Electrical Power: A Quantitative and Qualitative Comparison of Energy Resources

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Rationale

Energy. Everyone uses the word in many different contexts, but can they actually define it? Energy and power are often used interchangeably, but they are not the same. What is the difference between energy and power? Where does energy come from? How does electricity get to our homes? What are the pros and cons of various energy sources used to produce electricity? I am writing this curriculum unit for my Physics students, and these are some of the questions I want them to be able to answer at the end of this unit.

Energy is one of the core ideas and a crosscutting concept in the Next Generation Science Standards (NGSS). My students generally understand the Law of Conservation of Energy, and are able to perform calculations involving the transfer of energy (e.g. gravitational potential energy to kinetic energy). They do not, however, know about generating electrical energy or power. For example, based on the Delaware Physics Pre-Test I have given the past five years, nearly all of my students believe nuclear energy is always bad because of the nuclear disasters they have heard about in the news. They have never learned about how much energy can be generated from nuclear reactions using very small quantities of uranium. I have three main goals for this curriculum unit. I want my physics students to first learn the vocabulary and the facts about different types of electric power generation. Second, I want them to compare and evaluate electric power generated from different resources both qualitatively and quantitatively based on multiple criteria. Finally, I want them to know about the state of Delaware's overall electric energy use and how that usage is supplied.

I have been teaching math for 22 years, Chemistry for about seven years early on in my career, and Physics for the past five years at a vocational high school. It is one of the four schools, all high schools, in the New Castle County Vo-Tech School District in Delaware. Each of the four schools is a choice public school and draws from anywhere in New Castle County. My school has just over 1000 students in grades 9-12. The 2015-16 student population was 42.5% African American, 2.0% Asian, 14.9% Hispanic/Latino, and 39.5% White. Twenty-five percent of students were low income, 2% were English Language Learners, and 10.7% were supported by Special Education. Vo-Tech students take both academic and vocational courses each year. They are held to the same standards and take the same standardized tests as all public school students in the state. Vo-Tech students earn at least 12 credits in their chosen career (vocational) area. Approximately 40 – 50% of our graduates attend post-secondary educational programs at either two or four year schools. In their senior year, students are encouraged to seek co-operative employment for what amounts to half of their school time. Some “co-op” seniors work one-half of every day while others work full-time for two weeks and go to school for two weeks. Eligible seniors are also offered the opportunity to earn college credit from the local community college in a Dual Enrollment program. In some cases, their schedules do not allow them to take a physics class; however, students are given the option of taking an online physics course.

Our science courses are all one semester, 90-minute block courses. All Vo-Tech students take Physical Science in their freshman year and Biology in their sophomore year. They must earn a third science credit, which could be either Chemistry or Integrated Science. Chemistry is a prerequisite for Physics; students also have the option to take Environmental Science in their senior year. Since Physics is not a required course for graduation, the students enrolled are generally seniors that intend to go to a four-year college. Therefore, it is appropriate on many levels to ask my students to research, compare and contrast, evaluate, and justify their opinions about sources of electric power. This unit will address several of the NGSS Practice Standards. Specifically, students will Use Mathematics and Computational Thinking, Engage in Argument From Evidence, and Obtain, Evaluate and Communicate Information. This unit will include several Disciplinary Core Ideas: Nuclear Processes (PS1C), Definitions of Energy (PS3A), Conservation of Energy and Energy Transfer (PS3B), and Earth and Human Activity (ESS3). It will also incorporate some Crosscutting Concepts: Energy and Matter, Structure and Function, Interdependence of Science, Engineering and Technology, and Influence of Engineering, Technology, and Science on Society and the Natural World.

Background

As I began this seminar and later my research on electric energy and power production, I realized how limited and naïve my understanding of the topic was. I was familiar with renewable (solar, hydropower, wind, geothermal, biofuels) versus nonrenewable (fossil fuels, nuclear) resources. One thing I had never thought about was that the energy in nearly all resources originally came from the sun. In the case of fossil fuels dead plants and/or animals (originally kept alive by solar energy transferred via photosynthesis) were covered by sediment, and over time, with the help of increased temperature and pressure, and bacteria, transformed into petroleum, natural gas, or coal. Biofuels are made from plant material, converting solar energy into other useful energy forms when burned.[1] Wind occurs when the sun heats the Earth’s surface at different rates.[2] From my readings and seminar, not only did I learn how these various resources were used to produce electricity, but I also learned about factors that need to be considered when building power supply facilities.

Energy, in the science classroom, is defined as the ability to do work. There are many forms of energy: thermal (heat), kinetic, potential, mechanical, electromagnetic (light), chemical, and electrical. We know from the First Law of Thermodynamics that energy is conserved; energy can be transformed from one form to another but the total amount of energy remains constant. When I teach this to my students, I begin with a closed system, such as a book sitting on a table. In this example, $E_1 = E_2$, where E represents the amount of energy and the subscripts *1* and *2* refer to an initial and final time period, as in before and after. If an outside force (such as a student lifting the book) is exerted on the book, then the system is no longer a closed system and $E_1 + W = E_2$, where W represents the amount of work done. Subtracting E_1 from each side of the equation, $W = E_2 - E_1 = \Delta E$. Thus, work is equal to the change in energy of the open system. In this example, work is equal to the change in gravitational potential energy. Since Energy is measured in Joules in metric (or *SI*) units, Work is also measured in Joules.

Too often, the term power is used interchangeably with energy. We need to differentiate *energy* from *power*. Energy tells us how much work can be performed. Power tells us how much time is utilized to perform the work. In other words, power is the rate at which work is done. Mathematically, $P = \frac{W}{t}$, where P represents power, W is work, and t is time measured in seconds (s). The units for power are J/s, given the name Watt (W). Watts are familiar to students with respect to electricity, but we may need to make the connection for them with respect to work and power. For example, we can explain to students that a 100-Watt light bulb converts 100 Joules of electrical energy to light and heat every second. A 40-Watt light bulb uses less power, and therefore, is less intense/bright.

