Future Energy: Opportunities and Challenges

Part III. Energy Demand

Chapter 19. Energy and Climate Change

Future Energy:
Opportunities and Challenges

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19
Energy and Climate Change

The Main Points

- **A balance between solar radiation absorption and radiation emitted by the earth determines the average earth temperature.**
- **Solar radiation and radiation emitted from the earth occur at different wavelengths.**
- **Atmospheric gases preferentially absorb radiation at certain wavelengths.**
- **Water vapor is the major absorber of earth radiation emissions.**
- **Carbon dioxide is the major earth radiation absorber that is released as a result of human activity.**
- **Fossil fuel combustion and deforestation cause increases in atmospheric carbon dioxide.**
- **There is no doubt that atmospheric gases affect the earth's temperature, but predicting the temperature rise for a specific change in atmospheric gas concentration is difficult and uncertain.**
- **Data show that the concentration of atmospheric carbon dioxide is increasing.**
- **Data show that the average earth temperature began increasing after the Industrial Revolution.**
- **The scientific consensus is anthropogenic gases in the atmosphere are causing global warming.**

19.1 Introduction

Many processes for energy production, especially fossil fuel combustion, result in the release of gases into the atmosphere. Some of these gases are strong absorbers of radiation emitted from the earth. The greenhouse effect is the heating of the atmosphere by trapping radiated heat energy from the earth.

Understanding the science of climate change is essential in assessing the impact of energy-related activities. The science is unfamiliar to many, but rests on firmly validated physics. Appendix J provides a short summary of the underlying physics of radiation production and absorption. A more descriptive explanation appears in the following sections.

19.2 Physics of the Greenhouse Effect

All substances whose temperatures are above absolute zero emit electromagnetic radiation. Figures 19-1 and 19-2 show the emission spectra for the sun (average surface temperature = 5800 kelvins) and for the earth (average surface temperature = 288 kelvins or 15°C or 59°F). The sun's emission spectrum peaks at a wavelength of 0.5 microns, and the region with significant amplitude lies mostly between 0.2 and 1.5 microns. (A micron is a unit of length equal to one millionth of a meter.) The earth's emission spectrum peaks at a wavelength of 10.1 microns and the region with significant amplitude lies mostly between 4 and 30 microns. The wavelengths at which significant emissions from the sun and from the earth occur are essentially distinct and non-overlapping.

Photons can be absorbed, reflected, or transmitted in interactions with matter. The relative probabilities of these occurrences depend on the target material involved and the wavelength of the photon.

The exchange of energy between two emitting and absorbing bodies is a crucial concept in greenhouse effect discussions. If a body absorbs radiation

