Chapter 1
Introduction

1.1 Introduction

Concern about the inevitable depletion of the fossil fuels that are now the major sources of energy has been greatly reduced, due to the recent development of fracking technology, as described in the Preface, and which will be further discussed in Chap. 23. However, there is another matter that is very important in considering the effective use of the energy that is available. This involves the relationships between the several types of energy, and also the various different uses of energy.

Worldwide energy consumption is between 500 and 600 EJ ($5–6 \times 10^{20}$ J). In terms of consumption rate this is 15–18 TW ($1.5–1.8 \times 10^{13}$ W). The USA consumes about 25 % of the total, although its share of the world's population is only about 5 %.

A recent estimate of the major US sources of energy is shown in Table 1.1. The distribution of energy use, by major category, is indicated in Table 1.2.

These different types of applications have different requirements for access to energy, and different characteristics of its use. One of the important problems with the effective use of available energy supplies is that the schedule of energy use is often not synchronous with its acquisition, even from natural sources. Thus buffer, or storage, systems are necessary.

This requirement for storage mechanisms is highly dependent upon the type of use. Those that consume fossil fuels, or their derivatives, for combustion purposes, such as for space heating or internal combustion-powered automobiles, require one type of storage and distribution system. Another, quite different, category involves the various applications that acquire their energy from the large-scale electric power transmission and distribution (T&D) grid. In that case, there are two types of storage systems to consider. One involves the electric power grid system itself, and the time dependence of its energy supplies and demands, and the other has to do

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Table 1.1 Major sources of energy used in the USA in 2007 [1]

Source	Percent of total
Petroleum	39.4
Natural gas	23.3
Coal	22.5
Renewable energies	6.6
Nuclear electric	8.2
Total	*100*

Table 1.2 Major uses of energy [1]

Type of use	Percent of total energy use
Transportation	28.6
Industrial	21.1
Residential, commercial buildings	10.3
Electric power	40.0
Total	*100*

with storage mechanisms applicable to the various systems and devices that acquire their energy from the grid.

There are mechanisms whereby one type of source or storage technology is converted another. One example is the use of pumped-hydro storage to both take electricity and return electricity to the grid, as will be described later. Pumped-hydro technology actually operates by a mechanical storage mechanism, as it is based upon the gravitational difference between two different water storage reservoirs. Another is the use of flywheels to reversibly convert mechanical energy into electrical energy.

It will be seen that there are many different types of energy storage methods and technologies. Some of the largest of these are owned and/or operated by energy suppliers. Smaller ones are primarily related to energy users.

1.2 Storage in the Fuel Distribution System

In the simplest case, natural fuels such as wood, coal, or crude oil can be stored locally or within the transportation system, in piles, tanks, ships, and pipelines. For example, crude oil and some of the lighter petrochemical products are stored in tanks in oil depots (sometimes called oil terminal tank farms) in the vicinity of the refineries. These are often near marine tanker harbors or pipelines. This type of transient buffer storage generally has a relatively small capacity, however, and must be supplemented by other methods that can handle much larger amounts of energy.

1.3 Periodic Storage

A number of energy sources do not provide energy at a constant rate, but instead, are intermittent. Sometimes, they have a good measure of periodicity. As an example, some of the biofuels, such as switch grass, sugar cane, corn, and oilseeds are only available during part of the year. Likewise, solar, wind, and ocean motion energy sources have roughly daily cycles.

The time dependence of the uses of energy often does not correspond to the time variance of such sources. If these were to match perfectly, there would be no need for a storage mechanism. Perfect time-matching is not likely, however. Instead, at least part of the energy is supplied into some type of storage mechanism, from which it is (later) extracted when it is needed.

What is preferable is a situation in which the combination of current energy production and stored energy match the energy and power requirements at all times. This is sometimes called "load management," but it should actually be called "resource management." Overcapacity in either energy sources or storage systems is expensive, and a great deal of attention is given to how to most effectively and inexpensively meet the needs of energy users.

