Physics in the Universe: Unit 3

Energy Conversion

Background for Teachers and Instructional Suggestions

We use ***energy*** every moment of every day, but where does it all come from? Our body utilizes energy stored in the chemical potential energy of bonds between the atoms of our food, which were rearranged within plants using energy from the Sun. The light energy shining out from our computer was converted from the electric potential energy of electrons from the wall socket that flowed through wires that may trace back to a wind turbine, which did work harnessing the movement of air masses, which absorbed thermal energy from the solid Earth, which originally absorbed the energy from the Sun. Each of these examples represents the ***flow of energy*** within different components of the Earth ***system***. With each interaction, energy can change from one form to another. These ideas comprise perhaps the most unifying crosscutting concept in physics and all other science, ***conservation of energy**.* The first law of thermodynamics elaborates on this idea by saying that the total energy of an isolated system is constant, and that although energy can be transformed from one form to another, it cannot be created nor destroyed. Conservation of energy requires that changes in energy within a system must be balanced by energy flows into or out of the system by radiation, mass movement, external forces, or heat flow. The vignette for the 4-course physics provides a framework for discussing many of these energy forms and how they convert from one to another. This instructional segment selects a subset of processes that follow a storyline of tracing the energy flow of our electricity back to various power plants and renewable energy sources. This approach provides integration with timely issues in engineering and Earth science.

Electricity in Daily Life

Before students jump into the physical processes that allow us to generate electricity, students should be able to compare the range of different electricity generation methods currently utilized. This basic familiarity will make all of the physical principles more tangible, but it also allows students to engage in a real-world decision making process (*EP&C Principle V*) because each of these ***energy*** sources has advantages and disadvantages (*ESS3.A*). More than half of the electricity in California was generated from fossil fuels in 2013 (California Energy Commission Energy Almanac 2015). Many fossil fuel power plants emit toxic pollutants and can impact the health of ecosystems and people nearby (*EP&C Principles IV*). Fossil fuels also emit greenhouse gases that do not have a direct impact on health but contribute to global climate change (*ESS2.D; EP&C Principle III; HS Chemistry course instructional segment 4*). At the same time, these fuel sources are cheap and plentiful. New technology in the last few years has made other energy sources increasingly viable and California has pledged to increase the use of these renewable energy sources to one third of California's electricity supply by 2020 (up from less than 20% a decade earlier). What issues have been driving California's decisions? Excellent classroom resources exist for teaching about different electricity generation strategies, including formats where students debate the relative costs and benefits of each energy source[1] (*HS-ESS3-2*).

The Physics of Power Plants

A power plant can be thought of a ***system***, and ***energy*** is constantly ***flowing*** out of the system in the form of electricity. The energy in all systems is finite, so a power plant would quickly run out of energy if it didn't have a constant source of fuel. Each power plant is built to produce a certain amount of energy in a given time (i.e., "power"), and the power output of most plants can be easily found. Students can use internet resources to find the power generation capacity and fuel source of the power plant closest to their school. They can then create a mathematical **model** *(HS-PS3-1)* to calculate the amount of fuel required to operate the power plant in a day or a year, knowing that the electrical ***energy flowing out of the system*** has to equal the energy from the fuel sources entering into the system (at this point, students can neglect efficiency – it will be introduced later).

At the middle grade level, students have explored various forms of ***energy***, determining the factors that affect kinetic energy (MS-PS3-1) and potential energies (MS-PS3-2), the relationship between kinetic energy and thermal energy (MS-PS3-4),

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[1] http://www.switchenergyproject.com/education/CurriculaPDFs/SwitchCurricula-Secondary-Introduction/SwitchCurricula-Secondary-GreatEnergyDebate.pdf

and the concept of energy transfer in engineering design (MS-PS3-3) and scientific **explanations** (MS-PS3-5). Clarification statements for several of these PEs explicitly state that calculations are excluded from the middle grade level. In high school, students are now ready to quantify the amount of energy objects have and transfer during interactions. The high school chemistry course also pays explicit attention to these topics with emphasis on thermal and chemical potential energies.

