1 Basic Principles, Definitions and Unit Measures

1.1 Introduction

In this chapter, we explain the meaning of energy and electricity. We introduce tools and concepts that will be needed in the following chapters. Indeed, the physical laws that govern electricity constrains the economic activity of players. In order to understand why, we need briefly to describe the basics of energy and electricity.[1]

1.2 Basic Principles of Energy

Electricity is a shortcut word for electric energy. It is a form of energy. But, what is energy? There are several possible definitions. In brief, energy is whatever enables a body to do work. Work, in the physical sense, is a displacement against a resistance; we thus have a possible definition of energy, as stated in Newton's second law of motion:

DEFINITION. ***Energy:*** *the capability to do work, i.e., a displacement against a resistance*:

$$E = F \cdot x; \tag{1.1}$$

where F is a force, measured in Newtons, and x is a displacement, measured in any unit measure of distance, such as meter. Therefore, energy, E, is measured in Newton-meters. It is also measured in joules, where one joule corresponds to one Newton-meter:

DEFINITION. ***Joule****: the work done, or energy transferred, by an object when a force of one Newton displaces it for one meter.*

The above definition refers to work done, or energy *transferred*. Where is that energy transferred? In order to understand, it is useful to distinguish between usable work and residual heat, where the former could also be usable heat, while the latter is the residual heat that is always generated when some energy does work but cannot be captured in any useful way. Let us explain this concept better. We have said that the energy that exerts

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[1] This chapter presents just an introduction to the topic. For a more thorough discussion, see Shepherd and Shepherd (2014).

a force does *work*. Heat is energy that does not carry out work. A force is the product of mass (m) and acceleration (a):

$$F = m \cdot a. \tag{1.2}$$

For the case of linear motion, acceleration is the rate of change of velocity (v):

$$v = \frac{dx}{dt}; \tag{1.3}$$

$$a = \frac{dv}{dt}; \tag{1.4}$$

where the unit measure of velocity is meters per second (or any other ratio of distance over time), and acceleration is meters per second squared (it is simply the derivative of distance per time over the same unit measure of time). Therefore, we have:

$$\begin{aligned} E &= m \cdot a \cdot x; \\ E &= m \cdot \frac{dv}{dt} \cdot x; \\ E &= m \cdot \frac{dv}{dx}\frac{dx}{dt} \cdot x; \\ E &= m \cdot v \cdot \frac{dv}{dx} \cdot x. \end{aligned} \tag{1.5}$$

Equation (1.5) shows that energy is the product of the linear momentum, i.e., the (linear) velocity that holds the mass, and the term $\frac{dv}{dx} \cdot x$, which represents the applied force that gives rise to the relative change in the velocity, for a given distance.

A mass possesses two kinds of energy: potential energy and kinetic energy. The first depends on the position of the mass, the latter on its motion. The potential energy is given by the gravitational force, applied to a mass at a given height (h) above a given plane:

$$E_{P_e} = g \cdot m \cdot h; \tag{1.6}$$

where g is the gravitational constant, whose value is $g \cong 9.81\ m/s^2$ (note that it is an acceleration). We say that a mass of one kilogram, placed at a height of one meter, that receives a constant acceleration of one meter per second squared, has a potential energy of one joule. The kinetic energy associated with a linear motion depends on the mass and the velocity by means of the following equation:

$$E_{K_e} = \frac{1}{2} \cdot m \cdot v^2. \tag{1.7}$$

Equation (1.7) shows that linear momentum is nothing other than the rate of change of kinetic energy with respect to velocity: $\frac{dE_{K_e}}{dv} = mv$. From Equations (1.5) and (1.7), we can easily see the relationship between kinetic energy and work done:

$$W = \frac{dE_{K_e}}{dv}\frac{dv}{dx} \cdot x; \qquad W = \frac{dE_{K_e}}{dx} \cdot x. \tag{1.8}$$

The work done, i.e. the energy transferred, is just the change in the kinetic energy between any two locations (i.e. for a given displacement).

