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AP® Environmental Science

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Professional Development
Workshop Materials

Special Focus:
Energy and Climate Change

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Special Focus: Energy and Climate Change

Important Note: The following set of materials is organized around a particular theme, or "special focus," that reflects important topics in the AP Environmental Science course. The materials are intended to provide teachers with resources and classroom ideas relating to these topics. The special focus, as well as the specific content of the materials, cannot and should not be taken as an indication that a particular topic will appear on the AP Exam.

Introduction

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An AP Environmental Science course includes the scientific study of topics that have daily relevance in the lives of students. Newspapers and magazines frequently report on the same environmental issues that AP Environmental Science students are discussing in class. An AP Environmental Science course should provide students with the scientific and intellectual tools required to critically evaluate the reports about the environment they encounter in the media. It is important that an AP Environmental Science course be dynamic—changing to reflect the most recent findings of the science that composes its curriculum.

One environmental issue which has been the subject of much recent attention in the media is global climate change. The considerations above, along with the magnitude of the problem, contributed to the choice of energy and climate change as the theme of these materials. The objective is to provide AP Environmental Science teachers with resources they can use to supplement the units they teach on energy and climate change. The articles include activities that students can use to evaluate their personal energy consumption, to compare alternative energy sources, to analyze and make connections using a systems-thinking approach to understanding climate change, to increase their understanding of the greenhouse effect, and to practice successfully converting between various energy and power units. Moreover, the materials contain thought-provoking passages that may be used to initiate class discussions on all these topics.

The importance of educating an informed citizenry alone would validate the selection of energy and climate change for special focus. The weight of these topics in the Topic Outline of the *AP Environmental Science Course Description* provides a more practical rationale. Preparing students to answer questions about energy resources and global climate change is a critical task for AP Environmental Science teachers. Over the years, the AP Environmental Science Exam has included free-response questions that tested student knowledge of nuclear and coal-fired power plants, home heating, electric vehicles, and alternate sources of energy. Furthermore, explanations of the mechanism of global warming and its consequences are often point-worthy responses to questions on the AP Exam that require students to describe or discuss the environmental consequences of a human activity. Future sets of themed materials will continue to assist teachers as they prepare their students for a lifetime of learning about the environment.

Electric Power from Sun and Wind

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Many environmental problems are related to energy consumption. A college-level environmental science survey course should include the following energy-related topics: acid mine drainage, oil spills, acid rain, global warming, nuclear waste disposal, and catastrophic flooding due to failure of water retention dams. These are just examples and one could generate a much longer list. Approximately 85 percent of the energy used by our society is generated by burning fossil fuels, and energy experts think that energy-related environmental impacts could be reduced by switching to renewable energy resources such as wind power and solar energy. In this module, we will explore the feasibility of using the sun and wind to generate a significant amount of global electric energy.

This quantitative module describes the electric energy generated by wind turbines and photovoltaic arrays. The efficiency and cost of these technologies are compared and their abilities to reduce carbon dioxide emissions are estimated.

Electric Power

About a third of the energy consumed globally is used to generate electricity. Annual consumption of electric energy equals approximately 16 trillion kWh (16×10^{12} kWh) globally, and approximately one-quarter of that energy (4.0 trillion kWh) is consumed in the United States. On average each of the 6.5 billion people on earth consumes approximately 2,500 kWh of electric energy each year. Divide this amount by the number of hours in a year (8,760) to calculate the average per capita global electric power consumption: 285 watts (roughly three 100-watt light bulbs).

Exercise 1 develops rough estimates of these figures using data from typical U.S. electric utility bills. This exercise produces good estimates if the electric bill of a four-person family is assumed to equal "$150/month" and electricity costs 10 cents per kilowatt-hour.

This exercise will help students understand the difference between energy (expressed in kilowatt-hours) and power, the rate of consuming energy (expressed in watts): power = energy / time.

Over the next 20 years, global annual electric energy consumption is projected to increase by 10 trillion kWh, and U.S. annual consumption is projected to increase by 1.5 trillion kWh. Although it is expected that most of this increased demand for electric energy will be supplied by consuming fossil fuel resources, some of this electric energy will likely be supplied by renewable energy resources.

Renewable Energy

Most electric energy is produced by fossil fuel power plants (mostly coal-burning plants) and by nuclear power plants. Approximately 17 percent of global electric power is produced by renewable energy, mostly by hydroelectric power plants. A tiny fraction (about 0.023 percent) of global electric energy is produced by other forms of renewable energy such as wind power and solar power. In the following sections, we will consider the feasibility and cost of using the sun and wind to produce electricity.

Electricity from the Wind

Wind turbines convert the kinetic energy in the wind into electric power. The overall efficiency of this conversion process is around 35 percent. Wind farms are located in areas with strong persistent winds such as the American Midwest, coastal zones, and mountain passes. A typical utility-scale wind turbine is rated at 1.5 MW, although turbines rated at 3.5 MW have become common. The rating of a turbine means that with sufficiently high wind speed, the power generated by the turbine will equal the rated power. A 1.5 MW turbine running at its rated power for 24 hours a day for a full year would produce 13 million kWh of electric energy. Because winds are variable, wind turbines run at their rated power only a fraction of the time. This fraction is called the turbine's **capacity factor**; this factor depends upon the location of the wind turbine.

Exercise 2 estimates the cost of using wind turbines to supply 10 percent of the projected 1.5 trillion kWh increase in U.S. electric energy demand over the next 20 years. Although many environmentalists would argue that the most cost-effective and environmentally responsible approach to this project would be to reduce demand through more efficient use of electricity, the $45 billion cost of the turbines spread over 20 years seems quite modest.

This exercise introduces the concept of **payback time**, the time it takes for the benefits of a project to equal its cost. This concept is important to students' understanding of the economic viability of an investment. The payback time estimated in this exercise indicates that wind power is economically practical.

Students should be introduced to the controversies involving the large-scale application of wind power technology. For example, Cape Wind, the offshore wind park proposed for the shallow water between Cape Cod and Nantucket, has supporters and opponents among environmental groups. Some groups are concerned that the project will interfere with migrating birds and harm marine ecosystems; other groups think the environmental advantages of using clean renewable energy will greatly outweigh its negative impacts.

Electricity from the Sun

Solar cells are semiconductor materials that convert sunlight directly into electricity. Practical electricity-generating devices made from solar cells are usually called photovoltaic (PV) panels. Arrays of PV panels are currently providing electricity for signal lights, remote power needs, residences, and electric utilities.

Exercise 3 estimates the cost and payback of using residential rooftop PV systems to supply 10 percent of the projected 1.5 trillion kWh increase in U.S. electric energy demand over the next 20 years.

The results of exercise 3 are interesting because they indicate that the solar energy resource is adequate to produce a substantial amount of electricity using a fraction of existing residential rooftops. On the other hand, these results also illustrate the high cost of photovoltaic power systems. Many analysts believe that substantial decreases in the cost of PV systems are needed before these systems will be used to generate significant amounts of electric energy.

Exercise 1: Electric Energy Consumption

1. What is your average monthly household electric bill? ____________________ ($/month)

2. How much do you pay for electric power? ____________________($/kWh)

3. Calculate the corresponding average monthly energy use for your household. ______ ______________________________ (kWh/month)

4. How many people are there in your household? ____________________

5. Calculate the **per capita** monthly residential electric energy use for members of your household. ____________________ (kWh/month/person)

6. Calculate the **annual** per capita residential electric energy use for members of your household. ____________________ (kWh/year/person)

7. In the U.S., residential electric energy consumption is about one-third of overall electric energy consumption. Calculate the annual per capita **total** electric energy consumption by members of your household. ____________________ (kWh/year/person)

8. Assuming this per capita energy use is average, calculate the **U.S. annual total** electric energy consumption. ____________________ (trillion kWh/year)

9. The U.S. consumes about 25 percent of global electric power. Estimate **global annual** total electric energy consumption. ____________________ (trillion kWh /year)

10. Calculate the global annual **per capita** total electric energy consumption. __________ ______________________________ (kWh/year/person)

11. Compare your calculated global annual **per capita** total electric energy consumption value to your calculated U.S. annual **per capita** total electric energy consumption value.

Exercise 2: Windpower

Consider a wind turbine that is rated at 1.5 MW. This means that with sufficiently high winds, it will produce 1.5 MW or 1,500 kW of power. The installed cost of this turbine is $1.5 million.

1. If this turbine runs at its rated power 100 percent of the time for a full year, how much energy would it produce in a year? ______________________ (million kWh/year)

2. This wind turbine has a **capacity factor** equal to 0.38. This means that over a year, it will produce only 38 percent of its theoretical maximum energy production. How much energy does this turbine actually produce in a year? ______________________ ______________________ (million kWh/year)

3. Over the next 20 years, U.S. annual electric energy consumption is projected to increase by 1.5 trillion kWh/year. How many 1.5 MW wind turbines would be needed to supply 10 percent of this additional energy? ______________________

4. Calculate the cost of installing these wind turbines. ______________________ ______________________ ($)

5. Assuming the electric energy produced by these turbines is worth 5 cents per kilowatt-hour, these turbines would generate electric energy worth $7.5 billion per year. Calculate the simple payback period for these turbines. (Payback period is the time it takes for a system's net benefits to equal its cost.) ______________________ ______________________ (years)

Exercise 3: Photovoltaic Power

A grid-connected residential PV system is placed on the roof of a 2,000-square-foot suburban house. The PV array with an area equal to 50 square meters (about 500 square feet) covers half of the south-facing part of the roof. The power rating of this PV system is 5.0 kW, meaning that it will produce 5.0 kW under peak sunlight conditions. The installed cost of this system is $50,000.

1. The PV system is operating in a location where the annual average daily incident solar energy (the insolation) on the array equals 5.0 kWh/m^2/day. Calculate the average amount of solar energy incident on the PV array each day. ________________ ________________________________ (kWh/day)

2. The efficiency of the PV system equals 10 percent (that is, 10 percent of the solar energy incident on the array is transformed into useful electric power). Calculate the daily average electric energy produced by this system. ____________________________ _____________ (kWh/day)

3. Calculate the average amount of electric energy produced by this system each year. ____ (kWh/year)

4. Over the next 20 years, U.S. annual electric energy consumption is projected to increase by 1.5 trillion kWh/year. How many rooftop PV systems would be needed to supply 10 percent of this additional energy? ____________________________________

5. Calculate the cost of installing these residential PV systems. ______________________ _________________________ ($)

6. Assuming the electric energy produced by these PV systems is worth 10 cents per kilowatt-hour, these residential systems would generate electric energy worth $15 billion/year. Calculate the simple payback period for these PV systems. (Payback period is the time it takes for a system's net benefits to equal its cost.) _____ ____ (years)

Key to Exercise 1: Electric Energy Consumption

Sample answers (based on an electric bill of $150/month) appear in bold.