1.3.1 Long-Term, or Seasonal, Storage

Although there are exceptions, such as the local storage of wood mentioned in the Preface, seasonal storage generally involves very large installations, such as reservoirs and dams that accumulate water primarily during the rainy (or snowy) season of the year. Electric power is produced in hydroelectric facilities by passing water through large turbines. The water collected in such facilities is often used for agricultural purposes, as well as for energy production. Agricultural needs also vary with time during the year.

1.3.2 Daily and Weekly Storage

A number of energy sources produce energy on a daily cycle, related to the periodic characteristics of the sun, tides, and sometimes, wind. It is thus necessary to have mechanisms whereby this energy can be available when needed, and temporarily stored when not needed. But energy from these sources can also vary with the time of the year, and can be significantly affected by changes in the weather, on both long and short time scales. It is common for these sources to be connected to the large electrical transmission grid, providing energy to it when they are in operation. Thus the grid also acts as a buffer and storage medium.

1.4 The Problem of Load Leveling

The electrical load varies significantly with both the location and the time of day. An example is shown in Fig. 1.1. The major components, industrial, commercial and residential, require energy at different times during the day. For example, residential use includes lighting, space heating and air conditioning, and often electric water heaters and cooking appliances.

The magnitude of the electrical power demand also varies with the time of the year. There is more power used in the winter for heating, and in the summer for air conditioning. The variation with time during the day is also generally greater in the summer than in the winter.

The use of energy also varies with the day of the week in many cases. Whereas it is easy to understand that there is a daily pattern of energy use, the needs are not the same every day of the week because many activities are different on weekends than they are during workdays. This can be seen in Fig. 1.2, which shows a typical pattern of weekly energy use [2].

Whereas both the time dependence and the magnitude can vary appreciably with both location, the weather, and the time of year, these general patterns are almost always present, and pose a serious problem for the electric utility firms that both supply and manage the transmission and distribution electric power grid.

The electric utilities can supply this power to the grid from a number of different sources. Often two or three different technologies are employed, depending upon the load level. The least expensive is the use of coal or oil in large base-load facilities. Thus, the utilities try to cover as much of the need as possible from such

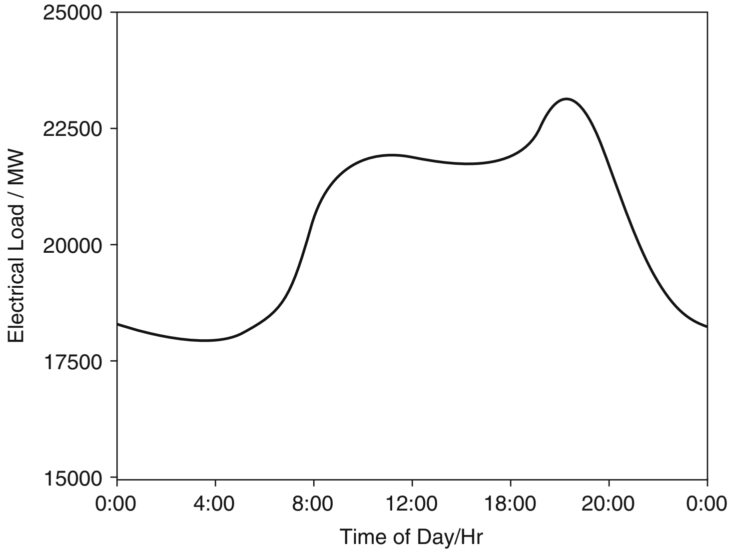

Fig. 1.1 Example of the time dependence of the daily electrical power demand

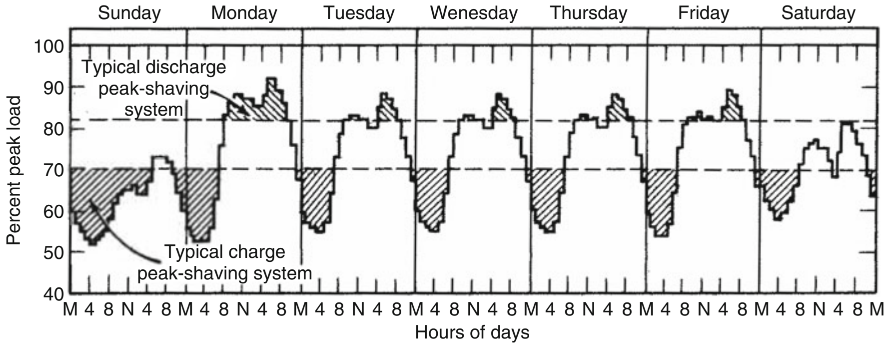

Fig. 1.2 Hourly data on electric load during a full week, showing possible use of a storage system. After [2]

