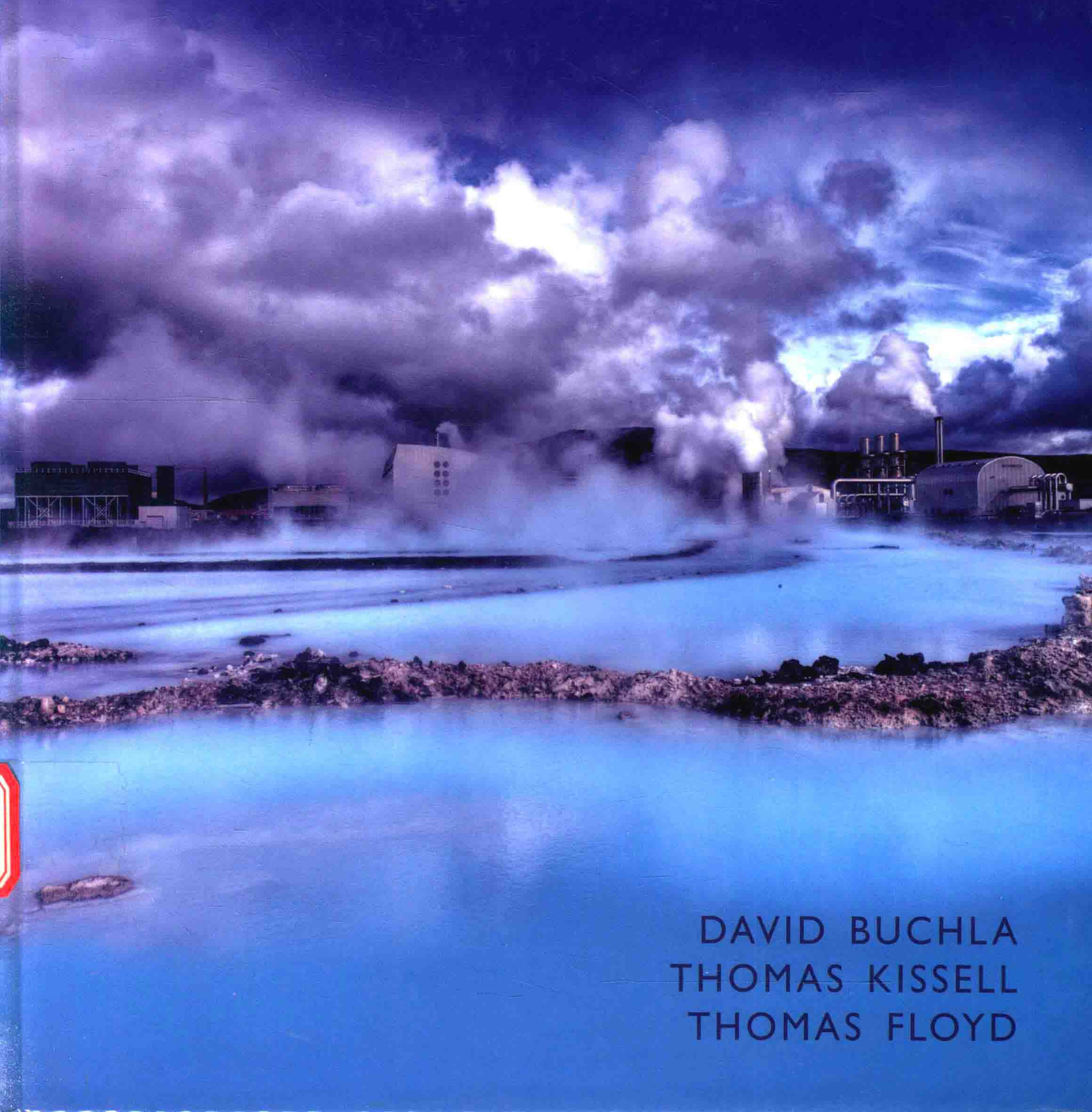
RENEWABLE ENERGY SYSTEMS



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PREFACE

Renewable Energy Systems is an introductory text with broad coverage of all the major renewable energy systems, resources, and related topics. The major types of systems are solar, wind, geothermal, biomass, and hydropower (including water in rivers and oceans). Related topics include electrical fundamentals, charge controllers, inverters, generators, fuel cells, the electrical power grid and the smart grid.

In the past few years, interest in renewable energy has grown in both the public and private sectors, with significant government support for research and for constructing large systems, such as solar installations, wind farms, and other projects. As a result of this research, exciting new technology is being developed that attest to a future with a variety of new opportunities. Innovations in the field include more efficient multijunction photovoltaic (PV) cells and cells with built-in charge storage using supercapacitors, high-flying wind turbines, systems for capturing tidal and wave energy in the ocean, and enhanced algae-growing methods, to name a few. Many people are optimistic about the future potential of renewable energy for supplying a larger portion of the worldwide energy needs.

Energy is a complex topic involving competing interests, but in general there is broad agreement by the public that the world needs to move toward more renewables for supplying energy needs. A single technology cannot solve all of the energy needs of the future or is best in all situations because resources vary significantly by location. In addition, different applications often compete for finite resources. For example agricultural land can be used for food production or for growing corn for ethanol or for a utility PV system. It is clear, however, that more people must understand renewable energy and its promise and limitations including all viable renewable energy technologies, sources, energy conversion systems and the environmental impacts (both positive and negative).

Renewable energy systems convert basic resources into usable forms of energy, including electricity, heat, and mechanical motion. In some cases, the renewable source is used to create a fuel, as in the case of ethanol or hydrogen fuel for use in fuel cells. Fuel cells in themselves are not a renewable source: Fuel cells may convert solar or other renewable source to the fuel used by the fuel cell but most fuel cells convert natural gas (a fossil fuel) to electricity. Fuel cells are becoming more important in providing electrical energy, particularly in remote areas or for backup power.