For this unit, I am most interested in the generation of electricity that is used by individual consumers. Therefore, I need to consider how energy is transferred and transformed from each energy resource, but ultimately I want to consider the amount of power generated from each. One authority in the Energy field, Vaclav Smil, recommends "Power Density" as the way to compare energy resources. He defines power density as "the energy flux in a material medium."[3] It quantifies the power received and converted per unit of land, water, or other surface.[4] The units for power density that Smil uses are watts per square meter (W/m^2) of Earth's surface. The power densities he calculates standardize the measurements for comparison, but they do not account for the quality of the power.

In my readings, I learned about many factors that should be considered when evaluating energy sources. The first factor I want my students to consider, of course, is power density. The second factor is location, as in where the original energy resource is located, whether it needs to be transported to where it will be converted into electrical energy, whether it needs to be stored, and how it is transmitted to customers. The third factor is negative byproducts, including waste, emissions, and noise. Factor number four is consistency and reliability, as in whether electricity demand can be met at any time without the need for backup. The fifth factor is efficiency, or the amount of stored energy in the resource that can be converted to electricity, and the final factor is safety.

Generating Electricity

The most common process for generating electricity at a large power plant is by burning a fuel to generate pressurized steam. Most commonly, the steam is produced either by burning fossil fuels (coal or natural gas) or by fissioning uranium.[5] The burning of fossil fuels transforms chemical energy stored in chemical bonds into heat/thermal energy. The steam, at high pressure and temperature, expands in a turbine. As the expanding steam passes through the turbine blades it loses heat energy and, therefore, does work, forcing the blades to rotate. In other words, thermal energy in the steam is converted to rotational (kinetic) energy of the turbine blades. The turbine's rotating blades are connected to an axle in its center that drives a shaft connected to a magnet. This rotating magnet, surrounded by coils of wire in an electric generator forms a strong magnetic field that causes electrons in the coils to move. The magnet's rotation continuously changes polarity with respect to the wire coils. The flow of electrons (current) changes in response to the magnet's polarity because like charges repel and unlike charges attract. The end result is the generation of alternating (AC) current.

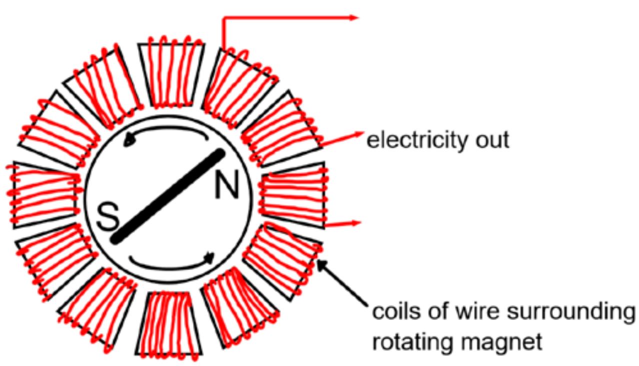

Figure 1 – AC Electric Generator

As we learned in our seminar, Thomas Edison originally generated direct (DC) current to supply electric power to homes. However, too much electrical energy was "lost" in power lines as heat energy. Joule's Law explains why more heat is generated as current flows further from its source: $P = I^2R$, where P is the power (rate of electrical energy flow) measured in Watts (Joules/second), I is the current measured in amperes, and R is the resistance of the wire measured in ohms. As DC electricity is transmitted through wires, which naturally have resistance, the amount of power lost is equal to the amount of heat that is absorbed by the wire. Nikola Tesla proposed the solution that was accepted by George Westinghouse in the late 1800's.[6] By generating alternating (AC) current, electricity can be transmitted to consumers at high voltages (measured in kilovolts).

Combining Ohm's Law, $V = IR$, and Joule's Law, we can see the advantage of AC electricity transmission. Rearranging Ohm's Law as $R = \frac{V}{I}$, and substituting into Joule's Law we get $P = I^2 \cdot \frac{V}{I} = IV$. Therefore, it is possible to generate the same amount of power with a low current and high voltage. Onsite transformers at power generating plants increase the voltage so AC current can travel long distances. Substations along the way to consumers reduce the voltage to levels that can be used. For example, the voltage entering our homes is approximately 110-120 volts (yes, it varies depending on the distance from the pole to the house).

Fossil Fuels

Fossil Fuels are a group of energy resources comprised of hydrocarbon molecules. Examples of fossil fuels are coal, petroleum, natural gas, oil shale, and tar sands. All of these fuels were produced from organic material over millions of years. Being organic, their energy originally came from the sun through photosynthesis. However, less than 2% of the sun's (electromagnetic radiation) energy absorbed by a plant is converted to chemical energy in plant mass.[7] All fossil fuels have a high energy density, that is, they contain a lot of energy per unit of mass or volume. Table 1 shows a comparison of energy densities of different resources.

