as electrical insulators because their electrons are locked in bonds and therefore resistant to the movement that is necessary for electric currents. As students learn to communicate such information, they obtain a better appreciation of **cause and effect [CCC-2]**. For example, students should be able to explain that electromagnetic interactions at the molecular level (causes) result in properties (effects) at the macro-level and that these properties make certain materials good candidates for specific technical applications.

IS3

Physics in the Universe Instructional Segment 3: Energy Conversion and Renewable Energy

We use **energy [CCC-5]** every moment of every day, but where does it all come from? Our body uses 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 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 [CCC-5]** within different components of the Earth **system [CCC-4]**. 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 [CCC-5]**.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

Guiding Questions

- How do power plants generate electricity?
- What engineering designs can help increase the efficiency of our electricity production and reduce the negative impacts of using fossil fuels?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS2-5. Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current. *[Assessment Boundary: Assessment is limited to designing and conducting investigations with provided materials and tools.]*

HS-PS3-1. Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known. [Clarification Statement: Emphasis is on explaining the meaning of mathematical expressions used in the model.] *[Assessment Boundary: Assessment is limited to* *basic algebraic expressions or computations; to systems of two or three components; and to thermal energy, kinetic energy, and/or the energies in gravitational, magnetic, or electric fields.]*

HS-PS3-2. Develop and use models to illustrate 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). [Clarification Statement: Examples of phenomena at the macroscopic scale could include the conversion of kinetic energy to thermal energy, the energy stored due to position of an object above the earth, and the energy stored between two electrically-charged plates. Examples of models could include diagrams, drawings, descriptions, and computer simulations.]

HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.* [Clarification Statement: Emphasis is on both qualitative and quantitative evaluations of devices. Examples of devices could include Rube Goldberg devices, wind turbines, solar cells, solar ovens, and generators. Examples of constraints could include use of renewable energy forms and efficiency.] *[Assessment Boundary: Assessment for quantitative evaluations is limited to total output for a given input. Assessment is limited to devices constructed with materials provided to students.]*

HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. [Clarification Statement: Examples of models could include drawings, diagrams, and texts, such as drawings of what happens when two charges of opposite polarity are near each other.] *[Assessment Boundary: Assessment is limited to systems containing two objects.]*

HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.* [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] *[Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.]*

HS-ESS3-2. Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.* [Clarification Statement: Emphasis is on the conservation, recycling, and reuse of resources (such as minerals and metals) where possible, and on minimizing impacts where it is not. Examples include developing best practices for agricultural soil use, mining (for coal, tar sands, and oil shales), and pumping (for petroleum and natural gas). Science knowledge indicates what can happen in natural systems—not what should happen.]

HS-ESS3-3. Create a computational simulation to illustrate the relationships among management of natural resources, the sustainability of human populations, and biodiversity. [Clarification Statement: Examples of factors that affect the management of natural resources include costs of resource extraction and waste management, per-capita consumption, and the development of new technologies. Examples of factors that affect human sustainability include agricultural efficiency, levels of conservation, and urban planning.] *[Assessment Boundary: Assessment for computational simulations is limited to using provided multi-parameter programs or constructing simplified spreadsheet calculations.]*

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

HS-ETS1-2. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a practice or disciplinary core idea.

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems [SEP-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS2.B: Types of Interactions PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer PS3.C: Relationship Between Energy and Forces PS3.D: Energy in Chemical Processes and Everyday Life ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

Highlighted California Environmental Principles and Concepts:

Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services.

