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SAVE IT FOR LATER

BATTERIES KEEP US ENERGIZED

By Chris Eboch

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In 2010, a powerful 7.1 magnitude earthquake hit Haiti. International aid organizations raced there to provide food, medicine, and shelter, but overlooked was the need for light and a way to power emergency cell phones.

While batteries can provide energy when no electric grid is available, lights and cell phones draw a lot of power and thus their batteries must be replaced or recharged regularly—a challenge during a crisis.

Andrea Sreshta and Anna Stork were inspired to develop cheap solar powered lights with built-in phone chargers. Solar lanterns are now distributed by humanitarian groups in disaster areas or war zones, used by hikers in remote areas, and kept in homes in case of power outages.

Solar-powered products harvest energy from the sun and store it in batteries for use at night or on cloudy days. Batteries charged by solar power also move the rover on Mars and support science experiments in remote areas.

One research project in Antarctica needed equipment to work through the winter after the scientists departed. Car-sized batteries with attached solar panels store enough energy to run for about two weeks without the sun.

"When the sun comes back, the solar panel starts charging the battery," says Senior Staff Scientist Pnina Miller. "The equipment turns back on, all by itself. Then we go back in the summertime and retrieve the data," she said.

While solar power has the potential to power everything from lights to entire households, it is only as good as its storage battery. Batteries can keep things running in extreme environments, or in our daily lives, but they come with challenges and costs.

THE BENEFITS OF BATTERIES

In scientific terms, energy is the ability to do work. Modern life uses energy for transportation, running electronics, powering appliances, lighting, and heating and cooling buildings—and the amount of energy people use grows with each generation.

Unfortunately, about two-thirds of the energy produced worldwide is lost before it reaches customers. Energy gets lost as it is converted to electricity, largely as heat energy. Sometimes energy is poorly used: Lights stay on in empty rooms, outdated equipment doesn't work efficiently, while other energy is collected but not used.

Batteries can store energy through electrochemistry in which electricity is generated by the movement of electrons from one element to another in a reaction known as oxidation-reduction, or redox for short.

In a redox reaction, one species loses electrons as it undergoes oxidation, while another species gains electrons as it is reduced. An electrochemical cell converts chemical energy into electrical energy or takes electrical energy and converts it into chemical energy.

Solar-powered chargers can replenish the battery on your cell phone.

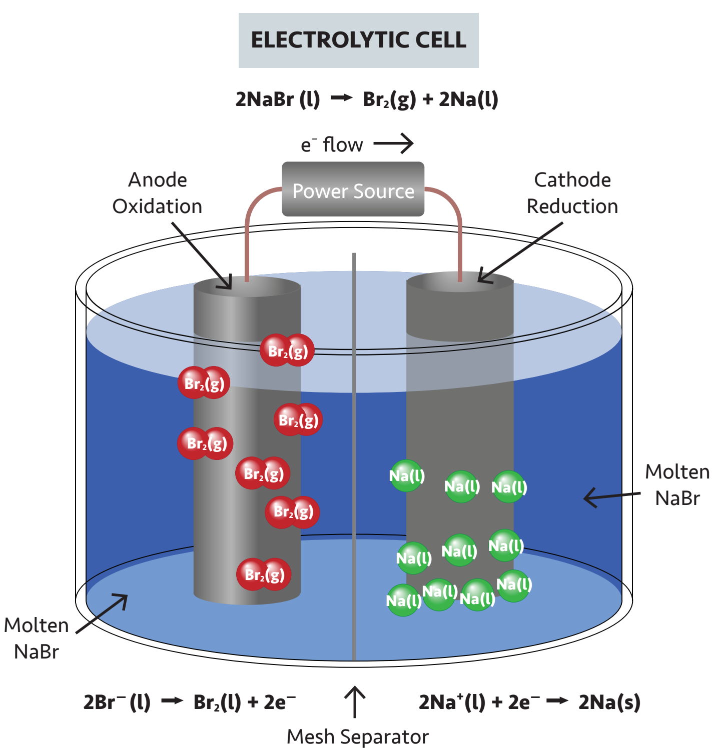
Every battery is an electrochemical cell or a series of cells. Each cell contains two electrodes: the cathode, where reduction (gaining of electrons) takes place, and the anode, where oxidation (loss of electrons) takes place.

