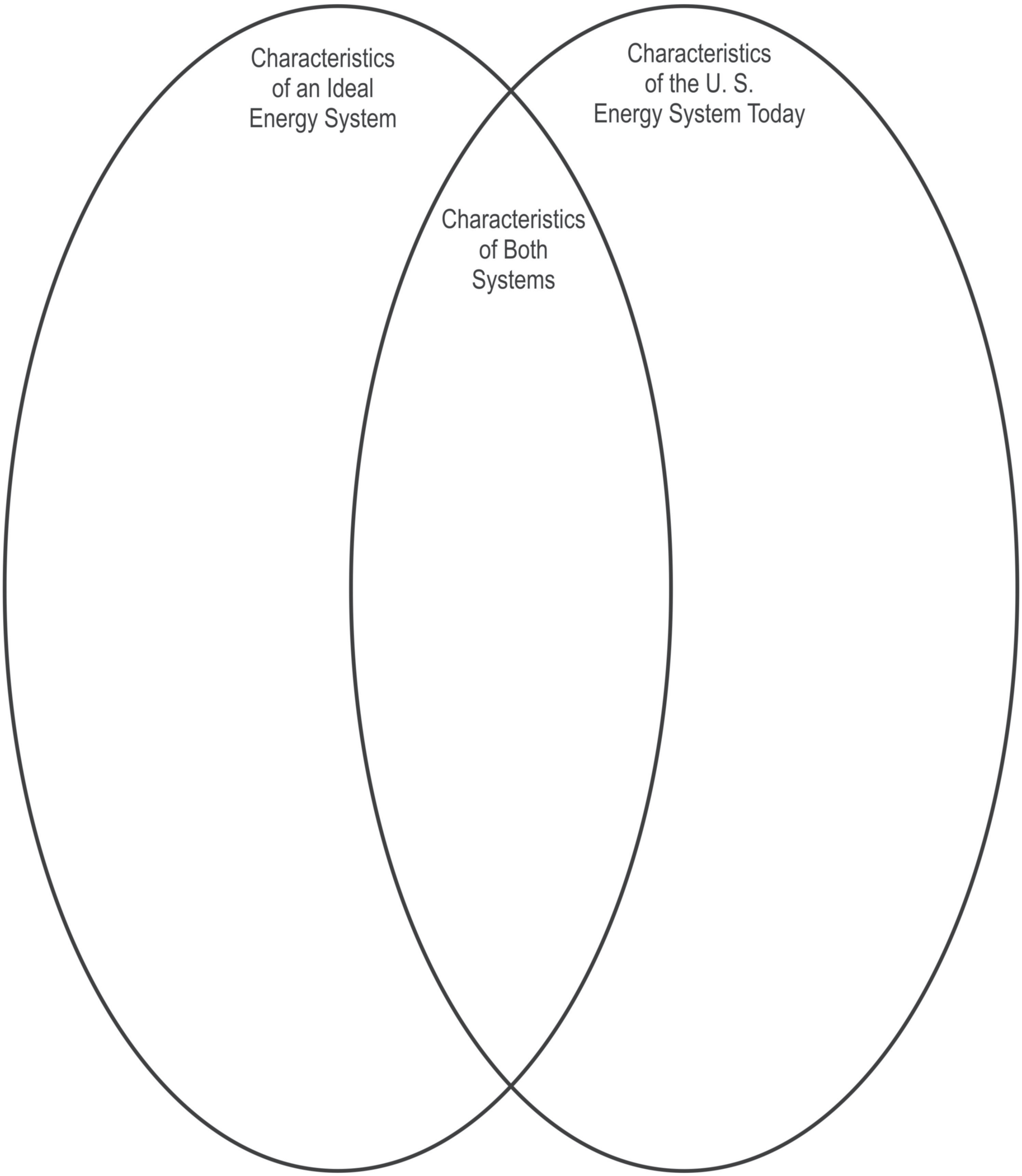
| Essential Details | Essential Details | Essential Details | Essential Details |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |

So what? What's important to understand about this?