1. What is your average monthly household electric bill? **$150**

2. How much do you pay for electric power? **$0.10/kWh**

3. Calculate the corresponding average monthly energy use for your household.
   $150 / $0.10/kWh = 1,500 kWh

4. How many people are there in your household? **4**

5. Calculate the **per capita** monthly residential electric energy use for members of your household. **1,500 kWh / 4 = 375 kWh/month/person**

6. Calculate the **annual** per capita residential electric energy use for members of your household: **12 × 375 kWh = 4,500 kWh/year/person**

7. In the U.S., residential electric energy consumption is about one-third of overall electric energy consumption. Calculate the annual per capita **total** electric energy consumption by members of your household.
   3 × 4,500 kWh = 13,500 kWh/year/person

8. Assuming this per capita energy use is average, calculate the **U.S. annual total** electric energy consumption. **298 million × 13,500 kWh = 4.0 trillion kWh/year**

9. The U.S. consumes about one-fourth of global electric power. Estimate **global annual** total electric energy consumption. **4 × 4.0 trillion kWh = 16 trillion kWh/year**

10. Calculate the global annual **per capita** total electric energy consumption.
    16 trillion kWh / 6.5 billion = 2,500 kWh/year/person

11. Compare your calculated global annual **per capita** total electric energy consumption value to your calculated U.S. annual **per capita** total electric energy consumption value. **U.S.: 13,500 kWh/year/person → 13,500 kWh / 8,760 h = 1,540 W/person**
    Global: 2,500 kWh/year/person → 2,500 kWh / 8,760 h = 285 W/person
    Global value is about one-fifth the U.S. value.

Key to Exercise 2: Windpower

(Answers appear in bold.)

1. If this turbine runs at its rated power 100 percent of the time for a full year, how much energy would it produce in a year?
   1,500 kW × 8,760 h/year = 13 million kWh/year

2. This wind turbine has a capacity factor equal to 0.38. This means that over a year, it will produce only 38 percent of its theoretical maximum energy production. How much energy does this turbine actually produce in a year?
   0.38 × 13 million kWh/year = 5.0 million kWh/year

3. Over the next 20 years, U.S. annual electric energy consumption is projected to increase by 1.5 trillion kWh/year. How many 1.5 MW wind turbines would be needed to supply 10 percent of this additional energy?
   0.10 × 1.5 trillion kWh/year / 5.0 million kWh/year/turbine = 30,000 turbines

4. Calculate the cost of installing these wind turbines.
   30,000 turbines × $1.5 million/turbine = $45 billion

5. Assuming the electric energy produced by these turbines is worth 5 cents per kilowatt-hour, these turbines would generate electric energy worth $7.5 billion per year. Calculate the simple payback period for these turbines. (Payback period is the time it takes for a system's net benefits to equal its cost.)
   $45 billion / $7.5 billion/year = 6 years

Key to Exercise 3: Photovoltaic Power

(Answers appear in bold.)

1. The PV system is operating in a location where the annual average daily incident solar energy (the insolation) on the array equals 5.0 kWh/m^2/day. Calculate the average amount of solar energy incident on the PV array each day.
   50 m^2 × 5.0 kWh/m^2/day = 250 kWh/day

2. The efficiency of the PV system equals 10 percent (that is, 10 percent of the solar energy incident on the array is transformed into useful electric power). Calculate the daily average electric energy produced by this system.
   0.10 × 250 kWh/day = 25 kWh/day

3. Calculate the average amount of electric energy produced by this system each year.
   365 days/year × 25 kWh/day = 9,125 kWh/year

4. Over the next 20 years, U.S. annual electric energy consumption is projected to increase by 1.5 trillion kWh/year. How many rooftop PV systems would be needed to supply 10 percent of this additional energy?
   0.10 × 1.5 trillion kWh/year / 9,125 kWh/year = 16 million

5. Calculate the cost of installing these residential PV systems.
   16 million × $50,000 = $800 billion

6. Assuming the electric energy produced by these PV systems is worth 10 cents per kWh, these residential systems would generate electric energy worth produce $15 billion/year. Calculate the simple payback period for these PV systems. (Payback period is the time it takes for a system's net benefits to equal its cost.)
   $800 billion / $15 billion/year = 50 years

Understanding Climate Change and Our Rivers and Lakes: Systems Thinking

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Note to Teachers

The following exercise on global climate change should help your students think about the "big picture," how a phenomenon that affects an ecosystem in a particular way may trigger a series of events that impacts many other parts of the ecosystem. Some environmental issues are properly thought of in a more limited context; for example, the effects of a sewage discharge on a small lake may be mostly confined to that ecosystem.

Global climate change, however, will not only affect many different portions of ecosystems: an impact on one component may ripple through the entire system. In this example, students will learn how a changing climate have many different direct and indirect effects on both terrestrial and aquatic parts of ecosystems. Once the students have worked through this exercise, you might encourage them to examine other environmental issues—such as acidic deposition and ozone depletion—to identify the connections and examine the "big picture."

Exploring Causes and Effects in Environmental Science

In many issues environmental scientists face, it's all about the connections—how events in one place end up causing problems in places far away. Systems thinking requires us to consider the "big picture."

For example, we now know that the impacts of acid deposition on sensitive ecosystems may result from actions many kilometers upwind. Gases released into the atmosphere from midwestern smokestacks cause part of the northeast's acid deposition problem. In this case, the "system" extends from the smokestack in Ohio to the lake in the Adirondacks ultimately acidified by atmospheric inputs.

There are few better examples of environmental complexity and the need for a systems approach than climate change. Because of the connections between the landscape and water, our rivers and lakes are particularly vulnerable in a changing climate.

Special Focus: Energy and Climate Change

The casual observer, when asked how climate change will affect lakes and rivers in the future, might reply, "Well, they'll warm up a bit and maybe they'll dry up." In fact, while one outcome of a warmer climate may be lower water levels in our lakes and rivers, the story is much more complicated than that. Let's think about the system and the connections.

Suppose you've been hired by your state's environmental protection agency, and your first assignment is to evaluate what climate change is going to do to one of the state's premier brook trout streams, Johnson's Run. The stream originates in the foothills and travels through pristine forests before discharging into Joe's Pond, a small lake that supports a population of rainbow trout.

Your first reaction is to breathe a sigh of relief: what an easy first task! You go to the library and discover that the upper temperature limit for both trout species is about 25°C. Data from the state agency indicate that the temperature of Johnson's Run never rises above 18°C in the summer and that of Joe's Pond, never above 19°C. Even with the predicted 2°C increase in water temperature expected in your state by 2100, you conclude that the trout should be fine; they'll be well within their temperature tolerance limit.

You tell this to your boss, but she isn't satisfied. She starts yelling, "You're forgetting about the connections! Yes, you got the most obvious direct effect—but think like a watershed, think about the connections."

She sits you down and goes over a few of the basics of streams and lakes. She tells you to think of streams as water highways. Coarse particulate organic matter (CPOM) like leaves and other vegetation is carried into the stream during wet weather. After being broken down in the stream, this material serves as the energy source for the stream's food web. If something disrupts this flow of matter, the entire food web of the stream, including the benthic invertebrates and the fish, may suffer.

Also remember the stream's role as a conduit. Johnson's Run is an artery for transferring materials from the watershed into Joe's Pond. Anything that disrupts the stream's energy dynamics may, in turn, affect the pond. While state regulators usually try to reduce the amount of limiting nutrients like phosphorus released into systems like Joe's Pond from streams like Johnson's Run, remember that vital elements like calcium and carbon also move into the pond in this manner. Altering the normal flow of these elements may have serious consequences downstream.

If streams are nature's highways, lakes and ponds are its sinks. What enters a lake from the atmosphere and, more importantly for most lakes, from its tributaries has a substantial effect on the lake and may determine whether it has good or bad water quality. Some systems, like Lake Tahoe in California and Nevada, are very deep and tend to trap entering materials for very long periods, while others—shallow reservoirs, for example—may flush entering materials out very quickly. So the exact role of any molecule of a nutrient entering a lake will depend on the characteristics of that lake.

What's key to remember are the connections: watershed to stream and stream to lake. It's all one unit. If climate change affects any part of the system, it may affect everything else.

Now let's take a harder look at some of the challenges that those trout may face in future decades.

Brook Trout in Johnson's Run

1. **Food:** Even if the adult trout are able to survive in a warmer Johnson's Run and can successfully spawn during the expected warmer winters and springs, what are those trout going to eat? Can the benthic macroinvertebrates like immature stoneflies and mayflies they rely on for food also survive as the temperatures increase? Will the numbers of other, less desirable, species increase and crowd out the favored species in the trouts' diet?

   Also, with climate change, there may be less rainfall throughout the watershed. Less rainfall means less CPOM washing into the stream to support those benthic macroinvertebrates so important to the trout. Remember that if one part of the stream's food web is compromised, harmful effects may reverberate throughout the web.

2. **Stream conditions:** Many small streams rely on groundwater recharge to maintain minimum flows during dry summer months. With climate change, there may be less recharge occurring during those crucial dry periods and some streams may dry up, threatening all stream life, including the trout.

   Another factor to ponder is the fate of those tall leafy trees that shade the stream from the hot summer sun. As these canopy species decline or disappear with the warming climate, the water in the stream may be heated further from greater exposure to the sun.

3. **Unwelcome invaders:** With warmer temperatures, new species may appear in Johnson's Run. Invasive fish species will move north as streams become warm enough to support them, and they may outcompete the trout, threatening them with extinction. Also, fungal and bacterial diseases will become an increasing risk to the trout population as stream temperatures warm and become more hospitable to the growth of some pathogens.

Rainbow Trout in Joe's Pond

As messy as the situation is in Johnson's Run, it's even more challenging in Joe's Pond. Consider these possibilities.

1. **Physical conditions:** As the pond's waters warm during the summer, the upper layer, or epilimnion, will extend deeper into the lake and force the rainbow trout into the ever-shrinking cool bottom layer, the hypolimnion. Since warmer pond temperatures may increase bacterial decomposition of organic matter in these deeper waters, reduced levels of dissolved oxygen may pose an additional threat to the trout, and they may disappear as they literally run out of room to survive.

   In addition, if there is a reduced volume of water coming into the lake from Johnson's Run, fewer materials such as dissolved organic carbon (DOC) from decomposing vegetation will be carried into the lake. DOC is responsible for filtering out ultraviolet (UV) radiation in lakes. With less DOC, the trout will be exposed to higher levels of UV radiation, particularly given the phenomenon of ozone thinning that you've learned about. Their reproductive capacity may be reduced, and they might even be at higher risk of developing skin tumors.

2. **Food web problems:** As Joe's Pond warms up, the circulation of its waters, a critical mechanism for distributing key nutrients throughout the water column, will probably be reduced, resulting in fewer nutrients being made available to the base of the pond's food web and a subsequent reduced productivity of the phyto- and zooplankton populations. Fewer plankton means less food, particularly for the young rainbow trout. With less energy available to the trout population, less reproduction and reduced growth rates may be expected in any surviving fish.

3. **Toxic substances:** Warmer temperatures may even change the dynamics of toxic substances like mercury in Joe's Pond. While there are no point-source discharges of this highly toxic element into the pond, transport from distant sources like fossil

fuel–burning power plants and deposition onto the pond and its watershed may result in elevated concentrations in the pond's sediments.