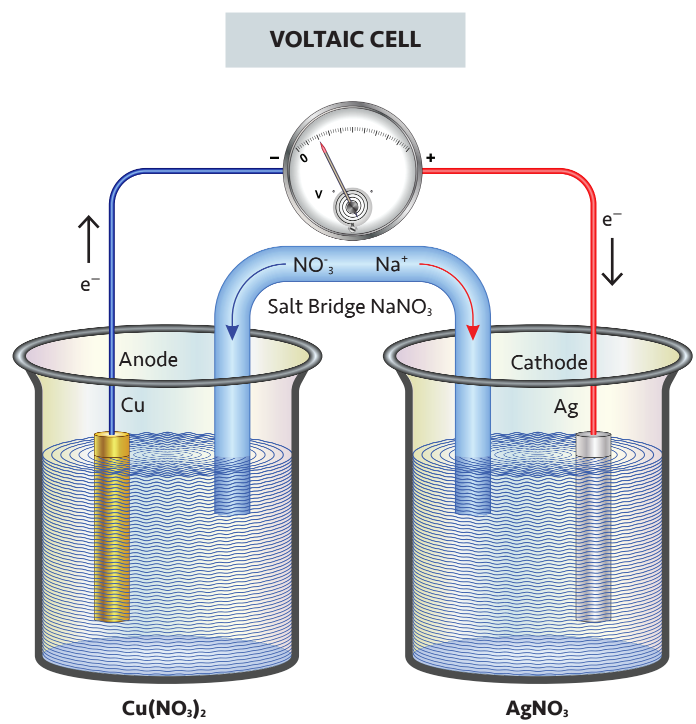
These electrodes are electrical conductors used to make contact with an electrolyte: A substance, usually a liquid, that contains ions. Ions are atoms or molecules with an electrical charge.

Electrochemical cells that work spontaneously (a reaction occurs by itself) to produce a flow of electrons through a spontaneous redox reaction are voltaic cells, while electrochemical cells that use electrical energy to power a nonspontaneous redox reaction are electrolytic cells.

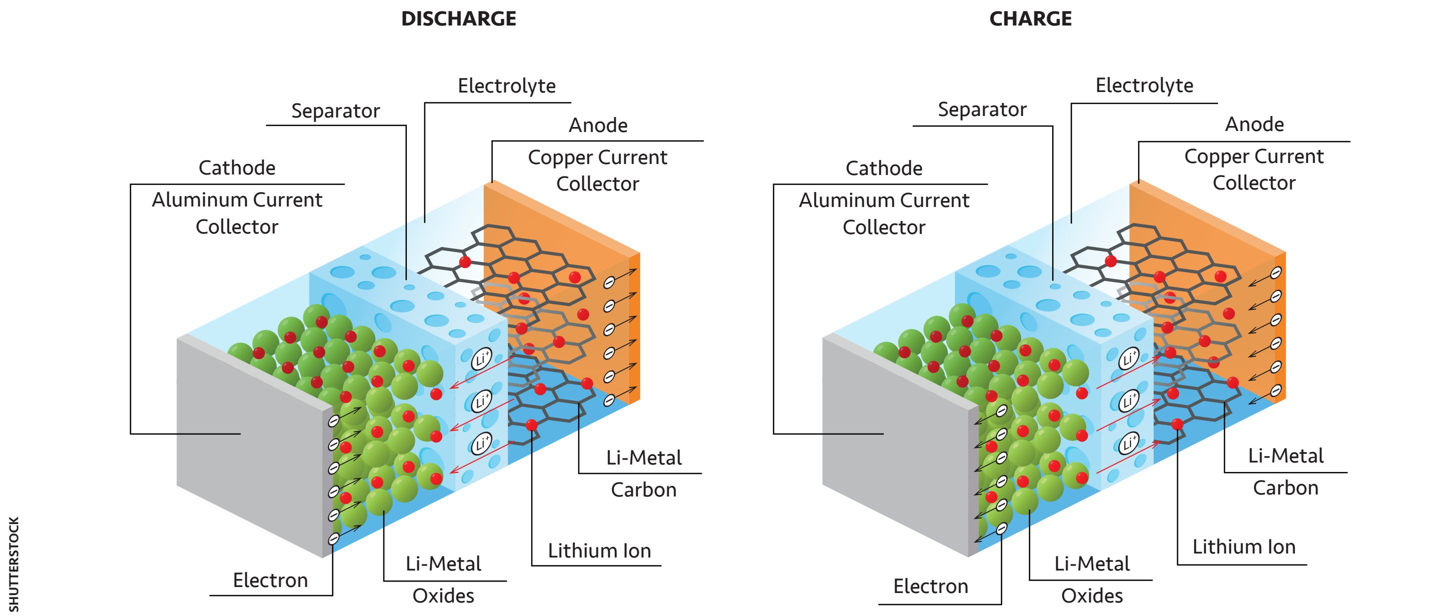
Rechargeable batteries, like the ones in your cell phone or laptop, act as both a voltaic cell and electrolytic cell. When you use your device but aren't plugged in, the batteries are discharging spontaneously: a voltaic cell.