Facts
Opinions
Advantages
Hydrogen
Disadvantages
Future

# COMPARING THE U. S. ENERGY SYSTEM TO AN IDEAL ENERGY SYSTEM

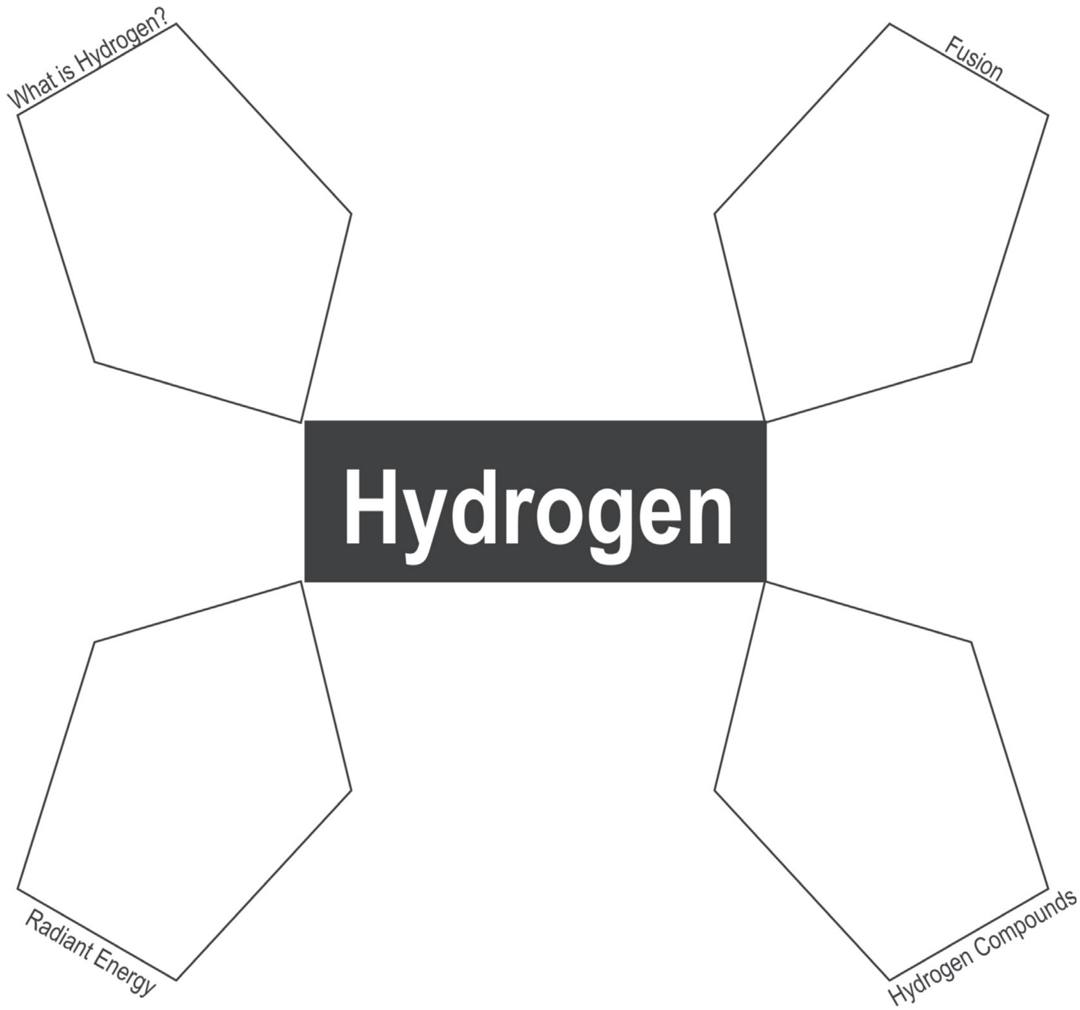
Use the information in the background material to complete the Venn diagram below comparing the U. S. Energy System today to an Ideal Energy System. Underline the most important problem with the U. S. Energy System today and write a paragraph explaining why you think it is important and what you think should be done to solve the problem.



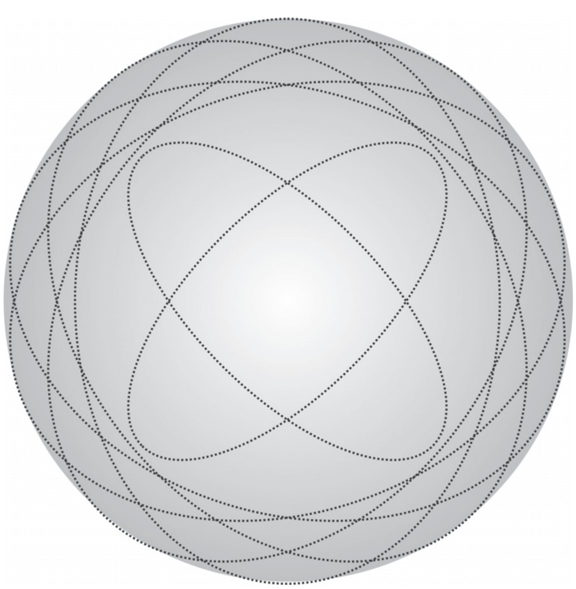

 

# Hydrogen‡ Atomic Structure‡ and‡the Periodic Table‡

As you read the information in the background material, complete the activities below.



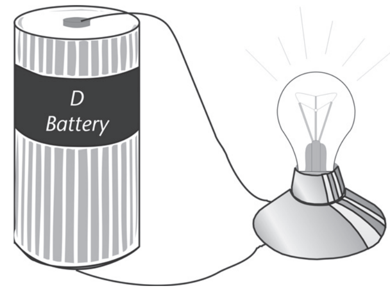

Draw an atom of nitrogen. Make the protons black, the neutrons green and the electrons red.



Discover a new element, name it, give it a symbol, and put it in the Periodic Table.