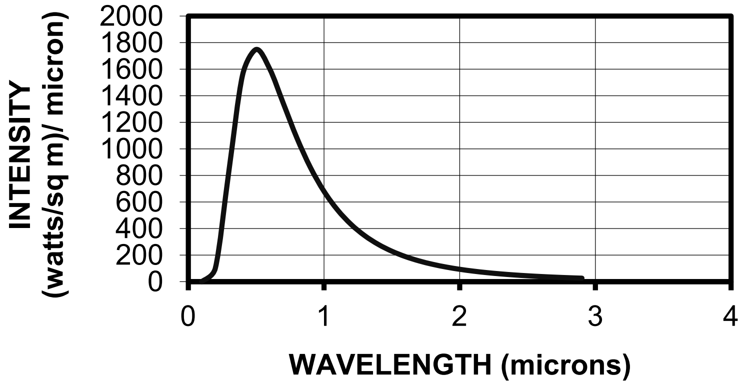

Figure 19-1. The Solar Spectrum

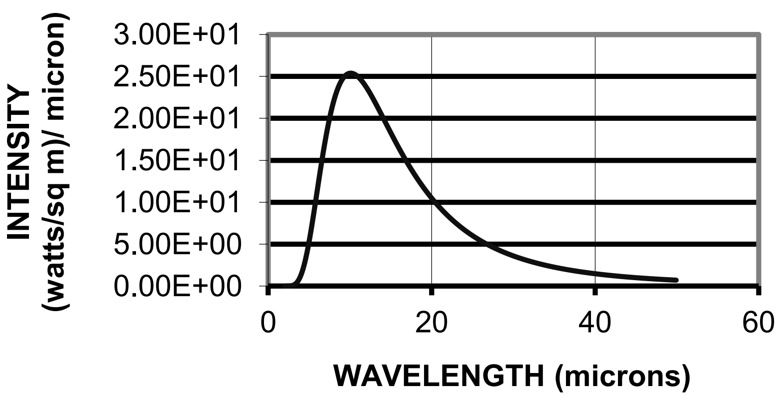

Figure 19-2. Earth's Radiation Spectrum

from another body, its temperature increases until its radiated energy equals the absorbed energy. Such is the case for the earth's temperature.

19.3 The Greenhouse Gases

The atmospheric gases with major photon absorption probabilities in the **sun's** emission spectrum are water, molecular oxygen, and ozone. The atmospheric gases with major photon absorption in the **earth's** emission spectrum are water, carbon dioxide, methane, nitrous oxide, ozone, and certain compounds of carbon and halogens (such as Freon). Water vapor is by far the largest absorber of radiation emitted from the earth. Water vapor is responsible for 90 to 95 percent of the atmospheric absorption of earth radiation emissions.

Because of the atmospheric absorption of earth emissions, some of the photons emitted from the earth do not escape into outer space. The earth's temperature must increase to achieve the energy transfer to outer space needed to balance the energy from incoming radiation.

The earth's temperature is higher than it would be if there were no greenhouse gases in the atmosphere. The increase in the earth's average temperature above the temperature that would occur if there were no greenhouse gases is estimated to be around 33°C (59°F). This warming is essential for life on earth. The concern is changes in the greenhouse effect due to human activities will further increase the earth's temperature and make it less suitable for sustaining life.

The greenhouse gases in the atmosphere include those that occur naturally and those that are due to human activities. Water vapor occurs because of evaporation (mostly from the oceans), and its atmospheric concentration is independent of human activities unless those activities cause changes in the rate of evaporation. Concentrations of the other important greenhouse gases in the atmosphere are the result of natural and manmade sources.

Carbon dioxide is the major contributor to anthropogenic global warming. The concentration of carbon dioxide in the atmosphere depends on the rate at which it is removed from the atmosphere by carbon sinks as well as the rate at which it is released to the atmosphere. The movement of carbon between the various carbon sources and sinks is called the carbon cycle. The three components of the carbon cycle are carbon in the atmosphere in the form of carbon dioxide, carbon in living and dead terrestrial and aquatic plants, and carbon dioxide dissolved in ocean water.

Carbon sinks can serve to reduce increases in atmospheric greenhouse gases, but the removal is not immediate, unlimited, or without deleterious side effects.

First, consider the anthropogenic production of carbon (6.3 billion tons per year) relative to inventories in the atmosphere (730 billion tons), in terrestrial vegetation and soil (2,000 billion tons), and in the oceans (38,000 billion tons)[1] (see Figure 19-3). The annual anthropogenic contributions to atmospheric carbon are a bit less than one percent per year of the total atmospheric inventory.