Then, when you recharge the battery, they become electrolytic cells, where electricity flows into the system from the power source. This is nonspontaneous and forces the flow of electrons and ions to reverse.





LITHIUM-ION BATTERY



The distinction between discharge and charge in a Lithium-ion battery lies in the direction of electron flow. When discharging the reaction is spontaneous and the electrons move from the lithium within the graphite through the device to the metal oxide. When charging the reaction is reversed by an external power source and electrons move from the metal oxide to the graphite and lithium.

Whether your battery is accepting or releasing energy, nothing happens until it is coupled to an external circuit. The electrons must have a completed pathway to flow through.

Credit for the first usable battery is generally given to Italian physicist Alessandro Volta, who built a simple battery in the early 19th century. His voltaic pile device used alternating zinc and silver discs.

Volta separated the discs with layers of cloth or paper soaked in either sodium hydroxide or saltwater to form the electrolyte. Volta's pile underwent a spontaneous reaction and, thus, spontaneous electrochemical cells are called voltaic cells.

Around 1834, Michael Faraday experimented with the voltaic pile and derived the quantitative laws of electrochemistry, the study of how electricity relates to chemical reactions. Electricity can be generated by movements of electrons from one element to another.

Advances in materials eventually produced smaller, more powerful batteries, which are now used in all types of portable equipment.

DISPOSABLE OR RENEWABLE?

Batteries can make energy portable or save it for a rainy day, but batteries run down and stop working over time. Some batteries must be discarded at that point, while others can be recharged.

Rechargeable batteries work the same way as nonrechargeables, except the redox reaction can be reversed using an external energy source. For example, plugging a battery charger into a wall socket provides direct current voltage to recharge the battery.

Rechargeable batteries can be used hundreds of times, delaying the need for new batteries. That means less mining for resources, less energy spent recycling dead batteries, and fewer toxic materials in landfills.

So, why do we have disposable batteries? They're cheaper, and they can hold a charge for years when not used, making them better for important but seldom-used items such as emergency flashlights.

Disposable lithium-iodine batteries find use in medical implants such as pacemakers and places where replacing or recharging batteries is difficult. These batteries use a lithium anode and a solid complex of iodine (I_2) as the cathode. The electrodes are separated by a layer of solid lithium iodide (LiI), which acts as the electrolyte by allowing the diffusion of Li^+ ions. The solid electrolyte causes resistance, so only a low current can be drawn, but they are reliable and last a long time.

RECHARGEABLE LITHIUM-ION BATTERIES

Among rechargeable options, lithium-ion batteries (LIB) are common for home use. LIBs have an anode

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HOW DID THE BATTERY GET ITS NAME?

By Michele Hathaway

Batteries are everywhere—in flashlights, fire alarms, cellphones, cars, remote controls, video games, and hundreds of other devices. Imagine a life without batteries. That would change everything!