# Electrolysis‡

**Voltaic cells** or batteries are divided into two parts. One part produces free electrons from chemicals inside it in a process called **oxidation.** The other part binds free electrons to chemicals inside that part in a process called **reduction**.




An **electrode** is a **conductor** that can carry electrons to or from a substance. The negative electrode, which is attached to the part of the battery in which free electrons are produced, is called the **anode.** The electrode on the part of the battery in which electrons are consumed is called the **cathode** and is labeled as the positive electrode. If the battery is attached to a **circuit**, free electrons from the anode travel through the circuit to the cathode. If a load is included in the circuit, the moving electrons—**electricity**—can do work. The electricity produced can light a bulb in a flashlight, for example.

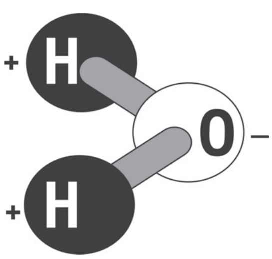
An **electrolyte** is defined as a substance (often a liquid) through which electricity can pass, or a substance that **dissociates** (breaks down) into ions when electricity passes through it. The electrolyte in a PEM fuel cell, however, allows protons (hydrogen ions) to pass through it, not electricity. An **ion** is an atom that has lost or gained one or more electrons, giving it a positive or negative charge, respectively.

There are several types of voltaic cells. A **dry cell** is a voltaic cell in which the electrolyte is a paste. A flashlight battery is an example of a dry cell. Lead-acid storage batteries, such as those used in cars, have a liquid electrolyte and contain a group of cells connected together. **Fuel cells** are voltaic cells in which an external fuel undergoes a chemical reaction—oxidation—producing an electric current.

**Electrolysis** is the opposite process—an electrical current is used to produce a chemical reaction. The container in which electrolysis is carried out is called an **electrolytic cell**.

Electrolysis occurs when enough electrically charged ions are present in an electrolyte to conduct an electric current. The atoms in water are held together by **covalent bonds** (shared electrons) and are more difficult to break apart than atoms with **ionic bonds**.

Distilled water does not conduct an electric current well because distilled water contains no ions of dissolved salts or minerals. The addition of a small amount of an **electrolyte** such as salt (NaCl), sodium hydroxide (NaOH—caustic soda), or sodium sulfate ($Na_2SO_4$) allows water to conduct electricity more easily. With the addition of an electrolyte, the water molecules ($H_2O$) can be separated into hydrogen and oxygen by running an electric current through it. A battery will produce the electricity in the experiment you will conduct.

