Curriculum Units by Fellows of the National Initiative
2019 Volume IV: Energy Sciences

Driving in the Future: How Far Will that Battery Take You?

Curriculum Unit 19.04.01, published September 2019
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Introduction

Energy Demand

In the late 1990's, worldwide demand for energy was predicted to peak at 13 TW by the year 2001.[1] The relentless pace of technological advances along with an exponentially growing population has pushed that demand to 17.4 TW in 2015.[2] Our unabated demand for more energy to power our lifestyles, has so devastated our planet's natural resources and ecosystems that we are on the brink of the planet's 6th mass extinction event.[3] There are many interconnected factors that are driving this environmental catastrophe; however, global warming and its associated climatic changes (extreme weather events, sea level rise, prolonged fires, droughts, etc.) pose the greatest threat to the sustainability of life as we know it.[4]

The increase in greenhouse gas (GHG) emissions as a result of human activity is recognized as the root cause of global warming. These gases (predominantly carbon dioxide formed from the combustion of fossil fuels) rise into the atmosphere where they trap solar radiation that would normally escape into space. The continual increase in the concentration of GHGs has intensified the Earth's natural greenhouse effect which has led to the gradual rise in global temperatures.

Data collected since the middle of the industrial revolution illustrate the relationship between increased CO_2 emissions and global temperatures. The data show that CO_2 emissions have increased from 280 ppmv (parts per million by volume) in 1860 to over 476 ppmv in 2017.[5]

As a result, the earth's global mean temperature has increased approximately 1.0°C relative to pre-industrial levels.

Although world leaders have tried to craft realistic international agreements that would mitigate the threats of climate change, they have yet to fully enact a comprehensive unified plan of action.

Thus, it seems that we will continue to ignore the evidence of global warming and draw ever closer to the threshold (2^0 C above pre-industrial levels) beyond which the effects of climate change will become irreversible.

The Stone Age Didn't End Because They Ran Out of Stones[6]

The data on energy use in all sectors of the global economy confirm the continued dominance of fossil fuels. Recent developments, however, suggest that a change may be on the horizon.[7] The use of fossil fuels is so profitable because energy corporations have not (until recently) been held accountable for the effects of their product on the environment and public health.[8] Presently there are many legislative efforts throughout the world that levy taxes and fines that require the industry to pay for the damages they have caused.[9]

> By requiring plants to invest in countermeasures to air pollution, the legislation implicitly put a price on some of the human health impacts of coal pollution. And by making coal more expensive, clean-air regulations also reduce pollution, as alternatives to coal become more cost-competitive[10]

Most economists predict that the combination of decreasing profits, coupled with the rise of more efficient, economical renewable energy technologies (see *Giant Batteries and Cheap Solar Power are Pushing Coal off the Grid* [11]), will end of the era of coal fired power plants in the United States and in most industrialized nations worldwide.[12]

Recent advances in solar, wind, and battery technology suggest that these newer technologies are poised to become the resources that can meet our energy needs while respecting our desire to protect our environment. And although our federal government has failed to adopt policies that acknowledge the need for responsible climate legislation, private citizens, local municipalities, interest groups, and multinational organizations around the world have undertaken initiatives to save our planet. Fossil fuels will eventually disappear, not because we will run out of them, but because they will no longer be relevant to our way of life.

> The current energy change is driven not by convenience or by a new discovery, but by society. People want novel and cleaner services, and these can be provided with much less energy. Consumers will drive demand for new technologies and new services, and changes in behavior and preferences will drive new ways of providing them. The future could be very different from today.[13]

Rationale

I believe that my most important task as science educator is to use the curriculum in ways that will prepare my 10th and 11th grade Chemistry students to become critical, informed, and engaged young adults. Learning science is not just remembering facts and theorems; rather it is an opportunity to use scientific habits of mind to analyze the difficult problems confronting our society. At this moment in our collective history, I believe that climate change (and all of its associated consequences) is a crisis that threatens the sustainability of all life on our planet. And given that there is no national will to address the issue, the crisis will likely deepen before sensible policies are enacted.

For this reason, I feel that it is incumbent upon me to provide my students the knowledge and perspectives that will help them determine how best to address this issue in their lives. There is almost universal consensus that the increasing concentrations of GHG from our combustion of fossil fuels is the root cause of climate change. Many believe that shifting to renewable energy sources will decrease these emissions and help mitigate the effects of climate change.

While necessary attention is given to the ways in which the fossil fuel industry has harmed our planet, it important to note that all forms of energy production (renewable sources included) can impact society and the environment. These consequences are often overlooked as some are often hidden, or unintended and difficult to quantify.[14] Zero emission vehicles may have a large environmental impact (footprint) given where and how their electricity is generated. While it is true that they are all zero emission vehicles, they may not all be carbon neutral.

The principal goal of this unit is to provide my students an understanding of the energy resources and technologies that will be available to them as they mature and to help them determine how they can contribute to our transition towards green sustainable energy.

Content Objectives

The initial objective of this unit addresses the relationship between carbon dioxide emissions and increasing global temperatures. Following this, students will evaluate the benefits and consequences of renewable and non-renewable energy resources. These beginning goals will establish the evidence for climate change and the need to transition towards renewable energy sources. Once we have met these objectives, the class will begin the study of electrochemistry as it relates to primary and secondary cells (rechargeable batteries). The primary focus of these lessons will be to understand how the processes of reduction and oxidation create electrical current in primary cells, and how these processes (when reversed) help to recharge secondary cells.