Petroleum was formed from marine plants and small underwater organisms such as plankton that was covered by sediments over time. With increasing sediment, temperature and pressure, along with bacteria, the organic material was transformed into petroleum within sedimentary rock.[8] Natural gas is formed by the same process as petroleum and is often found in the same location. The natural gases that are recovered are the smallest hydrocarbons: methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). Larger hydrocarbon molecules are recovered as liquid petroleum.[9]

Coal is formed from fallen trees that were covered by water and sediment that, over time, protected them from oxygen in the air. As a result, the wood compressed, formed a substance called peat, and with more sediment and increased pressure and temperature released hydrogen and oxygen. The result was a porous material with a higher percentage of carbon. The coal often contains inorganic material from rocks and soil that covered the trees throughout the process.[10]

Oil shale was also formed from plants but contains a significant amount of inorganic material also. Only the carbon-based organic material can be burned; the inorganic material (shale rock) cannot be burned. Therefore, in order to use oil shale as a fuel, it must first be processed, which leaves behind a lot of inorganic waste.[11] Tar sand is another source of hydrocarbons. Thick, black, heavy (and gooey) hydrocarbon-rich tar covers sand particles near the surface of the earth. Tar sand is recovered primarily from areas in Canada and Utah and then separated above ground.[12]

Generating Electricity from Fossil Fuels

Of the fossil fuels described above, coal and natural gas are the ones most commonly burned in boilers at power plants. (Petroleum is used primarily for transportation and heating oil, not electricity generation.) The boilers are tall buildings that contain tubing with circulating water inside. The steam is released into turbines placed in series and located in "machine halls" where the electricity generators are as well. Burning coal creates fly ash and other pollutants, such as sulfur dioxide, that must be contained and/or neutralized. Some of the neutralized waste can be recycled into other products, but much of it is stored onsite and then ultimately disposed of elsewhere. The steam that is discharged from turbines must be condensed and cooled. It can be recycled for steam generation if it is cooled in cooling towers. Otherwise, the steam is cooled in onsite (manmade) ponds or by being circulated through draft towers. The electric power plant may be located near the source of coal, reducing the need and cost of transporting and storing the coal. However, if the power plant is located far from the mine, coal must be transported and stored, requiring greater land area.[13] Coal's energy content per unit mass is 22-25 x 10^6 J/kg. Using the density for bituminous (high quality) coal quoted from The Engineering ToolBox website,[14] the energy density of coal ranges from 2.6 x 10^{10} to 3.7 x 10^{10} J/m^3. Considering the land area required for the actual power plant including service buildings, coal mining, and transportation of the coal, the power densities that Vaclav Smil calculated for coal-fired power plants range from 100 W/m^2 to 1000 W/m^2. The range in power densities accounts for the quality of the coal (amount of sulfur that needs to be contained), location of the plant, cooling process, etc.[15]

The process for generating electricity from natural gas is the same as that for coal. However, natural gas is a cleaner fuel and emits less CO_2 than other fossil fuels. It does not produce fly ash or sulfur dioxide when burned, eliminating the need for waste storage areas and desulfurization units. Therefore, less land area is required for natural gas-fired power plants. Additionally, heat expelled out the back of gas turbines can be tapped to produce even more steam to generate more electricity, increasing the efficiency of the process. Other advantages of burning natural gas over coal include the fact that boilers can be powered up very quickly, natural gas is often recovered from existing oil fields, and the boilers are capable of burning either gaseous or liquid fuel (LNG).[16] Natural gas is typically liquefied before transporting it (often via pipeline). The energy content of liquefied natural gas is 35,000 J/m^3. The power density for an efficient, compact natural gas-fired power plant starts at approximately 2000W/m^2, but that number decreases over time as the supply is depleted at the source, requiring more drilling.[17]

Nuclear Fission

Nuclear fission is essentially a reaction in which a neutron with the proper energy (kinetic energy directly related to the square of its velocity) strikes the nucleus of an atom that is able to absorb it and create an unstable isotope. That unstable atom then splits into two or more atoms.[18] Uranium-235 is the only practical element in nature that is able to absorb neutrons of the proper velocity. The atomic number of uranium is 92, meaning there are 92 protons in the nucleus and 235 – 92 = 143 neutrons. When the uranium atom fissions, and two or more smaller atoms are formed, neutrons are released. (Smaller atoms generally contain approximately equal numbers of protons and neutrons in their nuclei, and cannot absorb all of the extra neutrons from Uranium.) "In the case of uranium, an average of 2.4 neutrons per fission event are released."[19] To increase the probability that the excess neutrons will continue to cause fission of other uranium atoms in a chain reaction, uranium is enriched to increase the concentration of the needed uranium-235 isotope. Nuclear fission is an example of Einstein's equation, $E = mc^2$, where E is the energy created from a very small amount of mass, m, from an atom and c is the velocity of light, ~3×10^8 m/s. From this perspective, it makes sense that a huge amount of energy is created from a very, very small change in mass.[20] Bradley E. Layton from Drexel University quotes the energy density of a purified sample of enriched uranium-235 as 1.5×10^{15} J/m^3, which is far greater than fossil fuels.

Generating Electricity from Nuclear Fission

There are many common components in fossil fuel-fired power plants and nuclear power plants. They all have large halls for turbogenerators (turbines driving electricity generators) and cooling processes, and they all rely on heating and pressurizing steam to rotate the turbine blades. Unique to a nuclear power plant is a reactor vessel where the nuclear fission reaction occurs and is controlled. It has four essential components: 1) *fuel rods* that contain the uranium-235 to be fissioned, 2) a *moderating material* such as water, light hydrocarbons, beryllium or carbon. The purpose of the moderating material is to control the velocity of the neutrons that are emitted from fission reactions so that they have the proper velocity to continue the chain reaction, 3) *control rods* that are moved up and down to control the rate of the reaction. Control rods are made of materials that can also absorb neutrons but do not fission; they "intercept neutrons" and slow down the reaction when they are lowered into the reactor, and 4) a *coolant* that surrounds the fuel rods to absorb heat from the fission reaction.[21] The coolant then transfers that heat to produce the steam that drives the turbine. The structures on a nuclear power plant site take up a small percentage of the land area included in Vaclac Smil's power density calculation. However, there is often a large buffer area near the sites, and they are built in areas with low population. Cooling ponds can also consume a large area of land. Smil calculated power densities in the range of 70 – 1660 W/m^2, depending on "fenced-in areas, cooling arrangements, and the origins of the fuel supply."[22]