The middle grade PEs are written broadly such that students might come into high school with knowledge of different forms of ***energy***. Here, students should organize what they know about these different forms of energy to make the distinction between energy from particle motion, potential energy due to interactions between particles, and radiation. Potential energies arise from forces that act at a distance like gravity and electromagnetism (as discussed in instructional segment 2). Students "**develop and use a model** that ***energy*** at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects)" (*HS-PS3-2*). In other words, the sum of the kinetic and potential energy of component particles (energy of motion and position) must total the bulk energy measured at the macroscopic level. Using diagrams, drawings, descriptions, and/or computer simulations, students should be able to illustrate this summative relationship. This performance expectation is designed to help students bridge concepts traditionally associated with chemistry (e.g. the energy of atoms and molecules) with the concepts traditionally associated with physics (e.g. the energy of macroscopic objects). Students can develop this model by making a poster of the different stages in a typical thermoelectric power plant (Figure 5). To generate electricity, these power plants use heat energy to eventually produce electricity (most fossil fuel, nuclear, geothermal, and even concentrated solar power plants fit in this category). They usually heat water into steam, which changes the relative position of the particles from being densely packed in a liquid into particles that are much farther apart. This change in relative position requires an increase in the electrostatic potential energy of the water molecules, which we see macroscopically as having 'absorbed' the latent heat of vaporization. The power plants then convert thermal energy into kinetic energy during one stage of their process. Individual molecules (usually water molecules heated to steam) are moving very fast and collide with a turbine, transferring some of the kinetic energy in randomly moving molecules (i.e., thermal energy) into the systematic motion of the turbine (i.e., kinetic energy of the object). The turbine will turn the crank of a generator to convert the kinetic energy into electricity, but it will not be 100% efficient because molecular collisions will result in energy being transferred to particles moving in random directions again, detracting from the total energy available in the object to move the crank forward. At the macroscopic level, we attribute this lower efficiency to the process we call friction. At each stage, students **communicate** the forms of ***energy*** at both the microscopic and macroscopic level.

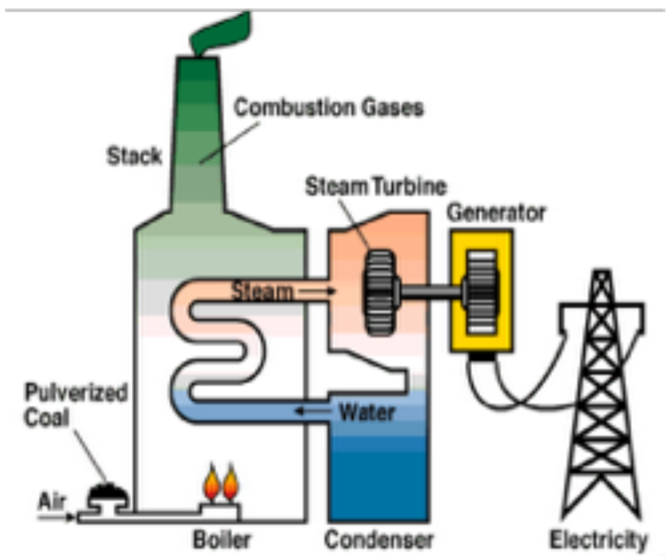

Figure 5. Schematic of a power plant. (Center for Climate and Energy Solutions 2015)

Converting Kinetic Energy to Electricity

Electric generators are an essential component in nearly all types of electric power generation, including coal, nuclear, natural gas, geothermal, tidal, wind turbines, hydroelectric (basically everything except fuel cells and solar photovoltaic). Students might try to apply their understanding of microscopic collisions to the ***energy*** conversion processes within a generator to come to the incorrect conclusion that these collisions impart kinetic energy to electrons, which move through a circuit. In order to overcome this misconception, students must replace that notion with a correct model for energy conversion between kinetic energy of objects and electricity. This model requires that students continue their exploration of electric and magnetic forces from instructional segment 2.

For many years, scientists considered the electricity and magnetism to be independent of each other. In 1819 Hans Christian Øersted discovered that electric current generates a magnetic force, and in 1839, Michael Faraday showed that magnetism could be used to generate electricity. Each discovery demonstrated that the two were connected, but it was not until 1860 that James Clerk Maxwell developed a mathematical **model** to show how electricity and magnetism are related. During this section, students will follow in the footsteps of these famous scientists by **planning and carrying out investigations** that illustrate the interactions between electricity and magnetism (*HS-PS2-5*). These interactions are essential for understanding how most electricity is generated in power plants.

