Chapter 4
Fundamentals of Energy Science

4.1 Introduction

Before we can explore the array of technologies that will help us make the transition to more sustainable energy systems, we have to have a clear understanding of energy itself. Energy, primarily from the sun, flows through ecosystems and provides all living things, including our own bodies, the capacity to live, grow, repair tissue, reproduce, and do work. As it does so, its form may change from electromagnetic radiation flowing through space, to chemical energy stored in plants, to heat that keeps us warm, to potential energy as we climb a mountain, and to kinetic energy as we ski back down again. We use solar energy that plants captured and stored eons ago to heat our homes, generate our electricity, and drive our cars. As energy works its way through nature and human societies, it is constantly being transformed from one form to another. Although none is lost as it is stored, converted, and used, its quality is constantly being degraded to less and less useful forms, eventually ending up as relatively useless, low-temperature heat.

Understanding energy is one of the keys to understanding the universe and how physical and living systems work. In fact, a simple definition of **energy** is that it is the capacity to do **work**. Our own sensory perceptions and personal experiences have given us all an inherent understanding of energy transformations and flows. We know about heat transfer (if only to put on a jacket or take it off), we know about the chemical energy released during combustion (as we accelerate to the next stop light), we know about the energy of moving objects (if only to get out of the way of that oncoming car), and we know about radiant energy as we warm ourselves in front of a nice campfire. We even know something about the fairly esoteric concept of **entropy**, as our workshop gets more and more cluttered with sawdust and scraps as we build a nice piece of furniture for our home. Certainly we have an intuitive understanding of many important energy systems, such as refrigerators, lights, cars, and furnaces, if only to operate them even though we may have only a vague notion of how they actually work.

Although a thorough explanation of the physics and chemistry of energy is well beyond the scope of this textbook, we can fairly easily develop an intuitive and somewhat quantitative feel for these energy transformations and flows. The vocabulary and basic principles presented here will provide the necessary foundation to understand the energy systems to be described in subsequent chapters.

The chapter begins with an introduction to the concept of energy itself, along with some units and conversions. It then explores some basic forms of energy, including mechanical, thermal, chemical, electrical, nuclear, and electromagnetic energy. What society cares about, of course, is not joules or British thermal units (Btus) but how we can transform various forms of energy into useful work to

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cool our beer, heat our homes, and take us where we want to go. The "rules of the road" that dictate what we can theoretically accomplish with a Btu or a joule and what we cannot do (such as create a perpetual motion machine) are introduced using the first and second laws of thermodynamics. With those fundamentals under our belts, we will be prepared for the following chapters, which explore some of the most important energy conversion systems.

4.2 Basics of Energy Science

Just what is energy? A precise answer to that deceptively simple question is surprisingly difficult. A common definition is that energy is "the capacity for doing work." Well, you and I are capable of doing work; does that mean we are energy? Although that may sound funny, Einstein's famous relationship between matter and energy, $E = mc^2$, says yes, we have mass, and mass and energy are inextricably linked to each other. But then, what is work? Work can be defined as the product of the force needed to move an object times the distance that it moves. But isn't thinking sometimes hard work? Moreover, work is not the only form of energy. For example, heat is another form of energy, but then what is heat? Well, heat is energy transferred from one object to another by virtue of their temperature difference. So, what is temperature?

Energy is a complicated concept. But we can go far just by relying on our intuitive sense that energy is the ability to cause physical things to change. Energy allows us to make things get hotter, move faster, go uphill, and so forth.

4.2.1 Introduction to the First and Second Laws of Thermodynamics

Energy may change forms in any given process, as when chemical energy in wood is converted to heat and light in a campfire, or when the potential energy of water behind a dam is converted to mechanical energy as it spins a turbine, and then into electricity in the generator of a hydroelectric plant. The first law of thermodynamics says we should be able to account for every bit of energy in such processes, so that in the end we have just as much as we had in the beginning. With proper accounting, even nuclear reactions involving conversion of mass to energy can be accounted for.