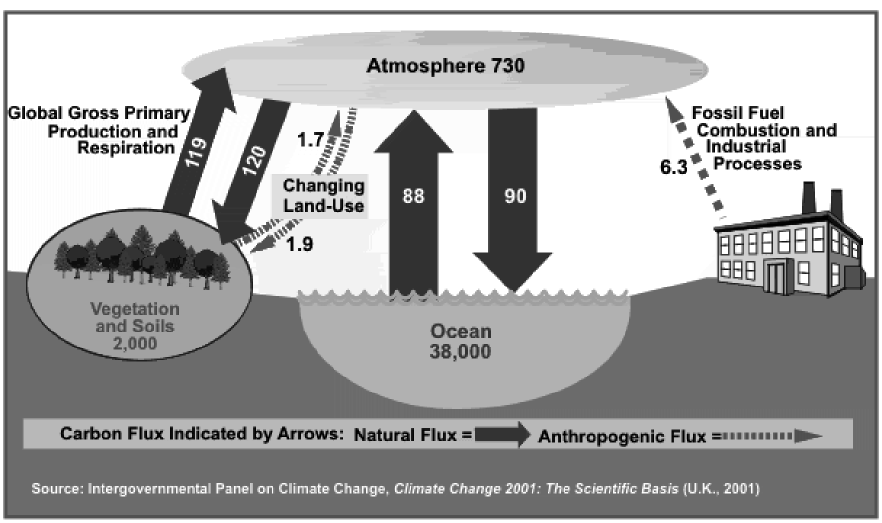

Figure 19-3. The Carbon Cycle
(courtesy of Intergovernmental Panel on Climate Change)

Measurements of atmospheric carbon dioxide have been made for air samples taken atop Mauna Loa in Hawaii[2]. The graph of the data appears in Figure 19-4. The sawtooth behavior is due to seasonal variations in the natural absorption of carbon dioxide by plants and in carbon dioxide release through microbial aerobic digestion of dead plant matter. The clear upward trend of carbon dioxide concentration is the concern in the context of global warming. The increase in atmospheric carbon concentration is about 1/2 percent per year.

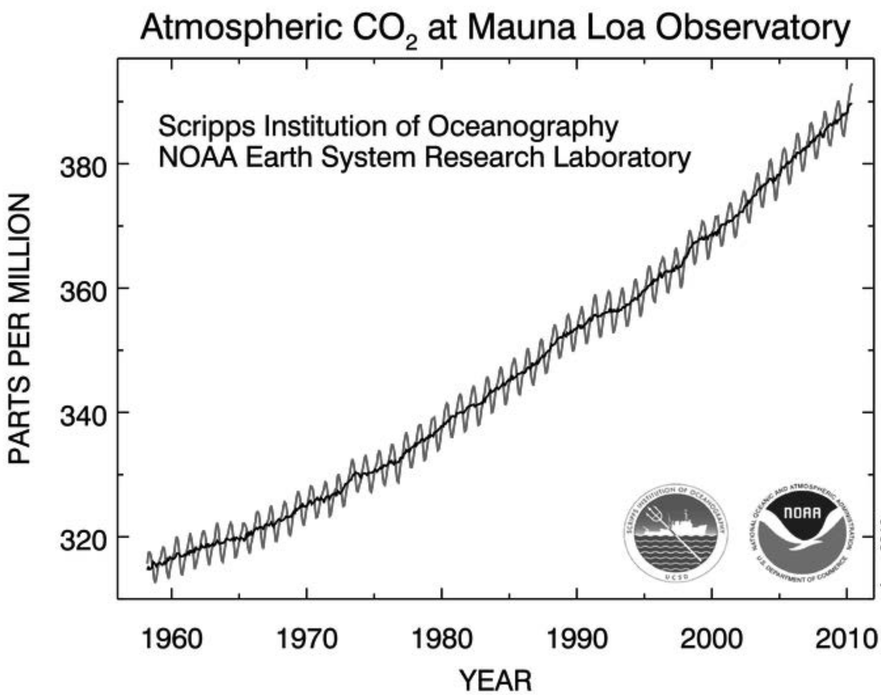

Figure 19-4. Carbon Dioxide Measurements at Mauna Loa
(courtesy of National Oceanic and Atmospheric Administration)

The fate of carbon introduced into the atmosphere depends on the exchanges between the three carbon reservoirs. Around 120 billion tons of carbon per year move back and forth between the atmosphere and terrestrial vegetation and soils, and around 90 billion tons per year move back and forth between the atmosphere and the oceans.

The difference between the carbon release rate into the atmosphere (around 1 percent of inventory per year) and the measured increase in carbon inventory (around 1/2 percent) is due to transfer of carbon to the oceans and to terrestrial sinks. One consequence is an increase in the acidity of ocean water.