But why do we call them batteries, and what do all those letters and numbers mean?

Benjamin Franklin (1706–1790 CE), a founding father of the United States, coined the term battery, a military word for weapons functioning together, to describe a cluster of glass Leyden jars linked together.

Leyden jars were the earliest form of a capacitor, a storage device for electrical energy.

While Franklin used the term batteries for his Leyden jars, capacitors are fundamentally different from batteries. A capacitor is a charge storage device, while batteries convert chemical energy into electricity.

THE FIRST BATTERY

When Alessandro Volta (1745–1827 CE), an Italian physicist and chemist, invented the first battery in 1800, he adopted Franklin's term, and the name stuck.

Volta's battery was a voltaic pile, consisting of alternating layers of zinc metal and either copper or silver separated by cloth soaked in saltwater. When a wire was attached to alternative ends, zinc and copper, for example, it produced a steady electrical current as the zinc was oxidized (lost electrons), and the water in the damp towels was reduced (gained electrons) to hydrogen gas.

The ions moved through the wet paper to maintain an electrically neutral charge overall, and the electrons were attracted by the wire connected to the ends. The unit for electrical potential, the volt, was named after its inventor.

HOW DO ALKALINE BATTERIES WORK?

Batteries are composed of one or more electrochemical cells. Each cell consists of two electrodes separated by an electrolyte: the anode where oxidation takes place, and the cathode where reduction occurs.

In a typical alkaline battery, the anode is made of zinc powder. The Zn is oxidized according to the following reaction:

$$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2e^-$$

When the electrodes of the battery are connected with a wire or device, these electrons flow to the cathode, which is the site of reduction.

The manganese dioxide cathode in an alkaline battery is reduced according to the following equation:

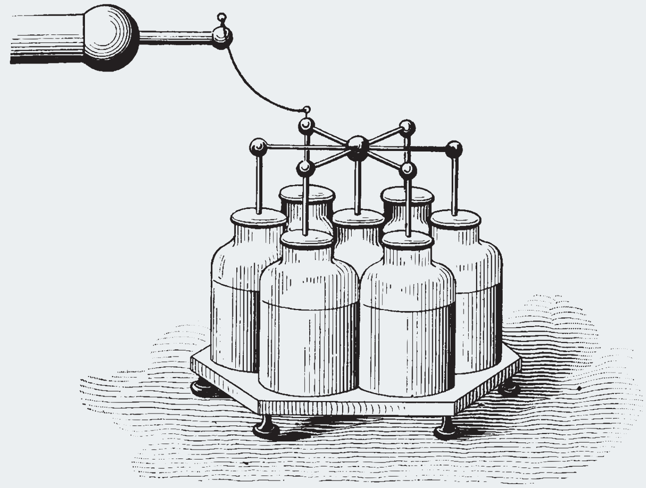
$$2MnO_2(s) + H_2O(l) + 2e^- \rightarrow Mn_2O_3(s) + 2OH^-(aq)$$

The flow of electrons from anode to cathode is what powers the device; it's what we call electricity.

What about the electrolyte? Your typical alkaline battery uses a paste of potassium hydroxide (KOH) or ammonium chloride (NH_4Cl) as an electrolyte.

KOH is what gives alkaline batteries their name; it is an alkali metal that accepts hydroxide ions in water solutions. In this case, KOH is present as a paste and its purpose is to keep the system electrically neutral.

So, while the external wire provides the pathway for the flow of electrons, the electrolyte provides a pathway for the transfer of charged ions. Without this balance, the reaction would stop running.



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Battery of Leyden Jars. Leyden jars could be connected to each other to produce more electricity at once.

WHAT'S IN A NAME?

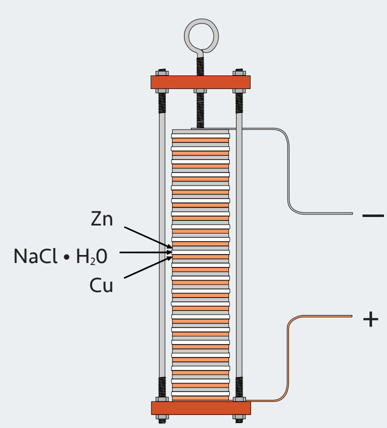
In the centuries since Volta's discovery, batteries have become very useful and necessary power sources, and many types and sizes of batteries were developed to meet different needs.