The increased bacterial activity that will accompany warmer lake temperatures may convert more inorganic mercury in the pond's sediments to methylmercury, a highly bioavailable and toxic form, posing an additional threat to the trout.

As if all this isn't enough to ponder, consider this. You're going to have to look at each watershed in the state individually to determine the potential impacts of climate change. Factors that often vary among watersheds, like particle size and the nutrient content of soils, types of vegetation, and the role that groundwater plays in keeping streams running during dry periods, will play crucial roles in determining how much any particular stream or lake will be affected by climate change.

What's more, you're probably going to have to reevaluate Johnson's Run because it will change from year to year. Remember, climate change may produce weather extremes; some years will be very wet and others very dry. What happens to the brook during drought conditions may be very different from what happens during wet years.
For example, if flash flooding begins to increase in severity with heavier summer thunderstorms, you may have to worry about bank erosion moving substantial amounts of sediments downstream into Joe's Pond. This might cause a very different set of problems for those rainbows.

The bottom line is that climate change will have a host of effects on our rivers and lakes and that these effects will likely be highly variable and perhaps difficult to predict. Some of the changes will be direct, but many will occur because of events occurring elsewhere in the watershed. The trick is to understand the connections that link all our rivers and lakes to the landscapes around them.

Note to Teachers

Below are some exercises and questions that I use with my students when teaching this "systems thinking" lesson.

Additional Exercises

1. Imagine you have a similar job on the Great Lakes. Considering all the connections, list the possible impacts of climate change on the Great Lakes ecosystem. Give specific examples of likely impacts. Be sure to include at least the perspectives of

the following people: a fisheries manager, a water supply superintendent, and a public health official.

2. One of the crucial steps in combating climate change is a reduction in the release of greenhouse gases like carbon dioxide. There is a lot of talk now about how much CO_2 is released by both traditional energy sources (coal, oil, nuclear) and renewable sources like wind and solar. For example, advocates of nuclear power correctly claim that its operation releases no CO_2. But that's only part of the story. What about the mining of the uranium? The transport of waste material? A life-cycle assessment can be used to evaluate the entire process, from the beginning of the cycle, when a fuel is mined or a wind turbine manufactured, to the end of the cycle, when the plant is torn down and disposed of. Do a life-cycle comparison for nuclear, coal, and wind power in terms of carbon dioxide. Be sure to list all the steps in the cycle that might lead to the release of CO_2 and affect how much of the gas is released. What do you conclude from your life-cycle assessment?

Questions

1. Why is it important to consider the "connections" when assessing the potential effects of climate change on watersheds? Give a specific example.
2. How might humans living in the watershed be affected by some of the potential changes we identified for Johnson's Run and Joe's Pond?
3. Identify one specific effect that climate change might have on the food web of Johnson's Run. Do the same for Joe's Pond.
4. How do the differences in the physical properties of Johnson's Run and Joe's Pond influence the impact that climate change might have on each system? List at least two examples for each system.
5. Why is it likely to be difficult to predict the effects that climate change might have on a particular watershed?
6. Which system, Johnson's Run or Joe's Pond, do you think will suffer most from climate change? Why? What additional information might make it easier for you to answer this question?
7. What's the possible connection between climate change and the behavior of mercury in lakes?

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Special Focus: Energy and Climate Change

Energy Balance as a Basis for the Greenhouse Effect and Global Warming

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Preface for the Teacher

This article describes the greenhouse effect from a physical science perspective and is somewhat more analytically detailed than what is generally given in introductory environmental science texts. It can give you (and your students) a fuller and more complete understanding of both the greenhouse effect and global warming. You can use the material as background for lectures or supplementary reading for students to enhance textbook assignments and stimulate classroom discussion. The questions at the end of the piece can help you assess students' comprehension of the subject, as part of either an in-class dialogue or a written test.

If you use the article for lectures only, it is recommended that you begin with a discussion of temperature and heat and the various means of heat transfer. Students should understand that radiation is the only way for the Earth to receive energy from and release it to outer space. Discuss the concept of thermal equilibrium, emphasizing the balances between energy input and output that are needed to maintain constant temperature for a given system. A good analogy in this respect is to discuss how to keep the water level constant in a leaky bucket by matching inflow with outflow. Finally, you should copy the energy distribution diagram provided in this article and use it to explain the distribution of radiative energy within the Earth's atmosphere. Have students check for energy balance by adding the numbers for input and output at each level—top, middle, and bottom of the atmosphere. This diagram is key to understanding the greenhouse effect and can be used to explain global warming through disturbance of the energy flows shown. This should stimulate a discussion of the potential causes of energy imbalances, whether such imbalances already exist, when we might realize it, and what might be done to mitigate the effects of global warming.

Although climate modeling and greenhouse gases are mentioned below, these topics are not discussed in detail. In class, you should note the nature of the solar spectrum—combining ultraviolet, visible, and infrared radiation—highlighting infrared as the wavelength range that is primarily associated with radiative heating and cooling of the Earth. You can also add the role of trace gases and the identification of the origin, concentrations, and fluxes of these gases to lead to a discussion of personal environmental responsibilities and to an examination of mitigation strategies to avert global warming.

Introduction

Although global warming is one of the key environmental topics of today, few environmental textbooks provide a satisfying scientific explanation of the phenomenon. One reason for this may be that a detailed explanation requires more science background than is typical for the introductory environmental science student. Another may be that such an explanation is not considered necessary in order to comprehend the environmental consequences of increased global temperatures. On the other hand, many critics of global warming rely on physical explanations to challenge environmental predictions. Accordingly, environmental science teachers and students need to have a thorough understanding of the phenomenon so that they can justify predictions and answer reasonable questions and criticisms.

First, it is important to distinguish between the concept of global warming and that of the greenhouse effect. The greenhouse effect is a well-known scientific phenomenon that engenders little or no controversy in the scientific community. In fact, it is well recognized that the Earth remains at a habitable temperature only because of greenhouse warming provided by the atmosphere. Without such an effect, the surface temperature would be some 60°F cooler than at present, much too low for life as we know it.

In contrast, global warming is a much more controversial and speculative phenomenon that possibly could result from increasing atmospheric concentrations of certain radiatively active trace gases. Moreover, some of the dire environmental consequences of global warming—such as rising ocean levels, coastal flooding, ecosystem shifts, crop failures, increased severe weather, floods, and droughts—are even more uncertain and depend on the accuracy of complex computer models to predict future weather and climate. Whereas implications of the greenhouse effect can be determined directly from fundamental scientific principles, environmental scenarios predicted for global warming are subject to the limitations of stochastic models which, as critics point out, cannot be relied upon to predict the weather a week in advance, let alone several decades in the future. This is not to say that the predictions of such models are incorrect, only that one should recognize that the conclusions carry with them much more scientific uncertainty than those of global warming itself. Understanding this difference in predictability is of interest to everyone but especially important for the environmental science student.

Special Focus: Energy and Climate Change

Heat and Temperature

We often refer to objects as being hot or cold or of being at a certain temperature, but we would not speak of an object as "having heat." One might say that an object has a lot of "thermal energy," referring to the internal energy associated with the random motions of the molecules composing the object, but such energy is not expressed as heat until it is externalized. In this sense, heat is analogous to work in mechanical terms. We do not speak of objects as "having a lot of work" but rather as having a certain amount of potential or kinetic energy and the ability to do work when this energy is converted from one form to another. Similarly, an object may have a lot of internal energy, but this is not expressed explicitly as heat until this energy flows from one object to another. Thus we can say that heat is thermal energy that flows from one object to another because the temperature of one is greater than the temperature of the other. If the two objects are at the same temperature, then no net heat is transferred.

Since heat is simply another form of energy, one might surmise that the units used to measure it should be the same as those of energy, for example, the **joule** in the SI system of measurement. This is indeed the case, but for historical reasons special units such as the **Btu** and the **calorie** are also used to quantify heat. Because different units are used in specific contexts, it is important to become familiar with the varied terminology and to be able to convert from one system to another.[1]

Thermal Equilibrium

Historically, heat was thought of as an invisible fluid (caloric) that permeated all matter and could be released, for example, by breaking the material apart. Although we now know that heat is not a fluid but just another form of energy, the fluid concept is still valuable because heat moves from higher temperatures to lower ones just as fluids move from higher gravitational levels to lower levels. Pascal's principle tells us that liquids "seek their own level."[2] That is, when two containers of water are connected, water will flow from the container with the higher level into the lower one until the levels are the same. Similarly, when two objects of different temperature are placed in contact, heat will flow from the one with a higher temperature to the one with the lower temperature

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[1] For additional information on energy units and conversions, see the article "An Energy Primer for the AP Environmental Science Student" by the author on page 45 of this collection.

[2] See, for example, R. A. Serway and J. S. Faughn, *College Physics*, 4th ed. (New York: Saunders College Publishing, 1995), 265.

until the temperatures are equal. In other words, a constant temperature defines when two objects are in **thermal equilibrium** just as a fixed water level determines when two containers of fluid are in gravitational equilibrium. If the temperature is constant, then no net energy is being transferred. Conversely, if no net energy is absorbed or released, then the temperature of the object will not change.

Kinetic Theory

Kinetic theory is the branch of thermodynamics that deals with the connection between the microscopic properties of matter and the macroscopic aspects of heat. A fundamental result of kinetic theory is that **the absolute temperature of a gas is directly proportional to the average translational kinetic energy of the molecules composing it.**[3] In other words, temperature is a direct measure of the energy of molecular motion. Higher temperature means increased molecular motion, and low temperature implies reduced molecular motion. Saying that object A is hotter than object B means that the average kinetic energy of molecules in object A is greater than those in object B. And the fact that temperature and kinetic energy are proportional means, for example, that if the temperature is doubled then the molecular kinetic energy is also doubled.

Heat Transfer

If two objects of different temperatures are placed in contact, we know that the cooler object warms up and the hotter one cools down. In this process, heat is transferred from the hotter object to the cooler one, thereby reducing the thermal energy of the former and increasing it for the latter. Since temperature reflects the average kinetic energy of the molecules of a substance, the molecules of the cooler material must speed up while those of the hotter one slow down. How is this accomplished? Physics recognizes only three ways for heat to be transferred: **convection**, **conduction**, and **radiation**.

Convection is the transfer of heat by the macroscopic displacement of molecules. In this case, a group of molecules actually displaces or exchanges position with others, thereby producing a change in the average molecular speed of the group and a different temperature. The exchange can produce heating or cooling depending on which group is being replaced. A baseboard radiator, for instance, is able to heat an entire room because the heated layer of air near the floor rises and is replaced by cooler air which, in turn, is

[3] For example, see Serway and Faughn, *College Physics*, 313.

heated, and so on. The resulting convection currents allow the heated air to move to all parts of the room. Convection applies to gases and fluids but clearly cannot be a means of transferring heat between solid objects whose molecules remain fixed in one location. **Conduction** is the process whereby heat is transferred within or between objects without need for macroscopic displacement of the molecules. In this case, the thermal energy moves, but the molecules of the material do not. When one end of a metal rod is placed in a flame, for example, the entire rod soon becomes hot. Heat is conducted from one end to the other, even though the molecules of the metal remain fixed. This is accomplished by transferring vibrational energy from one molecule to the next down the line, like shaking one end of a beaded elastic string. In materials like glass, this transfer is not very efficient, but in others like copper it can be very effective. In general, materials that are good conductors of electricity are also good conductors of heat. The reason for this is in the electronic structure of these materials. In conductors, many electrons are not bound closely with individual atoms but rather are free to roam about. In fact, these electrons act cooperatively and can even sustain waves on their own. And they can transfer vibrational energy or heat quickly from one location to another in the solid.

