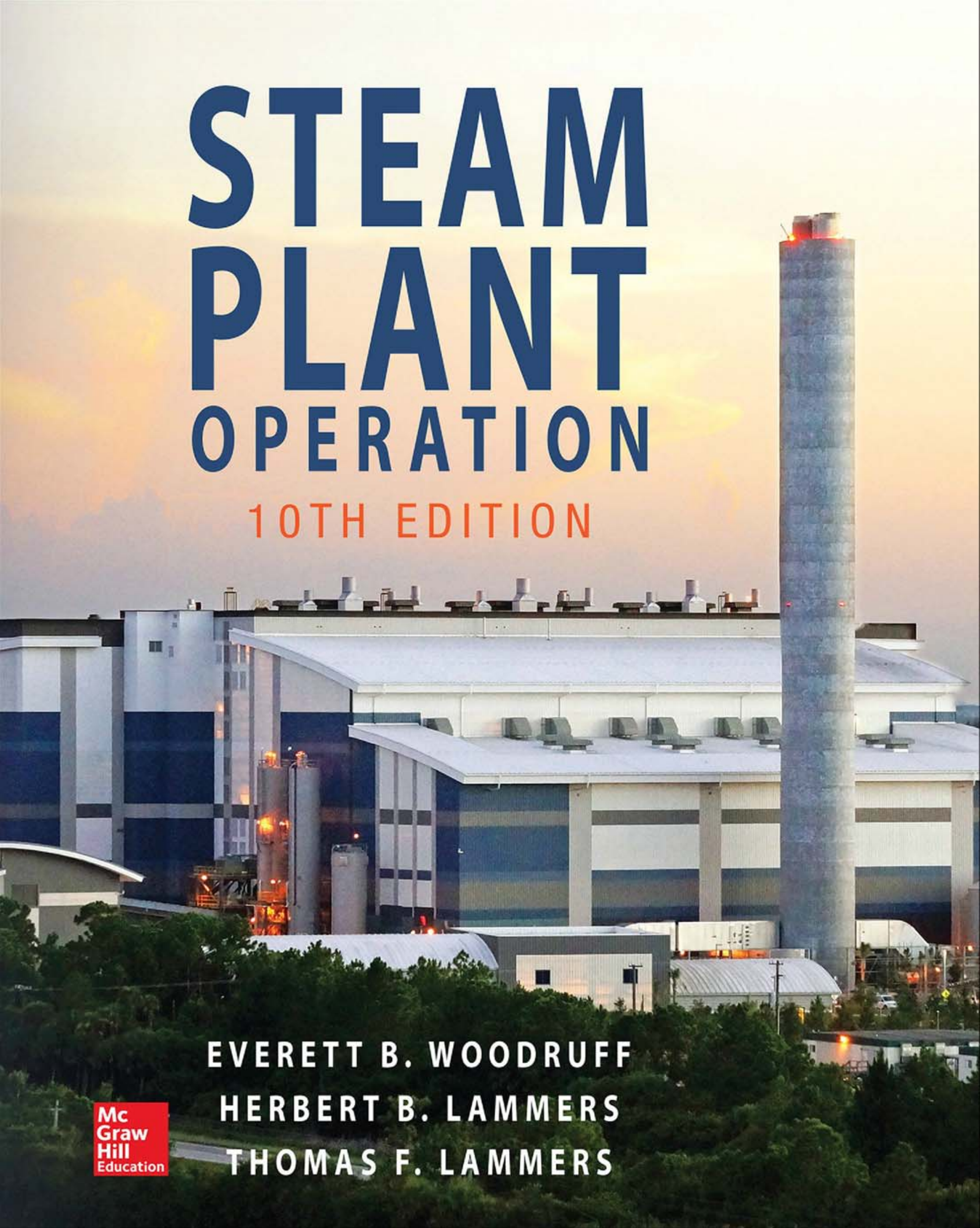

STEAM PLANT OPERATION

10TH EDITION

EVERETT B. WOODRUFF
HERBERT B. LAMMERS
THOMAS F. LAMMERS

McGraw Hill Education

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Tenth Edition

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To my wife Marianne, who has always given me her love and support,
and
in memory of my Dad, who started this book,
which has helped so many over the years.