The principal objective of this unit is to explore how our society might transition from our reliance on fossil fuels towards renewable, sustainable energy sources. Therefore, the remaining lessons will focus on how renewable sources can meet our energy demands. Given that the bulk of our fossil fuel resources are used for transportation purposes, the unit will then explore how rechargeable battery technology can be used to power the next generation of electric vehicles.

Teaching Strategies: (Aligned to the Content Objectives)

In order to analyze the factors that contribute to global warming, students will complete a guided inquiry that analyzes the relation between increased carbon dioxide emissions and rising global mean temperatures. The class will then engage in a collaborative research on the benefits and consequences of renewable and non-renewable energy sources and how best to address the issue of global warming. As part of the debate, students will engage in a collaborative research of renewable and non-renewable energy sources followed by a class debate on the merits of each resource. Each student will propose how they plan to use these resources in ways that can protect the environment and meet their life needs. In order to study the redox reactions in primary and secondary cells, students will complete a laboratory on single displacement reactions. As part of this activity, they will balance the reduction and oxidation reactions in both types of cells. We will extend the analysis of rechargeable batteries through a collaborative web quest that explores which types of electric vehicles are most efficient and least harmful to the environment. Students will end the unit by completing a guided inquiry that evaluates their ecological footprint.

Content Background

Non-Renewable Energy and Climate Change

Fossil fuels provide energy for nearly all of our human activities. Although our nation demands energy for a wide range of uses, the vehicles we use for transportation required approximately 28% of the energy resources in 2017. The combustion of petroleum products (gasoline, diesel, jet fuel) produced approximately 29% of the country's greenhouse gas emissions in 2017.[15]

$2C_8H_{18}$ (l) + $25O_2$ (g) -> $16CO_2$ (g) + $18H_2O$ (g) (Combustion of Gasoline)

The combustion of coal and natural gas for the generation of electricity required 63% of our energy resources.[16] These processes produced 28% of the nation's GHG emissions.

C (s) + O_2 (g) -> CO_2 (g) (Combustion of Coal)

CH_4 (g) + $2O_2$ (g) -> CO_2 (g) + $2H_2O$ (g) (Combustion of Natural Gas)

Although we believe that the coal fired power plant is in decline, many remain online, while other plants are using natural gas as a substitute. Additionally, the major portion of our energy resources is used for transportation which continues to rely heavily on petroleum as the main energy resource. Thus, it is important to note that, although there are many concerted efforts to move towards renewable energy sources to generate electricity, we continue to rely heavily on coal, petroleum, and natural gas for our energy needs.[17]

Electrical power plants use thermal energy from the combustion of (coal or natural gas) to convert water into steam that is then used to turn generators that convert the mechanical energy into electricity. The internal combustion engines in our vehicles convert the chemical energy in gasoline into mechanical energy. In each case, GHG emissions are produced, while much of the thermal energy is lost as waste heat.

Renewable Energy Sources

Renewable technologies convert various forms of renewable energy (solar, wind, hydro, geothermal) into electrical energy. Photovoltaic cells convert solar radiation into electrical energy while wind turbines use generators to convert the kinetic energy of the wind into electrical energy. None of these technologies emit greenhouse gases and (for the most part) they do little harm to the earth's ecosystems. Their profitability has been increasing over the last twenty years as their efficiency has steadily increased while their production costs have dramatically declined. Wind and solar energy are the more impressive of these sources as each has the capability of providing vast amounts of energy. They are, however, limited as they are not always available, and we do not have efficient ways of storing the electricity they produce. Thus, any strategy meant to move us away from a dependence on fossil fuels depends on the availability of technologies that can efficiently and economically store energy harvested from these renewable sources.

Storage Devices

Efficient storage devices (batteries) are the key to the successful transition to renewable energy sources. In order to effectively use renewable energy, we would need to harvest and store the energy (solar or wind for example) when it was available, store it and then use it at a later time when the resource was not available. These rechargeable batteries (secondary cells) would need to efficiently store large quantities of energy, discharge their energy as needed, and recharge quickly and efficiently.

There are already many different types of rechargeable batteries that serve a wide variety of purposes in our society. They are an integral part of the information revolution as nearly all portable electronic devices are powered by a rechargeable device. Rechargeable batteries are increasingly used in the transportation industry as components of hybrid, plug in hybrid, and fully electric vehicles. Using electricity as a replacement for internal combustion engines would be extremely beneficial given that most of our energy resources (and the resulting GHG emissions) result from the combustion of petroleum products.

Over the last 30 years, the efficiency and capacity of these devices has dramatically increased as new technologies have made it possible to use them as integral components of the change towards renewable energy sources. Massive storage devices are already planned as part of a large solar farm built by the 8minute Solar Energy company near Los Angeles, California.[18] The farm's photovoltaic cells will capture and store solar energy in an array of giant batteries that will supply up to 7% of the city's energy needs. The projected price will be 1.98 cents / kWh from the array and 1.3 cents / kWh for electricity from the battery: both prices are well below existing market prices from coal fired plants. These projected innovations in renewable energy production are possible because we have some way of storing the energy produced. Absent such a device, we would have no way of capturing this very abundant source of energy.