19.4 The Greenhouse Effect

Any changes in the radiation absorbed from the sun and/or changes in the radiation emitted by the earth will affect the earth's climate. The main human activities that cause changes in atmospheric carbon dioxide concentrations are fossil fuel combustion and deforestation. Both of these activities release carbon that previously had been isolated from the atmosphere.

Carbon dioxide is an important greenhouse gas because:

- It is the second most important absorber (after water vapor).
- It is released in energy production activities, mainly the combustion of fossil fuels.
- Its atmospheric concentration is increasing.

Some of the other greenhouse gases are even stronger absorbers of earth emissions than carbon dioxide, but they occur in much lower concentrations. Therefore, their effect is smaller. For example, methane enters the atmosphere through naturally occurring processes and through anthropogenic processes, but at a lower rate than carbon dioxide releases. However, a methane molecule has over 20 times the greenhouse effect of a carbon dioxide molecule. Limiting methane releases is second in importance only to limiting carbon dioxide releases in controlling global warming. The other greenhouse gases produce much smaller warming effects.

19.5 The Greenhouse Debate

There is no uncertainty about the physics that defines the cause-and-effect relation between atmospheric gases, photon absorption, and the greenhouse effect. Since the cause-and-effect relation between atmospheric gas concentration and global warming is firmly established science, the issue is whether the cause (increased concentrations of certain anthropogenic gases in the atmosphere) is capable of significantly altering the earth's climate.

Many publications provide historical climate data. The main issue is the change in climate in the period since the Industrial Revolution. If a noticeable climate change occurred following industrialization, it may be taken as a likely indicator of human impact. If, on the other hand, trends after industrialization are simply the continuation of trends that existed before industrialization, then non-anthropogenic causes are indicated.

The Intergovernmental Panel on Climate Change[3] and the U.S. National Oceanic and Atmospheric Administration[4] rely on the temperature, snow cover, and ocean level data shown in Figure 19-5. The trends starting in the late nineteenth century are apparent. These data support, but do not prove, the hypothesis that human activities are causing global warming.

Attribution of the source of increased carbon dioxide in the atmosphere relies on complex climate science. The essence of the main scientific argument rests on observation of the presence of isotopic variations of carbon isotopes in the atmosphere[5,6]. There are three isotopes of carbon: carbon 12, carbon 13, and carbon 14. Carbon 12, a stable isotope with six protons and six neutrons in its nucleus, is the most common isotope, accounting for 99 percent of atmospheric carbon. Carbon 13, a stable isotope with six protons and seven neutrons in its nucleus, accounts for 1 percent of atmospheric carbon. Carbon 14, a radioactive isotope with six protons and eight neutrons in its nucleus, exists in trace amounts.

Carbon 14 is formed by reactions in the upper atmosphere between nitrogen and neutrons that are formed from cosmic rays. Carbon 14 has a half-life of 5,730 years. Until 1954, the equilibrium atmospheric carbon 14 con-