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About the Authors

Everett B. Woodruff was a Project Engineer at A. M. Kinney, Inc., a leading architectural, engineering, and design process firm. He was involved in the design of industrial and utility power plants, and provided consultation in steam plant operation and maintenance, in plant performance test requirements, and in the development of overall power plant specifications.

Herbert B. Lammers was a consultant for various industries that were dependent on steam power plants for their reliable source of power. He provided expertise in the efficient combustion of various fuels and in the economic operation and maintenance of boilers and various power plant systems.

Thomas F. Lammers was a Senior Project Manager with Babcock & Wilcox Co., one of the world's leading designers and suppliers of steam-generating systems and related power plant equipment. During his 36 years with the company, Mr. Lammers had various management responsibilities in the areas of engineering, marketing, and project management. He is the author of the Fifth through Tenth Editions of *Steam Plant Operation*.

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Preface

This Tenth Edition of *Steam Plant Operation* reviews all sources of energy and how they contribute to the production of electricity. It points out the risks and potential problems that each source of energy faces. But the book continues to emphasize the importance of steam and how steam continues to play an important role in the generation of electricity as well as in the support of many industrial processes. The importance of steam cannot be overstated, as it is used in some manner to provide nearly 90 percent of the electricity produced in the United States and worldwide.

All energy sources must be explored in order to produce electricity economically, reliably, and in a manner which protects the environment. Each source has its issues and should be understood. Given the importance of steam in a large portion of our electric generation, this new edition continues to describe the systems and requirements that are necessary for its production and for the protection of our environment.

The sources of energy for the production of electricity have changed dramatically over the past 10 years from a predominant use of coal, which furnished approximately 50 percent of our nation's electricity, to a significant increase in the use of natural gas and renewables, primarily wind power. No doubt that this has changed the energy picture in the United States and worldwide.

Electric production in the United States through the use of natural gas has increased from about 20 percent to close to 30 percent. The renewable energy source of wind power has nearly quadrupled its electric production from about 1 percent to slightly more than 4 percent, a percentage that is still relatively small. These, however, are significant changes. The change in the use of natural gas, for example, can be immediately associated with the increased production of low-cost natural gas resulting from the drilling and extraction techniques associated with fracking.

Renewable energy sources, such as wind and solar, are increasing their share of electric production, but this production is intermittent and, therefore, conventional means of electric production must be available to support the continuous need for power. This requires coal-fired plants, natural-gas-fired combined cycle plants, and nuclear power plants to provide the base load power requirements as well as the backup power for renewables when their output is reduced or not operational because of lack of wind or sun.

This book has assisted many in the understanding of the fundamentals of a power plant since its first publication in 1935. My father, Herb Lammers, and his friend and co-author, Everett Woodruff, authored the initial editions of *Steam Plant Operation* and presented information in an easily understood format using illustrations and descriptions of the various systems found in a steam power plant.

This method of presentation has helped many to obtain their power plant operating license, and has helped many in the academic area to understand the complexities of a power plant, leading them to continue their studies in this technical field. The Tenth Edition continues to present information in that same clear and understandable manner.

The power industry continues to go through a difficult period, and I am sincerely grateful to the companies and organizations that have provided me with information included in this new edition. I specifically want to thank the individuals within these organizations who took the time to help me. Their assistance is greatly appreciated.

It is rare that a textbook can encompass ten editions over 80 years. But its longevity has resulted from the way information has been presented and how it has helped so many in power plant operations and in academics, where continued study is required. A number of the individuals who have learned from this book have made significant contributions and improvements to this critical technology of producing power which makes our lives so much better and productive.

I thank all of those who have helped me and encouraged me to complete this work. I am proud to continue the wonderful tradition of *Steam Plant Operation* with its Tenth Edition.