For this unit, I will focus on the three representative rechargeable batteries, the Ni-Cd, Ni-metal hydride (NiMH), and the Li-ion battery, as they are the more common devices in my student's everyday lives. While each of the batteries use a similar architecture, the NiMH and the Li-ion have features that make them more practical than the Ni-Cd device. I will begin my analysis of batteries with an exploration of the basics of redox reactions in primary cells, followed by an analysis of the Ni-Cd, Ni-MH, then the Li-ion battery.

Chemistry of Batteries

Batteries (also known as electrochemical cells) are devices that can convert the stored chemical potential between two electrodes (the positive cathode and the negative anode) into electrical energy via coupled reduction / oxidation (redox) reactions. The electrodes can be made from a wide variety of materials (in any physical state); however, they must be kept apart in order to avoid a direct transfer of electrons (known as a short circuit). The separation of the electrodes forces the electrons produced at the anode (the site where oxidation occurs) to flow through an

external circuit (where they do useful work) to the cathode (where reduction occurs). Although the electrodes are not in direct contact with each other, they are connected through a conductive medium (an electrolyte) that exists between them. The electrolyte maintains the equilibrium of ions in the battery so that charge can continue to flow between the electrodes. Redox reactions are the chemical processes that convert chemical potential in the battery's electrodes into electrical energy. There are analogous redox reactions in all types of primary and secondary batteries.

Reduction / Oxidation Reactions

When given combinations of metals interact, electrons can spontaneously flow from one metal to

the other. The coupled processes that occur during these interactions are known as reduction and oxidation (redox for short) reactions. For example, when a piece of solid aluminum (Al (s)), is placed in a solution of copper chloride ($CuCl_2$ (aq)), the aluminum metal will donate electrons to the copper ions in the solution. Equation (1) depicts the molecular equation for this reaction.

$2Al\ (s) + 3CuCl_2\ (aq) \rightarrow 2AlCl_3\ (aq) + 3Cu\ (s)$ (1)

During this process (known as a single displacement reaction), each aluminum atom donates three valence electrons to the copper ions in the copper chloride solution: (this changes the oxidation state of the aluminum atoms from Al^0 to Al^{3+}). Each of the 3 copper atoms receive two electrons which changes their oxidation state from Cu^{2+} to Cu.^{0} In order to analyze the flow of electrons, equation (1) can be rewritten in a series of ionic equations that show the oxidation states of the metals. Equation (2) is the total ionic equation that shows all of the ions in the reaction: (states are not included for clarity of the discussion).

$2\ Al^0 + 3\ Cu^{2+} + \boldsymbol{6\ Cl^{1-}} \rightarrow 2\ Al^{3+} + \boldsymbol{6\ Cl^{1-}} + 3\ Cu^0$ (2)

Eliminating the spectator ions that do not change oxidation state produces a net ionic equation (3).

$2\ Al^0 + 3\ Cu^{2+} \rightarrow 2\ Al^{3+} + 3\ Cu^0$ (3)

There are two reactions in equation (3) which can be analyzed separately in what are known as half reactions: equations (4) and (5).

$2\ Al^0 \rightarrow 2\ Al^{3+}$ (4)

$3\ Cu^{2+} \rightarrow 3\ Cu^0$ (5)

Although the reactions have the correct mass balance, they are not balanced as to charge. Charge is balanced by adding electrons (each carrying a $^{-1}$ charge) to balance the positive charges. Adding six negative charges to the appropriate side of each reaction yields equations (6) and (7).

$2\ Al^0 \rightarrow 2\ Al^{3+} + 6\ e^-$ (6)

$3\ Cu^{2+} + 6\ e^- \rightarrow 3\ Cu^0$ (7)

The two half reactions reveal the flow of electrons. Equation (6) is known as the oxidation half reaction because each aluminum lost electrons. Equation (7) is the reduction half reaction because each of the copper atoms gained electrons. This redox reaction is representative of all the reactions in batteries. In this reaction, the metals are in close contact with each other thus the electrons flow directly from one metal to the other. If, however the reactions are placed in separate reaction vessels and connected by a conducting medium, then the electrons will flow from the anode to the cathode through the external circuit. This flow of electrons (an electric current) can be used to do useful work.

Primary cells will continue to produce electrical energy as long as the materials within them remain viable. Once they are spent, primary cells are no longer useful. In secondary cells (rechargeable batteries), the chemical potential can be restored when a reverse electrical charge is applied across the electrodes.

A secondary cell is one in which the starting materials at the anode and cathode are recovered when a reverse electrical potential is applied to the cell. For example, the Ni-Cd battery is composed of a cadmium (Cd) metal anode and a Ni(III)-oxide hydroxide (Ni(O)OH) cathode. When the battery is discharged, the Cd is oxidized to Cd(II) hydroxide ($Cd(OH)_2$), while at the cathode the Ni(O)OH is reduced to Ni(II) hydroxide: $Ni(OH)_{2.}$ The reactions are as follows:

Oxidation at the anode: Cd (s) + $\boldsymbol{2OH^-}$ -> $Cd(OH)_2$ (aq) + $\boldsymbol{2e^-}$ (8)

Reduction at the cathode: $1e^-$ + Ni(O)OH + H_2O -> $Ni(OH)_2$ + OH^- (9)

Equation (9) must be multiplied by 2 in order to balance the electron flow between the two half reactions. This yields the following:

$\boldsymbol{2e^-}$+ 2Ni(O)OH + H_2O -> $2Ni(OH)_2$ + $\boldsymbol{2OH^-}$

Cancelling the hydroxides that appear on both sides of the reactions produces the overall net ionic reaction:

Cd (s) + 2Ni(O)OH + $2H_2O$ -> $2Ni(OH)_2$ + $Cd(OH)_2$ (aq) (10)

During the recharge period, the reactions are reversed so that $Cd(OH)_2$ is reduced back to Cd; while the $Ni(OH)_2$ is oxidized back to Ni(O)OH.