Students need to experience multiple situations to develop a **model** that changing the magnetic field through a conductive (wire) loop can cause an electric current to flow in the loop, and that a current flowing in a wire creates a magnetic field around the wire. Much like changing and dynamic mechanical forces in unit 1's egg drop can be analyzed one snapshot in time after another, these processes that involve changing fields build upon the understanding of static electric forces defined by Coulomb's Law in instructional segment 2. Drawing explicit connections between the static and time-varying cases is essential to understanding the relationship. Classroom activities should highlight application of these principles to electrical generators (turbines), electrical motors, and the myriad of applications of these principles in devices in our homes.

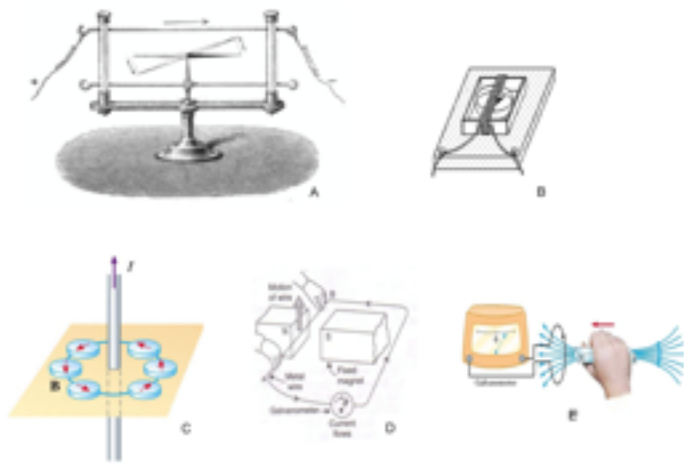

Figure 6 Students can plan and conduct a variety of investigations to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current. (Privat-Deschanel 1876)

Teachers might show Øersted's simple experiment in which he noticed that a compass needle would be deflected from magnetic north when an electric current passed through a wire that was held above the magnet (Figure 6a). Students should be encouraged to examine a variety of variables to characterize this relationship. For example, they can vary the direction of the wire, the voltage through the wire, and the number of winds of the wire around the compass (Figure 6b). Eventually they should discover that the deflection is greatest when the wire is aligned with the north/south orientation of the compass needle. In addition, they will notice that this effect is magnified by increasing the applied voltage or by increasing the number of winds around the compass and that a circular field exists around a current-carrying wire (Figure 6c). It should be emphasized that students are not just trying to verify Øersted's findings, but rather test variables to see their effect on creating a magnetic field to which the compass needle responds. Students can also place iron filings on a glass plate that lies on top of their wire coil and use that to map out the strength and orientation of the magnetic field. As they tap on the plate, the filings align with the magnetic field, with greater concentrations moving to those locations where the field is strongest. Adding a second magnet, students can use the iron filings to visualize the interaction between objects. Equipped with data on the direction and relative magnitude of the field, students can draw a qualitative **model** of the magnetic field using vectors at various locations surrounding the bar magnet (*HS-PS3-5*). In such a model, the direction of the field is indicated by the direction of arrows, while its magnitude is indicated by the length of these arrows. Upon **analyzing and interpreting their data*,*** students should be asked if they can see any engineering applications to this phenomenon, and discover that it is the basis for electric motors.

After seeing that an electric current creates a magnetic field, students should see if the reverse is also true. Once again, they should **plan and carry out an investigation** to see if a changing magnetic field can induce an electric current. The simplest investigation requires connecting a galvanometer to a wire loop to measure electric current in the wire. As they move the wire back and forth between two strong magnets (Figure 6d), students will observe the galvanometer needle deflect in opposite directions depending on which way the wire is moved (indicating that the electric current flows in different directions). Students should be encouraged to use this equipment to explore other variables. For example, they may coil the wire and move the magnet through the center of the coil and see a similar response but generating a stronger electric current (Figure 6e). Upon **analyzing and interpreting their data***,* students should be asked if they can see any engineering applications to this phenomenon, and discover the basis for electric generators.

Converting Light to Electricity

Solar panels convert light ***energy*** into electricity. Students will learn more about the nature of light in instructional segment 5, but the focus in this instructional segment is on understanding the qualitative interactions between light energy and the matter in solar cells well enough to communicate it to others (*HS-PS4-5*). Atoms in a solar cell absorb the light energy, which causes electrons to be knocked loose. Free electrons are a key ingredient to an electric current, but currents require those electrons to move systematically around a circuit. Silicon semiconductors are set up so that they have a systematic bias where electrons preferentially move in a single direction. How does this happen? Pure silicon forms systematic crystal structures, but adding small amounts of some types of elements disrupts those shapes and can even allow each silicon atoms to be in a configuration where it can accept an additional electron. Adding other specific elements causes the silicon atoms in the lattice to end up with an extra electron. Engineers make thin crystals of each type (one with contaminants that have extra electrons and one with ‘holes’ for additional electrons) and stack them on top of one another. Now, when light hits the atoms in this material, the free electrons are repelled by the extra electrons in one layer and automatically move towards the layer with space for additional electrons. As the Sun continues to shine and more electrons get knocked loose, they always flow in the same direction and set up a steady electric current. Students must be able to understand this interaction between light and matter well enough to **communicate** it to others (*HS-PS4-5*). Groups of students could make a fact sheet, a stop-motion animation, or skit to articulate the ideas.

