Diminishing Returns

Students illustrate the concept of energy efficiency through a relay race.

Grade Level: 5–8

Subject Areas: English Language Arts, Mathematics, Science, Technology Education

Setting: Classroom and large outdoor playing area (water will be spilled)

Time:
Preparation: 50 minutes
Activity: 50 minutes

Vocabulary: Compact fluorescent light bulb (CFL), Conversion device, Efficient, First law of thermodynamics, Incandescent light bulb, Inefficient, Light emitting diode (LED) light bulb, Second law of thermodynamics

Major Concept Areas:

- Natural laws that govern energy
- Development of energy resources

Getting Ready: Use a hammer and small nail to make holes in the cups and yogurt containers. Mark positions where students should stand during the relay and set up the relay materials (plastic containers, cups, water, etc.) at each position. Students can help with this before the relay begins. See ***Steps of the Relay Simulating Energy Conversion Process***. You should either play this game outdoors or with several towels laid out on the floor since there will be spilled water.

Objectives

Students will be able to:

- identify evidence of the second law of thermodynamics during the conversion of chemical energy to light energy; and
- calculate the system efficiency for a variety of conversion processes; and compare the system efficiency of certain conversion devices and systems.

Rationale

Students gain a better appreciation of how energy is used by investigating the second law of thermodynamics and how this law relates to system efficiencies. In addition, students learn how individual actions contribute to using energy more efficiently.

Materials

- 2 lamps, one lit with a 60-watt incandescent bulb and the other with a 12-watt LED light bulb
- Copies of the following pages:
  - ***Calculating System Efficiencies (optional)***
  - ***Steps of the Relay Simulating Energy Conversion Process***
- Each relay team of 12 will need the following:
  - 1 gallon of water NOTE: Other readily pourable material such as sand or grass seed can be used instead of water.
  - 1 plastic yogurt container (one pound size) with 1 hole in the bottom
  - 1 plastic yogurt container (one pound size) with holes covering one-third of the bottom
  - 6 small paper cups (5 of the cups should have one hole punched in the bottom)
  - Coal sample(s)
  - Stopwatch
- Find additional resources related to this activity on keepprogram.org > Curriculum & Resources

Background

Suppose you paid $100 a year to light your home. What if you found out that only $5 of this payment went toward paying for the light? Would you feel shortchanged?

What about the other $95 of energy you paid for? Where did it go? Would you be surprised to know that it was lost to the surrounding environment?

To find out where the $95 worth of energy went, it helps to understand the laws of energy. Energy is hard to conceptualize because it is constantly changing from one form to another. When this change happens it is called an energy conversion. We use energy conversions to meet our daily needs. Our bodies convert the energy stored in food into kinetic energy – the energy associated with movement. Electric power plants convert the energy stored in fuels such as coal into electricity. We then convert electricity into other useful forms in our homes, schools, and businesses using many different energy conversion devices. One such device is the light bulb, which converts electricity into light.

The first law of energy (or Law of Thermodynamics) states that energy can be neither created nor destroyed. Therefore, according to this law, the amount of energy before a conversion takes place must equal the same amount of energy after the conversion. So how does this explain why only $5 worth of energy out of the original $100 went to light the light bulb? What happened to the other $95 worth of energy?

Although the same amount of energy exists before and after an energy conversion, not all of the original energy is converted into a desired form of energy afterward. In other words, while the quantity of energy is the same before and after a conversion, the quality of the energy is different. This characteristic of energy is described by the second law of thermodynamics, which states that with each energy conversion from one form to another, some of the energy after a conversion becomes unavailable for further use.

To solve the energy conversion problem for lighting your home, it will also help to learn more about the conversion device – the light bulb itself. Many home still use incandescent light bulbs for lighting. An incandescent light bulb has a thin wire filament mounted inside it. When the bulb is turned on, an electrical current passes through the filament, heating it up so much that it emits light. In terms of the $100 used to light your home, $95 goes toward heating the filament while $5 goes to emitting light. The thermal energy (heat) that is produced by the light bulb is eventually dispersed to the surroundings. This dispersed thermal energy is often called waste heat, because it is very difficult to use this energy to do additional work later on.