Reduction: $Cd(OH)_2$ (aq) + $2e^-$ -> Cd (s) (11)

Oxidation: $2Ni(OH)_2$ -> 2Ni(O)OH + $2e^-$ (12)

In order to be considered an efficient rechargeable battery, the chemical reactions that occur during discharge must be fully reversible. This means that the reactions at each electrode must be a true reverse reaction with no additional products formed. If by products are formed, then the battery may become unstable, the electrodes may decay, or a short circuit may occur. Additionally, the starting materials must be recovered in their original physical state with no additional by products formed. If these conditions are not met, then the battery's lifetime may be shortened, or the device will fail to deliver adequate charge.[19]

Each type of storage device needs to meet a different set of requirements. Given that drivers have become accustomed to quick, convenient refueling, and the driving distances provided by a tank of gasoline, researchers are working to produce rechargeable battery technologies that provide the same level of reliable (relatively inexpensive) energy that gasoline / diesel fuel provides. At present the lithium-ion battery is (for a variety of reasons) the most promising rechargeable battery technology.[20]

Of the various battery types available for use in our vehicles (Pb-acid; Ni-Cd; Ni-MH; and Li-ion) the lithium-ion battery provides the highest energy density and power with a relatively high miles per charge value (currently 250 mi. / charge with a goal of 350 mi. / charge). Lithium's physical and chemical properties make it highly suited for rechargeable batteries. It has one of the lowest reduction potentials (-3.04 E^0 V) and, therefore, one of the highest cell potentials. It has one of the smallest radii of any singly charged cation and as a result has as an exceptionally high-power density. Although supplies may be limited in the future, there are sufficient deposits currently available for the world's needs. For these fundamental reasons, lithium will likely remain as the prime metal used in automobiles and portable electrochemical devices for the near future.[21]

Chemistry of the Li-ion Battery

Li-ion batteries rely on redox reactions at each of the electrodes to produce an electron flow. They must first be fully charged before they are used. During the charging process, the lithium ions in the lithium cobalt oxide ($LiCoO_2$) travel through the electrolyte to the Li_xSi anode where Li^+ combines with an electron and is reduced to Li. When no more Li can be deposited onto the anode, the battery is fully charged.

During the discharge, the lithium in the anode is oxidized to $Li^+ + e^-$. The electrons produced travel through an external circuit where they do work before returning to the cathode. At the cathode, these electrons reduce the cobalt oxide and combine with Li^+ to form $LiCoO_2$. When all the Li atoms generated during the charging process have returned to the cathode, the battery will need to be recharged.

The high charge density of the Li-ion battery results from the chemical properties of lithium and the architecture of its electrodes. Lithium atoms have the highest reduction potential of all metals; as a result, each cell of a Li-ion battery can deliver up to 3.6 V. Additionally, given its small size, many lithium atoms can be fit into the carbon matrix, giving the battery one of the highest mass to charge ratios of all batteries.

Electrodes

Lithium atoms at the anode are intercalated between successive layers of carbon atoms. Carbon compounds (graphite / graphene) can be used to intercalate lithium at the anode. Graphene is currently preferred as graphite can become unstable over time. Cathodes are typically made of a compound of lithium, oxygen and a transition metal with variable oxidation states. Cobalt is one preferred element as it can exist as Co^{4+} or Co^{3+} . The compound lithium cobalt oxide ($LiCoO_2$) is used extensively in Li-ion batteries. It has however shown to be thermally unstable as the oxide can decompose and produce oxygen if the battery overheats. Unless the oxygen is released, the battery poses a severe fire hazard.

Electrolyte

The electrolyte in the battery is usually an inert material that is a good ionic conductor that insulates the two electrodes, provides an abundance of ions that travel between anode and cathode and is thermally stable. The electrolytes can be non-aqueous solutions of lithium hexafluorophosphate ($LiPF_6$) in a mixture of organic carbonates such as ethylene carbonate, propylene carbonate, or diethyl carbonate, aqueous solutions of lithium salts in water or ionic liquids.[22]

Materials Science

While lithium-ion batteries are expected to dominate the industry for the near future, the demand for electrochemical storage devices for all energy sectors (such as long-haul trucking and aviation) will require the use of new macromolecules and polymers that can be tailored to meet the specific design parameters (such as architecture, charge capacity, electrolyte components, electrodes, etc.) These innovations along with new battery technologies (i.e. the Vanadium flow, the Na-S, and Al-ion battery [23]) will be necessary if we are to successfully develop electrical storage devices that "provide long-lasting solutions that can be commercialized and deployed at a cost that disrupts the market, which is currently dominated by the coal, oil, and gas industries".[24] Our ability to move away from fossil fuel technology will greatly depend on the efficiency of these future electrical storage devices.