Heat transfer processes can and often do take place simultaneously. When a pan of water is heated on a stove, for instance, heat is transferred by conduction from the pan to water molecules in the bottom layer of liquid. As this layer warms, it expands and rises and is replaced by a denser, cooler layer from above. That is, heat is transferred into the water from the pan by **conduction** but is transferred throughout the fluid largely by **convection**.

Radiation is the direct transfer of energy from one object to another without the need for any material in between. Solar energy is received and warms the Earth, for instance, even though the space between the Earth and the sun is virtually empty. A fireplace or campfire warms mainly by direct radiation. This is why you can be hot on one side and cold on the other when standing in front of a fire or space heater.

Equilibrium Temperature for the Earth

What does this discussion have to do with the greenhouse effect and global warming? For that matter, what does it mean when one refers to "the" temperature of the Earth? We know that the surface temperature of the Earth varies from place to place, from season to season, and from night to day. When scientists speak of "the" temperature of the Earth, they are referring to a time and spatially averaged temperature, measured at thousands of monitoring stations worldwide during all seasons of the year and times of day. It is a remarkable fact that when such measurements are collected together and averaged, the result is essentially constant from year to year. In fact, over the past 150 years that such measurements have been taken, the Earth's average annual temperature has not varied more than 0.5°C. Thus we can say with a good deal of confidence that, in the long run, the Earth is in thermal equilibrium with the outer space that surrounds it—that is, with a vacuum. Since heat cannot be conducted or convected through a vacuum, **the only way that thermal energy can enter or leave the Earth is through radiation**. So we can say that the Earth is in radiative equilibrium with space, and we can infer an equilibrium temperature by requiring a balance between the amount of radiative energy received and the amount emitted back to space.[4]

From direct observation, we know that the rate of solar energy incident at the top of the atmosphere is 1,370 watts/m^2. This figure is known as the **solar constant**, S_o, and refers to the rate at which energy is received above the atmosphere on a flat plate whose surface directly faces the sun. From the perspective of the sun, the Earth appears as a flat, circular disk of radius 6.4×10^6 m. Thus the rate of radiant energy incident at the top of the atmosphere is

$$P_{incident} = (\text{Power/Area}) \times (\text{Area of Disk}) = S_O \pi R^2$$

$$= (1{,}370\ \text{W/m2})\pi(6.4 \times 10^6 \text{m})^2 = 1.76 \times 10^{17}\text{W}.$$

Not all of this incident energy is absorbed by the Earth and the atmosphere. Some is reflected away and therefore unavailable for planetary heating. The fraction of energy reflected away is usually expressed as a decimal between 0 and 1 and is referred to as the **planetary albedo**. On average, direct measurements give a value of 0.30 for the planetary albedo of the Earth, meaning that only 70 percent of incident energy is absorbed. Thus,

$$P_{absorbent} = (0.70)(1.76 \times 10^{17}\text{W}) = 1.23 \times 10^{17}\text{W}.$$

If the temperature of the Earth is to remain constant, then energy must be radiated away at this same rate.

[4] Geothermal energy, as a byproduct of past nuclear energy, is also a component of the Earth's radiation budget, as is the heat produced by man through conversions of stores of fossil and nuclear energy into other forms. However, these sources are minuscule compared with the major radiative component and may be ignored for purposes of this computation.

The physical law governing the rate of radiation from a hot object is called the Stefan-Boltzmann equation.[5] This law says that an object radiates energy at a rate proportional to the fourth power of its temperature. Specifically, for an object of surface area A and absolute temperature T,

$$P_{emitted} = \sigma A T^4.$$

The constant of proportionality, $\sigma = 5.67 \times 10^{-3}$ W/m^{2}K^4, is called Stefan's constant. On average, we may consider the Earth's radiation to be emitted to space isotropically, or equally in all directions. The effective area for use in the Stefan-Boltzmann formula is therefore the surface area of a sphere whose radius is that of the Earth. Thus,

$$P_{emitted} = \sigma(4\pi R^2)T^4$$

$$= (5.67 \times 10^{-8}\ \mathrm{W/m^2K^4})(4\pi)(6.4 \times 10^6\ \mathrm{m})^2 T^4$$

$$= (2.92 \times 10^7\ \mathrm{W/K^4})T^4.$$

Equating emitted and absorbed power then gives a value for the equilibrium temperature T.

$$P_{emitted} = P_{absorbed},$$

$$(2.92 \times 10^7\ \mathrm{W/K^4})T^4 = 1.23 \times 10^{17}\mathrm{W},$$

$$T = 255\ \mathrm{K}.$$

A temperature of 255 K corresponds to a value of -18°C or about 0°F. Clearly, this is colder than what we observe for the average surface temperature of the Earth, but it agrees well with observations of temperature at the top of the atmosphere. The temperature at the Earth's surface, averaged over all latitudes and seasons of the year, is about 288 K or 15°C (59°F). The 33°C difference must be accounted for by the atmosphere. Indeed, this is the greenhouse effect, and we have it to thank for life as we know it on the Earth.

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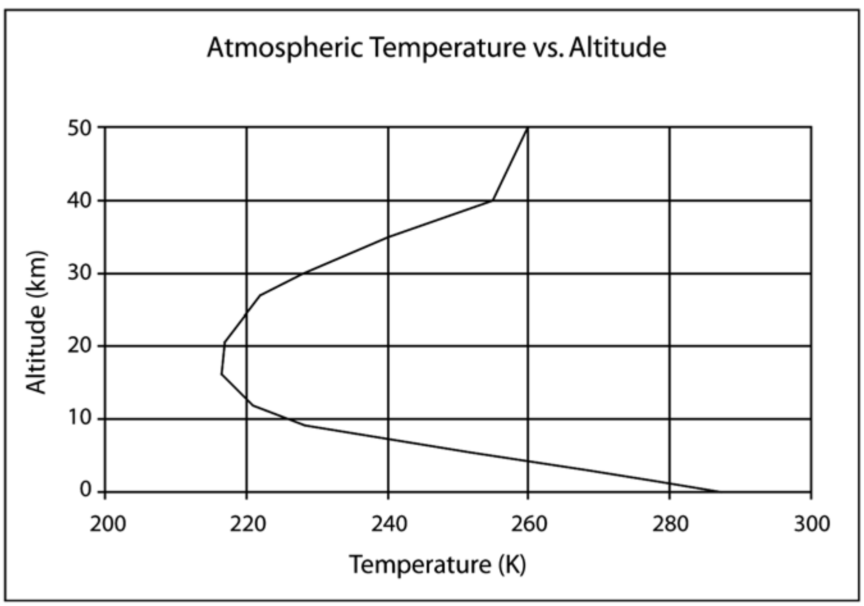
[5] For instance, see Aubrecht (2006), p. 236.

Effects of the Atmosphere

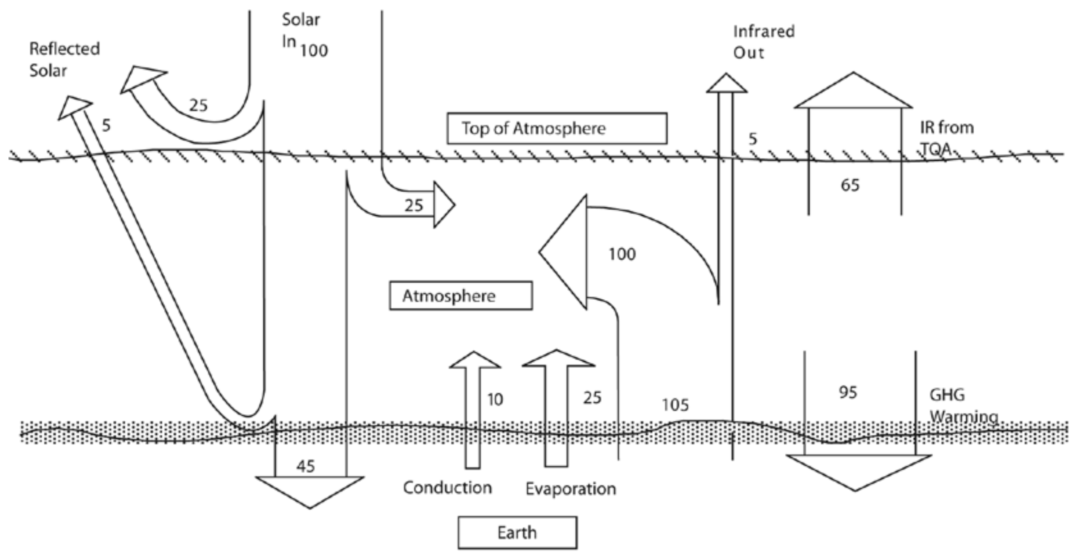
The above result of 255 K (–18°C) often is referred to as the "bare Earth" temperature because it is the equilibrium temperature for the Earth without an atmosphere. The difference between this value and the observed surface temperature of 288 K (15°C) is caused by infrared radiation directed toward the Earth from the bottom of the atmosphere.

On a simple model, we can consider the atmosphere as a long column of gas, heated at the top by the sun and at the bottom by the Earth. As such, we might expect that a vertical profile would exhibit higher temperatures at the ends than the temperature in the middle, and this is indeed the case shown in the figure below, which depicts the observed temperature of the atmosphere versus altitude above the Earth's surface.



While the atmosphere extends vertically to 100 km or so, 80 percent of the mass is found below 10 km, where most weather occurs, and more than 99 percent is found below an altitude of 50 km. Let us consider the energy balance within and external to the entire atmospheric column from the surface of the Earth to the top of the atmosphere around 50 km altitude. The diagram below illustrates how radiation enters and leaves the atmosphere and how energy is distributed within it. In this diagram, the wavy line near the top of the figure represents the interface between the atmosphere and outer space, and a similar line near the bottom of the figure represents the Earth's surface. Arrows represent energy flows into or out of the atmosphere or redistributions within it.

Remember that the rates of energy input and output must balance in order to maintain a constant temperature.