Using and losing $95 to waste heat rather than to light the bulb doesn't sound very efficient. In terms of energy use, the word efficiency describes how much of a given amount of energy can be converted from one form to another useful form. Because all energy conversion devices and technologies must comply with the second law of thermodynamics, none will ever perform with 100 percent efficiency. In fact, most conversion technologies have efficiencies that are less than 50 percent. An incandescent light bulb producing $5 worth of light from $100 of electricity yields an efficiency of 5 percent, which makes it an inefficient device for converting electricity into light.

The efficiency of the light bulb is further compromised by energy conversion processes associated with producing and transmitting the electricity to the light bulb. The energy resource most used to produce electricity in Wisconsin is coal. A number of steps are required to convert the chemical energy in coal into electricity (see ***Generating Electricity from Coal***) as it is not possible to convert the energy in coal directly into electricity. Each of these steps in the coal-fired electrical system involves an energy conversion that varies in efficiency, with energy being lost along the way as waste heat, sound, and other forms. The total efficiency of the whole process is called the system efficiency, which is equal to the product of the efficiencies of each individual step.

After going through various energy conversion processes, only about 26 percent of the energy stored in coal is available as electricity when it reaches homes. Household items such as televisions, washing machines, and light bulbs then convert the electricity they receive into other forms of energy (light, motion, heat, etc.). When these items are added to the electrical system, the overall efficiency of this system is reduced even further. For example, an incandescent light bulb with 5 percent efficiency adds a step in to the coal-to-electricity-to-light energy system and reduces this systems' efficiency from 26 percent to 1.3 percent (0.26 X 0.05 = 0.013 = 1.3 percent).

A coal-to-electricity-to-light system efficiency of only one percent is low, but it is an improvement over the efficiency of earlier electrical systems. For example, the average efficiency of power plants has risen from 3.6 percent in 1900 to about 33 percent today. Scientists and engineers continue to develop new technologies to make power plants and electrical transmission systems more efficient than they are today.

Technological advances have also increased the efficiency of light bulbs. Compact fluorescent light bulbs with efficiencies that are 3 to 4 times greater than incandescent bulbs were introduced in the 1980s. More recently, LED (Light Emitting Diode) light bulbs have become commercially available and are replacing both incandescent and compact fluorescent light bulbs. Instead of using an electric current to heat thin filaments, LED light bulbs use light emitting diodes made from semiconductor material to produce light that is similar in brightness and color to an incandescent light bulb. Even though they emit the same amount of light, a 12-watt LED light bulb feels cooler than a 60-watt incandescent light bulb. This is because the LED bulb converts more electrical energy into light and less into waste heat. LED light bulbs have efficiencies in the range of 25 percent, making them about five time more efficient than incandescent light bulbs.

Therefore individuals can make noteworthy contributions to the efficiency of the whole energy conversion system, even though they are at the "endpoint" of that system. For example, using LED bulbs would raise the overall efficiency of a coal-fired electrical system from 1.3 percent to 6.5 percent. This may not seem like much of an improvement, but the cumulative results of many people doing this are significant. If every household in Wisconsin replaced one 60-watt incandescent light bulb with a 12-watt LED bulb, enough electricity would be saved that a 600-megawatt coal-fired power plant could be retired.

Installing efficient light bulbs is just one action people can take to improve system efficiency. Efficient electrical appliances, such as air conditioners and refrigerators, are available and are becoming more affordable. Look for the ENERGY STAR® labels the government uses to identify energy efficient appliances. These energy efficient technologies allow individuals to do their part to improve the efficiency of how energy is delivered by electric utilities and how it is used by its customers.

Procedure

Orientation

Draw students' attention to the incandescent and compact fluorescent lights. Have students describe the main energy conversion they see. They should note that electrical energy is being converted to light energy. They may also know that heat energy is being generated. Ask students which bulb they think is more efficient; that is, which is better at converting electrical energy to the desired light energy rather than to heat. Note their answers.

Steps

1. Ask students to describe where the energy to light a light bulb comes from. If they say electricity, ask them where their electricity comes from. Tell students that most of the energy for electricity generation in Wisconsin comes from burning coal (about 56 percent). Mention that energy is stored in the chemical bonds of coal.