Thomas F. Lammers

Steam Plant Operation

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CHAPTER 1

Steam and Its Importance

1.1 Introduction

In the United States, electricity is a reliable and affordable service that we largely take for granted. For many years this service has consistently been associated with large power plants using coal, natural gas, and nuclear as their primary energy sources. These sources of energy resulted in approximately 50 percent of the electricity being supplied from coal-fired power plants and about 20 percent each from natural-gas-fired cogeneration plants and from nuclear power plants. The remaining 10 percent was supplied from a variety of energy sources, primarily from hydroelectric plants (6 percent), with the remaining 4 percent furnished by such energy sources as oil, biomass, and, most recently, the renewable energy sources of wind and solar.

However, this situation has changed dramatically as the electric power industry is undergoing a profound transition and industry leaders are in discussions on how this transition should evolve. Foremost in these changes are discussions on the use of fossil fuels, specifically coal usage, and the role that renewable energy sources like wind and solar will play in any transition. But together with these discussions are the changes that are occurring in the flow of electricity from the generator to the consumer.

The industry may no longer be a one-way power flow from a large generator to customers as it must consider multiple sources of generation, both large and small, in multidirectional power flow. The distribution grid must integrate a diverse set of energy resources, both large and small, from traditional large fossil-fired and nuclear power plants, hydroelectric plants, and relatively large wind farms and solar plants to much smaller energy sources such as rooftop solar systems.

Electricity customers need and expect reliable service and they are used to receiving it for their desktop and mobile devices, as well as the many appliances and air conditioners and lighting and industrial equipment that operate our homes and businesses efficiently, all at an economical cost.

Some customers would like to use rooftop solar panels for the generation of their own electricity. They would like this power to be reliable throughout the entire day, even during the night or on a cloudy day when such electricity generation through solar panels is diminished or is not even possible. Such customers also want a "two-way street" in that when their electric needs are satisfied, any excess electricity can be sold to the local utility. When their own electric generation is insufficient to meet their needs, they would require electricity to be furnished by the local utility. Thus a new type of an electric grid is necessary, and such a grid is evolving today.

By 2020, it is estimated that 80 percent of the industrial world's adults will have some type of computer in their pocket in the form of a smart phone or some other device, and they will be connected through the Internet and be able to manage and control their many household and business systems and possibly sell any stored electricity that they may have to the electric grid.

The way that technology has progressed in recent years, this concept is well within the realm of possibilities. But it will require a significant investment in grid modernization by incorporating sophisticated information, operating technology, and analytical capabilities.

The distribution of electricity will ultimately change from the traditional means of having power production passing through transmission lines to the ultimate user. Because of electricity being sold to the grid from such systems as solar panels when there is an excess, the transmission lines will have to accommodate this two-way flow of electricity. The state of Hawaii is a good example of this as many customers have installed rooftop solar panels. This practice has attracted many because of the high cost of electricity in the state and, maybe more important, because of the high percentage of sunny days throughout the year. Obviously, the cost of such solar panels has to be offset by the savings in electric cost. An economic evaluation should be made to determine the true benefit of such a system.

Why is low-cost electricity so important? We often forget that businesses require innovative systems and processes that require low-cost and reliable electricity in order to remain competitive in the world marketplace. And individuals are more and more connected to their various plug and play devices which they use for entertainment, comfort, convenience, and safety. So, for both at businesses and at homes, systems must be developed to manage their electrical energy.

The transmission grid connects utilities across regions to assure economy and reliability. Because the bulk of electricity is produced from large steady-state power plants which generate electricity in the most economical manner, utilities can draw power from reserves in different regions to ensure that electricity is available reliably as well as economically. This interconnection is extremely important. As an example, a region having hydroelectric plants producing low-cost electricity during a high-water season may provide electricity to another region. In times of low-water conditions, electricity would flow in the opposite direction to support their needs.