Many changes have occurred in recent years to renewable energy systems. For example, the capture of solar energy is shifting from smaller, customer-owned systems that are designed to supplement utility power, to large arrays that produce significant power (more than 1 megawatt [MW]) and are owned by utilities, the military, or industrial complexes. About half of solar power generation in the United States is in large utility power installations. Wind turbines have become massive with power outputs as high as 5 MW to 10 MW. Innovations in major systems like variable-speed generation and new power electronic and supervisory control systems are improving the efficiency of wind farms. New, enhanced geothermal production can capture more of the available energy with techniques such as fracking in hot dry rocks and injecting fluids in a closed-loop arrangement, which helps conserve water in desert environments. The organic Rankine cycle (ORC) is more prevalent in large systems because it can be used to obtain energy from lower-temperature sites. Future geothermal power plants may also be able to sequester carbon dioxide, actually helping the environment. Tidal energy has been captured in several parts of the world; a new crossflow turbine operates in the mouth of the Bay of Fundy, almost directly northeast of the coast of Maine, and a new wave energy system is being installed off the coast of Oregon. We have attempted to highlight these new systems and innovations throughout this text. In particular, the sidebars in many of the chapters feature innovative ideas; not all will eventually pan out, but they show the nature of this growing and dynamic field.

Chapter 1 presents an overview of the principal energy resources: fossil fuels, nuclear energy (including the future potential of fusion energy), and renewable energy, and where these resources are located. Most renewable energy is converted to electricity; for this reason Chapter 2 provides an introduction to electricity and magnetism, and discusses basic circuit laws, components, circuits, electrical measurements, and safety. Chapter 3 introduces the photovoltaic (PV) cell and its application to solar power systems. Solar modules and manufacturer's specification sheets are also covered. Chapters 4 and 5 continue the topic of solar energy with coverage of various types of solar energy systems and their operation, including concentrating systems and tracking methods for panels and heliostats. Chapter 6 discusses components that are important in many renewable energy systems, such as certain solar, wind, and fuel cell systems, with particular attention being paid to battery chargers, charge controllers, and inverters. Chapter 7 is an introduction to wind energy, including power in the wind, Betz's law, and an overview of wind turbines. Chapter 8 delves further into the operation of wind turbines with details of turbine control, measurements, and braking systems. Chapter 9 covers the major types of biomass and the systems used for converting biomass into oil or electrical power, and heat energy. Biomass has been used by humans for heat since our early ancestors first used wood fires for cooking and heat; today, biomass is used for power generation, heat, and biofuels (primarily ethanol). Chapter 10 gives an overview of geothermal energy and energy conversion systems for both electrical systems and heat pumps. Geothermal heat pumps are proving their worth in many areas, and geothermal energy is a significant resource that has barely been tapped. Chapter 11 covers various systems for extracting energy from moving water, including water from hydroelectric dams, streams, tides, and waves, and the methods for converting this energy to electricity. Chapter 12 discusses fuel cells and their applications, which have great potential to bring reliable power to remote locations of the world. Chapter 13 expands the discussion of magnetic theory, which was introduced in Chapter 2, and applies this to various types of electrical generators and how they are used in renewable energy systems. Finally, Chapter 14 gives an overview of the electrical grid, including the smart grid, and methods of power transmission, and it introduces the topic of three-phase ac and transformers.

Features

- The book is in full-color.
- Chapter openers have a chapter outline, objectives, key terms list, and introduction.
- Section openers in each chapter give a brief overview of what each section within a chapter covers.
- Section checkups contain questions related to each section within a chapter. Answers to section checkups are provided at the end of the chapter.
- Key terms are shown in bold and color in the running text. Definitions for key terms are provided at the end of the chapter and in the end-of-book glossary. Bold terms in black are defined in the end-of-book glossary only.
- Margin features are given throughout the book at appropriate places to highlight interesting innovations or historical information related to the topic being covered.
- Worked-out examples are provided throughout the text.
- Each chapter comes with abundant illustrations. Many are original and previously unpublished.
- Important formulas are numbered throughout each chapter, and they are listed at the end of each chapter for quick reference.
- A summary of the chapter discussion is provided at the end of each chapter.
- A true/false quiz, a multiple-choice quiz, and a set of chapter questions and problems appear at the end of each chapter.
- Answers to the chapter true/false multiple-choice quizzes are given at the end of the chapter.

- A suggested class discussion item appears at the end of each chapter under the heading For Discussion.
- A list of variables and their meanings is provided at the end of the book.

Instructor Supplements

To access supplementary materials online, instructors need to request an instructor access code. Go to www.pearsonhighered.com/irc to register for an instructor access code. Within 48 hours of registering, you will receive a confirming e-mail including an instructor access code. Once you have received your code, locate your text in the online catalog and click on the Instructor Resources button on the left side of the catalog product page. Select a supplement, and a login page will appear. Once you have logged in, you can access instructor material for all Pearson textbooks. If you have any difficulties accessing the site or downloading a supplement, please contact Customer Service at http://247pearsoned.custhelp.com/.

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PowerPoint slides that support the text with illustrated chapter summaries and discussions, new examples, selected key terms, and a true/false quiz are available for instructors.