2. Show students the basic steps in the conversion of the chemical energy in coal into electrical energy (see ***Generating Electricity from Coal***). Have students interpret what is happening at each step and identify reasons why 100 percent of the energy is not transformed from one stage of the process to another (second law of thermodynamics).

3. Demonstrate how to calculate the system efficiency (see ***Calculating System Efficiencies***) and work with students to figure out the system efficiency for converting chemical energy within coal to light energy.

4. Tell students they are going to simulate what happens to the chemical energy in coal as it is converted from one form to another during the electrical generation process. Review the ***Steps of the Relay Simulating Energy Conversion Process*** and what each step represents. Emphasize that throughout the simulation, the water represents the energy within coal (and electricity and light) and not the coal itself.

   Therefore, when water is spilled or not completely transferred from one stage of the relay to the next it means that energy was either lost as waste heat during the process or used to complete an energy conversion.

5. Divide the class into teams of eight students. Extra students can serve as time keepers or as "Law Enforcement" (see **Step 7**), or they can be added to the "transmission line" step of the relay. If there are too few students, reduce the number of students in the transmission line or have the relay be a demonstration where one group of students illustrates the process and the rest of the class provides comment.

6. Take the class to the large playing area and have the teams line up in different places. Make sure the distance between each of the team members is correct and that the containers and cups are distributed to the appropriate team members.

7. Share the following information with students before starting the game:

- The teams are racing each other.
- There are two ways to win: To be the first to finish and to be the team that ends up with the most water in their cup. The water in the cup represents light energy.
- The time keepers record how long it takes for the teams to complete the relay and which was fastest. An alternative is to allot time limits to each part of the relay and the time keeper can make sure team players do not stay too long on each task.
- While students should not try to spill water unnecessarily, they should also avoid being too careful (for example, blocking the holes in the containers is not allowed). Students representing "Law Enforcement" can make sure the second law of thermodynamics is obeyed. For example, they can interrupt the careful team and pour out some of their water. (The poured water represents either the energy used to mine and transport coal or a kind of "heat tax" that must be "paid" in order for an energy conversion to occur.)

8. Begin the relay. Note when the first team has completed passing all the "energy" (water) through the relay. After all the teams are finished, note which of the teams had the most water in their cup.

Closure

Discuss the results of the relay and what spilling water represented. Review how energy is used in each conversion process or transfer and mention that many energy transfers and conversions are inefficient. Discuss how the system could realistically be made more efficient and how the game could be adjusted to illustrate these efforts.

Emphasize realism, because students could try to transport water carefully, but even in this process they are using energy, which could be represented as a mandatory loss of water.

Point out that the last stage of the relay represents an incandescent light bulb, which converts only five percent of the electrical energy it receives into light. Provide students with information about the LED light bulb and how it is designed to be more efficient. How could they adjust the relay to simulate an LED light bulb that can convert 25 percent of the electrical energy it receives into light?

Assessment

Formative

- Can students describe the steps needed to convert the chemical energy in coal to light energy?
- Are students able to provide examples that explain why each step is not 100 percent efficient?

Summative

Ask students to identify how individuals can help improve system efficiency (students should mention actions such as using energy-efficient appliances). Have students develop a one-page advertisement for an energy efficient appliance.

Related KEEP Activities

Conducting "Station Break" prior to this activity would help students classify common energy conversions in their lives. Having students participate in "Digging for Coal" also enhances their understanding of efficiency and environmental issues associated with energy resource development. Students may need an overview of how electricity gets to their homes; see "Where Does It Get Its Energy?" Extend "Diminishing Returns" by having students complete exercises found in 6–12 Energy Sparks for Theme I: "The Laws of Thermo-dynamics." Use the surveys in "At Watt Rate" and "The Cost of Using Energy," along with the activities "Reading Utility Bills" and "Reading Utility Meters," to enhance students' appreciation of how much electricity they use and how much it costs to use it. Many ideas for increasing energy efficiency are found in Action Ideas: "Energy Efficiency Measures" in the Energy Sparks section. Another possible extension is found in 6–12 Energy Sparks for Theme II: "Make a Light Bulb."