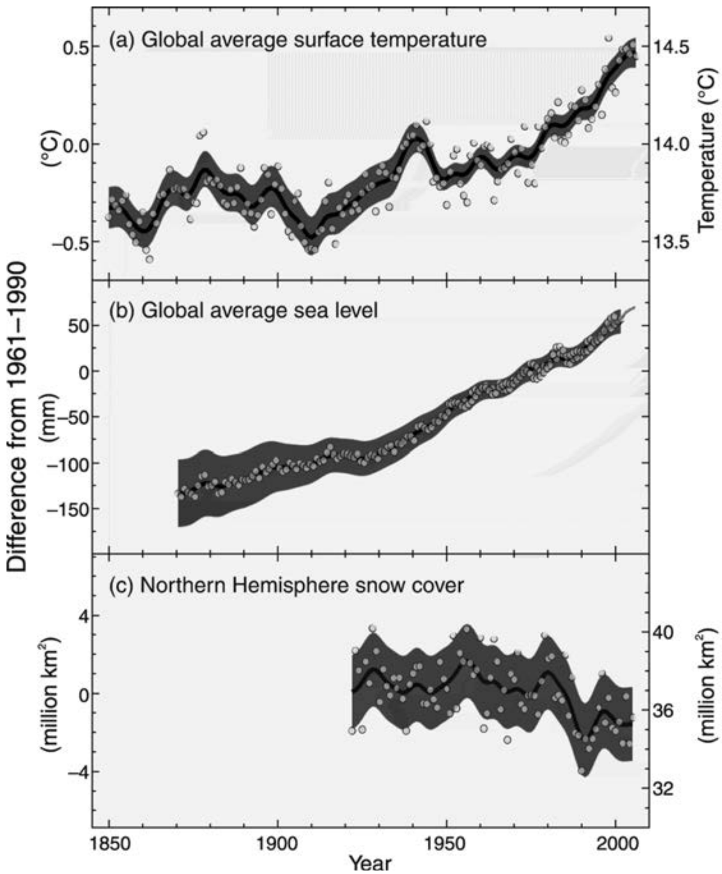

Figure 19-5. Climate-Related Changes
(courtesy of National Oceanic and Atmospheric Administration)

centration was the result of a balance between production in the upper atmosphere and loss by radioactive decay. After 1954, carbon 14 resulting from nuclear bomb tests altered the equilibrium. However, carbon 14 in tree rings provides a record of carbon 14 concentrations in recent decades. Carbon-containing materials that are isolated from the atmosphere have a steadily decreasing concentration of carbon 14 as radioactive decay proceeds. After several tens of thousands of years, the carbon 14 in isolated carbon is essentially gone. Such is the situation with fossil fuels that have been isolated for millions of years. Carbon with no carbon 14 will be called "old carbon," meaning it has been isolated long enough for the carbon 14 to decay to insignificant levels.

Carbon 13 provides a clue to the source of carbon found in the atmosphere. Chemical reaction rates usually do not depend strongly on the isotopic form of the chemicals involved. Photosynthesis is an exception. Photosynthesis favors reactions with carbon 12 over reactions with carbon 13. Consequently, biomass has a reduced proportion of carbon 13 relative to carbon 12 in its constituents. Carbon with reduced carbon 13 will be called "biomass-derived carbon."

The relative amounts of carbon 13 and carbon 14 in atmospheric carbon provide a signature that reveals the source of the carbon. Measurements show the percentages of carbon 13 and carbon 14 in the atmosphere are decreasing[3,5,6].

The decrease in the percentage of carbon 14 in the atmosphere indicates the added carbon is from a source that has been isolated from the atmosphere long enough for the carbon 14 to decay away. Fossil fuels and carbon-containing rocks have this property.

The decrease in the percentage of carbon 13 in the atmosphere indicates the source of the added carbon is one that originated in biomass. Fossil fuels have this property, and carbon-containing rocks do not.

The conclusion suggested by the carbon isotopic data is that the increase in atmospheric carbon is due to old and biomass-derived carbon. This is the characteristic of carbon that is released from the combustion of fossil fuels. Carbon from deforestation is "new carbon."

Of course, attribution of the cause of global warming requires consideration of all of those processes that can alter the balance between incoming solar energy and the emission of radiation from the earth.

The solar radiation reaching the earth may be altered by the following:

- Changes in the reflection of solar radiation back into space. (The fraction of incident radiation that is reflected into space is called the albedo, and its value is around 0.30. Suspended particulate matter (aerosols) in the atmosphere affects the albedo by provided sites that reflect sunlight. Aerosols may originate naturally (from events such as volcanic eruptions) or anthropogenically.

- Changes in the sun's energy output. (The sun's radiation emissions naturally undergo periodic small changes in intensity.)

- Changes in the earth's orbit around the sun and/or in the orientation of the earth's axis relative to the plane defined by the earth's orbit. (The earth's elliptical orbit around the sun undergoes shape changes that alter the earth-to-sun distance. The tilt of the earth's axis is known to have changed in the past, thereby altering the pattern of solar energy absorption.)