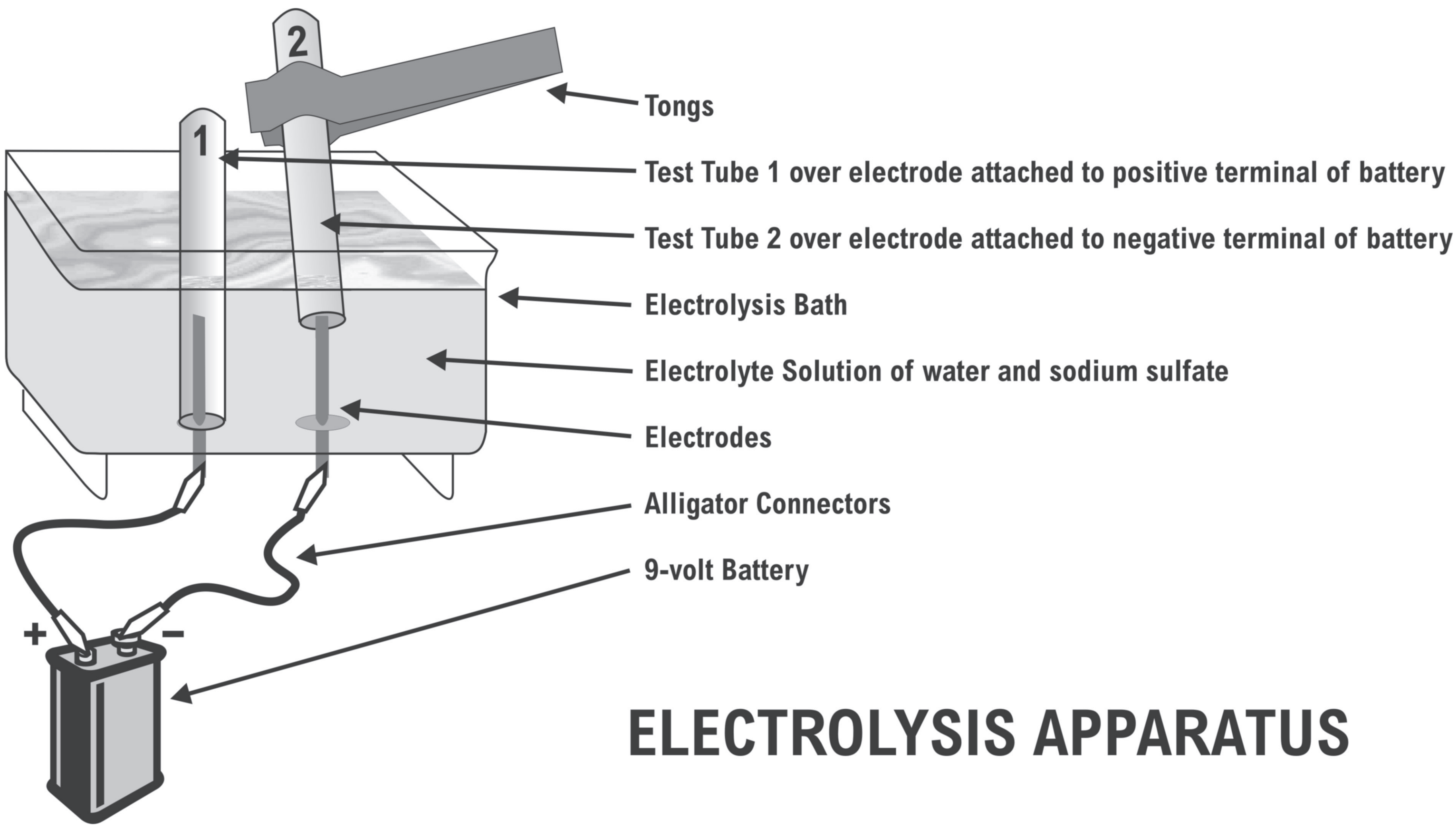



The chemical formula for water is $H_2O$. A water molecule is a **bipolar molecule**—the hydrogen atoms have a positive character and the oxygen atom has a negative character. During electrolysis, the water molecules undergo a **decomposition reaction**, separating the water into oxygen ions ($O^{--}$) and hydrogen ions ($H^+$).

This explains the attraction of hydrogen to the anode and the attraction of oxygen to the cathode. This decomposition is an **endothermic reaction** that requires the constant addition of energy to sustain. In the experiment you will conduct, electricity is provided by a battery.

In a circuit, electrons flow from the anode to the cathode. When an electric current is passed through water with an electrolyte, positively charged hydrogen ions ($H^+$) are drawn to the anode side of the electrical source. At the anode, each hydrogen ion gains an electron and becomes a hydrogen atom (H). Pairs of hydrogen atoms then combine to form molecules of hydrogen gas ($H_2$), which bubble up from the anode. Oxygen gas is produced at the cathode side of the battery as the oxygen ions give up electrons and combine to form oxygen molecules ($O_2$).

Hydrogen gas is lighter (less dense) than air and is **combustible**—it burns quickly when a flame is introduced. Oxygen gas is about the same density as air and facilitates combustion. When a glowing ember, for example, is introduced into a high concentration of oxygen, the ember will re-ignite.

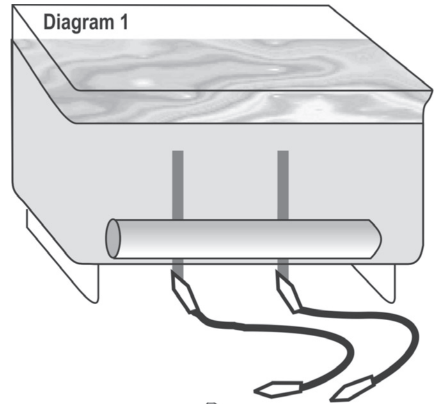



# ELECTROLYSIS APPARATUS

# Electrolysis Exploration‡

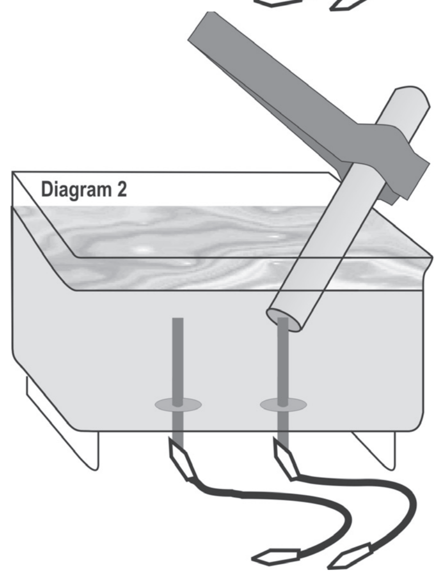
## Safety Warning‡

**WEAR EYE PROTECTION. FOLLOW ALL LAB SAFETY PROCEDURES.** The electrolyte solution you will be using is diluted sodium sulfate ($Na_2SO_4$). It can irritate body tissues. If the solution gets into your eyes, wash out your eyes in the eyebath immediately and report the incident to your teacher. If any solution comes into contact with your skin, immediately wash your skin well to remove the solution. You will also be using an open flame.