Today, batteries can be named for their size, chemistry, and voltage. Typical alkaline batteries are named alphabetically by size; originally A was the smallest, and the size progressed through the alphabet to the largest.

As electronics evolved, scientists made batteries smaller than size A, which they named AA and AAA. There are even AAAA batteries, used in laser pointers, glucose meters, and digital thermometers.

Over time, some sizes and types of batteries simply died out as newer and often smaller batteries replaced them. Batteries such as A and B are not commonly used now, while C and D are still used in flashlights.

Batteries can be different sizes and have the same voltage. This is because voltage is the potential difference that drives the movement of



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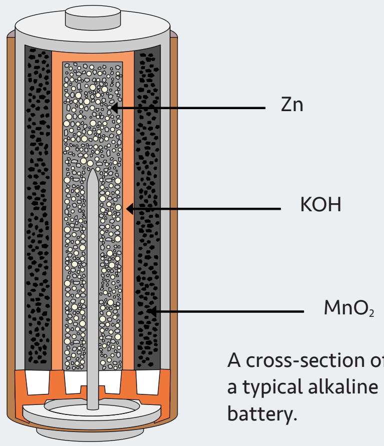
A Voltaic Pile. The zinc serves as the anode, while the copper serves as the cathode. When the positive terminal and negative terminal are connected, the circuit is completed and electrons flow through the wire.

electrons through an electric circuit, and is an intrinsic property—a property that is independent of the amount of material present.For example, the density of water is 1.0 g/mL at 25 °C whether you have one drop or enough for a swimming pool. Density is, therefore, an intrinsic property. But the mass of a substance is dependent on how much you have, which makes it an extrinsic property.

So, while larger batteries have more material, they do not produce any more voltage than smaller batteries, but they may power devices that require more power, or energy per unit of time. According to Ohm's Law: Power = Voltage * Current.



A cross-section of a typical alkaline battery.

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For example, a triple A (AAA) battery and a D battery have the same voltage (1.5V) because they are made of the same chemicals, but the D battery can produce more current—the number of electrons that pass a certain point over a period of time is greater.

One way to look at this is a bucket of water that carries a certain potential, if you connect a pipe to the bucket, it has a certain current when the water flows out. A larger pipe allows more water to flow and the current increases. In a similar way, a larger battery allows more electrons to pass through the wire faster, increasing its power.

NEW BATTERY NAMES

With so many new devices and so many new batteries needed to power them, it became apparent that the alphabet wasn't going to cut it when it came to naming. We were going to run out of letters. We could just keep adding As, or find a way to identify new batteries.

The International Electrotechnical Commission adopted the current designation system in 1992. Battery types are designated with a letter/number sequence indicating number of cells, cell chemistry, cell shape, dimensions, and other special characteristics.

Button and coin cell batteries, invented in the 1970s, are used for keys, watches, candles, and flashing shoes or light-up snow globes. A button battery is round with one flat side and one raised side. Coin batteries look just like their name—a coin that is flat on both sides.

Button and coin batteries are named for their chemical makeup, shape, and size. For example, in the CR2032 coin battery, the first letter stands for the main chemical (lithium) in the battery. The second letter is for the shape (round), and the number 2032 tells us the diameter is 20 mm and the height is 3.2 mm.

With the demand for clean energy to reduce carbon dioxide emissions that affect our climate, batteries are more important than ever. Batteries are here to stay. Our way of life would change drastically without them. One thing we can count on in the future are more new battery names to learn.

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made of very pure graphite (the same material found in a pencil), and the cathode is made of a mixed metal oxide containing lithium, oxygen and a transition element like cobalt. Electrons flow between these electrodes via a device, while the lithium ions travel through the separator.