- Changes in the concentration of gases that absorb incoming solar radiation. (A change in absorption of incident radiation is not a greenhouse effect, but it can affect the energy balance. A change in atmospheric absorption of ultraviolet light by ozone is more of a health issue than a climate issue.)

Climate scientists analyzed and evaluated all of the processes described above before reaching a conclusion about the causes for observed climate changes. The scientific consensus is that changes in the earth's energy balance are occurring, and that these changes are due to increased atmospheric absorption of earth's emissions. Furthermore, the consensus is that greenhouse gas concentration is increasing, that there is conclusive evidence that the increases are largely caused by human activities, and that the increases are causing increases in the earth's average temperature. The scientific consensus is expressed in numerous reports, the most important being those from the Intergovernmental Panel on Climate Change (IPCC)[3], a panel working under the auspices of the United Nations and the World Meteorological Organization.

A more difficult climate science question is the quantitative relationship between atmospheric greenhouse gas concentration and the resulting temperature rise. It would be quite simple to develop a good mathematical model if the earth were a homogeneous solid body surrounded by a stagnant gas. In reality, the earth is very inhomogeneous, has a majority of its surface covered by water, and is surrounded by a very mobile mixture of gases and water vapor. These factors complicate the development of reliable climate models. The main issues are nonlinearities and feedbacks.

Nonlinearities are phenomena that result in effects not being proportional to causes. Consider the hypothetical scenario of atmospheric warming causing the melting of a large glacier located on land. The melting water flows into the seas, causing a rise in sea level. Eventually, the warming causes the glacier to break off and fall into the sea, causing an additional, sudden rise in sea level. The sudden change in the effect of warming is a nonlinear effect. Such effects complicate the development of climate models.

Feedback is the return of the output from a system to combine with an external input and thereby augment or diminish the net input. For example, consider a gas furnace. The flow of gas to the furnace (the input) determines the room temperature (the output). A home thermostat uses the difference between the measured temperature and the desired temperature to feed back a signal to increase or decrease the heat input.

Feedbacks also occur in nature, and they can be negative or positive. They may even have both positive and negative effects. Consider a scenario in which greenhouse gases undergo an increase. This will initiate a surface water temperature increase, causing evaporation to increase. The resulting increase in cloud cover would reflect solar radiation and reduce the warming (a negative feedback because it counteracts the effect of the initiating event). On the other hand, the increases in atmospheric water vapor (a greenhouse gas) would increase the absorption of photons emitted by the earth, thereby increasing warming. This is a positive feedback because it augments the effect of the initiating event. The net effect would be determined by the relative strengths of the two processes.

Nonlinearities and feedbacks make climate modeling very complicated. Nevertheless, numerous climate models have been developed and are undergoing continuous refinements. Some are extremely complex and require the most powerful computers for implementation. Validity is checked by calculation of climate changes from the past and making comparisons with measured data. Generally, the models do a good job of matching observed data. This gives confidence that the models are also capable of predicting future climate changes caused by increasing greenhouse gas concentration in the atmosphere. However, these comparisons do not prove conclusively that predictions of future climate are correct. The future may include much larger climate drivers and feedbacks than those seen in the past and may face new, unanticipated nonlinearities.

The inability to develop perfect models should not be a basis for minimizing or ignoring the impact of greenhouse gases on climate. Even though we cannot predict the exact temperature rise for a specified increase in greenhouse gas concentration, it is clear that the temperature will rise. Models based on various approximations give a range of values for estimated temperature rises. These results, along with historical temperature data, indicate anthropogenic global warming is happening, and it constitutes a serious problem.

However, there are still those (including some scientists) who disagree with this assessment. It is likely that some of those who discount warming due to anthropogenic greenhouse gas concentration increases are driven by their philosophy rather than by science. Mitigation of global warming would surely require some regulation of business and personal activities, and increased regulation is anathema to political and economic conservatives.

Continued disavowal of human-induced global warming in the face of the scientific evidence can only be based on the belief that the measurements or the interpretation of the measured data are flawed. The informed consensus is that this is not the case.