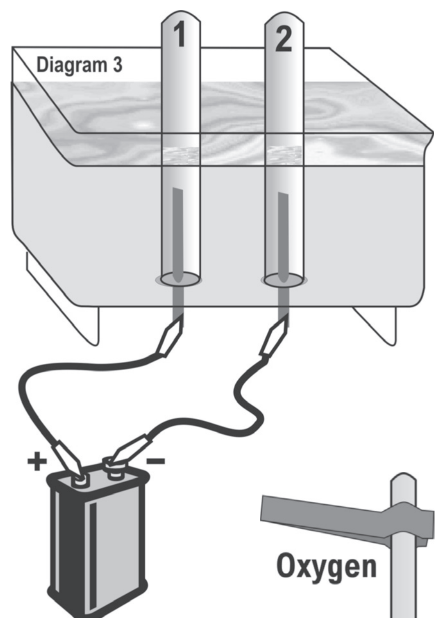

## Preparation‡

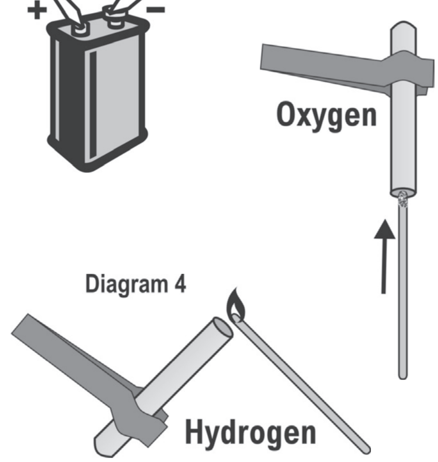
1. Attach the alligator clips to the electrodes on the bottom of the electrolysis apparatus. ***(Diagram 1)***
2. Fill the electrolysis apparatus with the electrolyte solution to about 1 cm above the tips of the electrodes. ***(Diagram 1)***
3. Immerse one test tube into the electrolysis apparatus to fill it with the electrolyte solution. ***(Diagram 1)***
4. Grip the test tube with the tongs and invert it onto one of the electrodes without lifting the mouth of the tube out of the electrolyte solution to make sure the tube remains filled with the solution. Fill the other test tube in the same manner. ***(Diagram 2)***
5. Connect the alligator clips to the terminals of the 9-volt battery. ***(Diagram 3)***
6. You should immediately observe bubbles rising into both tubes. If you do not observe them, check your connections.




## Procedure‡

1. Note on the Data Recording Form which electrode is connected to the anode of the battery and which one is connected to the cathode, using **Tube 1** and **Tube 2** designations.
2. Record the gas volumes in the test tubes at 3–minute intervals for 30 minutes or until one of the test tubes is nearly full of gas.
3. Disconnect the battery from the apparatus.
4. Record the color of the gases in the test tubes.
5. From your reading, determine which test tube contains hydrogen gas and which one contains oxygen gas.
6. ***These procedures must be conducted quickly or the gas wll escape!*** Have your partner light a splint. Use the tongs to lift the oxygen tube straight up, keeping it inverted. Quickly shake the tube to remove excess liquid and have your partner blow out the flame on the splint. Insert the splint straight up into the tube without touching the sides. Record your observations. ***(Diagram 4)***
7. Remove the hydrogen tube using the tongs and keep it inverted. Have your partner re-light the splint. Turn the tube to a 45$^{OÉ}$angle tilted up, and **immediately** bring the splint close to the mouth of the tube. Record your observations. ***(Diagram 4)***



# ELECTROLYSIS DATA RECORDING FORM‡

ANODE CONNECTION: TEST TUBE # ______ CATHODE CONNECTION: TEST TUBE # ______

HYPOTHESIS––GAS‡IN TUBE‡1: ______________ GAS‡IN TUBE 2: ______________

## DATA‡

**Physical Property—Color of Gas Produced**

Hydrogen: __________

Oxygen: __________

**Chemical Property**

Hydrogen—Burning Splint: ______________________________

Oxygen––Glowing Splint: ______________________________

## GAS VOLUMES PRODUCED‡AND RATIOS‡

| **Time** *(min)* | **Volume of Tube 1** *(cc or ml)* | **Volume of Tube 2** *(cc or ml)* | **Ratio** *(Hydrogen Volume: Oxygen Volume)* |
|---|---|---|---|
| **3** | | | |
| **6** | | | |
| **9** | | | |
| **12** | | | |
| **15** | | | |
| **18** | | | |
| **21** | | | |
| **24** | | | |
| **27** | | | |
| **30** | | | |

# Element Models‡

## Background‡

A covalent bond consists of two atoms that share a pair of electrons. A hydrogen atom has one proton and one electron. Hydrogen gas ($H_2$) is a **diatomic** (two atom) molecule that shares the two electrons. An oxygen atom has eight protons, eight neutrons, and eight electrons. Oxygen gas ($O_2$) is a diatomic molecule that shares two electrons in the outer shells of the atoms.

In a water molecule ($H_2O$), the single electron of each hydrogen atom is shared with one of the six outer-shell electrons of the oxygen, leaving four electrons that are organized into two non-bonding pairs.

## Key Terms

covalent bond   diatomic   shell   atom   proton   neutron   electron   molecule

## Overview‡

In this activity, you will create clay models of hydrogen and oxygen atoms, and hydrogen and water molecules.