Radiation Balance Diagram for the Earth and Its Atmosphere

Consider the left side of the diagram first. Of 100 units of solar energy incident at the top of the atmosphere, approximately 25 units are reflected away by air molecules or by the top of clouds. This energy does not enter the atmosphere and is unavailable for heating. Another 25 units are absorbed by the atmosphere and therefore do contribute to its heating. Only 50 units, or half of the incident energy, reaches the Earth's surface. Once there, another 5 units are reflected away, and the 45 remaining units are absorbed by the Earth. Note that the total reflected radiation, 25 + 5 = 30 units, corresponds to an albedo of 0.30 as mentioned previously.[6]

Now consider the second group of arrows at the bottom of the figure that point upward. Two of these are labeled "conduction" and "evaporation," and the numbers from left to right are, respectively, 10, 25, and 105 units. The first of these, "conduction," represents the transfer of heat from the Earth's surface to the molecules at the bottom of the atmosphere via conduction—that is, through physical contact but not by physical transfer of material. The second, "evaporation," represents convection currents. These are created by latent

[6] Sometimes the Earth's albedo is given as 0.10. This figure refers to surface reflection only, whereas the total "planetary albedo" combining surface and atmosphere is 0.30. Note that 10 percent of radiation reaching the Earth's surface is, indeed, reflected back to space in the above diagram.

heat that is released by evaporation of liquid water from the surface of the Earth and movement of these molecules to higher altitudes, thereby delivering heat energy to the atmosphere. The larger value of 105 represents infrared radiation emitted by the warm Earth into the bottom of the atmosphere. Five of these 105 units pass directly through to outer space without interacting with air molecules and therefore have no effect for atmospheric heating. The remaining 100 units of infrared radiation are combined with the 35 units from conduction and convection and with the 25 units of solar radiation to make a total of 160 units absorbed by the atmosphere.

In order for equilibrium to be maintained and the temperature to remain constant, the atmosphere must emit 160 units of energy too. Now look at the right side of the diagram, which shows 65 units of infrared radiation being emitted to outer space and 95 units of infrared being returned to Earth. The total of these two emissions exactly equals the 160 units necessary to maintain thermal equilibrium for the atmosphere. But why are the upward and downward emissions unequal? Remember that the top of the atmosphere is colder than the bottom. The Stefan-Boltzmann law tells us that hotter objects radiate energy faster than cooler ones, so we should expect more energy to be returned to Earth than is emitted to outer space. The returned infrared energy shown on the right of this diagram is, of course, the greenhouse effect.

Thermal equilibrium must prevail at every level of the atmosphere. In particular, if 100 units are incident at the top of the atmosphere, then we also must account for 100 units of outgoing radiation there. The 25 units of energy reflected by the atmosphere, together with the 5 units reflected from the Earth's surface, make up 30 of the total. This leaves 70 units of energy to be accounted for, and these are made up of 5 units emitted directly from the Earth and an additional 65 units from the atmosphere.

At the surface of the Earth, 140 units of energy are absorbed (45 from solar and 95 from returned infrared) and 140 are emitted (105 as infrared radiation and 35 via convection and conduction), again maintaining energy balance and thermal equilibrium.

Note the difference between the greenhouse effect for the Earth and that for an actual greenhouse. In the actual greenhouse, interior objects (including the air) are analogous to the Earth; the enclosure itself, be it glass panels, sheet plastic, or other material, replaces the atmosphere in the Earth system. In the actual greenhouse, the heated molecules inside are physically prevented from escaping; in the Earth system, hot molecules are free to move away and do so. In the actual greenhouse, infrared radiation is absorbed and reemitted by perhaps a 1 cm thickness of glass; in the Earth system, infrared is absorbed and reemitted by 50 kilometers of atmosphere. In the actual greenhouse, the thickness of the enclosing material is relatively unimportant so long as it sufficiently prevents the hot molecules from leaving; in the Earth system, the thickness and composition of the atmosphere is vitally important. The actual greenhouse heats by **preventing** convection cooling; in the greenhouse effect for the Earth, heating is accomplished by **enhancing** infrared radiation. To understand this more fully, we need to know a bit more about the solar spectrum, infrared radiation, the composition of the atmosphere, and why some molecules are infrared active and others are not.

Summary

To summarize the key points of this article, we recall that heat is thermal energy in transition and that temperature measures the average molecular kinetic energy of an object. Heat naturally flows from hot objects to cool ones and can serve to change temperatures. Heat can be transferred in only three ways: convection, conduction, or radiation. Radiation is the way energy is transmitted through empty space, such as solar energy. If no net heat is transferred between an object and its surroundings, the temperature remains constant, and the object is said to be in a state of thermal equilibrium. Conversely, a constant temperature implies that an object is in thermal equilibrium and that energy input equals energy output. This fact can be used to infer an equilibrium temperature for the Earth. Without atmosphere, the equilibrium temperature for the “bare Earth” is about 255 K (–18°C). This value is approximately correct for temperatures at the top of the atmosphere, but it is some 33°C cooler than actually observed at the surface. The difference is accounted for by the atmosphere, which absorbs and returns some of the infrared energy emitted by the Earth that otherwise would be radiated to outer space. This effect is called the greenhouse effect. An enhanced greenhouse effect, caused by an increase in infrared active gases in the atmosphere, would disrupt the present state of thermal equilibrium and lead to an increased temperature for the Earth. The process of changing from one equilibrium temperature to a higher one is the phenomenon referred to as global warming, and the gases that contribute to this process are called greenhouse gases. Carbon dioxide is an important greenhouse gas, but water vapor, methane, and other trace gases also can contribute to enhanced infrared radiation. The physical basis of the greenhouse effect is well understood, and the effects of increasing infrared active gases can be calculated with a fair degree of certainty. Most future environmental scenarios are based on an assumption of doubling the concentration of greenhouse gases such as carbon dioxide and using computer models to predict a new equilibrium temperature. These models are based on firm theory and can be calibrated by using historical data. But most such models suffer from a need to estimate unknown factors such as the effect of clouds or temporal increases in water vapor. Accordingly, environmental implications and specific regional climate predictions resulting from such models are more uncertain than global warming itself.

Questions

1. Explain in your own words the differences between **convection**, **conduction**, and **radiation** as the three forms of heat transfer.
2. Identify the form of heat transfer for each of the following as either conduction, convection, radiation, or some combination thereof.
   a. Warming oneself by a fireplace or campfire
   b. Boiling water in a pan on a stovetop
   c. Heating an entire room with baseboard electric heating
   d. Baking a potato in a microwave oven
3. Define the following terms in your own words:
   a. Solar constant
   b. Thermal equilibrium
   c. Stefan-Boltzmann law
   d. Albedo
4. According to the Stefan-Boltzmann law, if the temperature of a radiating object is doubled, by what factor is the energy output multiplied?
5. Without an atmosphere, would the Earth's equilibrium temperature be higher or lower than it is today? Explain.
6. Complete the math in this derivation (which appears on p. 27) to show that 255 K is the correct temperature for the "bare" Earth:

   $(2.92 \times 10^{7}\ \mathrm{W/K^4})T^4 = 1.23 \times 10^{17}\,\mathrm{W},$

   $T = 255\ \mathrm{K}.$

7. Suppose the Earth's albedo changed, say by decreased snow cover, to a value lower than 0.3. Would this act to increase or decrease the Earth's equilibrium temperature? Explain your reasoning.
8. Some people have suggested that we also have experienced "global dimming" in recent years, meaning that increased particulate load in the atmosphere has served to block sunlight, thereby reducing solar heating and causing global cooling. At the same time, most scientists agree that the actual observed temperature of the Earth has increased in the past few decades. How can these two observations be reconciled?

9. Check the numbers for radiative energy balance in the "Radiation Balance Diagram for the Earth and Its Atmosphere" (p. 29) to show how equilibrium is achieved at each of three levels: top, middle, and bottom of atmosphere.
10. Some critics of global warming have suggested that fluctuations in solar output could account for climate variability and increases in observed equilibrium temperatures for the Earth. At the same time, observations over many decades show that solar output is constant within 0.1 percent. Suppose that the solar constant, $S_o = 1{,}370\ W/m^2$, were increased by 0.1 percent. Use the new value in the balance equations to compute a new equilibrium temperature to show that the difference from this cause is negligible.

Answers

1. See definitions in the section "Heat Transfer" on pp. 24-25 of this article.
2. a. Fireplaces and campfires warm principally by **radiation**.
   b. Heat is transferred from the stovetop to the pan by **conduction**, but heat is transferred through the water mostly by **convection**.
   c. Heat from the baseboard unit is transferred to the room via **convection**.
   d. Microwave ovens use **radiation** to heat food.
3. a. Solar constant—The rate of radiant energy received from the sun at the position of the Earth's orbit above the atmosphere. Units are joules per square meter per second, or watts per square meter.
   b. Thermal equilibrium—A condition whereby the rate at which heat is received and absorbed by a body equals the rate at which heat is emitted. The condition is characterized by a constant temperature.
   c. Stefan-Boltzmann law—The law governing the rate of radiative energy output by a body whose temperature is above absolute zero. The law says that the rate of energy output, in terms of joules per second per square meter of surface area, is proportional to the fourth power of the absolute temperature of the object.
   d. Albedo—This term describes the reflectivity of an object in terms of the fraction of incident energy returned and not absorbed. For the Earth, planetary albedo is 0.30, meaning that 30 percent of incident solar energy is reflected back to space and does not contribute to planetary heating.
4. From Stefan-Boltzmann, output $\sim T^4$. Thus a doubling of the temperature would lead to an increase in radiative output by a factor of $2^4 = 16$.
5. Lower. Without an atmosphere, all of the Earth's radiative output would be able to reach outer space with none returned to the surface. The atmosphere serves to intercept some of the outgoing infrared radiation and return a portion to the surface, thereby leading to warming.

6. $(2.92 \times 10^7 \text{ W/K}^4)T^4 = 1.23 \times 10^{17} \text{W}$,

   $T^4 = (1.23 \times 10^{17} \text{W}) \div (2.92 \times 10^7 \text{ W/K}^4)$,

   $T = [(1.23 \times 10^{17}) \div (2.92 \times 10^7)]^{1/4} \text{ K}$

   $T = 255 \text{ K}$.

7. A decreased albedo means that less radiative energy would be reflected back to space, thereby implying an **increase** in the amount absorbed by the Earth. The increased absorption would lead to a higher equilibrium temperature, thereby enhancing the greenhouse effect and exacerbating global warming. This is referred to as a **positive** feedback process, indicating that the initial effect is increased by such action. Ironically, in this case a positive feedback leads to a negative environmental consequence.
8. Some climate researchers think that we have underestimated the effect of global warming because the effects have been offset to some degree by global dimming. What we observe today is the net result of increased warming from greenhouse gas additions balanced to a degree by cooling caused by particulates. Effective introduction of clean air regulations since 1970—and the consequent reduction of particulates since then—have allowed us to observe global warming effects that were previously masked. If atmospheric particulate loadings had not occurred, we would have seen the warming effects earlier. Ironically, this creates a dilemma in that further cleaning of the atmosphere might exacerbate global warming.
9. See the text below the "Radiation Balance Diagram for the Earth and Its Atmosphere" on p. 29.
10. From the equilibrium equations on pp. 26-27, we infer that the final equilibrium temperature for the Earth is proportional to the one-fourth power of the solar constant. Thus, a 0.1 percent increase in this value will lead to a temperature change by a factor of $(1.001)^{1/4} = 1.00025$. Multiplying the previously derived bare Earth temperature of 255 K by this factor gives a result of 255.06 K. Such a difference is below the precision of present measurements and therefore could not be observed.