Both kinetic energy and potential energy satisfy the principle of conservation of energy stated in the first law of thermodynamics, namely, that the internal energy of a system equals the work done by the system, and therefore total energy remains constant. Heat goes from hot to cold bodies, thus establishing the irreversibility of energy transfer in natural processes, as stated in the second law of thermodynamics. An example can usefully explain how these two laws are related to the energy concepts that we are introducing in this chapter and why they are important. Consider the short experiment described in the Example 1.1:

Example 1.1 A Simple Experiment Let us perform a simple experiment. Please, stand up (if you are reading this book seated in a public library or if you believe you might disturb someone around you, please don't do it, just imagine it!) and let the book fall to the ground. Then, take the book again, and continue to read it.

Done? Well, what has happened? We suppose you heard some noise. Why? Where does the sound come from? Figure 1.1 works out the experiment from the energy point of view.

Figure 1.1 represents the energy of the book that falls at different points in time: 1) when you were holding it in your hands standing up; 2) right after you left

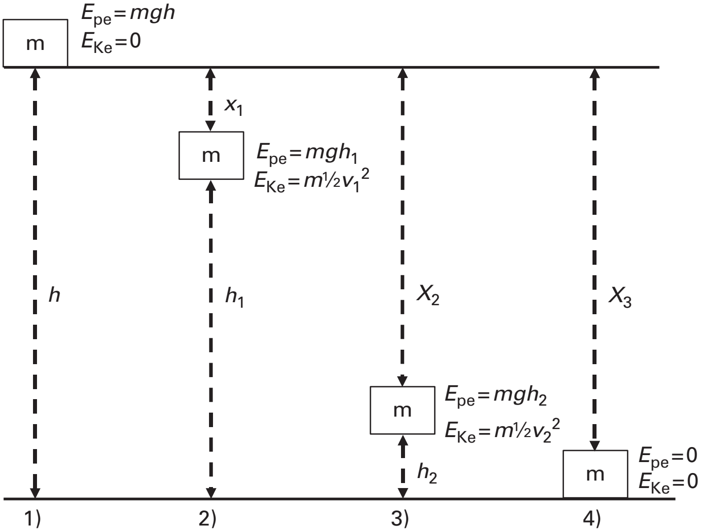


Figure 1.1 An example of energy associated to a mass *m* falling under gravity

it falling to the ground; 3) a few instants before it hit the ground; 4) after it hit the ground.

We can see that at point 1 all the energy of the book is potential energy. It is the product of the mass of the book, the height at which you are holding it in your hands and the gravitational constant. As soon as you release it, it starts falling, running some distance x_1, and therefore reducing the remaining height to h_1. Some of the potential energy, namely, the difference between the whole potential energy $m\,g\,h$ and the actual $m\,g\,h_1$, is converted into kinetic energy, measured by $\frac{1}{2}\,m\,v^2$. Obviously, the speed increases with the distance x, reaching its maximum just before the book hits the ground. At point 4, the book, after hitting the ground, has no more energy: there is obviously no kinetic energy (there is no velocity when the book lies on the ground), and no potential energy either, given that the ground is the datum plane (the height is zero). But the book has done work, i.e., there has been some energy that has displaced its mass through the distance x. Where has it gone? All the energy, i.e., the work done, which was accumulated in the change in the potential energy from zero (when the book was in your hand) to its maximum (right before it hit the ground) has been transferred to the system that contains the book (the room where you are doing your experiment) in several forms corresponding to different lengths of electromagnetic waves, namely, sound, heat, light, etc. This is why it is important to distinguish between work and residual heat. The energy transferred to the system cannot be recovered; it is somehow lost.

Let us have a further look at the consequences of the laws of thermodynamics. The second law of thermodynamics, stated differently, affirms that total entropy of an isolated system always increases over time. As a consequence, the energy transfer in a system is irreversible. Entropy, roughly speaking, can be defined as the amount of energy that cannot be converted into work. It is a measure of the spontaneous molecular disorder. It can be understood starting from the definition of change in entropy: $\mathrm{d}S = \mathrm{d}Q/T$, where S is entropy, Q is heat and T is the temperature (in degrees kelvin). Note that heat is not the same as temperature: the former is the amount of energy capacity (to do work either directly as thermal warming or indirectly through conversion in some other form of energy), while the latter is a measure of the hotness. Therefore, entropy is just the ratio of the heat over the temperature:

$$S = \int dS = \int \frac{dQ}{T} = \frac{Q}{T}. \tag{1.9}$$

The second law of thermodynamics simply states that:

$$dS \geq 0. \tag{1.10}$$

A machine, or a heat-work system, is defined by the energy that is used in it when doing work or that is added to it in order to perform the work. The consequence of the first law of thermodynamics applied to a heat-work system is that the energy of the machine corresponds to the difference between its initial and the final heat:

$$E = Q_l - Q_H; \tag{1.11}$$

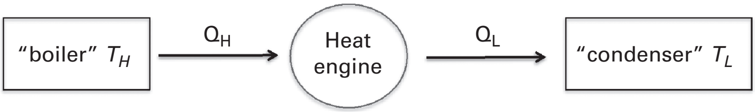


Figure 1.2 The ideal Carnot machine

Where Q_H is the initial heat and Q_L is the final one. According to the second law of thermodynamics, heat goes from hot to cold bodies, and not vice versa. We can describe the heat transfer in an ideal machine by means of the so-called Carnot machine, represented in Figure 1.2.

Assume there is an original source of energy stored at temperature T_H. Call it the boiler (to ease the metaphoric interpretation of the heat-work machine as a heat pump, for instance, a sink where water is boiling). The original energy is Q_H. The machine carries out work in the engine; for instance, the steam that derives from the boiling water is used to rotate a turbine. The amount of energy is $E = Q_L - Q_H$ (notice that this figure is negative because it represents the energy that is extracted from the machine, not added to it). Then the temperature cools down, for instance the steam temperature is reduced to T_L (steam is condensed in the condenser, which could as well be the atmosphere where it is released into). Notice that entropy is reduced when the liquid flows from the boiler into the engine, since heat is subtracted from T_H, while it is increased when the hotter liquid (or steam) flows into the condenser, since heat is added to T_L:

$$S = \int dS = -S_H + S_L = \frac{Q_L}{T_L} - \frac{Q_H}{T_H}; \tag{1.12}$$

Where S_H is the entropy of the energy transfer from the boiler to the engine, while S_L is the entropy added to the system when energy is added to the condenser. Given that $dS \geq 0$ we have:

$$\frac{Q_L}{Q_H} - \frac{T_L}{T_H} \geq 0;$$

$$\frac{Q_L}{Q_H} \geq \frac{T_L}{T_H};$$

$$1 - \frac{Q_L}{Q_H} \leq 1 - \frac{T_L}{T_H};$$

and recalling that $E = Q_H - Q_L$ we have:

$$\frac{E}{Q_H} \leq 1 - \frac{T_L}{T_H}. \tag{1.13}$$

The left-hand side of the equation above represents the ratio of the energy output of the machine over the energy input. We can call this term the efficiency of the system, usually denoted by η:

DEFINITION. ***Energy Efficiency* (η)**: *the ratio of the energy output of a system over the energy input.*

The right-hand side ratio is the ratio of the final temperature over the original one, measured in kelvin. The absolute zero kelvin is not reachable in a physical system, therefore the right-hand side will always be less than one. Equation (1.13) then shows that the efficiency of an energy system, albeit theoretical, will always be less than one, i.e., it is not possible to fully convert all energy input Q_H into usable work. Some of it will always be lost, i.e., transferred to the environment where the system is placed.

Notice that the efficiency stated in Equation (1.13) is a theoretical one, also called Carnot efficiency, since it corresponds to the application of the second law of thermodynamics to a theoretical machine. In reality, the efficiency of a machine will be far less than the Carnot one, since further losses are employed in all energy transfer processes. But in any case, Equation (1.13) shows that all energy transfer processes inevitably imply some inefficiency, which can be reduced by improving the process, but never eliminated.

1.3 Primary Energy Sources and Energy Carriers

There exist several forms of energy that can be classified on the basis of their properties (energy forms), or on the basis of the substances that contain the energy (energy sources):

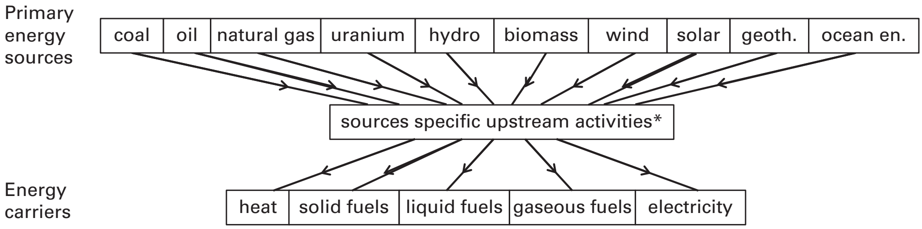
- Energy forms: mechanical, chemical, thermal, radiant, nuclear, electrical.
- Energy sources: coal, oil, gas, uranium, hydro, biomass, wind, solar, geothermal, ocean energy.