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Generating Electricity from Coal

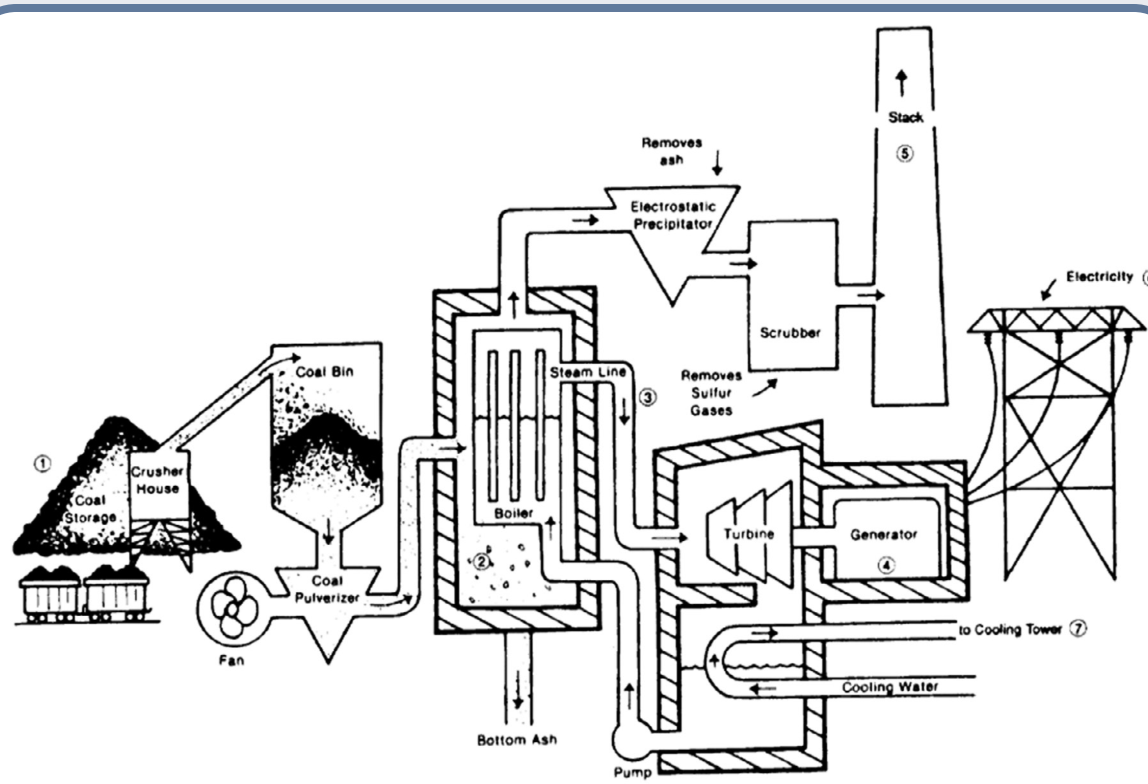
Let's examine a system for lighting an incandescent light bulb, using energy that originally comes from coal.

The coal that is mined contains a certain amount of energy. But energy was used to mine the coal, which must be counted as part of the input. After being washed and sorted, the coal must next be transported to the power plant. It takes energy to transport coal. This energy use must be added to the input side of the ledger.

Coal (1) (the numbers refer to the related sections of the figure below) is burned in the furnace (2) at the electric power plant. The steam (3) turns a turbine that turns the generator (4). Each of these conversion steps has its own efficiency. In the end, only about one-third of the energy of the coal entering the plant is converted to electrical energy (6). The other two-thirds is wasted as heat. It goes up the stack (5) with the hot exhaust gases or into the cooling tower (7).

The electrical energy must now be transported over high-voltage transmission lines and a lower-voltage distribution system. As the energy flows through transformers (to step the voltage up or down), it heats up the conductors and disappears into the surroundings. Therefore, energy is lost during transmission.