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Personal Energy Audit

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Note to Teachers

This energy audit is an example of a long-term data collection project; the time frame can vary from two weeks to four. The actual report should be due one week after the end of data collection. Students will gain experience in collecting, organizing, and analyzing a set of real data. The project relates to the following points on the AP Environmental Science topic outline (found in the Course Description):

V. Energy Resources and Consumption
A. Energy Concepts
(Energy forms; power; units; conversions; Laws of Thermodynamics)

F. Energy Conservation
(Energy efficiency; CAFE standards; hybrid electric vehicles; mass transit)

VI. Pollution
A. Pollution Types
1. Air Pollution
(Sources—primary and secondary; major air pollutants; measurement units; smog; acid deposition—causes and effects; heat islands and temperature inversions; indoor air pollution; remediation and reduction strategies; Clean Air Act and other relevant laws)

C. Economic Impacts
(Cost-benefit analysis, externalities; marginal costs; sustainability)

VII. Global Change
B. Global Warming
(Greenhouse gases and the greenhouse effect; impacts and consequences of global warming; reducing climate change; relevant laws and treaties)

The project has three main areas:

1. Electrical appliance inventory (type, quantity, and consumption)
2. Data collection (daily meter readings)—Students should try to read their meters at the same time every day or every other day. If a student lives in an apartment and doesn't have access to the electric meter, she or he may either complete the audit for a relative or friend's house or estimate total household usage rates by examining appliances in the household and keeping a log of how frequently they are used. If the second option is chosen, the student should compare her or his estimated use to the family's monthly electric bill.
3. Analysis and discussion

Rubric

a. Data and descriptions—25 points
b. Discussion—25 points
c. Bibliography/References—5 points
d. Bonus points—Up to 5 points if multiple electric bills are included in the project; up to 5 points if SO_2 and CO_2 emissions are calculated and included in the discussion

Scoring

50–55 → A (90–100)
45–49 → B (80–89)
40–44 → C (70–79)
35–39 → D (60–69)
30–34 → F (40–59)

Personal Energy Audit

Most of the principles set forth in this environmental science course are illustrated in all aspects of life's activities, from the personal to the planetary level. One area of critical importance is energy consumption, particularly electrical energy consumption. The fuel of choice for electricity production in the United States is coal. About two-thirds of the SO_2 emitted into the atmosphere is a result of burning coal in electrical power plants. The use of pollution control devices, or scrubbers, can effectively reduce the amount of SO_2 emitted, but the majority of power plants in the U.S. have not been equipped with scrubbers. About 80 percent of the incidence of acid rain in our atmosphere is attributed to these emissions. Global warming is also impacted by the combustion of fossil fuels to produce electricity. About one-third of CO_2 emissions are due to the production of electricity. Coal produces more CO_2 per energy unit than either oil or natural gas due to its carbon content. Approximately 0.77 kg of CO_2 is emitted per kilowatt-hour of energy produced. (This value will vary depending on the actual carbon content of the coal and the efficiency of the power plant.) There are no pollution control devices that can convert carbon dioxide into an environmentally harmless substance. The only way to reduce the CO_2 emissions associated with the combustion of fossil fuels is to reduce consumption.

All of us have a stake in all levels of energy use and production, but it is certainly easier to assess our impact when examining personal energy habits and attitudes. In this assignment you will examine your personal energy habits with regard to electricity consumption and the impacts those habits have on the environment. Having a thorough understanding of your own system's dynamics and connections will lead to an easy transition to understanding the energy dynamics at a broader level, for example, those of a regional or global system. Positive changes that can be made effectively at an individual level can be amplified at the national level.

Therefore, keep in mind the following ideas when evaluating your home as a small part of a larger shared energy system:

1. Areas where reduced consumption will result in monetary savings (for you)
2. Changes on both a personal level and a household level that will be reflected in an improvement to a larger, shared system (for example, reduced electricity consumption leading to reduced fuel consumption by the utilities, less air pollution, less peak electricity consumption, and so forth)

Analysis of Electricity Consumption

A. Reading and Recording Electricity Consumption

Read the electric meter at the same time every day for a 10- to 14-day period and record the values. If you do not have access to your electric meter, calculate an average daily value based on your utility bill. Make daily notes on the patterns of electricity use in your household, particularly the use of large appliances. Note the usual settings for the air conditioner and water heater, the amount of cooking done, the type of lights used, the amount of laundry done, and so forth. Also, make notes on aspects of the weather that may affect heating or cooling. Weather notes should include cloud cover and high and low temperature readings for that day. Report local temperature readings and thermostat settings in degrees Celsius. The data table for these notes may look like table 1:

Table 1: Meter Readings, Observations and Usage Notes for the Period of April 1–April 14, 2006

Date	Meter Reading (kWh)	Daily Usage (kWh)	Weather Observations	*Notable Appliance Usage*
4/1	92178	—	Sunny, 30°C (high), 21.5°C (low)	Air conditioning setting: 24°C
4/2	92284	106	Partly cloudy	Laundry day

B. Calculating Monthly Energy Consumption (in Kilowatt-Hours) and Cost for Electrical Appliances

These calculations should be completed for the following appliances: air conditioner, water heater, refrigerator, lights (incandescent and fluorescent separately), television, washer, dryer, stereo, computer, and any other electrical appliance that may affect your consumption.

1. In order to calculate the electrical energy consumption per month of each item, use one of the following methods:
   a. Check the appliance label and find the wattage rating. **Note:** Many air conditioners have a SEER (seasonal energy efficiency ratio) sticker that can be used to locate the wattage rating. The SEER = Btu / Wh.
   b. Calculate the power (P) measured in watts (sometimes called the wattage) by multiplying the current (I) measured in amperes or amps (sometimes called the amperage) times the voltage (V), usually 110 V or 220 V.

      $\boldsymbol{P = I \times V}$.

   c. Consumption for a hot water heater can be calculated by the following equation:

      Energy consumed in kWh/month = $N(2\Delta T - 17.6)$

      where
      N = the number of people in the house
      and
      ΔT = the difference, in degrees Fahrenheit, between unheated cold tap water and the hottest water from the hot tap.

   d. Call an appliance store, repair shop, or your electric utility and ask for this information.
   e. Consult the literature that was packaged with the appliance for energy usage and/or wattage ratings.
2. To calculate the cost of running each appliance for one month, take the following steps.
   a. Determine the energy (E) consumed each day by each appliance using the equation $E = P \times t$ (energy = power × time). To do this, you should multiply the wattage of the appliance by the amount of time in hours the appliance is used each day.
   b. Determine the energy (E) consumed by the appliance each month by multiplying the daily energy consumption (the result from step a) by 30 (the number of days in one month).
   c. Divide the monthly energy consumption (the result from step b) by 1,000. (This converts your answer into kilowatt-hours.)
   d. Multiply the number of kilowatt-hours used by the appliance each month (the result from step c) by the cost of electricity. (You can calculate this value from an electric bill or obtain it by calling your local power company.)
   e. Example: Calculate the total monthly electricity consumption (in kilowatt-hours) and the total monthly cost (in dollars) of a 200-watt bulb that operates 8 hours per day. Assume the cost of electricity is $0.09/kWh.
      200 W × 8 hrs/day × 30 days/month = 48,000 Wh/month.
      48,000 Wh/month / 1,000 W/kW = 48 kWh/month.
      48 kWh/month × 0.09 $/kWh = $4.32/month.
3. In order to determine the amount of CO_2 released by your electricity consumption each month, multiply the number of kilowatt-hours used per month by the kilograms of CO_2 produced per kWh. (See table 2 below.) If a coal-burning power plant is the main source for your electricity, the amount of SO_2 emitted per month can be approximated by multiplying the number of kilowatt-hours used per month by kilograms of SO_2/kWh. Consult your local power utility to determine the fuel mix used to generate electricity in the area. (If coal or oil is used, determine the amount of SO_2 produced.)

Table 2: Carbon Dioxide and Sulfur Dioxide Emissions, by Source, for Generating Electricity

Fuel	CO_2 Emitted (kg/kWh)	SO_2 Emitted (kg/kWh)
Coal	0.97	0.006
Natural gas	0.47	~0.0
Oil	0.112	0.005

4. Arrange the calculations for the various appliances in a table (table 3). The following headings should be included in the table : Appliance, Wattage, Hours of Use/Day, Hours of Use/Month, kWh Consumed/Month, CO_2 Released/Month, Cost/Month. Indicate the method you used to determine the wattage of the appliance. Calculate the total kilowatt-hours used per month and the total cost for this amount. Compare this to a current electricity bill. If it is off by more than 30 percent, recalculate your usage. On a separate sheet of paper, show the formulas you used in determining these values and sample calculations for each category on this table.
5. If you can get one, compare a utility bill from a summer month (a time of heavy air-conditioner usage) with one for March or April (a time of minimal air-conditioner or heater use). Estimate what amount of the summertime bill is due to air-conditioner use.
6. Inspect and report on the following for your house, apartment, or trailer:
   a. The amount, location, and quality (type and R-value) of insulation
   b. The amount of shade provided by trees or shrubs
   c. The condition, composition, and color of the roof
   d. The air circulation in the attic
   e. The tightness of the fit for doors and windows
   f. The color of outer walls (that is, whether your dwelling absorbs or reflects heat)
   g. Any other features that may affect the dwelling's heat balance

The Report

A. Data and Descriptions

1. Table 1: Meter readings with usage notes and usage estimate for a 10–14 day period (1 page)
2. Description of your dwelling (as in part 6, a through g, above) (1/2 to 1 page)—an illustration or photograph may also accompany the description.
3. Table 2: Appliance power consumption (wattage) and estimated energy usage (see part 4, above) (1 page)

4. Table 3: Tabulation of your electrical energy consumption for each of the following areas: cooling, heating, water heating, lighting, refrigerator use, freezer use, stove use, electronics use, and miscellaneous. Determine the percentage each contributes to your monthly electrical energy consumption. Display all of this data in a pie chart.
5. Calculation page: Equations used and sample calculations for each category in table 2 and table 3.

B. Discussion (2 or 3 Pages)

In this section, analyze what you have learned through this project and make some detailed suggestions about how you and the members of your household can conserve energy by changing patterns of consumption. Examine the economics of these changes and their possible impact on the emission of pollutants from power plants. Some well-intended changes may carry an economic disadvantage (that is, they may not be cost effective at this time), or you may be thwarted in attempts to make certain alterations in your lifestyle. In these cases, suggest what steps could be used to remedy this situation. Supplement the discussion with drawings, graphs, or charts, as appropriate. The focus of this discussion should be on your own dwelling. Avoid lengthy discussions on global, national, or theoretical problems.

C. Title all graphs, tables, and figures. Include a bibliography.

D. Include copies of your electric bill, if available.

Extensions

1. Reexamine your electrical energy consumption and divide it into peak and off-peak use. Investigate the impacts of shifting your electrical load into off-peak periods. (If you analyze your peak and off-peak use, include the results of your analysis in the discussion portion of the paper.)
2. Complete a CO_2 budget for your household.
3. Visit a local power plant.