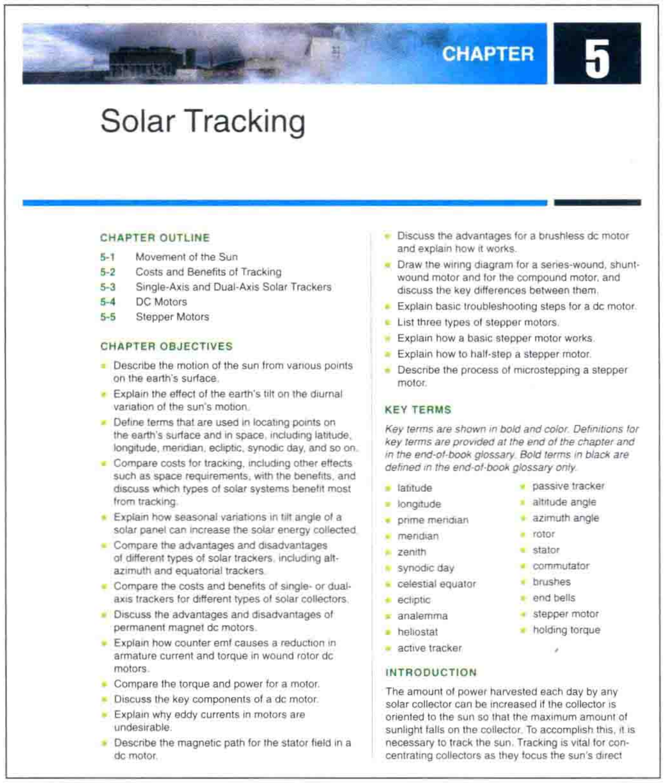
Online Instructor's Manual

Answers and solutions to all questions and problems are in the Instructor's Manual.

Illustration of Features

- ***Chapter opener*** Each chapter begins with a full-page opener.

FIGURE P-1 Typical Chapter Opener



CHAPTER 5

Solar Tracking

CHAPTER OUTLINE

5-1 Movement of the Sun
5-2 Costs and Benefits of Tracking
5-3 Single-Axis and Dual-Axis Solar Trackers
5-4 DC Motors
5-5 Stepper Motors

CHAPTER OBJECTIVES

- Describe the motion of the sun from various points on the earth's surface.
- Explain the effect of the earth's tilt on the diurnal variation of the sun's motion.
- Define terms that are used in locating points on the earth's surface and in space, including latitude, longitude, meridian, ecliptic, synodic day, and so on.
- Compare costs for tracking, including other effects such as space requirements, with the benefits, and discuss which types of solar systems benefit most from tracking.
- Explain how seasonal variations in tilt angle of a solar panel can increase the solar energy collected.
- Compare the advantages and disadvantages of different types of solar trackers, including alt-azimuth and equatorial trackers.
- Compare the costs and benefits of single- or dual-axis trackers for different types of solar collectors.
- Discuss the advantages and disadvantages of permanent magnet dc motors.
- Explain how counter emf causes a reduction in armature current and torque in wound rotor dc motors.
- Compare the torque and power for a motor.
- Discuss the key components of a dc motor.
- Explain why eddy currents in motors are undesirable.
- Describe the magnetic path for the stator field in a dc motor.
- Discuss the advantages for a brushless dc motor and explain how it works.
- Draw the wiring diagram for a series-wound, shunt-wound motor and for the compound motor, and discuss the key differences between them.
- Explain basic troubleshooting steps for a dc motor.
- List three types of stepper motors.
- Explain how a basic stepper motor works.
- Explain how to half-step a stepper motor.
- Describe the process of microstepping a stepper motor.

KEY TERMS

Key terms are shown in bold and color. Definitions for key terms are provided at the end of the chapter and in the end-of-book glossary. Bold terms in black are defined in the end-of-book glossary only.

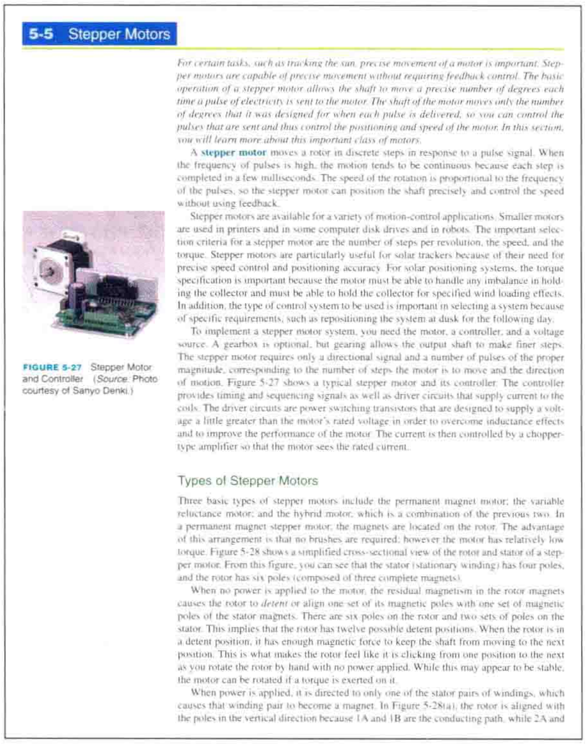
- latitude
- longitude
- prime meridian
- meridian
- zenith
- synodic day
- celestial equator
- ecliptic
- analemma
- heliostat
- active tracker
- passive tracker
- altitude angle
- azimuth angle
- rotor
- stator
- commutator
- brushes
- end bells
- stepper motor
- holding torque

INTRODUCTION

The amount of power harvested each day by any solar collector can be increased if the collector is oriented to the sun so that the maximum amount of sunlight falls on the collector. To accomplish this, it is necessary to track the sun. Tracking is vital for concentrating collectors as they focus the sun's direct

- ***Section opener*** Each section within a chapter begins with a brief introduction and overview.

FIGURE P-2 Typical Section Opener



5-5 Stepper Motors

For certain tasks, such as tracking the sun, precise movement of a motor is important. Stepper motors are capable of precise movement without requiring feedback control. The basic operation of a stepper motor allows the shaft to move a precise number of degrees each time a pulse of electricity is sent to the motor. The shaft of the motor moves only the number of degrees that it was designed for when each pulse is delivered, so you can control the pulses that are sent and thus control the positioning and speed of the motor. In this section, you will learn more about this important class of motors.