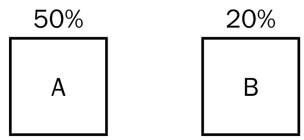
The remaining energy now arrives at the lamp. At this point, most of the energy is lost in the process of heating the filament in the incandescent light bulb. Only five percent of the energy entering the light bulb is actually converted to visible light. This illuminating energy is finally absorbed by some object within the room and converted into heat.



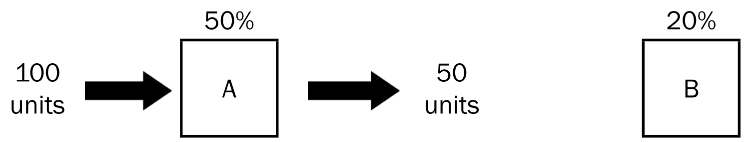
Source: National Coal Association

Calculating System Efficiencies

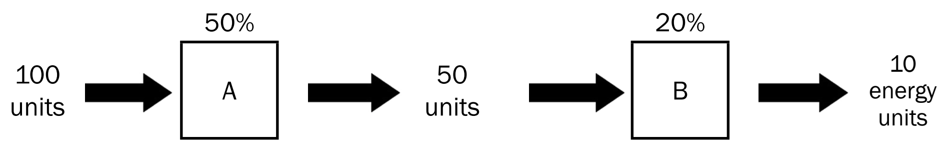
Imagine a system that has only two components. Component A has an efficiency of 50 percent and component B has an efficiency of 20 percent. Make a drawing like this on the board.



Suppose we put in 100 units of energy. How many units of useful energy will we get out of A?
Answer: 50 percent of 100 units = 50 units



So, we have 50 units we can put into B. How many units of useful energy will we get out of B?
Answer: 20 percent of 50 energy units = 10 energy units



What is the efficiency of the whole system?

Answer: $\frac{\text{energy out}}{\text{energy in}} = \frac{\text{10 units}}{\text{100 units}} = $ 10 percent

Is there a way of calculating the system efficiency without calculating what's left after each step? Some students may perceive that there is. If not, point out that multiplying the efficiencies of all components gives the system efficiency:

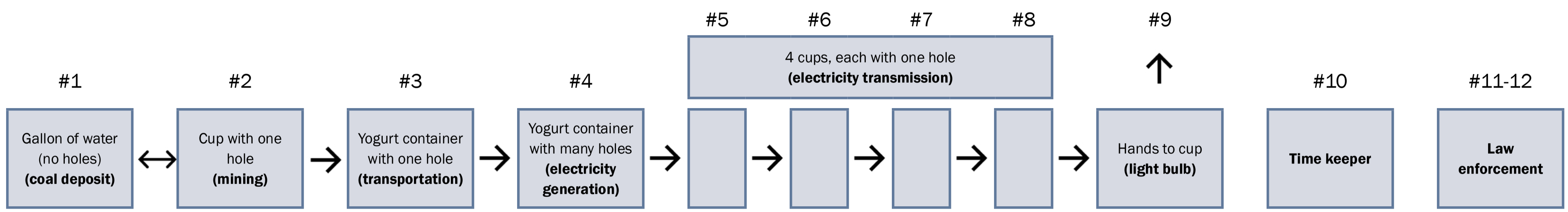
Answer: 50 % × 20 % = 10%

Therefore, for the system efficiency for converting chemical energy in coal to light energy is as follows:

Mining		Transportation		Electrical Generation		Transmission		Lighting		
96%	x	97%	x	33%	x	85%	x	5%	=	1.3%

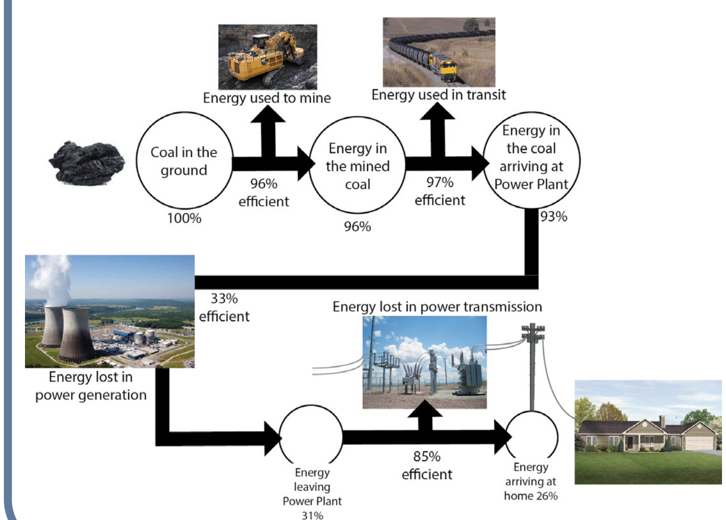
Steps of the Relay Simulating Energy Conversion Process