Special Focus: Energy and Climate Change

Books for Reference

Global Tomorrow Coalition. *The Global Ecology Handbook: What You Can Do About the Environmental Crisis*. Boston: Beacon Press, 1990. ISBN: 0-8070-8501-4.

Miller, G. Tyler. *Living in the Environment: Principles, Connections, and Solutions*. 14th ed. Belmont, California: Thomson, 2005. ISBN: 0534997295.

Priest, Joseph. *Energy: Principles, Problems, Alternatives*. 4th ed. Reading, Massachusetts: Addison-Wesley, 1991. ISBN: 0-201-50356-5.

World Resources Institute. *The 1994 Information Please Environmental Almanac*. New York: Houghton Mifflin, 1993. ISBN: 0-395-67742-4.

World Resources Institute. *World Resources 1992–93*. New York: Oxford University Press, 1992. ISBN: 0-19-506230-2.

Web Sites for Reference

Ames City Government: Common Household Appliance Energy Use
Wattage for various electrical appliances
www.city.ames.ia.us/ElectricWeb/energyguy/appliances.htm

California Energy Commission: Consumer Energy Center—Small Appliances
Small appliance electrical consumption
www.consumerenergycenter.org/home/appliances/small_appl.html

Energy Information Administration: Official Energy Statistics from the U.S. Government—State Data
www.eia.doe.gov/emeu/states/_states.html

Energy Star: Home Energy Analysis
Part of a program run by the EPA
www.energystar.gov/index.cfm?c=home_improvement.hm_improvement_index_tools

Pacific Power: Time of Use Frequently Asked Questions
www.pacificpower.net/Article/Article17183.html

Rocky Mountain Institute: Climate—Household CO_2 Savings: Appliance Measures
www.rmi.org/sitepages/pid351.php

Will Smith: Climate Change—Electricity Consumption of Common Domestic Appliances
www.willsmith.org/climatechange/domestic.html

World Resources Institute: EarthTrends—Environmental Information
Various data tables on energy and resources
http://earthtrends.wri.org

An Energy Primer for the AP Environmental Science Student

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Even for practicing scientists and engineers, energy concepts and terminology can sometimes be confusing and ambiguous. Confusion arises because different disciplines often employ different systems of measurement and use specialized vocabulary unique to a particular industry. The situation can be especially troublesome for the introductory environmental science student who may not have completed even a first course in physics. And the problem is not alleviated by the typical environmental textbook where energy terms are introduced only in a piecemeal fashion as needed in the context of a specific environmental topic. Thus, the introductory environmental science student is often left with a fragmentary, confusing, and unsatisfactory introduction to energy concepts and terminology. This is particularly worrisome because energy use is at the heart of most environmental problems. Moreover, the environmentalist must be able to communicate with people in many different disciplines. Accordingly, he or she must be familiar with the different systems of measurement and be able to convert readily from one to another. This article provides a brief introduction to the major systems of measurement used in science and technology with a special focus on energy terms useful for the environmentalist.

Systems of Measurement

There are two systems of measurement in common use in the world: the United States Customary System (USCS, formerly called the British system) of feet, pounds, and seconds, in everyday use in the United States, and the metric system of meters, kilograms, and seconds, in use everywhere else. In 1960 the metric system was adopted by an international committee in Paris as the worldwide standard for science and is now referred to as the Système International or SI. The U.S. is the only major country that still uses the British system of measurement (even Britain has gone metric!), but this system is well ingrained in American society and is unlikely to see an early demise. A subset of the metric system is the centimeter-gram-second (cgs) system that is commonly used in atomic physics and chemistry.

All physical quantities, such as velocity, acceleration, force, momentum, and energy, ultimately can be expressed in terms of three basic units of length, mass, and time. These three quantities are referred to as **fundamental units** because they can be used to define all other elements in a particular system of measurement. The table below summarizes the fundamental units for the three common systems of measurement.

System	Length	Mass	Time
SI (mks)	meter	kilogram	second
SI (cgs)	centimeter	gram	second
USCS (fps)	foot	slug	second

Because the mass unit **slug** is uncommon, the USCS is referred to as the foot-pound-second (fps) system, but strictly speaking, the pound (lb) is a unit of force, not mass. Conversely, in the SI system the mass unit of kilogram is often used to express force (of gravity), as in a person's weight, for example. In this sense, a convenient conversion factor between the systems is to use the "weight equivalent" of 2.2 lbs for a 1 kg mass.

Work and Energy

Physicists define energy as "the ability to do work," but in a sense this begs the question because work itself is still undetermined. The term **work** in physics is defined as force multiplied by the distance through which the force acts. Thus we get the idea that energy is the property that allows one to move objects from one place to another and thereby accomplish some physical labor or "work." Energy itself may appear in a variety of forms—e.g., solar energy, electrical energy, chemical energy, thermal energy, and nuclear energy—but the bottom line is that all forms can be used to do work. Thus all units of energy must ultimately be reducible to those of work—i.e., force × distance. From Newton's law, we know that force is mass × acceleration. So extending the above table, we have:

System	Force =	Mass ×	Acceleration
SI (mks)	newton	kg	m/s^2
SI (cgs)	dyne	gram	cm/s^2
USCS (fps)	lb	slug	ft/s^2

And finally, we have the table for energy:

System	Energy =	Force ×	Distance
SI (mks)	joule	newton	meter
SI (cgs)	erg	dyne	cm
USCS (fps)	ft-lb	lb	ft

Note that although the newton and joule are named for persons, they are not capitalized when used as a unit of measurement. However, the corresponding symbols (N and J) are capitalized when used independently.

The Newton

The SI unit of force, the newton (N), is of course named in honor of Isaac Newton. From the above, we see that 1 N = 1 kg-m/s^2, which is equivalent to about 0.225 lbs. Note that 1 N is not equal to the weight of 1 kg.

The Joule

Similar to the unit of force, the joule (J) is named in honor of Sir James Prescott Joule, a famous nineteenth-century British scientist who performed many precise energy experiments. One joule is the amount of work done by a force of one newton acting through a distance of one meter. From a practical, everyday standpoint, the joule is a relatively small amount of energy, but it is used most often in scientific work. The energy content of one large donut, for instance, is about 10^6 joules.

The Calorie

Through a series of cleverly designed experiments with pulleys, weights, paddle wheels, and precisely measured temperatures in containers of water, Joule convincingly demonstrated the equivalence between mechanical energy and heat. Until that time, people thought that heat was some sort of ephemeral property of materials, like a fluid, that was released when solid objects were broken into smaller pieces. They called this property **caloric**, from which the term **calorie** is derived. Joule showed that heat and mechanical energy are equivalent, and his careful measurements gave us what we refer to today as the "mechanical equivalent of heat":

1 calorie = 4.186 joules.

You may recall that one calorie is the amount of heat required to raise the temperature of one gram of water by one Celsius degree. One kilocalorie would increase the temperature of 1 kg of water by the same amount. The kilocalorie is sometimes referred to as a "big" calorie and written with a capital C, namely, as Calorie. Obviously, this practice has much potential for confusion, so the reader must be constantly alert as to a writer's intention when speaking of calories. To further confuse the issue, food calories are always "big" calories. Thus, when one speaks of 100 Calories in a slice of bread, for instance, the implication is that 100 kilocalories or 4.186×10^5 J would be released through burning the dried biomass.

The energy content in fuels is measured by burning them to exhaustion and capturing the heat that is released. This heat can be transferred, say, to a container of water where a temperature increase is measured. Knowing that one calorie per gram is required to increase the temperature of the water then allows one to determine the energy content of the fuel in terms of calories. This number can then be converted to other energy units using Joule's conversion factor.

The Btu

Another popular unit of heat energy is the Btu (British thermal unit). One Btu is the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. Using the conversion factors of 2.2 lbs/kg and 1.8 F°/C°, and Joule's equivalent, we find that:

1 Btu = 252 cal = 1,055 J.

One Btu is approximately the amount of heat released by burning one large kitchen match.

Btus are commonly used in the United States to rate water heaters, furnaces, and air conditioners. A typical natural gas household water heater, for instance, might be rated at 40,000 Btu/h and a furnace at twice this, or 80,000 Btu/h. These numbers, of course, give the rate at which heat can be produced by the burners of these units. The heating values for fuels are often stated in terms of Btus per unit weight. Coal, for instance, has a typical heating value of 25 million Btu/ton, and petroleum 37 million Btu/ton.

The Therm

Gas companies in the U.S. often measure sales in terms of "thermal units" or **therms**. One therm is defined as 100,000 Btu, and natural gas at normal temperature and pressure has a heat value of 1,030 Btu/ft^3. Thus, one therm is very nearly equal to 100 cubic feet of natural gas:

1 therm = 10^5 Btu/1,030 Btu/ft^3 = 97.1 ft^3 ≈ 100 ft^3.

Gas companies also use "American Engineering" terminology instead of standard SI scientific notation. In this notation, the Latin abbreviations of C for 100 and M for 1,000 are employed as numerical prefixes, but because of the potential confusion between the standard scientific notation of C for centi (10^{-2}) and M for mega (10^6), the engineering abbreviations are not usually written with capitalization. For instance, 1 ccf = 100 cubic feet, and 1 mcf = 1,000 cubic feet, and one million cubic feet is written as 1,000 × 1,000 cf or 1 mmcf.

Power

Power is the term that is used to describe energy flow. Power is defined as "the time rate of doing work" and normally is measured in joules/second. In the SI system, the unit of power is the watt (W), named in honor of James Watt, inventor of the steam engine:

1 watt = 1 joule/second.

No separate unit is ascribed to power in the cgs system. In the USCS system, power is measured in "practical" units of horsepower (hp), where 1 hp = 550 ft-lbs/s. This is equivalent to 746 watts, or about 0.75 kW.

Perhaps because most electric appliances are rated in terms of their power requirements, power and energy are often confused when dealing with electrical energy. But just as when filling the tank of your car at the gas station you must ultimately pay for the total number of gallons pumped, not the rate at which you pumped it, so with electricity we pay for the total number of joules of electrical energy consumed, not the power or rate at which it was delivered.

In the U.S., electrical energy is usually measured in terms of kilowatt-hours (kWh), because this is a practical unit for the utility company as well as the customer. The relation between kilowatt-hours and joules is easy to determine:

1 kWh = 1,000 J/s × 3,600 s = 3.6×10^6 J.

Again, we see how small a joule is in practical terms. One kWh is the energy required to power ten 100-watt lightbulbs for one hour. The average home in the U.S. uses about 10,000 kWh of electrical energy per year.