Nuclear power plants run 24/7, so they are constantly generating electricity. Since nuclear fission uses such a small amount of uranium to initiate the chain reaction, fuel supply is not a concern, and nuclear power is a reliable source of electricity. Nuclear power plants do generate more thermal pollution than fossil fuel-fired power plants, and, therefore, must be located near a water supply (lake, river, ocean) that can be used to cool and condense the steam. Because of location requirements, electricity from nuclear power plants will always need to be transmitted long distances. Contrary to what many people believe, nuclear power plants do not create air pollution and cannot explode. The danger from a system failure in the reactor vessel comes from the fission reaction proceeding too quickly, producing excessive heat that causes the reactor to literally melt. When a reactor melts, harmful radiation is released into the atmosphere. The most recent meltdown in the news, at the Fukushima Daiichi power plant in Japan, was caused by a power outage from a tsunami. Without power, control rods couldn't be lowered and coolant couldn't be pumped in to the reactor vessels. Another safety concern is the storage of fuel rods because their radioactive decay time (to reach a safe level) is millions of years.[23]

Solar Energy

"Our sun delivers to earth a constant supply of 1,300 to 1,400 watts of power per square meter."[24] Unfortunately, much of that radiation is absorbed by the atmosphere, reflected back to space by clouds and Earth surfaces, and is reduced because of the curvature of the Earth. The final tally for usable solar energy that strikes the earth's surface is approximately 100 W/m^2.[25] Solar energy can be used directly for heating by strategic placement of windows (facing South) or pumping water through pipes on a roof. We learned about two processes that generate usable electricity from sunlight: solar thermal power plants and photovoltaic cells.

Photovoltaic cells use solar energy to excite electrons within the cell that move through wires to create a current. The PV cells are made of several layers. The two innermost layers are made from silicon, a semiconductor that conducts electricity only under certain conditions. One of the silicon layers is doped with phosphorous, which provides extra electrons. The second layer is doped with boron, which creates "holes" that can accept electrons. The two silicon layers are between two layers of a conducting material (aluminum), with a layer of glass on the top and bottom. When photons of light excite electrons in the silicon layers, the electrons are freed to move, leaving a hole. The freed electrons create an electrical current that can do work as they travel from the negatively-charged silicon layer through the top conducting material to a wire that is connected to the lower conducting material, and then return to the positively-charged silicon layer.[26]

Generating Electricity from Photovoltaic (PV) Cells

The current produced by PV cells is direct current (DC) and must be converted to alternating current (AC) by an inverter so that appliances in our homes can use it. The current efficiency of PV cells for generating electricity from sunlight ranges from 10% to 30%.[27] Generating electricity from sunlight is obviously more attractive in sunny, arid (desert) locations than in northern locations with fewer sunny days. Additionally, PV cells cannot generate electricity overnight, so homes either need batteries to store electricity, or use electricity from the power grid when the sun is not shining; homeowners with PV cells can "return" and sell excess electricity to their local providers during the day and purchase it overnight. Although it requires a lot of energy to purify the silicon used in PV cells, during operation, photovoltaic cells do not produce any pollution, are extremely safe, and last a long time because there are no moving parts (other than electrons).

Photovoltaic cells connected in a grid on rooftops have power densities between 10-25 W/m^2. When PV panels are arranged in a "solar park" on a piece of land, they are positioned with an optimal tilt to receive the maximum possible solar radiation. Additional land area is also needed for access roads, spacing between panels for servicing, for inverters, transformers and other service structures. Therefore, the power density for large solar parks is only 4-9 W/m^2.[28]

Generating Electricity from Solar Thermal Power Plants

A solar thermal power plant uses an array of parabolic mirrors called heliostats to direct and concentrate sunlight towards a receiver. Computers are used to align the heliostats to the optimal position for directing the sunlight to the receiver on the top of a tower in the center of the array. The concentrated sunlight heats a molten salt that is capable of storing the heat until it is needed to generate electricity. The heated molten salt is stored at ground level and then pumped to a boiler where it heats water to produce the steam to turn turbine blades that ultimately generate electricity in the same way as other thermal power plants. As the steam cools, the water can be recycled and reheated as needed. Likewise, the molten salt cools and can be pumped back to the receiver to be reheated. Thus, the process of generating electricity using concentrated solar is quite efficient, clean, and reliable – not as intermittent as PV cells. Smil calculated power densities of solar thermal power plants to be 10-50 W/m^2.[29]

Generating Hydroelectric Power

Water from rivers and reservoirs can be used to turn turbines, thereby producing electricity by converting kinetic energy of the water to mechanical energy in the turbine. The turbine then drives the rotation of a coil in a magnetic field to produce electrical energy in the same way as a thermal electricity power plant. The amount of power that can be produced by flowing water depends on the drop in height, water flow, and head (related to the pressure exerted by water at varying depths). Dams and reservoirs are sometimes built to control the water flow, but consume land area; in some cases dams flood farmland and affect fish spawning and other wildlife. Hydroelectric power can only be generated when there is a source of water, and if it is dependent on river flow, droughts can negatively affect the power supply. On the positive side, dams are relatively cheap to operate and maintain, do not create air or thermal pollution, and have approximately 80% efficiency.[30] In some places, water is pumped from low to high elevation reservoirs during off-peak hours to generate potential energy that can be used during peak hours of need. With all of the variability, power densities for hydroelectric power plants range from 1-100 W/m^2.[31]