The chart ***Converting Chemical Energy to Light Energy*** explains how students can simulate the chemical energy to light energy conversion process. The last three columns focus on the conversion process and the efficiency of each step. An explanation of what contributes to the inefficiency is found in the parentheses. The location of the students during the relay is diagrammed below (distances between students will depend on size of playing area; start with about six feet between all students except the ones in the transmission line who should be about an arm's length apart). To accurately represent the energy used or lost as heat during the steps, encourage students to be hasty during the relay so that they do spill water.



1. Student #1, representing a coal deposit, has a gallon of water with no holes.
2. Student #2, representing mining, transfers one cup of water (with a hole in the bottom) at a time from the gallon of water to the yogurt container with one hole, which represents transportation.
3. Student #3, representing transportation, transfers water from the yogurt container with one hole to the yogurt container with holes covering a third of its bottom, which represents electricity generation.
4. Student #4, representing electricity generation, holds the yogurt container with many holes.
5. Students #5-8 stand in a row to represent a power line (electricity transmission). Each student has a cup with a hole in the bottom. Transmission is demonstrated by the first student receiving a cup of water and pouring the water into the next student's cup who passes it down the line. The first student refills their cup when it is emptied and continues the process until the water runs out or the relay is complete. Each student can only use one hand.
6. Student #9, representing the light bulb, cups their hands to receive water and pours it into a paper cup (without a hole in the bottom). The relay is done when the cup is filled or when the water supply runs out.
7. Student #10 is the Time Keeper, who records how long it takes the team to fill the cup.
8. Students #11-12, representing Law Enforcement, make sure teams are not being too careful.

The Efficiency of Electric Power Delivery Systems



Converting Chemical Energy to Light Energy

Location of energy	Represented by	Energy content	Steps in the conversion process	Efficiency	Steps of the relay simulating energy conversion process
In the chemical bonds of coal in the ground	Bowl of water in gallon container at one end of the relay field	100% energy in coal	Coal is mined out of the ground. (Energy is needed for mining process.)	96%	The student representing the miner takes water one cupful at a time to the yogurt container with one hole in the bottom, which represents a train car.
In the chemical bonds of coal in trains	Water in the yogurt container with a small hole in the bottom	96% of original energy in coal	Coal is transported to the plant. (Energy is needed by trains to carry the coal.)	97%	A second student carries the yogurt container to the power plant and pours water into the yogurt container that has holes covering one-third of its bottom.
In the chemical bonds of coal that arrives at the power plant	Water in the yogurt container with many holes	93% of original energy in coal	Coal is processed and burned at the power plant. Burning is used to boil water that creates steam which turns a turbine and generates electricity. (Large amount of excess heat energy from steam, friction, etc. is released.)	33%	A third student holds the yogurt container and spins around in a circle.
In the electricity generated by power plant	Remaining water in the container	31% of original energy in coal	Electricity is transmitted to homes through power lines. (Energy is used to overcome resistance and is lost as heat.)	85%	A row of students pass cups of water to each other one at a time (each cup has a small hole in the bottom. The last student pours water into the cupped hands of the "light bulb" student.
In the electricity traveling to lam with incandescent light bulb	Water in student's cupped hands	26% of original energy in coal	The electricity passes through the filaments in an incandescent light bulb. (Most of the energy is used to heat the filaments that generate light.	5%	A final student transfers that water from his or her cupped hands into the paper cup (with no hole in the bottom).
In the light energy being emitted from the light bulb	Water in the final cup	1.3% of original energy in coal			