Like all taxonomies, this is artificial, and the frontiers of the definitions are rather weak. For instance, thermal energy is also referred to as heat, while radiant energy can be referred to as light and electromagnetic radiation, even though electromagnetic radiations of different length are indeed heat, light, sound, electricity, etc. Moreover, a given energy source can be classified in one or more energy forms. For instance, uranium is the only source of nuclear energy that we are able to convert through fission of its nucleus into electric energy, while solar energy is indeed radiant energy but also thermal and electrical energy.

Electrical energy is energy due to the movement of electrons induced by electromagnetic force, as we will explain in Chapter 2. In this chapter, it is useful to introduce a further classification of energy that helps to analyze the specificities of the electricity sector. We can consider different levels of energy usage, either directly or through some transformation. In particular, it is useful to distinguish between primary energy sources and secondary energy sources, also called energy carriers:

DEFINITION. ***Primary energy source***: *an energy source that can be directly used in some system.*

DEFINITION. ***Energy carrier***: *an energy source that derives from the transformation of some primary energy source.*



* = depend on sector specific investments. For hydrocarbons: prospecting; exploration; extraction; refining; distribution.

Figure 1.3 Primary energy sources and energy carriers
Source: our adaptation from Sims et al. (2007), Figure 4.1.

The above definitions require some further comments. All energy sources, when used, are converted; after all, this is what we have seen in the description of the Carnot machine. Therefore, all sources require some system to be used. These energy sources can be directly used, in the sense that they exist in some form and can be used in the system. The energy carriers, on the contrary, do not exist as energy sources, but are the product of the conversion of some primary energy source into some other form of energy. From the point of view of economics, energy carriers are intermediate products of some primary transformation process. They are produced in order to be further used. Electricity is an example of an energy carrier.

Figure 1.3 helps to understand the difference between primary energy sources and energy carriers. The figure shows that primary energy sources of different forms can be transformed to give rise to different energy carriers. For instance, from hydrocarbons we can obtain heat by burning coal, oil or gas, but also from biomass or geothermal energy. Liquid fuels, such as gasoline or diesel, are derived from the refining of hydrocarbons, but also from coal (called Synfuel), natural gas or biomass. Gaseous fuels come from the cultivation of gas fields, but also from the refining of other hydrocarbons or even from biomass. The economic activities that allow the usage of primary energy sources are called upstream activities. For hydrocarbons, these are the activities of prospecting, exploration, extraction refining and distribution. For other primary energy sources, not all of these activities are relevant, while some other parts of the upstream activities require significant investment to obtain the carrier, such as research and development for ocean energy, for instance or cultivation for biomass

Electricity, as an energy carrier, is obtained from the conversion of several primary energy sources. These primary energy sources are transformed into fuels that are then further converted into electricity through power generation. For instance, oil or coal can be burned to generate heat that is converted into electricity in thermal power plants, or the potential energy of water contained in a dam is converted into electricity exploiting the kinetic energy of water through hydropower production. Note, however, that any energy conversion implies some loss of energy. Therefore, for the case of electricity, we must consider losses due to the efficiency rate of power production, as well as the losses due to the efficiency of the whole process of making electricity available to end consumers, called Electricity Supply Chain (ESC) (see further below). The efficiency of the ESC is sometimes referred to as system efficiency. The reason why it is useful to convert primary energy sources into electricity even if this implies losses, or sometimes even converting some other energy carriers into electricity for instance by burning gas or gasoline in engines, will be apparent when explaining the properties and characteristics of electricity as an energy carrier.