## Materials‡

3 colors of modeling clay

Plastic straws

Scissors

## Procedure‡

1. Use one color of clay to represent protons, one color to represent neutrons and a third color to represent electrons. *Remember that protons and neutrons are much bigger than electrons when you're making your models.*
2. Use different lengths of plastic straws to represent the electron shells, attaching the electrons to the ends of the straws. *Remember that the first electron shell can hold two electrons and the second shell can hold up to eight electrons.*
3. Create three-dimensional clay models of a hydrogen atom, a hydrogen molecule, an oxygen atom, and a water molecule.
4. Draw diagrams of each of your models and label each part in the space below.

### Hydrogen Atom   Hydrogen Molecule   Oxygen Atom   Water Molecule‡

# What Is A Fuel Cell?

In principle, a fuel cell operates like a battery. Unlike a battery, a fuel cell does not run down or require recharging. It can produce energy in the forms of electricity and heat as long as fuel is supplied. A fuel cell consists of an electrolyte membrane sandwiched between two catalyst-coated electrodes. Oxygen passes through one electrode and hydrogen through the other, generating electricity, water and heat.

Hydrogen gas ($H_2$) from a storage tank is fed into the anode of the fuel cell. When the gas comes in contact with the catalyst, the hydrogen molecules split into hydrogen ions ($H^+$) and electrons ($e^-$). The hydrogen ions pass through the electrolyte membrane to the cathode. The membrane does not allow electrons to pass through, so the electrons flow through a separate circuit (that can be used to do work) as they travel to the cathode. Oxygen molecules from the air enter the fuel cell through the cathode, split into oxygen atoms, and pick up two electrons to become oxygen ions ($O^{--}$). At the cathode, two hydrogen ions and one oxygen ion combine to form a molecule of water, which exits the fuel cell through the cathode.

## Materials‡

4 pieces of fringe six feet long to represent the anode and cathode

4 flashing bulbs to represent electrons

1 flashlight to represent work being done

1 piece of colored tape 12 feet long to represent the external circuit

15 hangtags (see roles below)

## Activity Overview‡

In this activity, students will assume roles to simulate a fuel cell system. Fifteen students are needed for the simulation to assume the following roles:

2 Anodes (A hangtags)

2 Cathodes (CA hangtags)

2 Polymer Electrolyte Membranes—PEMs (P han

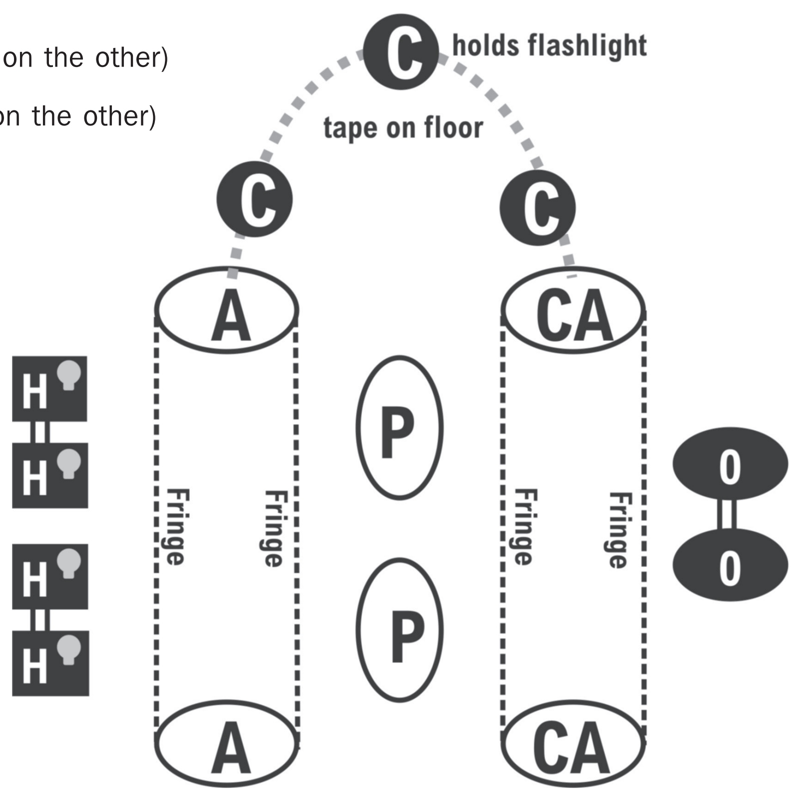
4 Hydrogens (hangtags with H on one side and $H^+$ on the other)