To apply the first law, it is first necessary to define the system being studied. The system can be anything that we want to draw an imaginary boundary around—it can be a tree, or a nuclear power plant, or a volume of gas emitted from a smokestack. In the context of global climate change, the system could very well be Earth itself. Quite often, what we really want to know is how efficiently a system converts energy in one form into useful energy in another form. For example, we might like to know how efficient a power plant is when it converts chemical energy in coal into electrical energy delivered to a transmission line. We can write the first law to express this as follows:

Eq. 4.1 $$\text{Energy into the system} = \text{Useful energy delivered} + \text{Wasted energy}$$

We want useful energy, which leads to the following definition of system efficiency

Eq. 4.2 $$\text{Energy efficiency } (\eta) = \frac{\text{Useful energy delivered}}{\text{Energy input}}$$

In practice, most of the systems we are interested in involve multiple energy transformations, each

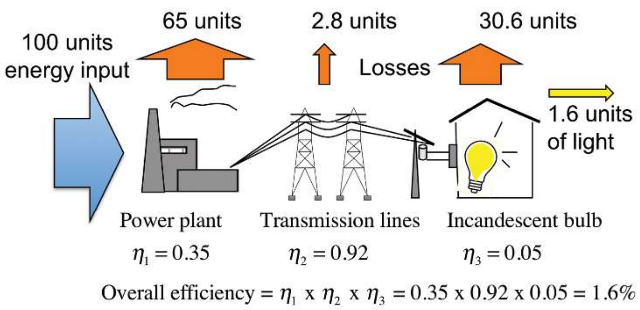

Figure 4.1 Primary Energy Efficiency of Incandescent Light Bulb

with its own efficiency. To find the overall efficiency from start to finish, we simply multiply the individual efficiencies. For example, consider a 35% efficient power plant putting electricity onto 92% efficient transmission lines that deliver electricity to a 5% efficient incandescent lightbulb. As Figure 4.1 indicates, that results in an overall efficiency of only 1.6%.

In the example shown in Figure 4.1 it takes about three units of input energy to deliver one unit of energy to loads, which is a reasonably accurate and handy rule for the U.S. power grid. For example, that suggests that if we replaced a 60-watt incandescent bulb with an equivalent 10-watt LED, the 50 watts saved by the lamp would actually save close to 150 watts of input power at the power plant. That is a huge savings.

To summarize, then, the first law of thermodynamics tells us that energy is neither created nor destroyed as it makes its way through the universe. In other words, the first law gives us a bookkeeping system that allows us to keep track of *quantities* of energy.

The second law of thermodynamics, on the other hand, tells us that even though no energy is lost during transformations, there will invariably be a loss in the *quality* of that energy. The quality of energy has to do with its ability to do useful things for us. For example, electricity is a very high-quality form of energy because it can do everything from powering your TV to heating your house. Low-temperature heat, on the other hand, is a very low-quality form of energy. You may be able to warm your hands on a cup of coffee, but you certainly can't plug your computer into it. The second law tells us that no matter how hard we may try, every time we do something with energy there is always some loss in energy quality, which usually means some of it ends up as fairly useless waste heat.

We can imagine any number of processes that would satisfy the first law but that we know cannot occur. I can run some electricity through a heating element to heat my coffee, but I can't heat the element and expect to be able to get an equivalent amount of electricity back again. The second law takes care of such concerns by informing us about the direction in which processes can go. Electricity to heat is easy; heat to electricity is not.

The implications of the second law are profound. It "outlaws" many things, ranging from perpetual motion machines to the possibility of a warm cup of coffee spontaneously heating itself up by stealing heat from the cool air in your kitchen. It dictates the maximum possible efficiency of your current automobile's engine and the fuel cell that may someday replace it. It tells us strange things about continuously increasing disorder in the universe. While you are cleaning up your room, making it more orderly, the power plant making electricity for your vacuum cleaner is creating even more disorder elsewhere as it converts an organized chunk of coal into disorderly gaseous and particulate emissions from its stack. We will explore the second law more carefully in Chapter 10, which discusses such things as heat engines and power plants.