When the battery is discharged, the lithium atoms stored in the graphite anode are oxidized, creating lithium cations and electrons. Electrons travel through the device, while lithium cations move through the electrolyte to the cathode. At the cathode, the electrons reduce the cobalt making the metal oxide negatively charged. This negative charge is balanced by the incoming lithium cations.

When the battery is charged, the flow of electrons is reversed. The cobalt is oxidized, and the electrons are pushed back to the graphite by the external power source. As the metal oxide loses its negative charge and the graphite gains it, the lithium ions are attracted back to the graphite. The charge is then transferred from the graphite to the lithium cations to make neutral lithium atoms.

Although relatively expensive, LIBs perform well in devices like laptops and cell phones, particularly those that drain power quickly.

THE ENVIRONMENTAL IMPACT OF BATTERIES

In addition, LIBs are often used for storing energy on the electric grid and in electric vehicles (EVs). People who buy EVs generally want to help the environment with reduced carbon emissions and minimize reliance on fossil fuels; unfortunately, EV batteries are another source of pollution.

"The most common materials used in LIBs are lithium, graphite, and metals such as cobalt, nickel, and manganese," says analytical chemist Sarah Hendrickson, who has worked on green-battery research.

"Lithium mining uses *a lot* of water—approximately a half a million liters, or 130,000 gallons, of water to extract a ton of lithium." Mining for battery components has caused toxic chemical leaks, polluted water systems, and poisoned animals and miners.

The damage doesn't end there. Batteries in landfills can leak dangerous metals and concentrated aqueous solutions of potentially corrosive salts. In some countries, regulations require battery recycling to keep the pollution out of landfills and reduce the need for new materials.

But recycling doesn't always solve the problem. Most lead recycling is done in economically disadvantaged areas with few pollution controls, so lead is released into the air, soil, and water.

Plus, improper storage and handling of batteries causes hundreds of fires each year in Canada and the United States alone.

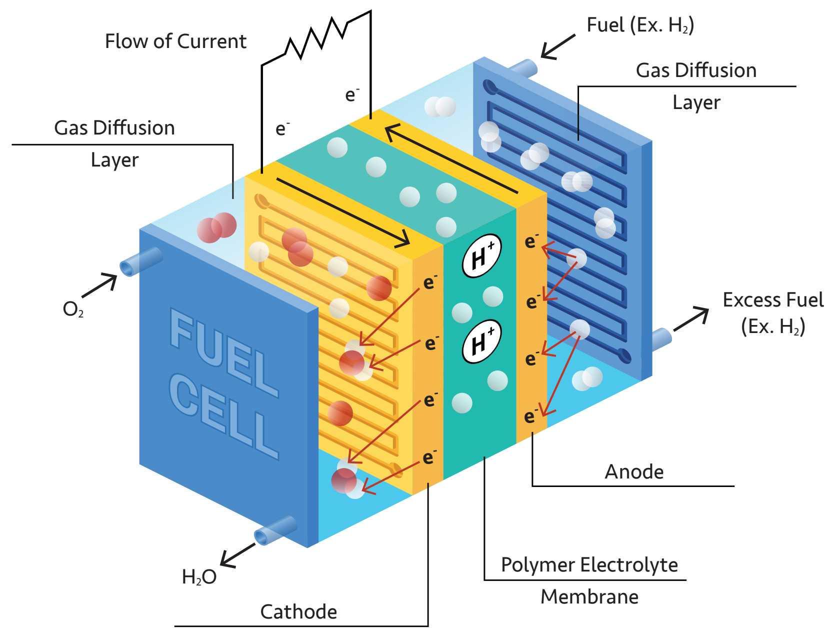
BETTER BATTERIES

Many governments and private companies are investing in research and commercialization of alternative batteries. Researchers are working to develop batteries that use materials that are less toxic and easier to obtain.

Lithium-sulfur batteries use a lithium anode with a cathode of sulfur and carbon instead of cobalt and nickel, removing some of the metals that cause environmental damage when mined. They have higher-energy density than LIBs, meaning they store more energy in the same amount of material. These batteries degrade quickly, however, as sulfur is lost into the electrolyte.