sources. However, these facilities are not very flexible, requiring 30–60 min to start up. In addition, utilities typically have a modest amount of *operating reserve*, additional capacity that is available to the system operator within a modest amount of time, e.g., 10 min, to meet the demand if a generator fails, there is another disruption in the supply, or there is a sudden additional large.

This operating reserve can be divided into two types. One, called *spinning reserve*, is extra generating capacity that can be made available by a relatively simple modification of the operational parameters of the major turbines that are in use.

The other is *supplemental*, or *non-spinning*, *reserve*. This label describes capacity that is not currently connected to the system, but that can be brought online after only a short delay. It may involve the use of fast-start generators, or importing power from other interconnected power systems. Generators used for either spinning reserve or supplemental reserve can typically be put into operation in 10 or so minutes.

In addition, there are additional secondary source technologies that are more flexible, but significantly more expensive, that can be used to handle any need for extra capacity. In some cases these involve the use of gas turbines, similar to the engines that are used to power airplanes, to drive generators.

1.5 Methods That Can Be Used to Reduce the Magnitude of the Variations in Energy Demand

It is self-evident that if the rapid large-scale variations in energy demand can be reduced, the less expensive base load technologies can play a greater role. An obvious solution would be to use *load shifting*, in which some energy needs are shifted from times when the overall demand is large to periods in which other needs are reduced. One way to encourage this is to use time-of-day pricing, a method that is used much more in Europe than in the USA at the present time.

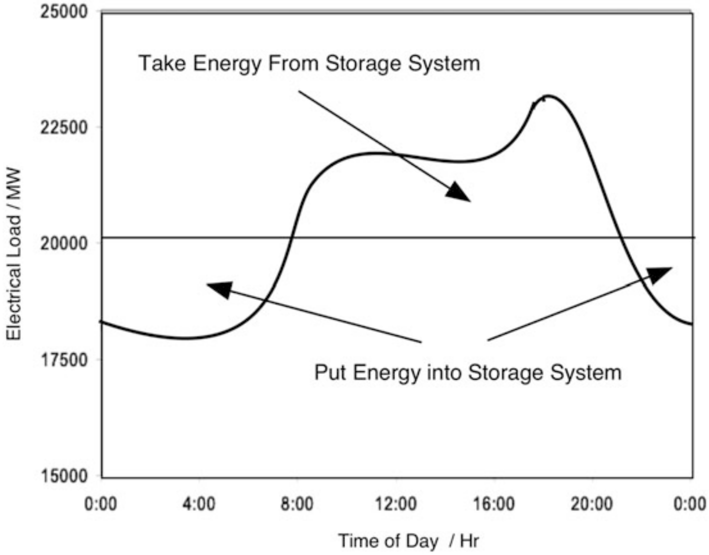

Fig. 1.3 Ideal situation in which energy storage methods flatten the time dependence of the energy supply requirement

The author lived for a number of years in Germany, and spent some time in a house that used hot water for space heating. A large amount of water was stored in a large insulated vessel that was heated electrically at night, when the power costs were very much lower than during the daytime. This hot water was circulated as needed throughout the day.

Another approach is to use energy storage methods to absorb electrical energy when it is available and inexpensive, and to supply it back into the grid system when the demand is higher. This is shown schematically in Fig. 1.3 for the ideal situation, in which the load curve would be entirely flattened.

The dominant means of electricity storage for daily load shifting now is the use of pumped hydro facilities. They are also used for both spinning reserve and operating reserve applications, and typically produce hundreds of MW for up to 10 h. Another, but not so wide-spread, approach involves the use of compressed air energy storage in underground caverns. Both of these technologies are dependent upon the availability of appropriate sites.