Those who disavow anthropogenic global warming represent a small minority of real or self-appointed climatologists, but they have received attention by the media and by government officials that is far out of proportion to their numbers. Their efforts have forced the scientific community to refine its analyses and to improve its dialogue with the public and with policy makers. On the other hand, the efforts of those who deny global warming have fostered confusion, have caused diversion of effort and funds from more useful pursuits, and have caused delays in important work and mitigation efforts.

19.6 Mitigation

Reducing atmospheric greenhouse gas concentrations will require voluntary lifestyle changes by citizens or changes brought about by government involvement, such as by imposing regulations that must be satisfied in order to build and operate systems and facilities and/or by creating economic incentives through taxing practices that release greenhouse gases. Government actions can also encourage energy conservation, energy efficiency, and energy production practices (such as reliance on renewable and nuclear energy) that do not contribute to global warming.

World governments negotiated an international treaty, called the Kyoto Protocol[7], designed to reduce atmospheric greenhouse gas concentrations. The protocol came into force in 2005. It had the goal of reducing collective world greenhouse emissions by 5.2 percent by 2012. Different countries were assigned different goals based on their emission levels and their state of economic development. The goals for individual countries may be higher or lower than the collective goal. Developing countries are excused from emission reduction in order to permit greater economic development. Countries in the developing category include China and India. Though the economies in these countries are considered to be in the developing stage, they are already major competitors in the world economy. The U.S. refused to ratify the Kyoto Protocol because of concerns that it would make U.S. industry less competitive with industry in exempt countries.

A key element of the mitigation strategy in the Kyoto Protocol is that of "emission trading." Emission trading is based on the concept of Cap-and-Trade. In a cap-and-trade arrangement, greenhouse gas emitters have emission allowances. If an emitter produces less than its emission allowance, it can sell emission credits to other emitters. The trading occurs between countries, between partnerships of multiple countries and between individual industrial emitters within a country. For example, an old power plant might be unable to meet its emission allotment without expensive system or operating changes. Credits could be purchased from another plant that emits less than its allowance. Critics say the cap-and-trade scheme only creates a new, cumbersome bureaucracy, it shifts the site where emissions occur, and it creates an unacceptable tax on energy production. However, the scheme creates an economic incentive for reducing emissions and thereby avoiding the need to purchase credits.

The Kyoto Protocol was difficult to negotiate, is limited in scope, and is caught in a conflict between compliance and competitiveness. As such, Kyoto must be viewed as a first step in developing effective international policies to reduce greenhouse gas emissions. A second climate change meeting was held in Copenhagen in 2009[8]. The U.S. and other developed countries made non-binding pledges to contribute billions of dollars to poor countries to help them in reducing carbon emissions. Copenhagen is generally viewed as a step forward, but with minimum real progress on controlling climate change.

It is noteworthy that some feel that we should simply adapt to climate change rather than trying to prevent it. For example, Lord Nigel Lawson[9], former Chancellor of the Exchequer in Britain, argues that adaptation is preferable to mitigation efforts. If global warming proceeds as feared, some of the predicted consequences are the flooding of coastal cities and major changes in the location of land suitable for farming. These effects would lead to large migrations of people and would require a rebuilding of a large part of the infrastructure that supports modern society. The adaptation argument is valid only if the hardship of making these changes is less than the hardship of mitigation activities. No one knows the answer to the question of relative hardships. The rationale behind adaptation is that global warming may not occur, and, if it does, we can handle it.