Sodium-ion batteries use sodium in place of lithium. These are highly efficient, don't require as much mining, and are potentially cheaper, because sodium is more abundant than lithium. They have

POLYMER ELECTROLYTE MEMBRANE (PEM) FUEL CELL



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a lower-energy density than LIBs, however. They can't store as much energy in the same amount of material, so it's hard to make them small and long-lasting.

Researchers are also working on lithium-air batteries that use a solid electrolyte, made from a ceramic polymer material, instead of a liquid electrolyte. This allows the battery to use oxygen from the air and removes the corrosive liquid electrolyte that breaks down over time and leaks.

There are many areas of research as scientists try to build batteries that work better with less environmental impact. It's challenging to identify the "best battery," because there are so many different uses for them. The power needs vary from electric-grid energy storage, cell phones, and smoke alarms to implanted medical devices.

FUEL CELLS: THE FUTURE?

Fuel cells are another big area of research. A regular battery contains all the reactants it needs to produce electricity. A fuel cell, on the other hand, needs a constant external supply of reactants.

While that sounds like a disadvantage, a fuel cell will keep making electricity as long as it has a fuel supply, without the need for recharging—an advantage if the fuel is cheap and plentiful.

Hydrogen fuel cells use oxygen and hydrogen as fuel. The hydrogen, stored in a fuel tank, is introduced to the anode. Oxygen from the air is introduced to the cathode. The fuel-cell catalyst speeds up the electrochemical reaction.

During this reaction, the hydrogen molecules break apart into two hydrogen ions (H^+) and electrons. The hydrogen ions travel through an electrolyte membrane to the cathode.

Meanwhile, the electrons are forced to travel through an external circuit, which provides power to the device or machine. The electrons then join the hydrogen ions at the cathode, where they react with a catalyst and oxygen molecules to form water.

Hydrogen fuel cells do not produce harmful emissions the way burning gasoline does, and in theory, this fuel can be made from renewable sources. Oxygen is in the air. Hydrogen is found in water and plants.

While hydrogen is the most abundant element in the universe it usually exists combined with other molecules, so we can't easily pluck it from the environment; but improvements in technology have made it, and will continue to make it, easier to produce.

Polymer electrolyte membrane fuel cells use a polymer membrane as the electrolyte and hydrogen as fuel. The direct-methanol fuel cell also has a polymer membrane as the electrolyte, but it uses methanol (a liquid) instead of gaseous hydrogen.

NASA has used alkaline fuel cells as a source of electrical energy and drinking water on space missions. They use an alkaline electrolyte such as potassium hydroxide or an alkaline membrane. Several other fuel-cell types use different materials as the electrolyte. Each has advantages and disadvantages.

Several companies already make electric vehicles using hydrogen fuel cells, but these require a hydrogen-fueling station. At this time, California is the only U.S. state that has hydrogen fuel stations.

Hydrogen fuel-cell cars won't become common until hydrogen is widely available. That's a big reason why it's been hard to replace gas-powered vehicles—the gasoline fuel system is already in place.

THE SEARCH FOR ALTERNATIVES

The U.S. Department of Energy, national laboratories, universities, and businesses are working on the issues together. Companies spend billions of dollars to research, develop, and produce batteries every year.

But in the end, "there is nothing physical you can buy that does not have an environmental impact," Hendrickson says. "There is an enormous market for green alternatives to just about every product. There are no real guidelines or requirements for something to be dubbed 'green.' One must dig deeper to determine the real cost or benefit, and batteries are no exception."

Hendrickson contends that over time, "batteries will become cleaner and more powerful, just as the internal combustion engine has."

In the meantime, we can reduce energy use, use rechargeable batteries, pressure companies to develop better batteries, and try to properly recycle batteries. "Stay curious and keep asking questions," Hendrickson adds. You might just be one of the next generation of scientists making breakthroughs that keep us safely energized.

Chris Eboch is a science writer who lives in Socorro, New Mexico. Her most recent *ChemMatters* article, "Mad Scientists and Misinformation," appeared in the February 2024 issue.

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