Generating Electricity from Geothermal Energy

The core of the earth contains hot magma, below the earth's 50-mile thick crust. There are cracks in, or rifts between tectonic plates in the crust. The magma can move closer to the earth's surface, pressurized, via these cracks and rifts. If the magma reaches the surface, it may activate a volcano. If the magma does not reach the surface, but comes in contact with underground water, it will heat the water that may in turn create a geyser or hot water pool. Underground water that comes in contact with rocks heated by magma, and remains trapped underground, can be used to generate electricity. Wells can be drilled to reach pockets of pressurized hot water or steam. Clean (free of dissolved minerals or hydrogen sulfide) steam is the most useful because it can be used directly to turn turbine blades in turbogenerators, just as it does in other thermal power plants. Thus, thermal energy is converted into mechanical energy. If the steam does contain dissolved minerals or hydrogen sulfide, they must be removed to prevent damage to turbines.[32] Another option is to use the steam to heat another liquid that can then operate the turbine. There is no air pollution associated with geothermal energy; however, water flowing through pipes is very noisy. Cost-effective geothermal energy is only available to be tapped in active tectonic regions, along fault lines. Once tapped, the supply is reliable and consistently available since water can be pumped into the well/pocket to be (re)heated. According to Layton, water heated underground has an energy density of 0.05 J/m^3.[33] The land area required to capture geothermal energy is relatively compact and can often still be used for agriculture and animal grazing.[34] Smil estimates the power density of geothermal electricity-generation to be 45 – 113 W/m^2.

Generating Electricity from Wind

Wind is a renewable energy source that results from the sun heating the Earth unevenly. Warm air rises and cooler air moves downward. Wind, since it is moving, has kinetic energy. When wind flows past the propeller-type blades of a wind turbine, it is converted to mechanical energy that drives a shaft that rotates the coil in a magnetic field and produces alternating current. According to the German physicist, Albert Betz, the maximum amount of kinetic energy that a wind turbine can convert into mechanical energy is 59%.[35] The energy density of 7 J/m^3 given in Table 1 assumes a wind speed of 10 mph (5 m/s). The kinetic energy (*KE*) of the wind (density of air = 1 kg/m^3 at sea level) can be calculated as

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(1kg)(5m/s)^2 = 12.5 \text{ J/m}^3$$

which leads to

$$\text{Energy Density} = 0.59(12.5\text{J/m}^3) \approx 7\ \text{J/m}^3$$

Wind energy is clean energy, but intermittent and depends on wind speed as demonstrated above. The spinning turbines are noisy. Therefore, wind farms comprised of tens or hundreds of windmills must have a buffer zone between them and residential areas. It also makes sense to locate wind farms in windy regions, such as on mountain ridges or offshore in shallow water. As a result, the electricity generated must be transmitted via high voltage lines over long distances Wind turbines need to be spaced far enough apart (usually in a grid pattern) to avoid wave interference with each other, and to allow access roads between them for maintenance purposes. While the turbine spacing requires a large area, most of the land can be used for agriculture or animal grazing. Estimated power densities for wind–generated electricity span a wide range, 0.1-11 W/m^2, since wind velocities are so variable.[36]

Table 1 summarizes the information discussed above and allows a quantitative comparison of energy resources. I did not elaborate on wood/biomass as a resource for electricity generation because it is a minor contributor in the present day. Wood can be used to heat homes directly, and biomass waste can be burned to produce the steam in a thermal power plant. It has a high energy density, but low power density because of the large land area required to grow trees and plants that become the fuel supply.

Energy Resource	Energy Density (J/m^3)	Power Density (W/m^2)
Wood/biomass	10^7	0.6
Coal	2.6×10^{10} - 3.7×10^{10}	100 - 1000
Natural Gas	35,000	200-2000 (USA)
Uranium (enriched)	1.5×10^{15}	70 - 1600
Solar PV cells	1.5×10^{-6}	4-9
Solar Thermal	1.5×10^{-6}	10-50
Water	N/A	1-100
Geothermal	0.05	45-113
Wind	7	0.1-11

Table 1

I also did not discuss costs of the different power generation processes. In general, electricity from fossil fuel-fired power plants is inexpensive. The initial costs associated with some of the renewable resources such as solar and geothermal can be very high, although government subsidies can make them more attractive. Another avenue to explore is whether or not it is practical to convert to alternate resources. For example, there is not enough land area available to produce enough biomass to meet the demand of electric power in the USA.

Teaching Strategies

I plan to insert the first two activities described in this curriculum unit after the Conservation of Energy unit and before the Electricity unit in my Physics curriculum. I believe it will be a perfect transition and connection between the two. The entire unit will most likely extend over approximately two weeks.

Talking Points

Talking Points are a list of statements designed to initiate thought and discussion about a given topic. Participants (students) are asked to read each statement silently and circle a response: AGREE, DISAGREE, or NOT SURE. After they have had enough time to consider each statement individually (5 – 10 minutes, maximum), students take turns, in groups of four, to share their response and why they chose it. Going through each statement one at a time, each student explains his/her response *before* others can react. Once all group members have given their responses and reasons for the first statement, they can react and discuss their responses in an effort to gain understanding and clarification. They proceed through each statement, giving each group member a voice. This process takes 15-30 minutes, depending on the number of statements. At the end of the group discussions, going one statement at a time, a volunteer (or assigned Reporter) should share with the full class whether the group reached consensus about the statement and why. Talking Points can be used as a hook to begin a lesson/unit, or as a summarizing strategy or formative assessment after a lesson/unit.

Schoology

The Delaware Department of Education has adopted (purchased) a learning management system called *Schoology*. Teachers and students can access it from any computer, tablet or Smartphone; there is a downloadable app, also. My students use *Schoology* in multiple ways in different classes. All of them are familiar with how to login, access files, submit assignments, send messages to teachers, and write discussion posts. I upload class notes from my SMART Board files daily. I also add folders with extra practice problems or links to tutorials as needed. For this unit, I will have a folder that has links to useful videos and data. I will also include instructions for the research assignments, relevant articles, and questions to be answered in Discussion posts.