A **stepper motor** moves a rotor in discrete steps in response to a pulse signal. When the frequency of pulses is high, the motion tends to be continuous because each step is completed in a few milliseconds. The speed of the rotation is proportional to the frequency of the pulses, so the stepper motor can position the shaft precisely and control the speed without using feedback.

Stepper motors are available for a variety of motion-control applications. Smaller motors are used in printers and in some computer disk drives and in robots. The important selection criteria for a stepper motor are the number of steps per revolution, the speed, and the torque. Stepper motors are particularly useful for solar trackers because of their need for precise speed control and positioning accuracy. For solar positioning systems, the torque specification is important because the motor must be able to handle any imbalance in holding the collector and must be able to hold the collector for specified wind loading effects. In addition, the type of control system to be used is important in selecting a system because of specific requirements, such as repositioning the system at dusk for the following day.

FIGURE 5-27 Stepper Motor and Controller (*Source:* Photo courtesy of Sanyo Denki.)

To implement a stepper motor system, you need the motor, a controller, and a voltage source. A gearbox is optional, but gearing allows the output shaft to make finer steps. The stepper motor requires only a directional signal and a number of pulses of the proper magnitude, corresponding to the number of steps the motor is to move and the direction of motion. Figure 5-27 shows a typical stepper motor and its controller. The controller provides timing and sequencing signals as well as driver circuits that supply current to the coils. The driver circuits are power switching transistors that are designed to supply a voltage a little greater than the motor's rated voltage in order to overcome inductance effects and to improve the performance of the motor. The current is then controlled by a chopper-type amplifier so that the motor sees the rated current.

Types of Stepper Motors

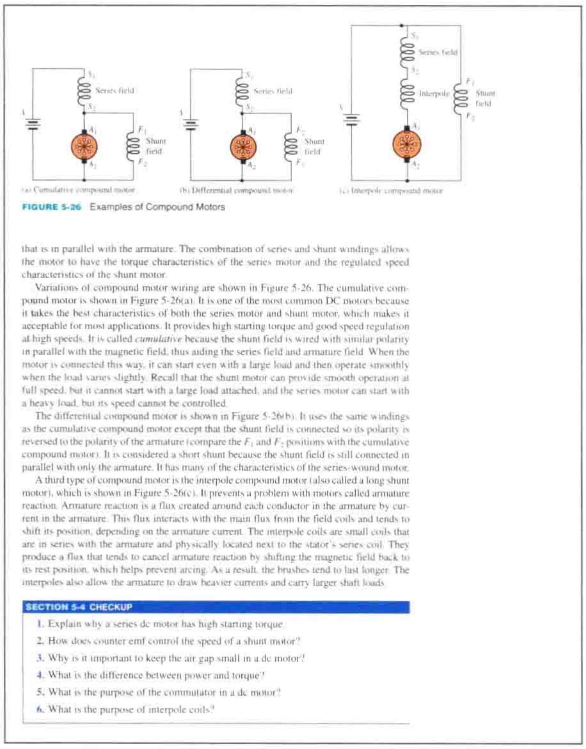
Three basic types of stepper motors include the permanent magnet motor; the variable reluctance motor; and the hybrid motor, which is a combination of the previous two. In a permanent magnet stepper motor, the magnets are located on the rotor. The advantage of this arrangement is that no brushes are required; however the motor has relatively low torque. Figure 5-28 shows a simplified cross-sectional view of the rotor and stator of a stepper motor. From this figure, you can see that the stator (stationary winding) has four poles, and the rotor has six poles (composed of three complete magnets).

When no power is applied to the motor, the residual magnetism in the rotor magnets causes the rotor to *detent* or align one set of its magnetic poles with one set of magnetic poles of the stator magnets. There are six poles on the rotor and two sets of poles on the stator. This implies that the rotor has twelve possible detent positions. When the rotor is in a detent position, it has enough magnetic force to keep the shaft from moving to the next position. This is what makes the rotor feel like it is clicking from one position to the next as you rotate the rotor by hand with no power applied. While this may appear to be stable, the motor can be rotated if a torque is exerted on it.

When power is applied, it is directed to only one of the stator pairs of windings, which causes that winding pair to become a magnet. In Figure 5-28(a), the rotor is aligned with the poles in the vertical direction because 1A and 1B are the conducting path, while 2A and

- ***Section Checkup*** Each section within a chapter ends with a series of questions related to the section.

FIGURE P-3 Typical Section Checkup



(a) Cumulative compound motor (b) Differential compound motor (c) Interpole compound motor

FIGURE 5-26 Examples of Compound Motors

that is in parallel with the armature. The combination of series and shunt windings allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor.

Variations of compound motor wiring are shown in Figure 5-26. The cumulative compound motor is shown in Figure 5-26(a). It is one of the most common DC motors because it takes the best characteristics of both the series motor and shunt motor, which makes it acceptable for most applications. It provides high starting torque and good speed regulation at high speeds. It is called *cumulative* because the shunt field is wired with similar polarity in parallel with the magnetic field, thus aiding the series field and armature field. When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly. Recall that the shunt motor can provide smooth operation at full speed, but it cannot start with a large load attached, and the series motor can start with a heavy load, but its speed cannot be controlled.

The differential compound motor is shown in Figure 5-26(b). It uses the same windings as the cumulative compound motor except that the shunt field is connected so its polarity is reversed to the polarity of the armature (compare the F_1 and F_2 positions with the cumulative compound motor). It is considered a short shunt because the shunt field is still connected in parallel with only the armature. It has many of the characteristics of the series-wound motor.