About 2.5 % of the total electric power delivered in the USA is currently cycled through such a large-scale storage facility, most commonly pumped hydro. This is different from the practices in Europe and Japan, where about 10 % and 15 %, respectively, of the delivered power is cycled through such storage facilities. In Japan this is a reflection of both higher electricity prices, and a much greater difference between peak and off-peak energy costs.

The development of additional pumped hydro facilities is very limited, due to the scarcity of further cost-effective and environmentally acceptable sites in the USA. Countries with more mountainous terrain have an obvious advantage.

Several additional advanced medium and large-scale energy storage technologies are being developed to help with this problem, including Na/Na_xS and flow batteries. These will both be discussed later in this text.

1.6 Short-Term Transients

In addition to these major variations in the energy demand, there are also many short-term transients. This is illustrated in Fig. 1.4.

These transients can lead to generator rotor angle instability, leading to oscillations and unstable operating conditions. Voltage instability can also occur when the load and the associated transmission system require a large amount of reactive, rather than real, power. This can result in a sudden and drastic voltage drop. As a result, short-term (less than 5 min) power outages can also occur, which can be very costly.

A different type of technology is necessary to take care of this problem, which is currently handled by making small adjustments in the frequency. However, fast-reaction high-power storage mechanisms would be ideal for this application.

As will be discussed later, the rapid response characteristics of flywheel systems make it possible to use them to reduce the problem of short-term transients in the load upon the electrical grid. Other options that are being used in some places include Cd/Ni, hydride/Ni, and even Pb-acid battery systems. Super-capacitors are also of interest in situations in which their limited energy storage capacity is not a problem. These systems are all discussed in later chapters in the text.

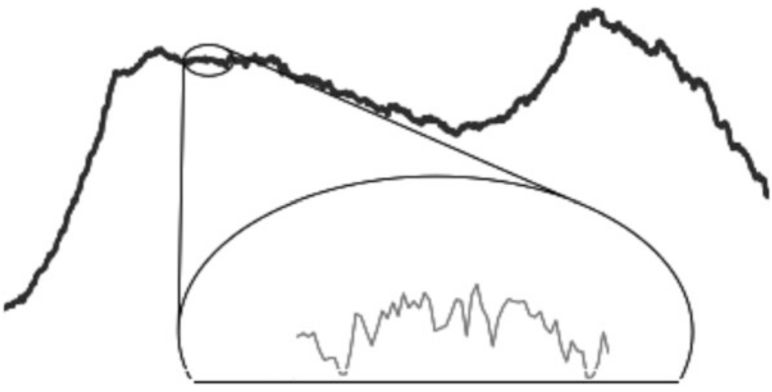

Fig. 1.4 Short-time transients superimposed upon the load curve. After [2]

1.7 Portable Applications That Require Energy Storage

In addition to these traditional medium- and large-scale considerations, attention has to be given to the fact that a large number of additional uses of energy, with quite different energy storage requirements, have become very important in recent years. Very obvious examples are the many small-to-medium-size electronic devices that one now encounters everywhere. A large fraction of these are portable, and thus require batteries for their operation. Their important parameters are quite different from the stationary applications mentioned above.

An additional area of application for energy storage that has become especially visible in recent years involves vehicles, and both full-electric and hybrid internal combustion—electric vehicles are becoming increasingly numerous. In these cases, the electrical energy storage components are critical with respect to both performance and cost.

The important characteristics required by these various types of applications vary widely. As a result, a number of different technologies play major roles.

1.7.1 Storage Methods for Use with Portable Electronic Devices

Devices such as computers, telephones, music players, camcorders, and personal digital assistants, as well as electronic watches and hearing aids are now ubiquitous. Almost all of these now are powered by one or another type of electrochemical battery. There are several reasons for this. One is that the need for energy is sporadic, rather than steady state. Thus there is no need to be continually connected to a fixed energy source. Batteries can either be recharged or replaced as needed.

The amount of energy stored per unit weight, the specific energy, is quite high for some types of batteries. This is obviously important for applications in which weight is important. But in some other cases the volume of the energy source, the energy density, is critical. A great deal of progress has been made in these directions in recent years. Then there is the issue of price, and especially, safety. The latter has become more of a problem the greater the amount of energy stored in small packages. These matters, and some of the important battery technologies, are discussed in some detail in later chapters in the text.