There have been major changes in recent years on how electricity in the United States is generated. Many of these same changes are also found worldwide. What was a mainstay in electricity production for many years has changed dramatically from a dominant use of coal to its having a significant lesser role. Its decline has been replaced with an increased use of natural gas and renewables, primarily wind power, for our energy sources. As we shall see later in this chapter, electricity production from coal has declined over the past 10 years from near 50 percent of electricity production to about 39 percent, while natural gas use has increased from about 20 percent to 27 percent, and wind power has increased its contribution from about 1 percent to 4 percent.

It is not for lack of our coal reserves that has caused this, as they are plentiful. There are two significant factors which have led to this change.

1. Environmental mandates have resulted in the retirement of many older coal-fired plants because of the high cost associated with meeting these new requirements.

2. The availability of large quantities of low-cost natural gas because of "fracking" drilling and extraction techniques has made natural-gas-fired cogeneration plants more attractive for the addition of new electric power plants.

Environmental activists have also played a role as they have strongly encouraged the use of renewable energy sources instead of coal and other fossil fuels. This subject is discussed later in this book as all energy sources have specific issues that have to be faced, and just because an energy source is not favored is not a reason to discontinue its use. All factors have to be investigated.

This does not mean that coal-fired power plants are going to be extinct in the near future. Even with more strict environmental regulations, the Environmental Protection Agency (EPA) expects that coal will continue to be a major source of electricity production through the 2030s.

So where does the use of steam play a part in all of this? As this book will explain, the use of steam in our power plants is just as important as it always has been. Steam is not only used for power production but also it provides energy for many industrial process applications as well as heating for various buildings and industries. We should not forget that, for about 90 percent of our electricity production, steam is used in some manner. The following is an impressive list of electric producing systems which use steam.

- Coal- and oil-fired power plants
- Natural-gas-fired cogeneration power plants
- Nuclear power plants
- Solar power plants
- Biomass and geothermal power plants

This book will continue to emphasize the importance of steam and how it is produced from various sources of energy for the generation of electricity and for a variety of other industrial applications. Because of the high percentage of energy that is used for the generation of electricity, this book will continue to focus on that aspect of the use of steam. We have become aware of a variety of terms which are used nearly every day regarding our sources of energy and the resulting effects on our environment. Some of the most used terms are alternative energy and renewable sources such as solar, wind, and biomass fuels. Discussions on these topics generally are combined with the possible improved effects on our environment from traditional energy sources—fossil fuels. These effects are often in the spotlight as we hear concerns over global warming and climate change. Although many of these references are related to our means of transportation and their use of oil-based products, they also are directed at the various methods of producing a critical energy source—electricity, which is so vital to our everyday way of life.

In today's modern world, all societies are involved to various degrees with technological breakthroughs that are attempting to make our lives more productive and more comfortable, both at home and at the workplace. These technologies include sophisticated electronic devices, the most prominent of which are computer systems, smart phones which can perform multiple tasks including computer functions, home and business management systems such as security, and various mobile entertainment applications. All of these systems in our modern world depend on a reliable and relatively inexpensive energy source—*electricity.* And these relatively new systems are in addition to those we traditionally think about—lights, motors, air conditioners, etc. In addition we see advances in the automotive world where electric cars are being developed in order to reduce the dependence on oil. These demands point out the fact that inexpensive and reliable electricity is critical to the sustained economic growth and security of the United States and of the rest of the world, and perhaps the most important fact is that electricity makes our lives better. The United States depends on reliable, low-cost, and abundant energy. Energy drives the economy, heats and lights our homes, pumps water, and provides transportation and security, among countless other activities. The efficient use and production of electricity and effective and reasonable conservation measures are paramount to ensuring low-cost energy as well as protecting our environment.

As an example, the United States uses about 35 percent more energy today than it did in 1975. There are more than 50 million additional homes and more than 100 million additional vehicles, and the gross national product (GNP) is over 10 times higher according to the U.S. Department of Energy. This emphasizes the need for the United States to have a flexible and comprehensive energy plan with policies necessary to provide long term reliable, secure, and environmentally acceptable energy supplies at predictable and affordable costs.