Classroom Activities

Lesson 1 – Introductory Concepts: Electrical Power (1/2 - 1 class period)

Essential Question: How is energy transferred and conserved?

Warm-up: Name as many renewable resources used to generate electricity as you can.

Activity #1: Talking Points

This is a sample handout for each student. The instructions are: Read each statement silently and circle your response. Be prepared to explain the reason(s) for your response to your group members.

1. A 100-watt light bulb is brighter than a 40-watt bulb because it converts more electrical energy to light and thermal energy each second.
   AGREE DISAGREE NOT SURE

2. Generating electricity from nuclear fission creates air pollution.
   AGREE DISAGREE NOT SURE

3. Renewable resources have the potential to generate enough electricity to power the United States.
   AGREE DISAGREE NOT SURE

4. Solar radiation has a power density that is ten times greater than wind turbines.
   AGREE DISAGREE NOT SURE

5. Energy in fossil fuels is from chemical energy stored in plants during photosynthesis.
   AGREE DISAGREE NOT SURE

After the groups discuss each question and their reasons, I will let each group share their responses with the class, but I will not tell them whether they are right or wrong at this time. I also will not provide them with definitions of any terms during this activity, although I will not stop them from looking them up during the activity.

Activity #2: Generating Electricity

Because there are common elements in generating electricity from different resources, I will show a couple of videos to introduce some of these basic ideas before the students do research in the next lesson. I listed five videos under "Teacher Resources" in Appendix B. I will definitely show the first one entitled "How a Gas Turbine Works" which illustrates how gas turbines generate steam that turns the turbogenerator to create the electric field needed to generate electrical current. Next, I will show both of the "AC vs. DC" videos to explain the difference between them and why AC current is used in our homes. I will not show the last two videos in the list at this time; if students don't report the information from their research, I will show them later in the unit.

Activity #3: Closing Activity – Vocabulary/"Silly Sentences"

Before leaving class, students will write a sentence that includes the following vocabulary terms in a way that a reader will understand its meaning. If the student doesn't know the meaning, he/she should write a "silly sentence" using the term. Students can share their silly sentences, if time allows. For homework, students will look up definitions of the vocabulary terms and either rewrite each silly sentence, or improve each serious one, if necessary.

Vocabulary terms: fossil fuel, hydrocarbon, electrical power, energy flux, thermal pollution, power density

Lesson 2 – Comparison of Energy Resources Used to Generate Electricity (~1 week)

Essential Question: How is energy transferred and conserved?

Warm-up: What are fossil fuels? Give as many examples as you can.

Activity #1: Student Group Research & Poster

Assign student groups of 2-3 students. (I will probably allow students to select their own groups because they will have to do work outside of class, and they will need to be in contact with each other.) Assign one energy resource per group. I would like a minimum of six groups (fossil fuels, nuclear fission, solar, hydroelectric, geothermal, wind turbines), ideally eight groups (split fossil fuels into coal and natural gas, and split solar into PV cells and solar thermal), and the option for nine or ten groups (add biomass or shale/tar sands). Energy resources can be assigned randomly or allow students to choose; I often use a random name generator to pick the order in which groups choose their topic.

I will post requirements for the research assignment online in *Schoology*. Each group will be responsible to learn about their assigned energy resource. They should be able to describe the origin of the resource, the type of energy it contains (chemical, kinetic, etc.), the process used to convert that energy to electrical energy (collection of the resource, transportation to the power plant, key "machinery" in the process, transmission of the product), the efficiency of the process, its consistency and reliability, any negative by-products, and the safety of the process. Depending on class time available, students may begin their research in class, or be given a due date for completion outside of class in approximately one week. After students have had some time to find their own resources, I will direct them to *Schoology* where I will provide them links to access the videos listed under "Students Resources" in Appendix C. I will also post excerpts from Vaclav Smil's "Power Density Primer" and Bradley Layton's "Comparison of Energy Densities…" articles that I used in compiling the values in Table 1 above.

Each group will create a poster (or other visual) illustrating how their assigned resource is used to generate electricity. The poster should include storage, transportation, by-products, efficiency, etc. Posters will be displayed around the classroom.

Activity #2: Individual Student Activity – Compile and Analyze Energy Resources

Each student will move from one poster to the next to compile information into a single chart like the one in Appendix D. After students have gathered information, groups will be called up one at a time so that other students have the opportunity to ask questions about the different energy resources. (This could also be done using Discussion posts in *Schoology*.) If necessary, I will help students complete the Power Density and Efficiency/Energy Density columns in the table. As an assessment, students will need to form an opinion and write a Position Paper stating the best resource for generating electricity in our community, justifying it using the information gathered.

Lesson 3 – How is Electricity in our State Generated? (2 class periods)

Essential Question: How is energy transferred and conserved?

Warm-up: Revisit the "Talking Points" handout from the start of this unit. Respond to each statement again, giving justification for your responses. Did your responses change?

Activity #1: Relative Amounts of Local Electric Power Resources

Students will first spend some time exploring data on the U.S. Energy Information Administration website (refer to Student Resources in Appendix C), accessed via a link in Schoology. Students will look at data for Delaware and the neighboring states of New Jersey, Pennsylvania, and Maryland, or others that may interest them. After 15-20 minutes, I will gather the class for discussion. As a class, they will identify the "base unit," that is the smallest energy resource from the smallest electricity-generating state (i.e. biomass/other renewables is 12,000 Megawatt hours, ~3% of Delaware's electricity generation). Next, in small groups first and then as a class, students will brainstorm how to build a model to show relative amounts of local electric power resources. They should consider what states to include, how to display them, and what common object(s) to use as building blocks to show relative amounts. I am picturing something like a 3-D pictograph, possibly on a map, but I don't want to restrict students.