1.7.2 Energy Use and Storage in Vehicles

Vehicle propulsion currently mostly involves the consumption of gasoline or diesel fuel in internal combustion engines. *Hybrid autos* are rapidly being introduced, but still represent only a small fraction of the total. They combine an internal combustion engine with a relatively small high-rate battery that can acquire some of the vehicle's kinetic energy during deceleration. This combination serves to reduce the amount of fuel used, but results in no change in energy source.

A relatively small number of *all-electric* passenger and commercial vehicles are being produced, as well. While most of the attention has been focused on the future of larger vehicles, some 60 million electric scooters and bicycles are already being used. They get their energy from the electric grid, typically by charging overnight. Another variant that is getting increased attention is the category called *plug-in hybrids*. These are different from the normal hybrids in that the on-board battery can be recharged (again, typically overnight) from the electric grid. The charging of the battery component allows these vehicles to travel a limited range on electricity alone. Thus if they do not drive very far, they get their energy from the grid. If they travel farther, the energy input is shared between the electrical grid and a petrochemical fuel.

As the number of plug-in hybrid and all-electric vehicles increases, the overall transportation energy demand will gradually move more toward electricity, and away from liquid fuels. But in addition, this part of the electric load will be mostly at night, where the other demands are reduced, and thus this will contribute to load leveling.

The energy storage devices used in both hybrid autos and plug-in hybrids are batteries. The desirable characteristics are different in the two cases, however. Hybrids have relatively small batteries, for the amount of energy that must be stored is limited. Instead, the rate of energy absorption during braking can be quite high. Thus these batteries must be able to operate at high rates, or high power. Metal hydride/nickel batteries are now primarily used for this purpose. However, almost all of the auto manufacturers who are involved in the development of these types of vehicles indicate that they expect to use lithium-ion batteries in the future, for they generally store considerably more energy per unit weight than the batteries currently used in vehicles, and also be able to operate at high power.

The all-electric and plug-in hybrid applications are different, for in order for the vehicles to have an appreciable range, a large amount of energy must be stored. This requires large, and thus heavy, batteries. And they must be optimized in terms of energy storage, rather than high power. As a result, it is reasonable to expect that this type of vehicles will be designed to employ two different types of batteries, one optimized for energy, and the other for power.

Another obvious factor is cost, especially for the potentially more desirable lithium-ion batteries. This is an area receiving a large amount of research and development attention at the present time, and is discussed in some detail later in this text.

1.8 Hydrogen Propulsion of Vehicles

There has recently been a good deal of interest in the use of hydrogen as a fuel for vehicular propulsion. There are actually two different versions of this topic. One is the direct combustion of hydrogen in internal combustion engines. This can easily be done, as it requires only slight modifications of current gasoline or diesel engines and the injection of gaseous hydrogen at relatively high pressures. The German auto firms BMW and Daimler Benz have demonstrated such vehicles over a number of years. In the BMW case, the hydrogen is stored as a liquid at a low temperature in an insulated tank. Early vehicles from Daimler Benz stored the hydrogen in metal-hydrogen compounds known as metal hydrides some time ago. These are essentially the same materials as the hydrides used in the negative electrodes of the common hydride/nickel batteries. Upon heating, the hydrogen is released so that it can be used in the engine.

The other hydrogen-powered vehicle approach, which was heavily promoted by the United States government for a number of years, is to use hydrogen-consuming fuel cells for propulsion. Fuel cell–propelled vehicles are currently being developed in Japan by Honda and Toyota, Hyundai in South Korea, as well as Audi, BMW, and Mercedes Benz in Germany. Other companies indicate that they are moving in this direction, but none in the USA at the present time.

But again, the hydrogen must be carried, and stored, in fuel cell-powered vehicles. Because of the metal component, the current metal hydrides are quite heavy, storing only a few percent hydrogen by weight. The United States Department of Energy has been supporting a substantial research program aimed at finding other materials that can store at least 6 % hydrogen by weight. This target is based upon the assumption that consumers will require a hydrogen-powered vehicle that has approximately the same driving range as the current internal combustion autos. It is obvious that the increasing interest in reduced-range vehicles that is so evident in connection with those that are electrically powered does not yet seem to have migrated to the hydrogen fuel cell community.