Electric Power Plants

Electric utility power plants are rated in terms of their capacity to deliver electric power. For instance, a large coal-fired or nuclear plant might be rated at 1,000 MW_e (megawatts). The "e" subscript on the W stands for "electric" and is a signal that the rating is for the "output" capacity of the plant, not the energy input. Input energy is usually measured in terms of the heating value for the fuel—Btus for coal, for instance. If the plant operates at, say, 40 percent efficiency, then the energy input required for such a plant can be computed as follows:

$$\text{Input} = \text{Output}/40\% = 1{,}000\ \text{MW}/0.4 = 2{,}500\ \text{MW}$$
$$= \frac{2{,}500 \times 10^6 \text{J/s} \times 3{,}600\ \text{s/h}}{1{,}054\ \text{J/Btu}}$$
$$= 8.54 \times 10^9 \text{Btu/h}.$$

If this energy is supplied by coal with a heating value of 25×10^6 Btu/ton, then coal would need to be input at a rate of

$$\frac{8.54 \cdot\ 10^9 \text{Btu/h}}{25 \cdot\ 10^6 \text{Btu/ton}} = 342\ \text{tons/hour}.$$

Operating at full capacity 24 hours a day, such a plant would consume about three million tons of coal per year.

Solar Energy

Another valuable use of power in environmental analyses deals with solar energy. The sun, of course, provides radiant energy for all life on earth, and the rate at which this energy is received is referred to as **solar flux**, representing the power per unit area received at a given location. At the position of the Earth's orbit, this number is about 1,400 W/m^2 and is referred to as the **solar constant**. This means that a flat panel of 1 m^2 placed outside the Earth's atmosphere and oriented perpendicular to the sun's rays would receive 1,400 joules per second of solar energy.

The atmosphere absorbs about half of this energy, so that 700 W/m^2 is about the maximum amount that reaches the Earth on a hot summer day in the tropics. Averaging over day and night for all seasons and all latitudes, this is further reduced to about 240 W/m^2 as the average solar radiation received at the Earth's surface. Cloud cover and other factors reduce these numbers even further. In the U.S., for example, Tucson, Arizona, enjoys an annual average solar flux of 250 W/m^2, but Cleveland receives only 160 W/m^2. Obviously, such numbers have implications for the merits of solar heating and cooling as well as biomass growth in various locales.

Summary

Because energy plays a fundamental role in all environmental problems, it behooves the student to become familiar at an early stage with energy concepts and terminology. The environmental scientist must also get accustomed to specialized terms that are used in different disciplines and industries. The gas company is not going to convert cubic feet into Btus for you, just as the electric company is not going to convert kWh to joules. It is the responsibility of the environmental student to be able to put units on a common basis in order to make valid comparisons. For instance, is a natural gas furnace more economical or more environmentally benign than baseboard electric heating for an average home? Could solar energy supply all the heating needs for a home in Cleveland? How much electricity could be generated by installing solar panels on the roof of a home in Arizona? How much biomass can be grown on an acre of land in Missouri? A thorough understanding of energy units and terminology will go a long way to help the environmentalist make such analyses easy and commonplace.

Practice Questions

1. Given that 1 kcal of heat is required to increase the temperature of 1 kg of water by 1°C:
   a. How many kcals would be required to heat 100 kg of water by 20°C for a bath?
   b. How many joules is this?
   c. How many Btus?
   d. If your water heater can supply 40 kBtu/h, how long will it take to heat this water?
2. a. Given that 1 kWh = 3.6 MJ and that 1 Btu = 1,055 J, show that 1 kWh = 3,412 Btu.
   b. Why would it be incorrect to use this conversion factor directly to determine the amount of coal required to generate electricity in a power plant?

3. A typical home in the northern U.S. might require 120 MBtu of heat for the average winter.
   a. If this heat were supplied by a natural gas furnace operating at 60 percent efficiency, how many cubic feet of gas would need to be purchased?
   b. At a cost of \$0.90/ccf, what would it cost to heat this house for one season?
   c. If a new 80 percent efficient furnace could be installed at a cost of \$4,000, how long would it take to pay back the cost of this furnace, assuming gas prices remained the same?
4. Suppose the house in question 3 is located in Cleveland, where the annual average solar flux is 160 W/m^2. If 10 m^2 of solar panels operating at 20 percent efficiency were installed on this house to collect and store solar energy in the form of hot water:
   a. How much energy could be gained in one year in this manner?
   b. What fraction of the annual heating requirement is this?
   c. Using the hot-water heating requirements for a bath from question 1(c), how many hot baths would this energy supply in one year?
5. The annual average solar flux in Tucson is 250 W/m^2. Suppose 10 m^2 of solar electric panels operating at 10 percent efficiency were installed on a home there.
   a. How many kWh of electricity could be collected by these panels in one year?
   b. What fraction of the annual electrical requirement of 10,000 kWh for the average home does this represent?
   c. How many square meters of solar panels would be required to supply 10,000 kWh per year?
6. Solar energy is converted naturally into wood biomass with an efficiency of about 0.1 percent. Suppose a wood lot of 100 hectares (10^6 m^2) is located in Missouri, where the average annual solar flux is 200 watts/m^2. Given that the heat value for wood is 12 MBtu/ton, how many tons of wood can be produced by this property each year?
7. With moderate winds, a modern large wind turbine can generate about 250 kW of electricity, whereas a large nuclear power plant can generate 1,000 MW.
   a. How many wind turbines would be required to give the same output as one nuclear power plant?
   b. Discuss some of the advantages and disadvantages to providing electrical power by each method.
8. Batteries are usually rated in terms of ampere-hours, indicating the current that the cell is capable of delivering for a specified time. A typical D-cell flashlight battery, for instance, might be rated at 3 ampere-hours. The total electrical energy available from such a battery is found by multiplying the ampere-hour rating by the battery voltage. Thus this same 1.5 volt D cell could deliver 4.5 watt-hours of electrical energy.

Convert this energy to kWh and compare the cost of electrical energy derived in this manner to that of standard "grid-based" electricity. Assume that the battery costs $1.00 and that electricity from the power company is available at $0.10/kWh.

9. The table below gives prices and heat energy content for various fuels that are commonly used for home heating. Fuel prices are given as a per-unit cost for fuel delivered to the home. Complete the table by filling in the last two columns and thereby compare the cost of home heating by these various methods. In your computations, assume that the home requires 120 MBtu of heat for a season and that gas- or oil-fired furnaces operate at 80 percent efficiency. Assume that electrical heating is 100 percent efficient.

Fuel	Price	Energy Content of Fuel	Cost per MBtu	Cost of Home Heating
Natural gas	$1.14/ccf	1,030 Btu/cf		
Propane	$1.69/gal	92 k Btu/gal		
Fuel oil	$1.93/gal	133 k Btu/gal		
Electricity	$0.10/kWh	3,412 Btu/kWh		

Answers

1. a. 2,000 kcal; b. 8.37 × 106 J = 8.37 MJ; c. 7,940 Btu; d. 11.9 minutes
2. b. The second law of thermodynamics prevents 100 percent conversion of heat to mechanical or electrical energy. A typical coal-fired power plant operates at about 33 percent efficiency, meaning that only one-third of the energy in the coal is converted to electricity.
3. a. 1,941 ccf; b. $1,748; c. 9.2 years
4. a. 9.57 MBtu; b. 8 percent; c. 1,200
5. a. 2,190 kWh; b. 21.9 percent; c. 45.7 m^2
6. 498 tons
7. a. 4,000; b. Answers vary
8. Battery energy: 4.5 Wh = 4.5×10^{-3} kWh.
   Cost per kWh: $1.00 / 4.5×10^{-3} kWh = $222/kWh.
   Comparison: Electrical energy from the battery costs $222/$0.10 = 2,220 times as much as that delivered by the power company.

9.

Fuel	Price[1]	Energy Content of Fuel	Cost per MBtu	Cost of Home Heating[2]
Natural gas	$1.14/ccf	1,030 Btu/cf	$11.07	$1,660
Propane	$1.69/gal	92 k Btu/gal	$18.37	$2,755
Fuel oil	$1.93/gal	133 k Btu/gal	$14.51	$2,177
Electricity	$0.10/kWh	3,412 Btu/kWh	$29.31	$3,517[3]

1. Prices quoted are for home delivery of respective fuels at rates available in the north central U.S. in 2005.
2. Computations assume a heating requirement of 120 MBtu for the "average" home in the northern U.S. Efficiencies of 80 percent are assumed for gas or oil furnaces. Heat from electricity is assumed to be delivered at 100 percent efficiency in the home.
3. Homes designed for electric heating are usually insulated more thoroughly than those designed for gas or oil.

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Contributors

About the Editor

David Hong teaches AP Environmental Science at Diamond Bar High School in Diamond Bar, California. He earned a B.S. in chemistry from California State Polytechnic University: Pomona, and an M.A. in educational administration from California State University: Los Angeles. Since joining the faculty at Diamond Bar High School in 1990, he has taught AP Environmental Science, AP Physics B, AP Physics C, physics, and chemistry. He has been an AP Environmental Science Reader and a College Board consultant since 1999, and is currently a member of the AP Environmental Science Development Committee. He has also participated in the Toyota International Teacher Program, a weeklong NASA Educational Workshop, the Aquarium of the Pacific's teacher excursion to the Sea of Cortez, and twice in the Department of Energy's Teacher Research Associate (TRAC) Program.

Thomas B. Cobb is a professor emeritus of physics and the former director of environmental programs at Bowling Green State University in Ohio. He is a former member and chair of the AP Environmental Science Development Committee, and has participated in the Reading for six of the seven years that the AP Environmental Science Exam has been given. At BGSU he introduced a course in environmental physics that is taken by most environmental majors. He is active in presenting training workshops in environmental science for the College Board.

Fred Loxsom is currently an endowed professor in sustainable energy studies at Eastern Connecticut State University, where he is developing an undergraduate program in sustainable energy. He earned an undergraduate degree with a major in physics from Bowdoin College and a Ph.D. in physics from Dartmouth College. For many years, he was a professor of physics at Trinity University in San Antonio, Texas, where he developed and taught courses for graduate and undergraduate students, including an introductory environmental physics course. He also team-taught a course in sustainable development in Costa Rica and carried out research in atmospheric physics and applied solar energy studies. He has been chair of the AP Environmental Science Development Committee since 2000.

Alan McIntosh has taught since 1983 at the University of Vermont, where he is a professor and chair of the Environmental Sciences Program in the Rubenstein School of Environment and Natural Resources. He received his B.S and M.S. in zoology from the University of Illinois and a Ph.D. in limnology in the Fisheries and Wildlife Department at Michigan State University. Before coming to Vermont he was on the faculties of Purdue and Rutgers universities. He currently teaches Introduction to Environmental Sciences to about 75 students each semester as well as specialty courses in toxic substances and pollution ecology.

Pamela Shlachtman received her bachelor's degree in chemistry from the University of Miami (1976) and a master's degree in environmental and urban systems from Florida International University (1986). She was an adjunct instructor in environmental sciences at Miami Dade College and Florida International University during the 1980s and has served as a science instructor in the Miami-Dade County Public Schools for the past 21 years, many of those as chair of the science department. Her professional accomplishments include designing and reviewing science curricula for the Miami-Dade County Public Schools, consulting for the College Board in AP Environmental Science, and the receipt of several Teacher of the Year awards. She coached her 2004 Canon Envirothon team to a first-place finish in the North American competition. She is currently a member of the AP Environmental Science Development Committee.

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