Principle II The long-term functioning and health of terrestrial, freshwater, coastal, and marine ecosystems are influenced by their relationships with human societies.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

Principle IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes

CA CCSS Math Connections: N-Q.1–3; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1,8; WHST.9–12.2.a–e, 7, 8, 9

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

The first law of thermodynamics elaborates on the **conservation of energy [CCC-5]** 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 can be neither created nor destroyed. **Conservation of energy [CCC-5]** requires that changes in energy within a **system [CCC-4]** must be balanced by **energy flows [CCC-5]** into or out of the system by radiation, mass movement, external forces, or heat flow. The vignette for the physics course in the high school four-course model (chapter 8) 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 in use. This basic familiarity will make all the physical principles more tangible, but it also allows students to engage in a real-world decision making process (EP&C V) because each of these **energy [CCC-5]** sources has advantages and disadvantages (ESS3.A). In 2013 more than half of the electricity in California was generated from fossil fuels (California Energy Commission Energy Almanac 2016). Many fossil fuel power plants emit toxic pollutants and can impact the health of ecosystems and people nearby (EP&C IV). Students can **analyze data [SEP-4]** from maps of the amount of pollution in their community (see the California Office of Environmental Health Hazard Assessment, Cal Enviroscreen 2.0 at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link47) and **ask questions [SEP-1]** about the pollution source and how it affects human health. 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 III; High School Three-Course Model Chemistry in the Earth System course IS4). 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 percent a decade earlier). What issues have been driving California's decisions? Excellent classroom resources are available for teaching about different electricity generation strategies, including formats in which students debate the relative costs and benefits of each energy source (HS-ESS3-2) (see National Energy Education Development Project, Great Energy Debate http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link48).

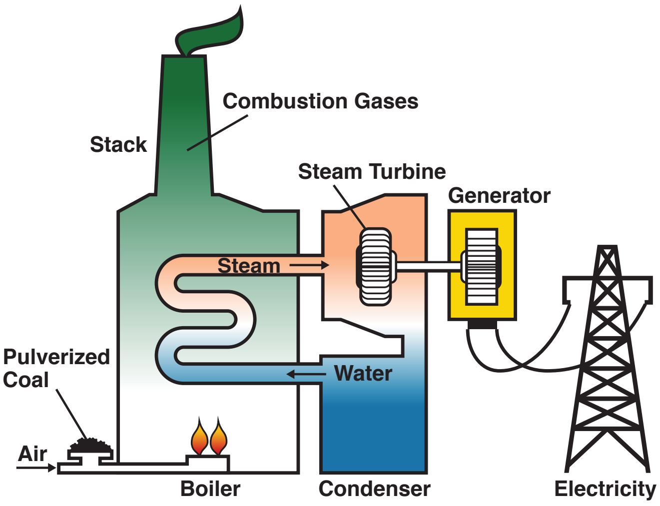
The Physics of Power Plants

A power plant can be thought of as a **system [CCC-4]**, and **energy [CCC-5]** is constantly **flowing [CCC-5]** 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 did not 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). 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 [SEP-2]** (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 [CCC-5]** 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).

In the middle grades, students explored various forms of **energy [CCC-5]**, 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), and the concept of energy transfer in engineering design (MS-PS3-3) and constructing scientific explanations (MS-PS3-5). Clarification statements for several of these performance expectations explicitly state that calculations are excluded from the middle grades level. In high school, students are now ready to quantify the amount of energy objects have and transfer during interactions. The high school chemistry in the Earth system course also pays explicit attention to these topics and emphasizes thermal and chemical potential energies.

The middle grades performance expectations are written broadly such that different students might come into high school with knowledge of different forms of **energy [CCC-5]**. 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 IS2). Students **develop and use a model [SEP-2]** that **energy [CCC-5]** "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 7.51). To generate electricity, these power plants use heat energy to produce electricity (most fossil fuel, nuclear, geothermal, and concentrated solar power plants fit in this category). They usually heat water to form 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. 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 turns the rotor of a generator to convert the kinetic energy into electricity. This process will not be 100 percent efficient because molecular collisions result in energy being transferred to particles moving in random directions again, reducing the total energy available to move the rotor. At the macroscopic level, we attribute this lower efficiency to the process we call friction. At each stage, students **communicate [SEP-8]** the forms of **energy [CCC-5]** at both the microscopic and macroscopic level.