Once ideas for the model have been narrowed down to a few feasible options, split students into groups to gather data and perform calculations. I will first make four groups, one per state (DE, NJ, PA, MD). As a group, they must determine the total amount of electricity generated in their state. This data can be found on the EIA website under the "Overview" tab on each state's page. There is a chart at the bottom of the page with a tab "Electricity" that breaks down electricity generation by source. There is more information under the “Analysis” tab that further breaks down renewable energy resources. After the group has determined the total amount of electricity, the groups should split themselves up to calculate the percentages produced by each resource. Students can fill in a Google document, or a chart hung up in the classroom as they finish their calculations:

(Measured in MWh)	Delaware	New Jersey	Pennsylvania	Maryland
Coal	22,000	109,000	4,668,000	1,492,000
Natural Gas	738,000	3,983,000	6,475,000	585,000
Nuclear		2,344,000	6,872,000	1,241,000
Hydro			77,000	27,000
Solar	~50	111,000	226,000	
Biomass		56,000		
Wind			150,000	
Other (renewables)	12,000			90,000

Finally, the class should consider the values in the chart to make a final decision on what common object(s) should be used as the smallest unit. Using data in the chart above, the base unit would be approximately 25,000 for coal in Delaware and hydro in Maryland. That means that nuclear and natural gas in Pennsylvania would be about 300 times as large. With that great a range, the base unit must be small…a grain of rice or a penny, perhaps? Volunteers should bring in enough of the objects to build the model, which can be built over time when students finish other assignments early. No matter the outcome of the model, students should gain an understanding of how electricity reaches their own homes, how much is consumed, and how it compares to other nearby states.

Appendix A – Next Generation Science Standards (NGSS)

Dimension 1: Scientific and Engineering Practices

Using Mathematics and Computational Thinking
Engaging in Argument From Evidence
Obtaining, Evaluating, and Communicating Information.

Dimension 2: Crosscutting Concepts

Energy and Matter
Structure and Function

Dimension 3: Disciplinary Core Ideas

Core Idea PS1: Matter and Its Interactions
HS-PS1.C: Nuclear Processes

Core Idea PS3: Energy
HS-PS3.A: Definitions of Energy
HS-PS3.B: Conservation of Energy and Energy Transfer

Core Idea ESS3: Earth and Human Activity
HS-ESS3.A: Natural Resources
HS-ESS3.D: Global Climate Change

Appendix B – Teacher Resources

Articles with Energy and Power Density Data

Layton, Bradley E. "A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter." *International Journal of Green Energy* 5, no. 6 (2008): 438-55. Accessed May 3, 2016. http://www.tandfonline.com.udel.idm.oclc.org/doi/full/10.1080/15435070802498036.

Smil, Vaclav. "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part I - Definitions)." *MasterResource* (web log), May 8, 2010. Accessed December 18, 2016. https://www.masterresource.org/smil-vaclav/smil-density-comparisons-v/.

Smil, Vaclav. "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part II - Coal- and Wood-Fired Electricity Generation)." *MasterResource* (web log), May 10, 2010. Accessed December 18, 2016. https://www.masterresource.org/smil-vaclav/smil-density-coal-wood-ii/.

Smil, Vaclav. "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part III -Natural Gas-Fired Electricity Generation)." *MasterResource* (web log), May 11, 2010. Accessed December 18, 2016. https://www.masterresource.org/smil-vaclav/smil-density-gas-iii/.

Smil, Vaclav. "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part IV -New Renewables Electricity Generation)." *MasterResource* (web log), May 13, 2010. Accessed December 18, 2016. https://www.masterresource.org/smil-vaclav/smil-density-new-renewables-iv/.

Smil, Vaclav. "Power Density Primer: Understanding the Spatial Dimension of the

Unfolding Transition to Renewable Electricity Generation (Part V - Comparing the Power Densities of Electricity Generation)." *MasterResource* (web log), May 14, 2010. Accessed December 18, 2016. https://www.masterresource.org/smil-vaclav/smil-density-comparisons-v/.

Videos

GE Power. "How a Gas Turbine Works." YouTube.com. https://youtu.be/zcWkEKNvqCA (accessed December 16, 2016). Excellent description of how chemical energy is converted to mechanical energy to produce electrical energy.

Mahl, Chris. "AC vs DC." YouTube.com. https://youtu.be/BcIDRet787k (accessed December 10, 2016). Illustrates AC and DC using PHET simulation

PBS Learning Media. "Energy Sources." WHYY.pbslearningmedia.org. http://whyy.pbslearningmedia.org/resource/phy03.sci.phys.energy.energysource/energy-sources/ (accessed December 10, 2016). Summarizes all sources of electricity. There are also support materials included to stimulate discussion.

ScienceOnline. "AC vs DC." YouTube.com. https://youtu.be/xyQfrzBfnDU (accessed December 10, 2016). Describes how Tesla solved Edison's problem of energy lost in power lines with direct current by generating alternating current.

Stafford, William. "Fossil Fuels – Coal, Oil, Natural Gas Formation." YouTube.com. https://www.youtube.com/watch?v=1KyjL_Mj6nc&feature=youtu.be (accessed December 18, 2016). Describes how energy from sunlight is stored in plants and animal matter over millions of years forms fossil fuels.

Appendix C – Student Resources

Elearnin. "Nuclear Reactor – Understanding how it works." https://www.youtube.com/watch?v=1U6Nzcv9Vws&feature=youtu.be YouTube.com. (accessed December 10, 2016). Illustrates components of nuclear reactors and how they generate steam to turn turbine blades.

Energy and Environmental News. "Energy 101: Solar Energy." YouTube.com. https://www.youtube.com/watch?v=NDZzAIcCQLQ (accessed December 10, 2016). Describes two ways in which solar radiation is used to generate electricity.