A third type of compound motor is the interpole compound motor (also called a long shunt motor), which is shown in Figure 5-26(c). It prevents a problem with motors called armature reaction. Armature reaction is a flux created around each conductor in the armature by current in the armature. This flux interacts with the main flux from the field coils and tends to shift its position, depending on the armature current. The interpole coils are small coils that are in series with the armature and physically located next to the stator's series coil. They produce a flux that tends to cancel armature reaction by shifting the magnetic field back to its rest position, which helps prevent arcing. As a result, the brushes tend to last longer. The interpoles also allow the armature to draw heavier currents and carry larger shaft loads.

SECTION 5-4 CHECKUP

1. Explain why a series dc motor has high starting torque.
2. How does counter emf control the speed of a shunt motor?
3. Why is it important to keep the air gap small in a dc motor?
4. What is the difference between power and torque?
5. What is the purpose of the commutator in a dc motor?
6. What is the purpose of interpole coils?

- ***Examples*** Worked-out examples illustrate and clarify basic concepts and procedures.

FIGURE P-4 Typical Examples

where

$\mathcal{R}$ = reluctance, in At/Wb
l = length, in m
μ = permeability of the material, in Wb/At · m
A = area, in m^2

EXAMPLE 13-2

What is the reluctance of a solid 6.0 mm diameter toroid (a toroid has a doughnut shape) that has a mean length of 12 cm and a relative permeability of 3,200?

Solution
Start by converting the dimensions to m and find the area:

$$l = 0.12 \text{ m}$$

The radius is 3 mm = 0.003 m

$$A = \pi r^2 = \pi (0.003 \text{ m})^2 = 2.83 \times 10^{-5} \text{ m}^2$$

The permeability of the core is found from Equation 13-1:

$$\mu = \mu_0 \mu_r = (4\pi \times 10^{-7} \text{ Wb/At} \cdot \text{m})(3{,}200) = 4.02 \times 10^{-3} \text{ Wb/At} \cdot \text{m}$$

$$\mathcal{R}_{CORE} = \frac{l}{\mu A} = \frac{0.120 \text{ m}}{\left(4.02 \times 10^{-3} \frac{\text{Wb}}{\text{At} \cdot \text{m}}\right) \times (2.83 \times 10^{-5} \text{ m}^2)} = \mathbf{1.05 \times 10^6 \text{ At/Wb}}$$

A typical magnetic circuit has one or more air gaps, so the total reluctance of the magnetic circuit increases when there is an air gap. The total reluctance in a magnetic circuit is the sum of the reluctance of each element, just as the total resistance in an electrical circuit is the sum of the resistances. An air gap increases the reluctance dramatically over solid magnetic materials such as iron. Example 13-3 illustrates this concept.

EXAMPLE 13-3

Assume the toroid in Example 13-2 has a 2 mm air gap cut in it.

(a) What is the reluctance of the air gap?

(b) What is the reluctance of the total toroid and air gap? (Assume the toroid has the same mean length as in Example 13-2.)

Solution
Assume the magnetic field lines in the gap have the same area as the toroid (2.83×10^{-5} m^2)

(a) $\mathcal{R}_{AIR} = \frac{l}{\mu_0 A} = \frac{0.002 \text{ m}}{(4\pi \times 10^{-7} \text{ Wb/At} \cdot \text{m}) \times (2.83 \times 10^{-5} \text{ m}^2)} = \mathbf{5.62 \times 10^7 \text{ At/Wb}}$

(b) $\mathcal{R}_T = \mathcal{R}_{CORE} + \mathcal{R}_{AIR} = 1.05 \times 10^6 \text{ At/Wb} + 5.62 \times 10^7 \text{ At/Wb} = \mathbf{5.72 \times 10^7 \text{ At/Wb}}$

As you can see in Example 13-3, the air gap is responsible for most of the reluctance. For this reason, the air gap is kept as small as possible in generators and motors to minimize the reluctance. Rotors should have minimal clearance with the fixed magnetic path.

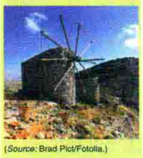
- ***Margin features*** Interesting sidebars are presented throughout the book. Their topics range from items with historical interest to new technology.

FIGURE P-5 Typical Margin Feature, Key Term, and Glossary Term

7-1 Power in the Wind

For hundreds of years, the wind has been studied scientifically, primarily to predict weather and its impact on human activities. In the last fifty years, advances in technology and the understanding of wind have been applied to the development of wind turbines. This understanding is important to developing and using the wind resource efficiently.

Ancient Wind Power



(*Source:* Brad Pict/Fotolia.)

Wind energy has been harnessed for centuries to grind grains (hence the name *windmill*) and pump water. The Greeks were known to use "watermills" called *hydraletës* as early as the first century BC. The photo shows an old Greek windmill that used sails to turn; these windmills can still be seen on some of the Greek Islands.

Physics of the Wind

The scientific study of the wind has helped scientists better understand wind and the causes of wind. This knowledge has led to better predictions of where the strongest and most continuous winds occur and to enable better placement of wind turbines. Wind varies from day to night, from season to season, and with environmental conditions such as ocean temperatures and cloud conditions. The ability to predict these effects in detail has proven to be challenging, even for the supercomputers of today.

Recall that in Section 1-4, global wind patterns were shown to be the result primarily of differential heating and the earth's rotation. Like all gases, air expands when heated and contracts when cooled. When the air is warmed, it rises and cools at high elevation, becoming denser. The rising and falling air currents cause large circulating cells of air. Superimposed on these large circulating currents of air are variations due to many other factors. Pressure variations in the atmosphere are one of the most important predictors of wind. To understand the energy in wind, it is helpful to review some physical science.