Figure 7.51. Schematic of a Power Plant



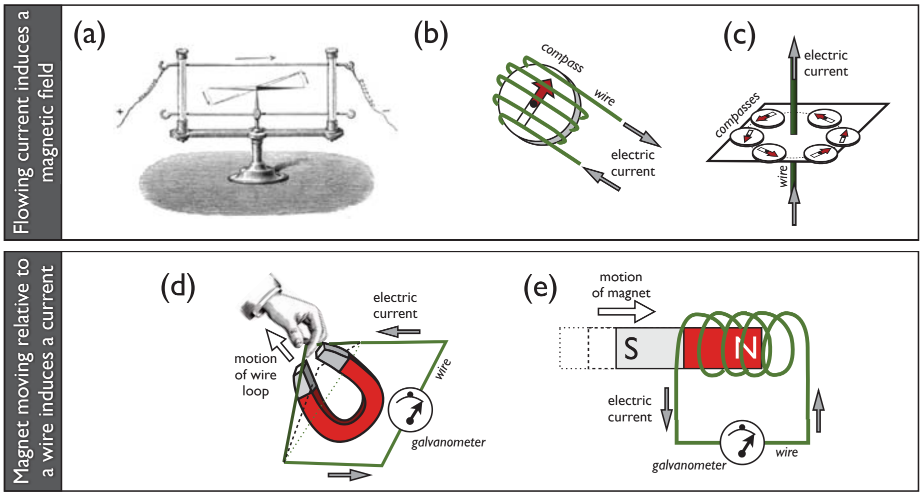
Converting Kinetic Energy to Electricity

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 [CCC-5]** conversion processes within a generator to come to the incorrect conclusion that these collisions impart kinetic energy to electrons, which move through a circuit. To overcome this preconception, students must replace that notion with a correct model for conversion of kinetic energy of objects into electricity. This model requires that students continue their exploration of electric and magnetic forces from IS2.

For many years, scientists considered electric and magnetic forces to be independent of each other, but 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. Finally, in 1860 James Clerk Maxwell derived equations that show how electricity and magnetism are related. Students will follow in their footsteps to **plan and carry out investigations [SEP-3]** that illustrate the relationship between electricity and magnetism (HS-PS2-5). These interactions are essential for understanding how most electricity is generated in power plants.

Students might recreate Øersted's simple **investigation [SEP-3** 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 7.52a). Students can be given the challenge of getting the compass needle to deflect a fixed amount (e.g., so that it points northeast at 45° instead of north). They will need to explore what happens when they change the direction of the wire, the voltage through the wire, or the number of winds of the wire around the compass (figure 7.52b) or move the compass to different locations around the wire (figure 7.52c). Students should then be able to create an informative poster **communicating [SEP-8]** how each of these variables **affects [CCC-2]** the compass needle.

Figure 7.52. Magnetic Fields and Electric Currents



(a): Ørsted's experiment illustrates that an electric current generates a magnetic field. (b and c): Sensitive compasses can detect the magnetic field surrounding a current-carrying wire. (d): Moving a looped wire through a magnetic field generates a current within the wire. (e): Moving a magnet through a looped wire generates an electric current. *Source*: M. d'Alessio with images from Privat-Deschanel 1876, 656, fig. 456 and OpenClipart-Vectors 2013c.

Students can also place iron filings on a glass plate that rests 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 permanent magnet, students can use the iron filings to visualize the interaction between the magnetic fields of the wire and the permanent magnet. Equipped with data on the direction and relative magnitude of the field, students can draw a qualitative **model [SEP-2]** of the magnetic field using vectors at various locations surrounding the wire (HS-PS3-5). In such a model, the direction of the arrows indicates the direction of the field, while the length of these arrows indicates its magnitude.