1.4 Energy Units and Energy Measures

Recall the following definitions of multiple of units as stated in the International System of Units[2] (SI):

Table 1.1 Multiples in SI units

Factor	Name	Symbol
10^3	kilo	K
10^6	mega	M
10^9	giga	G
10^{12}	tera	T
10^{15}	peta	P

We have already encountered the joule as the unit measure of energy. However, there are other possible unit measures for energy. Some of them derive from the way the energy concepts were discovered and defined throughout history. A first important equivalence is between joule and watt-second (Ws):

$$1 \text{ Joule} = 1 \text{ watt-second}. \tag{1.14}$$

What is a watt-second? In order to understand this we have to explain the relationship between energy and power.

DEFINITION. ***Power***: *the time rate of the work done by the energy.* $P = \dfrac{dE}{dt}$.

Power is an instantaneous (timeless) measure of the rate of conversion of energy, i.e., of doing work. Therefore, power and energy are linearly related to the time:

$$E = P \cdot t. \tag{1.15}$$

The unit measure of power in SI is the joule per second [J/s], called the watt [W]. Using the second as the unit measure of time in SI, we have the equivalence stated in Equation (1.14).

There are other measures of power, such as the horsepower [HP], an old British power unit: 1 HP ≡ 745.7 W ≡ 0.7457 kW.

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[2] See Taylor and Thompson (2008).

Some unit measures of energy are calories and British Thermal Units [BTU]. A calorie is defined as the amount of energy needed to raise the temperature of one gram of water by 1 degree Celsius. It corresponds to 4.1868 joules. The BTU is defined as the amount of energy needed to raise the temperature of one pound of water by 1 degree Fahrenheit. It corresponds to 1055.06 joules.

Using Equation (1.15) we can express power using all measures of energy. If time is expressed in seconds, its multiples are hours, days, etc. It is common to relate power to calories considering kilocalories per hour [kc/h], and 12,000 BTU per hours, called tonnes of refrigeration [12,000 BTU/h].

Similarly, it is possible to convert multiples of watt-second using the equivalences of times. For instance, we know that there are 60 seconds in a minute, 3,600 seconds in an hour. Therefore, 3,600 watt-seconds correspond to 1 watt-hour.

Time units are additive. Any combination of power and times that give rise to 3,600 watt-seconds correspond to one watt-hour. For instance, the power of 3,600 watts that generates energy for one second corresponds to 1 watt-hour. But we can also have one watt-hour if we have a power of 1,800 watts that does work for two seconds, since $1,800 \cdot 2 = 3,600$, or any other possible combination of power and time that give the same result.

There exist other unit measures for energy that take into account the average energy embedded in several energy sources. The purpose of these measures is to express the energy content of different primary energy sources using a common unit measure. Indeed, there exist several types of substances that we call coal, oil, gas, etc. depending on the different specific weight, sulfur content, caloric power, and so on. These sources have been standardized with respect to the energy content, and then all primary sources but oil converted in fractions of energy with respect to the energy content of oil. This latter is called Tonne of Oil Equivalent.

DEFINITION. ***Tonne of Oil Equivalent (TOE)****: the amount of energy embedded in a standard tonne of oil.*

It is also common to express the equivalence in terms of barrels of oil equivalent [BOE] rather than tonne. Taking into account that there are 158.987 liters in a barrel, using a standardized specific gravity of 0.88 (i.e. 1 l = 0.88 kg) we have a conversion of 1 BOE = 0.14 TOE. Obviously, for the oil itself the unit measure is rightly termed as just Tonne of Oil or Barrel of Oil.

Learning Outcomes

- Energy is the capability to do work. In physics, it is the force that makes a displacement against a resistance. It is measured in joules. The force depends on the mass; a mass possesses potential energy and kinetic energy.

- Energy follows the laws of thermodynamics. In the conversion process of potential energy into kinetic energy, some energy is transferred to the system in which the work is done in a form that cannot be recovered, called heat.
- The Carnot machine can be used to show that energy efficiency, namely, the ratio of energy output of a machine over the energy input, must be less than one because of the first and second laws of thermodynamics.
- There are several forms and sources of energy. Depending on the usage of energy, we can distinguish primary energy sources, directly used in energy systems, and energy carriers, derived from transformation of primary energy sources.
- There exist several unit measures of energy. One joule is equivalent to one watt-second, namely, the power of one watt for one second. Power is the instantaneous rate of conversion of energy. The International System has standardized the equivalences between the several unit measures of energy and of power.
- A Tonne of Oil Equivalent is a unit measure of primary energy based on the average energy content of oil, as a reference for primary energy source.