2 Oxygens (hangtags with O on one side and $O^{-\&}$on the other)

3 Circuit Members (C hangtags)

## Procedure‡

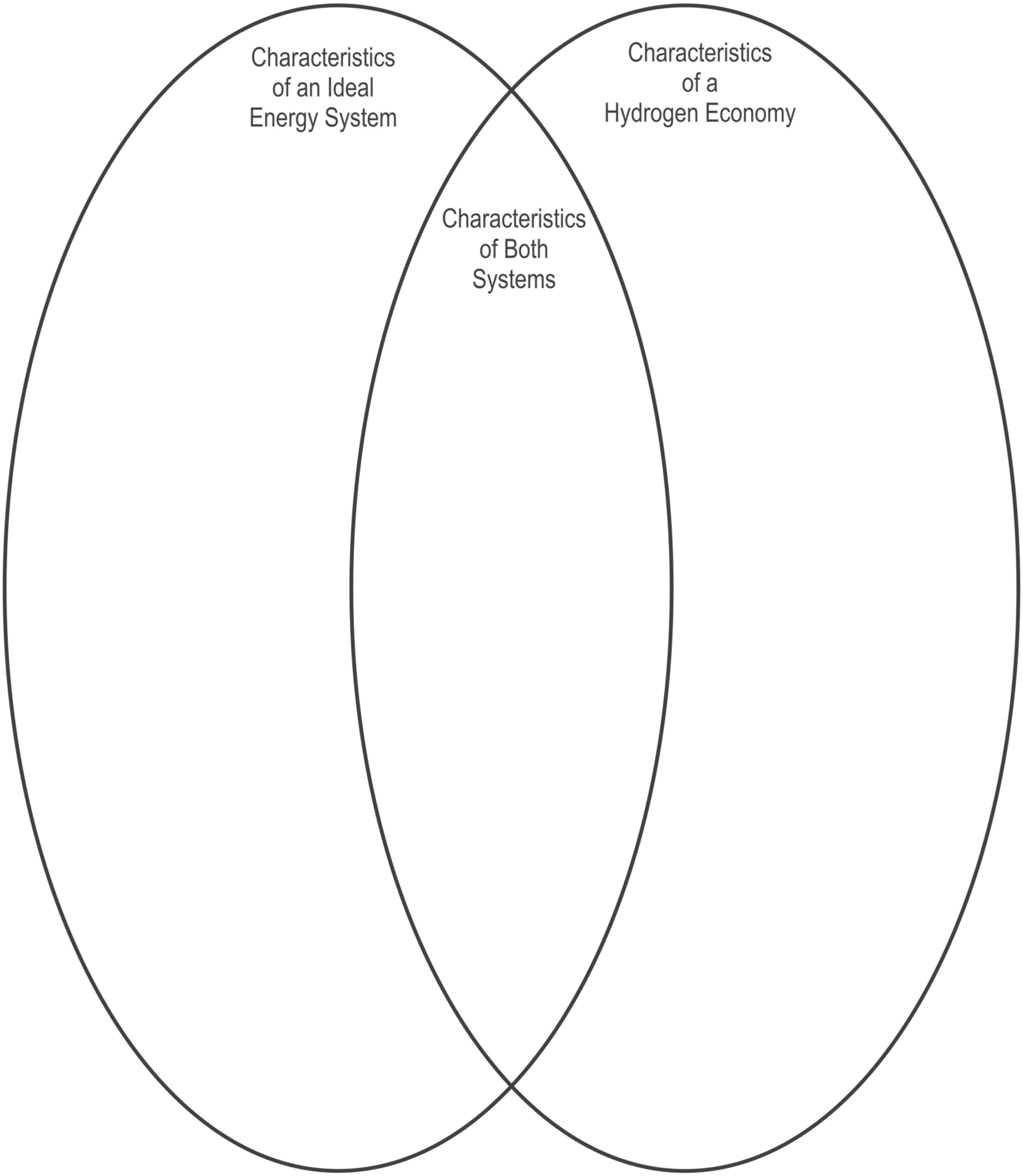
1. Choose roles, put on hangtags, hold the equipment you need, and use the diagram to set up the activity.
2. Simulate the fuel cell system several times, switching students' roles after each simulation.
3. Draw a diagram of a fuel cell and explain how it works using all of the roles in the simulation.



# COMPARING A HYDROGEN ECONOMY TO AN IDEAL ENERGY SYSTEM

Use the information in the background material to complete the Venn diagram below comparing a future Hydrogen Economy to an Ideal Energy System. Underline the most important challenge to reaching the goal of a hydrogen economy and write a paragraph explaining how you think the challenge could be met.



# GLOSSARY‡

**Absorption:** a process in which one substance permeates another.

**Adsorption:É**the attachment of molecules of gases, liquids, or dissolved substances to a solid surface.

**Anode:** The electrode of a fuel cell or battery that produces electrons.

**Atom:** The smallest unit of an element that can exist alone or in combination.

**Atomic number:** The number of protons in an atom's nucleus.

**Atomic mass:** The average mass of one atom of an element.

**Battery:** A device that creates electricity from a chemical reaction.

**Biomass:** Organic materials used as fuel.

**Biomass gasification:** Wood chips and agricultural wastes are superheated until they turn into hydrogen and other gases.

**Bipolar molecule:** A molecule that has both negative and positive poles.

**Carbon dioxide:** A colorless, odorless, incombustible gas formed during respiration, combustion, and organic decomposition. An important greenhouse gas.