It is interesting that a firm in Germany is producing military submarines that are powered by (quiet) hydrogen-consuming fuel cells, and metal hydrides are used to store the necessary hydrogen. The weight of the hydride materials is not a problem in the case of submarines, and some of the materials that are currently known are evidently satisfactory for this purpose.

1.9 Temperature Regulation in Buildings

As indicated in Table 1.2, a significant amount of energy is used in residential and commercial buildings. In addition to lighting, much of this is for the purpose of the regulation of the temperature in living and work spaces. In the winter, this involves the supply of heat, and in the summer it often requires temperature reduction by the use of air conditioning equipment.

In addition to the use of improvement thermal insulation, the magnitude of the related energy requirements can be reduced by the use of thermal storage techniques. There are several types of such systems that can be used for this purpose, as will be discussed in Chap. 4.

1.10 Improved Lighting Technologies

It was also shown in Table 1.2 that electric power now constitutes about 40 % of the total energy use in the USA. Of this, some 22 % is consumed by lighting. Thus over 8 % of the total energy use in the USA is related to lighting. On a global basis, about 2700 TWh, or 19 % of total electricity consumption is used for this purpose [3].

Most lighting today involves the use of incandescent bulbs in which tungsten wire is electrically heated to about 3500 K. The spectrum of the emitted radiation is very broad, covering both the range to which the human eye is sensitive, and also well into the infrared range, where the result is heat. Only about 5 % of the electrical energy consumed in these bulbs is converted to visible light, the other 95 % is heat. Thus this is a very inefficient process.

Lighting technology is changing fast, and it is reasonable to expect that its contribution to the total amount of energy use will decrease significantly in the future. The first step in this transition involves greatly increased use of fluorescent lamps, which have light emission efficiencies of about 20–25 %, rather than the 5 % of traditional incandescent bulbs.

Governmental regulations are now being employed in many locations to reduce the use of energy-inefficient incandescent lighting. A law in the State of California required a minumum standard of 25 lm/W by 2013, and 60 lm/W by year 2018. Other states are surely to move in this direction also. In addition to these local initiatives, the US Federal Government effectively banned the use of some sizes of the common incandescent lights after January, 2014 by passing the Clean Energy Act of 2007.

However, it is now generally expected that fluorescent light technology will be overtaken by light sources based upon semiconductors, light-emitting diodes, or LEDs. Development efforts in this direction have been underway for a long time, with large jumps in their effectiveness [3], and some LED products are now widely used as bicycle lights, in the tail lights of automobiles, and as street lights in cities. Although still having rather high initial costs, they are beginning to be employed in household lighting.

The major breakthroughs have involved development of GaN-based LEDs and the compositions and processes for making them that produce devices with various emitted wavelength ranges [3, 4]. It is now clear that this solid-state type of technology, which is some 15 times as energy efficient as incandescent lights, and which is moving quickly onto the commercial market, will play an even greater role in the future.

The relative energy efficiencies of these three technologies can be seen from the data in Table 1.3.

Table 1.3 Energy efficiency of different lighting technologies

Light source	Lumens per watt
Tungsten incandescent bulb	17.5
Compact fluorescent tubular bulb	85–95
White light-emitting diode	170

1.11 The Structure of This Book

This book is intended to provide a basic understanding of the various mechanisms and related technologies that are currently employed for energy storage. An initial chapter introduces relevant basic concepts. This is followed by a group of chapters that describe the most important chemical, mechanical, and electromagnetic methods.

The general principles involved in the various electrochemical technologies that are becoming increasingly important are then introduced, followed by a group of chapters on the most important battery systems. These are followed by a chapter that discusses the storage methods that are most important for the major areas of application.

Much of the discussion will involve both concepts and methods of thermodynamics, mechanics, electrochemistry and other areas of materials science. However, it is not necessary to already have a significant amount of prior expertise in such areas, for the background that is necessary will be presented when they are relevant to different portions of the text. A number of general sources in which further information can be found are included as references [4–11].

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