Pressure is defined as force per unit area and can be calculated by the following formula:

$$p = F/A \qquad \text{Equation 7-1}$$

where

p is pressure in newtons per square meter or pascals (Pa)
F is force in newtons (n)
A is area in square meters (m^2)

These units, which are perhaps unfamiliar, are derived units in the SI metric system. Several other pressure units are in common use, depending on application. The **pascal (Pa)** is a very small unit of pressure, so it is common in meteorology (weather science) to use the unit of the **millibar**. One millibar is equal to 100 Pa. A common pressure unit in the English system is the pound per square inch (psi). Each psi of pressure translates to 6,895 Pa. Another pressure unit is the **atmosphere (atm),** which is the pressure exerted by the atmosphere under specified conditions at sea level. One atm is defined as 1.013×10^5 Pa.

EXAMPLE 7-1

There are 4.448 newtons in one pound and 39.37 inches in a meter. Express atmospheric pressure in psi. (The number of Pa in 1 atm is 1.013×10^5.)

Solution
Set up the conversion so that units cancel:

$$1.013 \times 10^5 \text{ Pa} = 1.013 \times 10^5 \left(\frac{\text{n}}{\text{m}^2}\right)\left(\frac{\text{lb}}{4.448 \text{ n}}\right)\left(\frac{\text{m}}{39.37 \text{ in}}\right)^2 = \mathbf{14.7 \frac{lb}{in^2}}$$

In addition to the pressure units given above, meteorologists frequently use millimeters of mercury (mmHg) or occasionally inches of mercury (in Hg). These units represent the pressure exerted by the atmosphere on a column of mercury contained in an evacuated tube. The height of the mercury column is proportional to the atmospheric pressure. This value is often referred to as **barometric pressure**, which is the pressure exerted by the

- ***Key terms and other glossary terms*** Key terms are highlighted in bold and blue; these terms are defined at the end of each chapter *and* in the end-of-book glossary. Other important terms are shown in bold and black throughout the book; these terms are defined in the end-of-book glossary only. See the examples in Figure P-5.

Acknowledgments

The authors wish to thank Vern Anthony, Lindsey Gill, Rex Davidson, and Maren Beckman at Pearson Education; Penny Walker at Aptara; and Marianne L'Abbate at Double Daggers Editing Services for their help in bringing this book to reality. We relied heavily on the expertise of numerous reviewers who contributed to the content and coverage of the topics. These reviewers include James A. Buck, Wayne Technical & Career Center; Lazaro Hong, Pima Community College; and Dana Veron, University of Delaware.

Finally, we gratefully acknowledge the support of our wives, Lorraine, Kathleen, and Sheila. We dedicate this book to them.

David Buchla
Tom Kissell
Tom Floyd

BRIEF CONTENTS

CONTENTS

CHAPTER 1

Energy Sources and Environmental Effects

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe fossil fuel sources and major sectors for which it is used.
- Explain how a pressurized water reactor generates electricity.
- Discuss the advantages of fusion reactors as a future option for energy production.
- Explain the locations that you would expect to find the best resources for solar, wind, and geothermal energy.
- Compare the environmental impacts of various energy sources, including various renewable resources.
- List the type of information you would need to plan for a solar or wind power station.
- Explain what is meant by *biomass*. What are various biomass sources?
- Discuss the distribution of biomass resources.

KEY TERMS

Key terms are shown in bold and color. Definitions for key terms are provided at the end of the chapter and in the end-of-book glossary. Bold terms in black are defined in the end-of-book glossary only.

- fossil fuels
- hydrocarbon
- diagenesis
- kerogen
- bitumen
- catagenesis
- breeder reactor
- pressurized water reactor (PWR)
- Tokamak
- inverse square law
- solar constant
- global horizontal irradiance (GHI)
- direct normal irradiance (DNI)
- diffuse horizontal irradiance (DHI)
- biomass
- ethanol

INTRODUCTION

The Industrial Revolution ushered in an era of prosperity unlike any other in the long history of humanity. With it, came a surge in energy usage throughout the world, which has continued to increase to this day. The rate of energy consumption increased dramatically over a period of just a few generations near the end of the nineteenth century. The principal source of energy in the United States at the start of the nineteenth century was wood, with other sources (water and wind) playing a minor role. At the close of the nineteenth century, coal became the dominant energy resource because of its high energy content, ready availability, and demand from the railroads. During the twentieth century, coal continued to be an important resource, but petroleum moved up dramatically as motor vehicles became widespread. In the last part of the twentieth century, nuclear energy and natural gas became important parts of the energy mix.

It became obvious that the world was using fossil fuels at an increasing rate and that there is a finite limit to fossil fuels, so people have been looking for alternative energy sources. Renewable energy use has grown, but it still accounts for only a small fraction of the world's total energy consumed. Abundant renewable resources are available, but the issue is to find ways for them to be competitive economically with fossil fuels. The specific renewable energy that is best for a given location varies, so one best resource is not available for all places. This chapter focuses on the supply side of the major renewable resources and effects on the environment. Nearly all of the renewable resources have much less environmental impact than fossil fuels do, but many other issues must be considered (such as land use, costs, and resource availability) before developing a specific resource. This chapter focuses on the resources and explores these other issues. The bottom line is that no renewable source is entirely free of negative effects on the environment, and many issues are complicated by competing factors.

One important factor is *energy payback time*. It is important to keep in mind that all energy sources should be required to produce more energy than was expended in developing the sources. All sources require a certain amount of material for development. It requires energy to make the steel to build the drill rig to develop a natural gas well, and it requires more steel to build the pipeline to transport it. A certain amount of the natural gas that is produced must offset this energy cost. The time required to produce enough energy from the source is the payback time. Payback times vary widely with the particular source, but they need to be considered to evaluate any source of energy fairly.

1-1 Fossil Fuels: Oil, Coal, and Natural Gas

Fossil fuels are fuels formed over millions of years from decaying plants and marine diatoms. They are considered to be nonrenewable because they required millions of years to form and they are consumed at a rate that far exceeds their rate of formation. Fossil fuels account for a significant fraction of worldwide energy usage. Nuclear and renewable resources represent the remainder. Although this section is primarily devoted to discussing fossil fuels, a short overview of renewable sources is included.