According to the U.S. Energy Information Administration, approximately 40 percent of the total energy used in the United States is for the generation of electricity. (As a comparison, approximately 30 percent of U.S. energy consumption is for transportation.) The demand for electricity has generally increased in parallel with the country's GNP and it is expected that this path will continue in the future. Over the next 20 years, predictions have been made which will require nearly $700 billion for new investments to meet the increasing electricity needs of the United States alone. This will require that all economically feasible energy technologies must be carefully evaluated. This will demand not only new power plants of various technologies but also energy conservation in the form of energy saving systems which will provide energy efficient products and services.

This expansion of the electricity production must also be accomplished with an accompanying systematic reduction of emissions throughout the world. Although major reductions in pollutants have been accomplished over the past 50 years, further realistic reductions must be achieved. However, the goals for these further reductions must be both realistic and economical. Low-cost electric energy is vital for the economies of the United States and the rest of the world.

With the availability of electricity providing most of the industrialized world a very high degree of comfort, the source of this electricity and the means for its production are often forgotten. It is the power plant that provides this critical energy source, and in the United States nearly 90 percent of the electricity is produced from power plants that use steam in some manner as an energy source powering the turbine generators, with the remaining electricity produced primarily by hydroelectric power plants and by sources such as biomass, oil, wind, solar, and geothermal as outlined in Table 1.1. In other parts of the world, similar proportions are common for their electricity production. Even electricity produced from the energy sources of oil, biomass, solar, and geothermal utilizes steam to power the turbine generators.

(*Note:* It should be recognized that the percentages for these energy sources vary from year to year due to the availability and cost of each energy source and the type of systems that are operational. Also, the majority of natural gas is used in a gas turbine

Coal	39.5%
Natural gas	27.4%
Nuclear	19.0%
Hydroelectric	6.9%
Biomass (including municipal solid waste)	1.5%
Wind	4.1%
Oil	1.0%
Solar	0.2 %
Geothermal	0.4%
Total	100.0%

Source: Energy Information Administration (EIA).

Table 1.1 Energy Sources for Electricity Generation in the United States

generator with its waste heat producing steam in a secondary cycle that drives a steam turbine generator. This technology is called a cogeneration plant or a combined cycle system and is described later in this chapter.)

There are many factors which have led to the changes in energy sources for the production of electricity in the United States. Certainly the declining cost and availability of natural gas is a major contributor. New air pollution emission regulations have made many upgrades to coal-fired power plants too costly to implement. Many states have implemented mandatory requirements to utilize renewable energy sources and, associated with this, there have been financial incentives offered by both the federal and state governments for the conversion to renewable energy. And finally, there has been a slower growth in the demand for electricity because of improved efficiency standards for such items as lighting, appliances, etc., as noted later. All of these factors have contributed to how electricity is generated.

The power plant is a facility that transforms various types of energy into electricity or heat for some useful purpose. The energy input to the power plant can vary significantly, and the plant design to accommodate this energy is drastically different for each energy source. The forms of this input energy can be as follows:

1. The *potential energy* of an elevated body of water, which, when used, becomes a hydroelectric power plant.
2. The *chemical energy* that is released from the hydrocarbons contained in fossil fuels such as coal, oil, natural gas, and biomass fuels which becomes a fossil-fuel-fired power plant.
3. The *solar energy* from the sun, which becomes a solar power plant.
4. The *fission or fusion energy* that separates or attracts atomic particles, which becomes a nuclear power plant.
5. The *wind energy* that is generated from our natural environment and becomes a wind farm.

With any of these input sources, the power plant's output can take various forms:

1. The generation of heat for a process or for heating. (This would exclude wind energy.)
2. Electricity that is subsequently converted into other forms of energy such as lighting, motor drives, computer, safety systems, etc.
3. Energy for transportation, such as powering ships.

In these power plants, the conversion of water to steam is the predominant technology, and this book will describe this process and the various systems and equipment that are commonly used in today's operating steam power plants.