Chemistry and Environmental Impact of Batteries

Tables 1 and 2 below provide an opportunity to evaluate the performance features of common rechargeable batteries and their environmental impact. The batteries in Table 1 are "established" devices that are currently in use. Table 2 explores future designs. Both tables are adapted from: Armand, et.al. " Building a Better Battery" [25]

Table 1: Chemistry and Environmental Impact of Established Batteries

Battery Type	Features	Environmental Impact
Ni–MH (established)	Low voltage, moderate energy density, high power density Applications: portable, large-scale	Nickel not green (difficult extraction/ unsustainable), toxic. Not rare but limited Recyclable
Lead–acid (established)	Poor energy density, moderate power rate, low cost Applications: large-scale, start-up power, stationary	High temperature cyclability limited Lead is toxic but recycling is efficient to 95%
Lithium–ion (established)	High energy density, power rate, cycle life, costly Applications: portable, possibly large-scale	Depletable elements (cobalt) in most applications; replacements manganese and iron are green (abundant and sustainable) Lithium chemistry relatively green (abundant but the chemistry needs to be improved) Recycling feasible but at an extra energy cost
Zinc–air (established)	Medium energy density, high power density Applications: large-scale	Mostly primary or mechanically rechargeable Zinc smelting not green, especially if primary Easily recyclable

Table 2: Chemistry and Environmental Impact of Future Batteries

Lithium–organic (future)	High energy density but poor energy efficiency and rate capability Technology amenable to a low-cost Applications: large-scale, preferably stationary	Rechargeability to be proven Excellent carbon footprint Renewable electrodes Easy recycling
Magnesium–Sulphur (future)	Predicted: high energy density, power density unknown, cycle life unknown	Magnesium and Sulphur are green Recyclable Small carbon footprint

Al–CFx (future)	Predicted: moderate energy density, power density unknown	Aluminum and fluorine are green, but industries are not Recyclable
Proton battery (future)	Predicted: all organic, low voltage, moderate energy density, power density unknown	Green, biodegradable

Measuring Energy

Energy, though a central theme of this unit, cannot be easily conceptualized. It can, however, be described operationally as the "ability to do work", (i.e. the process of changing the location of an object or altering the temperature of a substance).[26]

Work occurs when a force acts on an object over a distance: this is summarized in the formula W = F x d. Where the unit of force is the Newton (approximately 4.4.5 lbs. of force) and the distance is 1 M (approximately 3 feet). The SI (Systeme International) unit for this work energy is the Joule which is defined as 1 J = 1 N·m.

Thus, the energy used to exert a force of 1 N over a distance of 1 meter is equal to 1 Joule. This type of translational (mechanical energy) is but one manifestation as many forms of energy exist. All forms of energy (solar (light and thermal), wind, electrical, geothermal, nuclear, tidal, etc.) are interconvertible and can be used to "do work". A fundamental law of thermodynamics states that in all conversions of energy the total energy is conserved; thus, while we may change its forms, energy can never be created or destroyed.

Measuring Electrical Energy

The concept of power is used to describe the rate at which energy is transformed from one form to another. The SI unit for power is the Watt (W) which is measured in Joules / second: 1 W = 1 J / s.

We are most familiar with this unit in our homes where our light bulbs are usually measured in watts. For example, a 60 W bulb converts 60 joules of electrical energy per second to either light or thermal energy. Many other electrical devices in our homes (microwaves, toasters, refrigerators) are measured in watts. (*Automobiles are rated using horsepower (hp) where 1 hp = 746 W). To describe larger quantities of power we will use the kilowatt (1 kW = 1000 watts) , or the Terawatt (1 TW = 10^{12} watts).

kWh

Power ratings in watts describe how much energy a device needs to function. In order to determine the amount of energy consumed, we multiply its power rating by the amount of time in use; thus,

energy = power x time.

For example, a heater that requires 1 kW of power used for one hour would use 1 kWh of energy.

E = 1 kW x 1 hr = 1 kWh.

A kWh is the standard unit of energy used to measure energy. It will be used throughout this unit to measure electrical energy.

Electric Vehicles

There are currently several variations of electric vehicles ranging from a mild hybrid (uses a Pb-acid battery in conjunction with an internal combustion engine: the battery provides power during braking or when the engine is off), a micro hybrid (a motor / generator assembly that provides power when coasting, or braking), a plug in hybrid (with the capability of the micro hybrid along with an electricity-only capacity), and finally the all-electric vehicle which relies solely on energy provided by a rechargeable battery.[27]

This unit will focus on the efficiency of fully electric vehicles as they depend solely on energy stored in their rechargeable batteries. Their efficiency is measured in number of miles (usually 100) per kWh. An additional factor is the range the car can travel on a fully charged battery (typically 100 -130 miles / charge). A complete listing of the efficiency of EV is available at: (www.fueleconomy.gov). To determine the cost of running an electric vehicle one can multiply the efficiency in kWh per 100 miles by the cost of electricity in a particular state. A similar calculation can be made to determine the cost to charge the onboard battery. With this information one can compare the efficiency various EVs.