**Carbon monoxide:** A colorless, odorless, poisonous gas, produced by incomplete burning of carbon-based fuels, including gasoline, oil, and wood.

**Carbon sequestation:** Capturing and storing gases containing carbon so they will not enter the atmosphere.

**Catalyst:** A substance that increases the rate of a chemical reaction without being produced or consumed in the reaction.

**Cathode:** The electrode of a fuel cell or battery that consumes electrons.

**Centralized generation:** Generation of electricity that is produced in large quantities off-site and then distributed to the consumers.

**Circuit:** The path through which an electrical current flows.

**Coal gasification:** Turning coal into gases using high temperature and pressure, then mixing the gases with steam to produce hydrogen.

**Compound:** Two or more elements chemically bonded together.

**Conductor:** A substance that conducts heat or electricity.

**Covalent bonding:** Bonds that occur when atoms are held together with shared electrons.

**Chemical energy:** The potential energy that is stored in the bonds of molecules.

**Decomposed:** Broken down into basic elements.

**Decomposition reaction:** A reaction that separates a substance into two or more different substances.

**Diatomic molecule:** A molecule with two atoms.

**Distributed generation:** Generation of electricity at or near the location of consumption.

**Distribution system:** The network of wires and other equipment that delivers electricity.

**Domestic:** Within a particular country.

**Dry cell:** A voltaic cell in which the electrolyte is a paste.

**Electrochemical energy conversion device:** A device such as a battery or fuel cell that uses a chemical reaction to produce electricity.

**Element:** A substance in which all of the atoms are identical.

**Electrical charge:** a force within a particle.

**Electricity:** A form of energy that is created by the flow of electrons.

**Electrode:** A conductor that can carry electrons to or from a substance.

**Electrolysis:** A process that uses an electric current to break a molecule apart.

**Electrolyte:** A substance through which electricity can pass or a substance that dissociates (breaks down) into ions when electricity is passed through it.

**Electron:** A subatomic particle that has a negative charge found in an orbit around the nucleus.

**Endothermic reaction:** A chemical reaction that requires the input of energy.

**Energy:** The capacity to do work or make a change.

**Energy carrier:** A substance or system that moves energy in a usable form from one place to another (for example, electricity).

**Energy efficient:** The input energy need per unit of output energy.

**Fossil fuel:** A fuel created by the decomposition of ancient organic materials.

**Fuel cell:** A device that produces a reaction between chemicals and generates an electric current in the process. A fuel cell does not run down or require recharging.

**Fusion:** A process in which atomic nuclei combine and release a large amount of energy.

**Greenhouse gas:** A gas that traps and radiates heat in the lower atmosphere.

**Hydrogen:** The lightest and most abundant element. A hydrogen atom consists of one proton and one electron.

**Ion:** An atom that has a net charge due to the loss or gain of an electron.

**Ionic bonding:** An attraction between oppositely charged ions that bonds two atoms.

**Membrane:** A material that forms a barrier and allows selective materials to pass.

**Methane:** ($CH_4$) A greenhouse gas that is a main ingredient in natural gas.

**Microbial production:** A process in which algae and bacteria under certain conditions use sunlight to produce hydrogen.

**Molecule:** Two or more atoms that are joined by chemical bonds.

**Neutron:** A subatomic particle that has no electrical charge found in the nucleus.

**Nonrenewable:** A resource that cannot be replenished in a short time and is considered finite.

**Nucleus:** The center of an atom that includes the neutrons and protons.

**Oxidation:** A chemical reaction in which atoms or ions lose electrons.

**Oxygen:** A chemical element consisting of eight protons, eight neutrons and eight electrons.

**Periodic table:** The arrangement of chemical elements by increasing atomic number that emphasizes periodicity in its design.

**Photoelectrolysis:** A process that uses sunlight to split water into hydrogen and oxygen.

**Polymer:** A large molecule made of many small repeating molecules.

**Proton:** A subatomic particle with a positive charge found in the nucleus.

**Polymer electrolyte or proton exchange membrane (PEM):** An electrolyte membrane that conducts positive ions and blocks negative ions.

**Radiant energy:** Energy in the form of electromagnetic waves. Energy from the sun.

**Reduction:** A chemical reaction in which atoms or ions gain electrons.

**Reformulated gasoline:** Gasoline that has been chemically treated to reduce air pollution.

**Renewable:** A resource that is inexhaustible or can be replenished in a short period of time.

**Shell:** An orbit around the nucleus of an atom in which electrons are found.

**Steam reforming:** An industrial process that uses high-temperature steam to separate hydrogen from the carbon atoms in methane ($CH_4$).

**Subatomic:** Smaller than an atom.

**Nuclear thermochemical production:** Extremely high heat produced from a controlled nuclear reaction is used to decompose water into hydrogen and oxygen gases.

**Valence electron:** Electron in the outermost shell.

**Voltaic cell:** A cell that converts chemical energy to electricity; a battery.

**Water ($H_2O$):** A clear, colorless, odorless, tasteless liquid that is essential for most plant and animal life and the most widely used of all solvents.

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