Snapshot: Evaluating plans for renewable power plants

The city where Mrs. G's city is located wants to build a new renewable energy power plant. They are considering two options, a series of small hydroelectric power dams on a river coming out of the mountains and a set of windmills in the flat sections of town where it is always windy. Mrs. G divides the class into small groups and she assigns each one to either create a proposal for wind energy or a plan for hydroelectric power. Teams begin by using **mathematical thinking** to calculate the amount of energy their proposed project would generate. The hydroelectric group assumes that the dams will harness gravitational potential energy and use the appropriate equations to evaluate the energy produced by different height dams (Energy = mass x g x height, where the water mass is determined by the average annual flow rate on the rive calculated using data collected by a USGS stream gauge that is available on the internet). The wind energy group assumes that the kinetic energy of the air is harnessed and uses the appropriate equations to evaluate the energy produced by different sized windmills (Energy = ½ x mass x velocity

density of air combined with the size of the blades and the speed of the wind. Wind velocity is calculated using the average values from a nearby weather station that posts hourly data on the internet). Mrs. G teaches the students about the concept of efficiency when it comes to electric power generation where only a fixed ***proportion*** of the energy is actually successfully converted to electricity (while a large fraction is wasted as heat). Each team **obtains information** about the efficiency of their energy generation technology and uses it update their estimate of the electrical energy they can generate. With these basic calculations, each team must develop a specific proposal for a power plant that will provide 30% of the city's energy. The wind teams must decide how many windmills, and the diameter of the blades. The hydroelectric teams must decide how many dams and their heights. Each team produces a report outlining the benefits of their plan. The class then hosts a town hall meeting where teams **communicate** their plans and present an argument that their proposal is better than the competing plans. This **argument should be supported by evidence** that goes beyond the simple energy calculations but also takes into account the relative benefits and impacts of each technology on natural systems (EP&C II; for example, dams destroy aquatic habitat, use large volumes of CO

Connections to the CA CCSSM:
Connections to CA CCSS for ELA/Literacy:
Connection to CA ELD Standards :
Connections to the CA EP&Cs: II, V

Engineering Energy Conversion Devices

Now that students have learned extensively about the theory behind ***energy conversion*** devices, they are now tasked with an engineering challenge to create one themselves (*HS-PS3-3*). The vignette in High School Four Course Model – Physics section of this *Science Framework* includes a template of what this design challenge might look like. The first stage of the engineering design process is to place the goal in the context of the major global challenge of providing affordable electrical energy without the problems associated with fossil fuels (*HS-ETS1-1*). Students evaluated the impacts of different electricity sources at beginning of this instructional segment, including a discussion of how fossil fuels contribute to global climate change. The High School Three Course Model – Chemistry in the Earth System course emphasizes physical mechanisms causing climate change and the High School Three Course Model – The Living Earth

course explores its effects on the biosphere. Depending on the sequence of courses within each school district, this instructional segment should draw strong connections to those courses. Designing, building, and improving energy conversion devices that are more efficient or that pollute less involves breaking down the complex global problem into more manageable problems that can be solved through engineering (*HS-ETS1-2*). Students have learned some of the scientific principles behind the engineering tools that can help address the challenge throughout this instructional segment. Students now choose to build their own wind turbines, hydroelectric power plants, solar panels, or other mini version of a power plant that transforms energy from less useful forms, such as wind, sunlight, or motion, into electricity (arguably the most convenient and useful form of energy in our modern world). Students learn to work within engineering constraints as they strive to maximize efficiency (generate the largest power output possible) while taking into account prioritized criteria and trade-offs (*HS-ETS1-3*). Students can measure outputs and then refine their designs to maximize efficiency given constant inputs. Students can also utilize existing computer simulations to investigate the impact of these different energy solutions (*HS-ETS1-4*).