Unit Activities

NOTE: This unit begins after the class has studied types of chemical reactions. Students have studied how photosynthesis reactions capture solar energy that over time becomes concentrated in fossil fuels. They have also studied the combustion of fossil fuels that release carbon dioxide into the atmosphere. The first lesson builds upon these understandings.

Greenhouse Gas Emissions and Global Warming: Guided Inquiry

Objective: To analyze how greenhouse gas emissions contribute to global warming and climate change

Standard:HS-ESS3-5 and CCSS.ELA-Literacy.RST.11-12.9

Instruction

Students will begin this lesson with a review of combustion reactions and their products. The class will then complete a set of analysis questions that evaluate the Keeling Curve Data. The class will discuss the evidence. The class will then analyze two short videos on “Lines of Evidence for Climate Change”. Once complete, the class will engage in whole group discussion to evaluate whether greenhouse gas emissions contribute to climate change. Each student will be asked to summarize and support their opinion.

Class Activities:

Analysis of Keeling Curve Data

Analysis of “Lines of Evidence” Chapters two and three

Whole Group Discussion of Evidence

Summary position narrative

Additional Information: URLs for each video, and the Keeling Curve are located in Teacher Resources: Day one.

Student analysis questions are located in Student Resources: Day One.

Renewable vs. Non-Renewable Energy Sources: Collaborative Research and Class Debate

Objective: To evaluate the benefits and environmental consequences of renewable and non-renewable energy resources.

Standard:ESS3-4 Earth and Human Activity

Instruction: This class begins with a discussion of each student's thoughts on climate change. All views should be respected. Once finished, the teacher will briefly review the difference between a non-renewable and a renewable energy resource. Students will then generate a list of all types of energy resources. The class will then divide into groups, (approximately four students per group), that will research the benefits and environmental consequences of the various types of energy resources: solar, wind, geothermal, hydroelectric, nuclear, fossil fuels (coal, natural gas, petroleum). Each group will be given a set of analysis questions to complete that will serve as the basis of the class debate. Each individual student will complete an evaluation of which type of energy resource they feel is the most beneficial and least harmful to the environment.

Class Activities

Collaborative research

Class Debate

Summary paragraph

Additional Information:

Research questions located in Teacher Resources.

Redox Reactions: Laboratory Activity and Guided Inquiry

Objective: To analyze reduction / oxidation half-reactions in single displacement reactions.

Standard: CCSS.ELA-Literacy.RST.11-12.3

Note: This class builds on the unit on types of chemical reactions. Students should be able to identify the reactants and products in the single displacement reactions and be able write total ionic and net ionic reactions. The focus of this day's laboratory is the identification and balancing of redox half reactions in primary cells. We will then explore the chemistry of secondary cells (rechargeable batteries).

Instruction

To begin, the class students will review the previous day's research and explain which type of energy resource they found most useful. The class will debate the merits of each resource (consensus is not necessary). Students should realize the many benefits of renewable resources; however, their major disadvantage is that they are not always available. In order to use these resources efficiently, their energy must be captured and stored for later use. The teacher will then ask students what devices they use to store electrical energy. The focus of this two-day activity will be on the chemistry of primary and secondary (rechargeable) batteries.

Class Activities: Laboratory on oxidation / reduction half reactions in single displacement reactions. Student groups will each be given materials for a single displacement reaction. They will need to identify the reactants and products of each reaction, then write the total and net ionic reactions. They will then be shown how to balance the half reactions and determine where the oxidation / reduction is occurring. (See equations 1-7 above).

Teacher will then explain how the electron flow between metals can be used to create an electrical current. Students will explore this concept by building a lemon battery. Each student group will be given sufficient materials to create a lemon battery that will light a small diode.

Students will be asked to identify the oxidation / reduction processes in the battery.

To prepare for the final day of this activity, students will be asked to note all of the batteries they use in their daily life, why they are important, and whether they are rechargeable or not. They should bring the list to class on the next day.

Additional Information:

Materials and laboratory procedures for both activities are located in Teacher Resources.

Day Two: Rechargeable Storage Devices: Laboratory Activity and Guided Inquiry

Objective:To analyze reduction / oxidation half-reactions in rechargeable batteries.

Standard: HS-PS3-3: Energy

Note: Balancing reactions of secondary cells is quite complex. In order to efficiently analyze the recharging process, I will ask students to reverse the reactions from our single displacement laboratory so that they can more easily visualize how the starting materials are regenerated during the recharge process. They will then analyze the reactions in the Ni-Cd rechargeable battery.

Instruction

The class will begin with a discussion of the batteries students use in their daily life. Some will be primary others secondary. Teacher will then explain the difference between the two types of cells and explain how recharging reverses the redox processes and regenerates the starting materials. Students will be asked to reverse the reactions of the displacement lab so as to regenerate the starting materials. Students should rename the oxidation as a reduction and the reduction as an oxidation. (Students should accomplish this without teacher’s assistance).

Once completed, teacher will introduce the reactions of the Ni-Cd cell as an example of an actual rechargeable battery. Students will then analyze the discharge process of the Ni-Cd cell (see equations 8-10). They will then be asked to predict the reverse reactions that occur during the recharging process (see equations 11 & 12). To end the day’s activity, the teacher will display the reactions in the Li-ion battery. Students will be asked to determine the discharge and recharge reactions.