Fossil Fuels

Fossil fuels are fuels formed from decaying plant and animal matter that was primarily formed over millions of years. Fossil fuels include coal, oil (petroleum), and natural gas. These fuels have been the primary energy source for over 200 years, but they will eventually have to be replaced by other sources because the world supply of fossil fuels is finite. The amount of each type of fossil fuel that is left is debated, but it is clear that the continued rate of use for any fossil fuel cannot be sustained. Today, fossil fuels supply approximately 80% of the energy consumed in the United States and about 87% worldwide according to the BP Statistical Review of World Energy.

An interesting tool for visualizing the sources of energy and ultimate outcome is the so-called spaghetti diagram, which was developed and used by Lawrence Livermore National Laboratory. Figure 1-1 shows the diagram with line width proportional to the percentage of each source; this one is for a recent year in the United States. It clearly shows the dependency on fossil fuels. The left side shows the various sources and the right side shows the demand sectors. Electricity is an intermediate step and not a demand in itself. Notice that the largest source of energy comes from petroleum. Approximately 72% of the petroleum is used in the transportation sector. In the case of electricity, 48% of electrical energy comes from coal-fired plants and, as you can see, the process creates a lot of rejected heat. Rejected heat is due to the inefficiencies in generating and distributing electrical power. Notice that electricity production is the primary user of coal. The best electrical generation plants are less than 50% efficient, and 5 to 10% of the energy is lost in transmission lines. It is important to be aware of the inefficiencies in the generating and distribution process because it affects other demand areas.

Renewable energy sources—biomass, hydroelectric, geothermal, wind, and solar—constitute only a small percentage of the overall mix at this time. All are covered in more detail throughout this text, but a quick overview of the current mix of renewable sources in the United States is shown in Figure 1-2. The mix has been changing rapidly in recent years, with significantly more wind energy. Biomass, the largest source, includes a variety of sources, including wood, waste, garbage, and even plants that are grown for fuel. Hydroelectric is the second largest source today because of the huge infrastructure of dams and power plants. Other sources (wind, geothermal, and solar) account for 14% of renewable use in the United States.

Worldwide consumption is continuing to rise for all fossil fuels. Fossil fuels include coal, petroleum and natural gas.

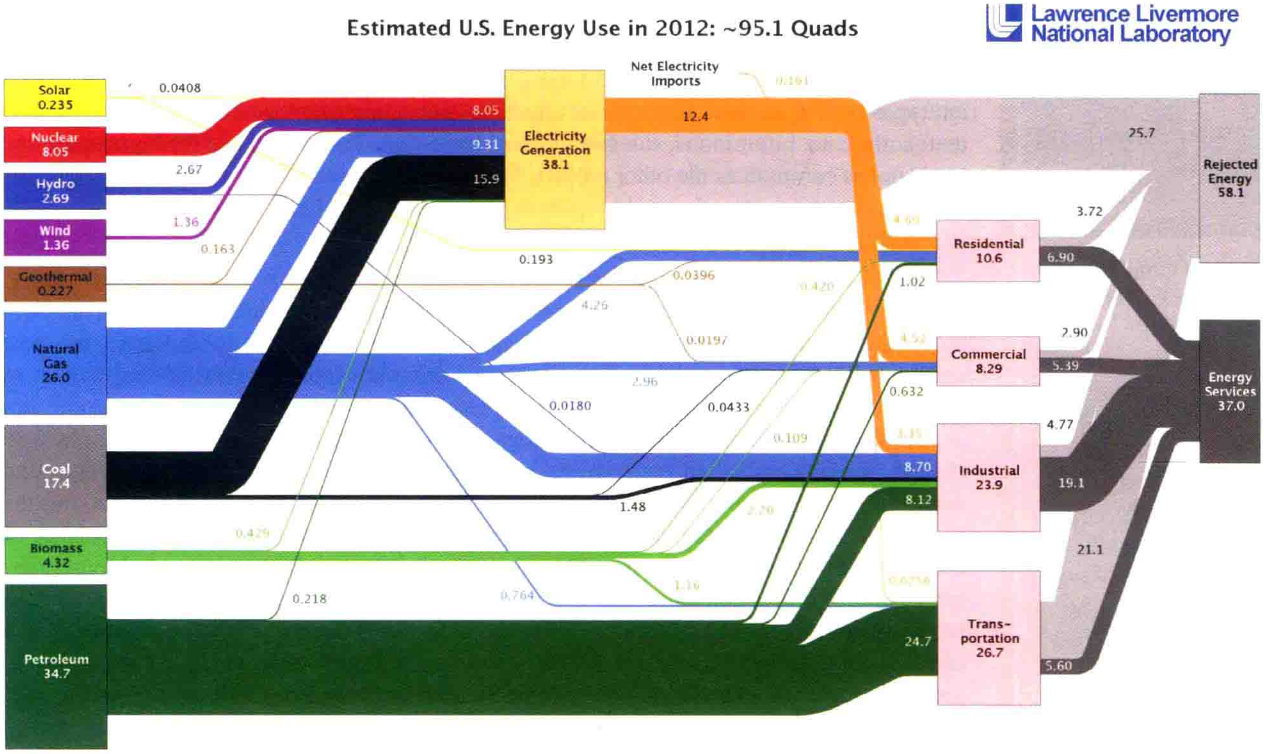


FIGURE 1-1 Energy Flow for the United States (*Source:* Lawrence Livermore National Laboratory. Reproduced by permission.)