19.7 Other Environmental Effects

Global warming is the energy-related environmental effect that has received the greatest attention. However, there are other byproducts of energy production that can harm people and damage the environment. The impacts on people and the environment are usually called external costs. These costs include pollution, ecosystem damage, changes in land use possibilities, and sickness or death of humans. External costs are impossible to determine unequivocally. It is difficult to attribute undesirable effects to specific causes, and it is impossible to put a standard value on something like sickness or death. Assessing external costs is further complicated by the delay that may exist between creating the impact and the appearance of resulting problems. Nevertheless, external costs are real, and it is certain that the true cost of energy production is significantly higher than current cost levels that ignore external costs. Examples of external costs follow:

Solids produced during energy-related activities constitute waste that must be stored, eliminated or recycled. (See Chapter 4.) These wastes often contain harmful components such as heavy metals or pathogens. Rain can dissolve harmful constituents of mine waste stored at mine sites. Water used to wash coal to remove dirt and rock can carry harmful materials into aquifers. Spillage of stored ash from a coal-burning power plant can contaminate land and water. The massive ash spill at the TVA Kingston Plant in 2008[10] illustrates the problem.

Gases produced in fossil fuel combustion cause acid rain that can damage structures, damage farmland, and harm humans and animals. The main culprits are oxides of nitrogen and sulfur that react with atmospheric water to form acids.

Oil spills at well sites or during transport have produced major environmental damage. The Exxon Valdez oil tanker accident in Alaska[11] and the Deepwater Horizon drilling rig accident[12] in the Gulf of Mexico illustrate the problem.

Residents near natural gas wells that use hydrofracturing technology have experienced groundwater contamination by hydrocarbons and other chemicals. (See Chapter 4.) Residents in these locations have experienced increased disease and death, and they blame the wells. Some drilling proponents claim the residents' allegations are false or that the problems are unrelated to drilling, but questions remain.

Radioactive wastes were addressed in Chapter 11. Radioactive waste includes high-level waste from nuclear reactors and low-level waste from reactors, medical facilities, and industrial facilities. The volume of radioactive waste is much smaller than other forms of waste, but isolation from the human environment is essential.

Using land for energy production purposes can have undesirable environmental effects. For example, strip mining alters land unless it is fully remediated, and dams convert dry land into lakes and alter natural river flows. Coal extraction by mountaintop removal methods in Appalachia has left scarred landscapes.

19.8 Conclusions

There will be no attempt to prove or disprove conclusively in this book that anthropogenic global warming is occurring. Rather, it should be noted that the reality of anthropogenic global warming is supported by science, and by the interpretation of that science by the great majority of qualified scientists. Mitigation efforts have begun, but much remains to be done.

It should also be noted that concern about global warming is but one of two reasons to reduce the use of fossil fuels. The other is resource depletion. Those who dispute the need to curtail fossil fuel use must disavow both concerns.

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Exercises

19-1. According to Figure 5-1, 4 units of solar energy are reflected by the earth for every 51 units of energy absorbed. All other energy effects occur in the atmosphere. Now consider a hypothetical earth with no atmosphere.

A. How much energy would be absorbed per square foot per day?

B. How much total energy would be absorbed and re-emitted per day?

C. Estimate the temperature of an earth with no atmosphere. (See Appendix J.)

19-2. Water vapor has the largest greenhouse effect by far. So why are people worried about carbon dioxide?

19-3. Explain why the solar emission spectrum and the earth emission spectrum enter into the physics of the greenhouse effect.

19-4. Outline and discuss the data from historical records of average earth temperature, sea level, and snow cover. Include their relevance to attribution of the cause of climate change.

19-5. Why are the Mauna Loa data important with regard to the attribution of causes for climate change?

19-6. Outline and discuss the role of carbon isotopic data on attribution of the causes for climate change.

19-7. Use the Internet to find an article that debunks anthropogenic climate change. Prepare an evaluation of the article.

19-8. Use the Internet to discover whether there have been additional major international agreements since Kyoto and Copenhagen. If so, discuss and interpret your findings.

19-9. Cap-and-trade is a controversial issue in the U.S. as this book is being written. What is the current government policy on cap-and-trade in the U.S.?

19-10. What do you think should be done about charging for the external costs associated with energy production?

19-11. Nonlinear effects occur when effects are not directly proportional to causes. Is the relation between potential energy and height linear or nonlinear? How about the relation between kinetic energy and velocity? Describe an example of nonlinear behavior in everyday life.