Class Activities

Reversing single displacement reactions and identifying the reduction / oxidation half reactions.

Analyzing the discharge and recharge processes in a Ni-Cd rechargeable battery.

Analyzing the discharge and recharge processes in a Li-ion rechargeable battery.

Additional Information:

Reactions for Ni-Cd and Li-ion reactions are located in Teacher Resources.

Energy Footprint: Guided Inquiry

Objective: To evaluate how our personal energy usage affects the environment and propose ways to reduce our carbon footprint.

Standards:HS-ESS3-1 and CCSS.ELA-Literacy.RST.11-12.9

Instruction: To start this activity students will refer back to their analysis of the impacts of the energy resources and the effects of greenhouse gas emissions on the environment. Teacher will first introduce the concept of ecological footprint (and the various component footprints), and then ask students if they know how much they and their families contribute to earth's burden.

Class Activities

Students will complete an on-line analysis of their ecological footprint. The results are reported in total earth burdens and broken down by component footprints. Students will download their results focusing on their energy and carbon footprint. Students will analyze their results and be asked to propose ways to reduce these footprints. Students will retake the survey once they complete the lesson on the "car of their future".

Additional Information: URL for ecological Footprint Analysis is located in Teacher Resources.

Future Transportation: How far will that battery take you? Guided Research

Objective: To evaluate the efficiency of rechargeable batteries in electric vehicles.

Standard: HS-ESS3-4 and HS-PS3

Instruction: Students will begin this activity by reviewing their transportation, energy and carbon footprints. The goal will be to propose how to reduce these footprints by "investing" in an electric vehicle. Students will be shown data on the energy efficiency of various electric vehicles, their battery capacity, their environmental impact, and charging requirements. Students will also be able to factor in the costs and environmental impact of electricity generation in various states. Students will use all available data to determine how to reduce their footprint.

Students will need to convert kWh / mileage in order to calculate the cost of driving their car.

Class Activities

Selecting your future electric vehicle:

Calculating the cost of driving: Converting kWh / mileage data

Where is it more economical to drive your EV? State kWh cost data

Where is electricity generation more sustainable? State electricity generation data

Additional Information: URL's for Electric vehicle data base, State kWh price data, and State Electricity Generation are located in Teacher Resources.

Appendix: Standards Narrative

The Next Generation Science Standard **HS-ESS3-5** ask students to analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems. **CCSS.ELA-Literacy.RST.11-12.9** is a common core standard that asks student to synthesize information form a range of sources to create a coherent understanding of a phenomena or concept. These standards are relevant to the first activity as students will engage in the analysis of the Keeling Curve data, and data on the effects of greenhouse gases to evaluate the theory of climate change.

Standard **HS-ESS3-1** is relevant to the evaluation of renewable and nonrenewable resources as it asks students to construct an explanation based on evidence for how the availability of natural resources, and changes in climate have influenced human activity. Students use data on the various types of resources as part of their debate on the merits of each resource.

The laboratory activities are informed by the common core standard **CCSS.ELA-Literacy.RST.11-12.3** The standard is applicable to the activity as it asks students to follow a multi-step procedure as outlined in the laboratory procedure. Standard **HS-PS3-3** informs the second day of the laboratory activities as students will explore the processes of rechargeable batteries. This is line with the standard as it asks students to analyze how devices work to convert one form of energy into another form of energy.

The activity in the unit asks students to evaluate how their energy needs impact the environment. Their goal is to explore how the use of electric vehicles will reduce their energy footprint. This lesson is guided by standard **HS-ESS3-4** which focuses on technological solutions that reduce impacts of human activities on natural systems. Although this standard is listed in the final activity, it is central to the entire unit.

Teacher Resources

Keeling Curve Graph Data available at:

https://commons.wikimedia.org/w/index.php?search=keeling+curve+&title=Special%3ASearch&go=Go&ns0=

1&ns6=1&ns12=1&ns14=1&ns100=1&ns106=1#/media/File:Mauna_Loa_Carbon_Dioxide.png

Climate Change and Greenhouse Gas Videos

Lines of Evidence Chapter Two: How do we know the earth is warming? Located at: https://www.youtube.com/watch?v=-IuVzcp39rs

Lines of Evidence Chapter Three: How do we know greenhouse gases contribute to global warming? Located at: https://www.youtube.com/watch?v=3JX-ioSmNW8

Renewable – Non-Renewable Resource Research: (The questions may be changed to suit your students)

Describe the following for your assigned energy resource.

1. Is it renewable or non-renewable?
2. Is this resource always available?
3. What are its major uses? Its benefits.
4. Can we use it directly or must we transform it in some manner before we use it?
5. Where does it come from? How is it formed?
6. How do we access this resource? Do we harm the environment when we get it?
7. Do we harm the environment when we use it? These are the environmental consequences
8. Do you (or your family) already use this resource?
9. Is this resource free? Or do we have to pay for it?
10. How was this resource formed? Has it always been here? Will it be here forever?

Single Displacement Laboratory Materials

These are suggested single displacement reactions; you may use any set of materials that will spontaneously react.

Strips of the following metals: Mg, Pb, Cu .Zn, Al, and Fe

Solutions (0.25 M): $Mg(NO_3)_2$, $Pb(NO_3)_2$, $Cu(NO_3)_2$, $Zn(NO_3)_2$, $Fe(NO_3)_3$, $AgNO_{3,}$ $Al(NO_3)_3$

Test tube racks with two test tubes.