Coal

Coal has been used as a fuel for more than 2,000 years, and historical records document its usefulness to the early Greeks, Romans, and Chinese as well as other cultures. Large-scale mining of coal was brought on by the Industrial Revolution with the development of the steam engine and improvements in steelmaking. Coal is a combustible rock that is composed mostly of carbon and hydrocarbons. A **hydrocarbon** is a molecule containing only hydrogen and carbon (but not all hydrocarbons are fuels). Coal is derived from ancient plant life, mainly trees. It is believed that these ancient terrestrial forests were flooded rapidly and eventually sank, where layer upon layer of dying plants was covered by sediments. Mild heat and pressure condensed the organic material into peat in a process called **diagenesis**. If enough heat and pressure is supplied, the organic material will undergo physical and chemical change to form coal. This process takes several million years and turns the peat

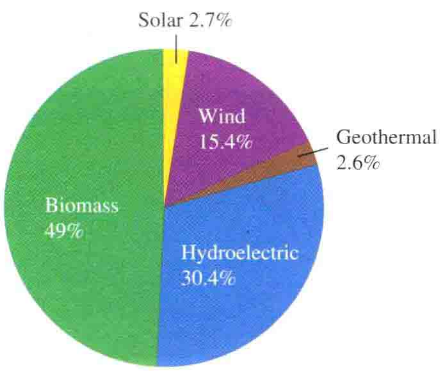


FIGURE 1-2 Renewable Energy Sources in the United States (*Source:* US Energy Information Administration.)

FIGURE 1-3 A Coal Seam in Sedimentary Rock (*Source:* David Buchla.)

La Brea Tar Pits

The La Brea Tar Pits in Los Angeles are part of an ancient reservoir that was not trapped by cap rock but migrated to the surface. The oil that seeped up became a tarlike substance as lighter fractions degraded and evaporated. Over thousands of years, animals that had come to drink surface waters were entrapped in the gooey tars. Predators were also trapped when they investigated the cries of trapped animals. The tar pits preserved the bones of these animals and today, the tar pits are the home of the world's only active urban Ice Age excavation site.

gradually into coal, which is found in sedimentary layers. Figure 1-3 shows a coal seam in a sedimentary rock formation.

Depending on the conditions and the amount of carbon in the original materials, different types of coal formed. Coal is classified into four main categories based on energy content: anthracite, bituminous, sub-bituminous, and lignite (anthracite has the highest energy, but is not as common as the other types.). Most coal today is used for generating electricity, but a smaller percentage is used by industry for making steel and other products.

Petroleum (Oil)

Petroleum is also a nonrenewable fossil fuel that formed in the distant past in a two-step process. The process starts when aquatic organic sediments are compacted and when heat and temperature break it down with the aid of microbes into a waxy material known as **kerogen** and a black tarlike hydrocarbon called **bitumen**. Bitumen can occur naturally or as a product of refining petroleum. Kerogen can undergo further chemical and physical change in a process called **catagenesis** if it is compacted and buried deeper underground where temperatures and pressures are higher. In this case, water is squeezed out and the kerogen breaks down into hydrocarbon chains by a process that is aided by the presence of certain minerals in marine deposits. This is equivalent to *cracking,* a term used by refineries when crude oil is converted to gasoline and other products. At the highest temperatures, natural gas forms. If the temperature is lower, oil forms. If the temperature is lower still, the kerogen remains unaltered. Carbon, with four electrons in its outer shell, has the ability to bond to other carbon atoms and form long chains and complex atomic arrangements with hydrogen and is the fundamental chemical structure in both petroleum and natural gas.

The density of the oil and natural gas is lower than the rock layers in which it is buried, so these substances would normally migrate to the surface. Instead, they are trapped by a layer of impervious rock called cap rock, which is typically shale. The cap rock traps the gas and oil in porous sedimentary rock formations. Large volumes of natural gas and viscous liquid oil are trapped in these underground regions called **reservoirs.** The natural gas is under pressure and escapes when the formation is drilled. Figure 1-4 illustrates how oil and gas and sometimes water are trapped underground by the cap rock. There are various types of oil and natural gas traps, but the common feature is that oil moves through the porous rock layer and is trapped by an impervious layer in the underground reservoir. Reservoirs that contain very hot water under pressure are useful as a geothermal heat source; geothermal resources are discussed in Section 1-5.

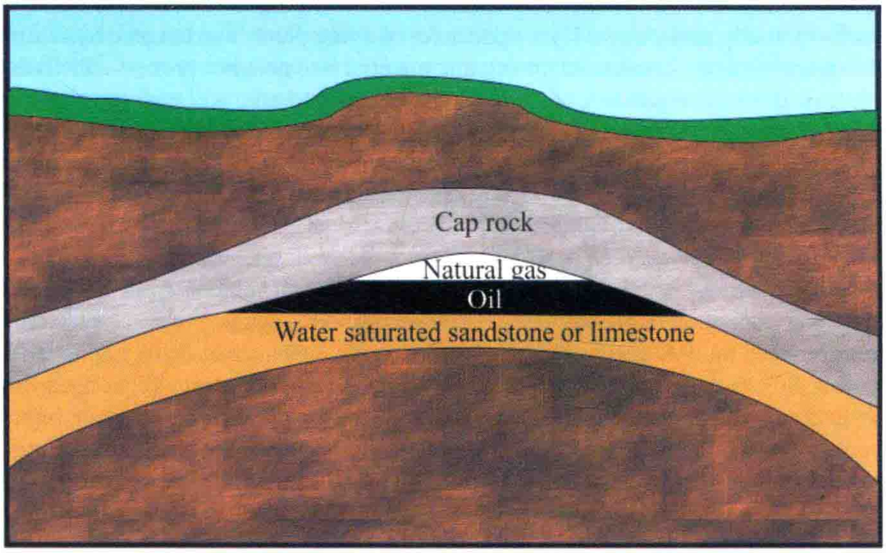


FIGURE 1-4 Underground Reservoir. The particular reservoir shown is an anticline. Other types have been identified by geologists.