After gathering evidence that an electric current creates a magnetic field, students should investigate if the reverse is also true. They **plan and carry out an investigation [SEP-3]** to see if a changing magnetic field can induce an electric current. The simplest investigation requires connecting a galvanometer in a loop and moving the far side of the loop back and forth between two strong magnets (figure 7.52d). 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 as the wire moves in different directions). Students can 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 (figure 7.52e). This principle is important for creating electric generators. While students may not be able to make that leap themselves, they should be able to **construct an explanation [SEP-6]** about how this principle could be used to make a generator in which there is a constant flow of electricity. Their explanation could rely on diagrams (pictorial **models [SEP-2]**).

Converting Light to Electricity

Solar panels convert light **energy [CCC-5]** into electricity. Students will learn more about the nature of light in IS5, 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 key ingredients of 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 in which 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 atom to be in a configuration with holes that can accept an additional electron. Adding other specific elements causes the silicon atoms in the lattice to have 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. Then, when light hits the atoms in this material, the free electrons are repelled by the extra electrons in one layer and automatically move toward 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 [SEP-8]** it to others (HS-PS4-5). Groups of students could make a fact sheet, a stop-motion animation, or skit to articulate the ideas.

Physics in the Universe Snapshot 7.13:
Evaluating Plans for Renewable Power Plants

Investigative phenomenon: Windmills and hydroelectric power plants convert energy from the movement of air and water into electricity.

The city where Mrs. G's school is located wanted to switch to 100 percent clean and renewable energy. They were 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 divided the class into small groups and she assigned each one to either create a proposal for wind energy or a plan for hydroelectric power. Teams began by using **mathematical thinking [SEP-5]** to calculate the amount of energy their proposed project would generate. The hydroelectric group assumed that the dams would harness gravitational potential energy and used the appropriate equations to evaluate the energy produced by different height dams (Energy = mass x g x height, where the water mass was determined by the average annual flow rate on the river calculated using data collected by a United States Geological Survey (USGS) stream gauge that was available on the Internet). The wind energy group assumed that the kinetic energy of the air would be harnessed and used the appropriate equations to evaluate the energy produced by different sized windmills (Energy = ½ x mass x velocity^2, where the mass is calculated using the average density of air combined with the size of the blades and the speed of the wind. Wind speed was calculated using the average values from a nearby weather station that had posted hourly data on the Internet).

Investigative phenomenon: Electric generators are not 100 percent efficient.

Mrs. G taught the students about the concept of efficiency when it came to electric power generation in which only a fixed **proportion [CCC-3]** of the energy would be successfully converted to electricity (while a large fraction would be wasted as heat).

Investigative phenomenon: Which clean energy power source will best meet the needs of our community?

Each team **obtained information [SEP-8]** about the efficiency of their energy generation technology and used it update their estimate of the electrical energy they could generate. With these basic calculations, each team had to develop a specific proposal for a power plant that would provide 100 percent of the city's energy. The wind teams had to decide how many windmills, and the diameter of the blades. The

Physics in the Universe Snapshot 7.13: Evaluating Plans for Renewable Power Plants

hydroelectric teams had to decide how many dams and their heights. Each team produced a report outlining the benefits of their plan. The class then hosted a town hall meeting during which teams **communicated [SEP-8]** their plans and presented an argument that their proposal was better than the competing plans. This **argument had to be supported by evidence [SEP-7]** that went beyond the simple energy calculations but also took 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_2 in their cement, and result in water lost to evaporation; wind turbines obstruct scenic views, occupy large amounts of land, and only provide intermittent energy). These competing factors enter into all real-world decisions about energy generation (EP&C V). Students could have used a spreadsheet program to try to quantify some of these effects as they compared the impact of each proposal on the local ecosystem (HS-ESS3-3).

Engineering Connection: Engineering Energy Conversion Devices

Now that students have learned extensively about the theory behind energy **conversion [CCC-5]** devices, they are now tasked with an engineering challenge to create one themselves (HS-PS3-3). The vignette in the High School Four-Course Model—Physics course (chapter 8) in this 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 the 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 use existing computer simulations to investigate the impact of these different energy solutions (HS-ETS1-4).