Procedure

Each group will conduct one reaction: Students should refer to the activity series to determine which reactions will proceed and which will not. Each group should select reactants that will produce a reaction. Students should observe and note all changes during the reaction.

Lemon Battery: Materials

Two lemons per group, sufficient alligator clips to connect the lemons in series to each other and to a small diode, small pieces of copper foil (or pennies minted before 1982) and large paper clips (or galvanized nails).

Procedure

Roll lemons so the they are soft to the touch, then make slits in one lemon, insert the electrodes and measure the volts. Attach the diode to the electrodes (if it does not light then reverse the connection). If diode still fails to light, then attach the second lemon in series: then recheck the voltage with the multimeter (it should be double the volts) then reattach the diode (it should light).

Ni-Cd Reactions

Oxidation at the anode: Cd (s) + ***2OH-*** -> $Cd(OH)_2$ (aq) + ***2e-*** (8)

Reduction at the cathode: *1e-* + Ni(O)OH + H_2O -> $Ni(OH)_2$ + *OH-* (9)

Equation (9) must be multiplied by 2 in order to balance the electron flow between the two half reactions. This yields the following:

2e- + 2Ni(O)OH + H_2O -> $2Ni(OH)_2$ + ***2OH-***

Cancelling the hydroxides that appear on both sides of the reactions produces the overall net ionic reaction:

Cd (s) + 2Ni(O)OH + $2H_2O$ -> $2Ni(OH)_2$ + $Cd(OH)_2$ (aq) (10)

During the recharge period, the reactions are reversed so that $Cd(OH)_2$ is reduced back to Cd; while the $Ni(OH)_2$ is oxidized back to Ni(O)OH.

Reduction: $Cd(OH)_2$ (aq) + *2e-* -> Cd (s) (11)

Oxidation: $2Ni(OH)_2$ -> 2Ni(O)OH + *2e-* (12)

Li-ion Discharge Reactions

Reduction at the Cathode: CoO_2 + Li^+ + e^- -> $LiCoO_2$

Oxidation at the Anode: LiC_6 -> C_6 + Li^+ + e^-

Students will predict the recharge reactions.

Ecological Footprint Analysis: located at: http://www.footprintnetwork.org/en/index.php/GFN/:

Students can log in with their school associated email; however, a subscription to the site provides the classroom access to various resources. Subscription is by donation. The classroom level membership provides classroom access for ecological footprint analyses. Students will be able to measure various footprints online and have their scores archived for future reference. Membership also provides weekly newsletters from the network, along with other resources to study and promote sustainable activity.

Selecting your future electric vehicle:

Electric Vehicle Database: Fuel Economy of Electric Vehicles:

https://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&path=1&year1=2017&year2=2019&vtype

=Electric&pageno=1&sortBy=Comb&tabView=0&rowLimit=10

State kWh price database: Electric Power Monthly:
https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_06_b

Energy Source of Electricity Generation by state:
https://www.nytimes.com/interactive/2018/12/24/climate/how-electricity-generation-changed-in-your-state.html?smid=nytcore-ios-share

Environmental Impact of electric vehicles: Cradle to Grave emissions lifetime of electric vs. ice auto:

https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

Alternative Fuels Data Base:

https://afdc.energy.gov

Electric Vehicles Benefits and Considerations:

https://afdc.energy.gov/fuels/electricity_benefits.html

Electric Charging Stations in Pennsylvania:
https://afdc.energy.gov/stations/#/analyze?region=US-PA&show_map=true&country=US&access=public&access=private&fuel=ELEC&lpg_secondary=true&hy_nonretail=true&ev_levels=all

Student Resources

Climate Change Analysis Questions

1. What is Climate Change?
    a. How does it differ from daily variations in the weather?
2. Describe two ways that climate change is affecting the Earth.
3. How are humans contributing to the current change in climate? (Two things).
4. What evidence did you see in the Keeling Curve data to support this belief?
    a. What was the relationship between carbon dioxide emissions and temperature in the graph?
5. A car gets very hot in the summer sun. Explain why this happens.
    a. How is this an example of a greenhouse effect?
6. What happens to incoming solar variation? (three events).
7. What does the Earth's natural greenhouse effect do for our survival? (What does it do to affect heat energy that is re-radiated by the earth and atmosphere? (What would the Earth be like without this natural effect?
8. How do greenhouse gases help to regulate the Earth's temperature?
9. Which human activities are responsible for the increase in the concentration of greenhouse gases?
10. What effect does the increased concentration of greenhouse gases have on the natural greenhouse

effect?

Keeling Curve Graph Analysis

1. What measurements are shown on this graph?
    a. When did the collection of these data begin?
    b. What's the name of the curve you drew (the scientist who discovered these data)?
2. What is the relationship between carbon emissions and temperature? (How do the emissions affect the temperature?)
    a. What is contributing to the increase in CO_2 emissions?
3. Do the values go up all the time? What do we call this?
    a. Why do the values go up and down?
4. Do the values generally go up over the course of time? What do we call this?
5. The mean temperature of the planet is 13.9 ^{0} How much has the temperature changed?
    a. What will happen to the mean temperature if carbon emissions continue increasing?

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