Renewable energy is constantly in the news as many believe it is the answer to our energy needs and will possibly eliminate "climate change," which is believed by many to be caused solely by man. Table 1.1 shows that renewable energy sources produce approximately 13 percent of the electric generation in the United States. These energy sources result from the following: hydroelectric, biomass, wind, geothermal, and solar.

More than half of this total of 13 percent comes from hydroelectric power plants (6.9 percent) followed by approximately 30 percent from wind (4.1 percent). The remaining energy from renewable energy sources, less than 20 percent, comes from biomass, geothermal, and solar and they produce only about 2 percent of the total electricity in the United States. Each of the renewable energy sources has an interesting background.

Large hydroelectric power plants are limited to only certain areas where the damming of rivers, lakes, etc., is feasible. Therefore, nearly all hydroelectric dams in the United States were built prior to 1980.

The energy from wind has increased substantially in the past 10 to 15 years. This increase is primarily resulting from federal financial incentives and renewable standards which have been mandated by state governments. (Refer to Sec. 1.8 for further information on wind power.)

Biomass energy has mainly resulted from the burning of municipal solid waste (MSW) in waste-to-energy plants. (This topic is discussed in Chap. 13.) Biomass energy also comes from the burning of wood wastes in lumber and paper mills for the production of steam, which is required for their production processes, and electricity, which is used for their in-plant needs as well as selling excess power to a local utility.

The small contributions from solar and geothermal plants have come from small scale installations.

It is interesting to note that the United States is second only to China in the generation of electricity from renewable sources. China leads because of its recent additions of large hydroelectric plants. For renewable sources which excludes hydroelectric plants, the United States produces the most electricity.

So, why isn't renewable energy more attractive than it is? A primary reason is cost. On a cost-per-kilowatt basis, renewable energy power plants are more expensive than coal-fired or natural-gas-fired power plants. (A waste-to-energy plant can be excluded from this conclusion as it has a primary purpose of handling municipal solid waste.) Federal subsidies have helped to reduce this cost for the supplier of wind and solar plants, but it obviously adds cost to the taxpayer. In addition, many of the plant sites are in remote areas requiring the addition of costly transmission lines. And finally, something the pundits seldom mention, when wind and the sun are unavailable, conventional power plants are still required to meet the power demands. Both wind and solar have a very low availability as compared to a fossil or a nuclear plant, as is discussed later.

A unique fact in the generation of electricity that is often forgotten is that it must be used as it is being generated. We see an example of the impact of a sudden surge in demand in our homes when an air conditioning unit is initiated and the lights dim momentarily. This results because the voltage must drop temporarily to compensate for the increase in demand.

The storage of electricity cannot be made by simply using batteries. They have limited use in electric power systems because of their relatively small capacity and high cost. There is also the frequency conversion problem as electricity is generated as alternating current (ac) which is used by the electric systems, for example, motors, air conditioning, lights, etc. A battery used for storage would produce direct current (dc), and thus a conversion back to ac would be required. This is a recognized problem and new battery development is ongoing and this situation could be improved in the future. Battery storage not only has its development cost issues but also it has associated costs that must be included in the overall evaluation. Such costs would include land procurement, permitting, transmission connections, and system control. These cost issues as well as the technical problems have to be resolved before battery storage is a viable solution for the storage and disposition of electricity. The issues associated with the storage of electricity and the conversion costs of DC to AC current for the ultimate release of electricity to the grid have to be resolved before the renewable energy sources of wind and solar replace fossil fuels as a significant reliable source of providing electricity. At present, however, wind and solar cannot provide the generation of electricity reliably without interruptions, and the storage of electricity remains a problem to be resolved. The successful design of efficient and cost effective battery storage systems remains an unknown at this time. Also, the manufacturing of batteries has its own environmental problems which are rarely, if ever, discussed by proponents.

Pumped storage hydroelectric power is a viable means of storing electricity, but it is an indirect method. However, it represents the largest form of energy storage. When the electric demand is low, which is generally at night, water from a low source, such as a lake, is pumped into a higher reservoir. At high electric demands during the day, water is released to the lower source through a hydroelectric turbine producing electricity. This is a very productive way in producing electricity, but it is obviously restrictive to certain areas.