Engineering Timelines. "How a photovoltaic cell works." YouTube.com. https://www.youtube.com/watch?v=he_JjrXEfN0 (accessed December 10, 2016). A description of solar cells.

GreenLiving Solar. “How Solar Panels Work.” YouTube.com. https://www.youtube.com/watch?v=dngqYjHfr98 (accessed December 10, 2016). An all visual (words and images) of how solar panels produce electricity for homes and offices.

Layton, Eric. “Concentrated Solar Power Simple Explanation.” YouTube.com. https://www.youtube.com/watch?v=JbJ7AVHBQfs (accessed December 10, 2016). Excellent description of how solar thermal electric power plant works.

Learn Engineering. “How do Wind Turbines work?” YouTube. https://www.youtube.com/watch?v=qSWm_nprfqE (accessed December 18, 2016). Describes design of blades and why there is a max efficiency of 59.3%.

Student Energy. “Hydropower 101.” YouTube.com. https://www.youtube.com/watch?v=q8HmRLCgDAI (accessed December 10, 2016). Excellent overview of how flowing water is used to generate electricity.

TED-Ed. “How do solar panels work? – Richard Komp.” YouTube.com. https://www.youtube.com/watch?v=xKxrkht7CpY#t=286.089415744 (accessed December 18, 2016). Excellent description of solar cells.

U.S. Department of Energy. “Energy 101: Geothermal Energy.” YouTube.com. https://www.youtube.com/watch?v=mCRDf7QxjDk (accessed December 10, 2016). Describes how geothermal energy is tapped and used to produce electricity.

U.S. Department of Energy. “Energy 101: Wind Turbines.” YouTube. https://www.youtube.com/watch?v=tsZITSeQFR0 (accessed December 10, 2016). Describes how wind is converted to electricity.

U.S. Energy Information Administration. “U.S. States, State Profiles and Energy Estimates.” http://eia.gov (accessed December 16, 2016). Search for Delaware (or other state) Profile Analysis of electricity usage and generation.

Appendix D – Comparison of Energy Resources Used to Generate Electricity

COMPARISON OF ENERGY RESOURCES USED TO GENERATE ELECTRICITY

Electrical Energy Resource	Location - Need to Store Raw Material	Location – Electricity Generated near Resource	Negative By-Products	Consistency/ Reliability	Efficiency (Energy Density)	Safety	Power Density (J/m^2)
Coal							
Natural Gas							
Nuclear Fission							
Solar PV cells							
Solar Thermal							
Hydroelectric							
Geothermal							
Wind Turbines							
Biomass							

[1] Wendell H. Wiser, *Energy Resources: occurrence, production, conversion, use* (New York: Springer, 2000), 21-22.
[2] Vaclav Smil, *Power destiny: a key to understanding energy sources and uses* (Cambridge: The MIT Press, 2015), 41.
[3] Smil, *Power Density*, 14.
[4] Smil, *Power Density*, 15.
[5] Smil, *Power Density*, 129.
[6] Quora. "What advantages does an alternating current have over direct current?" https://www.quora.com/What-advantages-does-an-alternating-current-have-over-a-direct-current (accessed 12/10/16)
[7] Vaclav Smil, "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part II - Coal- and Wood-Fired Electricity Generation)," *MasterResource* (web log), May 10, 2010, accessed December 18, 2016, https://www.masterresource.org/smil-vaclav/smil-density-coal-wood-ii/.
[8] Wiser, *Energy Resources*, 21-22.
[9] Wiser, *Energy Resources*, 89-90.
[10] Wiser, *Energy Resources*, 106-107.
[11] Wiser, *Energy Resources*, 155
[12] Wiser, *Energy Resources*, 162-163.
[13] Smil, *Power Density*, 131-133.
[14] http://www.engineeringtoolbox.com/density-solids-d_1265.html, accessed 10/30/16
[15] Smil, *" Power Density Primer (Part II).*"
[16] Vaclav Smil, "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part III -Natural Gas-Fired Electricity Generation)," *MasterResource* (web log), May 11, 2010, accessed December 18, 2016, https://www.masterresource.org/smil-vaclav/smil-density-gas-iii/.
[17] Smil, *Power Density*, 124-126.
[18] Wiser, *Energy Resources*, 204.
[19] Wiser, *Energy Resources*, 208.
[20] Wiser, *Energy Resources*, 204-208.
[21] Wiser, *Energy Resources*, 210-211.
[22] Smil, Power Density p155.
[23] Wiser, *Energy Resources*, 214-216.
[24] Bradley E. Layton, "A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter," *International Journal of Green Energy* 5, no. 6 (2008): , accessed May 3, 2016, http://www.tandfonline.com.udel.idm.oclc.org/doi/full/10.1080/15435070802498036, 439.

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25 Layton, p440

26 TED-Ed. "How do solar panels work? – Richard Komp." YouTube.com. https://www.youtube.com/watch?v=xKxrkht7CpY#t=286.089415744 (accessed November 6, 2016).

27 Vaclav Smil, "Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part IV -New Renewables Electricity Generation)," *MasterResource* (web log), May 13, 2010, , accessed December 18, 2016, https://www.masterresource.org/smil-vaclav/smil-density-new-renewables-iv/.

28 Smil, "Power Density Primer (Part IV)."

29 Smil, *Power Density*, 58.

30 Wiser, *Energy Resources*, 244-245.

31 Smil, *Power Density*, 192.

32 Wiser, *Energy Resources*, 249-253.

33 Layton, "A Comparison," 443.

34 Smil, *Power Density*, 93.

35 OMICS International. http://research.omicsgroup.org/index.php/Betz's_law, accessed November 6, 2016

36 Smil, *Power Density*, 63-69.