The development of new energy sources is extremely important to complement our traditional methods of producing electricity. There are locations in the United States and in the world where technologies such as solar, wind, and biomass may prove to make a vital contribution to our overall source of energy. This 10th edition of *Steam Plant Operation* incorporates information on these technologies, and, other than wind energy, solar and biomass plants also use steam to convert these energy sources into electricity. But the emphasis of this new edition will continue to be on the use of steam, developed from various energy sources, as its use in some manner results in nearly 90 percent of the electricity produced in the United States, with a comparable percentage in other parts of the world.

As in previous editions of this book, we will see that each power plant has many interacting systems, and in a steam power plant these can include fuel and ash handling; handling of combustion air and the products of combustion; feedwater and condensate; steam; environmental control systems; and the control systems that are necessary for a safe, reliable, and efficiently run power plant. This edition of *Steam Plant*

Operation continues to blend descriptions and illustrations of both new and older equipment, since both are in operation in today's power plant.

The demand for electricity can fluctuate significantly in the short term due to economic conditions, the weather, and the price of electricity. When looking at the demand over a longer period, a different pattern emerges. In the 1950s, the demand for electricity in the United States was increasing at a significant rate, nearly 10 percent per year. Over a 10-year period, this resulted in an electric demand which doubled, requiring the significant addition of power plants of increasing size in a relatively short period of time. The reason for this exceptional increase was primarily due to the addition of air conditioning throughout the country.

For example, areas in the Southwest and Southern portions of the United States became much more attractive for living after power plants became operational and provided the electricity necessary to meet the demand for air conditioning. Thus, cities like Phoenix and Atlanta increased dramatically in population after air conditioning made living and working conditions more tolerable to offset the heat and humidity conditions which are prevalent in those regions of the country. The rapid increase in demand did gradually decrease to less than 3 percent per year in the 1990s, and recently this has further declined to about 1 percent per year.

This decline in demand has resulted despite our population increasing, and it is expected to continue the trend of only increasing by 1 percent per year for the next 20 years. The major reason for this is new energy efficiency standards for such things as lighting, heating and cooling, and for various appliances. This reduction in demand is not expected to change even with the expected hybrid automobiles using electric plug-ins to regenerate their batteries. However, if electric cars become the choice of many in the next 20 years, the electric demand for this will have to be met with many more new power plants.

This does not mean that we can relax on our needs for power in the future. Even at the rate of 1 percent per year of increased demand, this means that new power plants will be required to meet more than 20 percent additional capacity necessary to satisfy the new demand as well as the replacement of retired power plants. All energy sources will be necessary to meet this new challenge: coal, natural gas, nuclear, and renewable energy.

By the year 2035, the U.S. Department of Energy has forecasted that the demand for electricity will increase by nearly 40 percent. This relates to the need for over 300,000 megawatts (MW) of some type of electricity from a variety of resources including coal, natural gas, nuclear power, wind, and other renewables. If this forecast were to be met just from additional nuclear plants, for example, 200 to 300 new plants would be required, approximately 10 or more each year. In order to meet this demand, it is recognized by industry leaders that coal, nuclear, and natural-gas-fired cogeneration plants are the only proven technologies that could provide the large amounts of electric power which will be required to meet the large demand for electricity in the future. At the present time, the cost of natural gas is low and available because of the use of "fracking" drilling and extraction technologies which have released vast quantities of natural gas. As we shall see later, the sources of energy have changed significantly because of this.

So in the United States, it is expected that the electricity demand will increase by 20 to 40 percent over the next 25 years. When compared to the increase in electric demand expected worldwide over the same time span, this increase in the United States is less than half of what the world will need, as it is projected that over a 90 percent increase will be required to meet the worldwide demand. Obviously, where electricity markets are well established and the consumption of electricity is known (e.g., appliances,