Energy in Science and Engineering

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Energy markets cannot be analyzed without discussing the relationship between energy and the natural sciences. Energy itself is a term with origins in physics. All types of energy conversion are based on physical, chemical, or biological processes. Professional statements regarding energy economics require an appropriate usage and correct interpretation of basic thermodynamic principles and properties.

The relationship between energy, the natural sciences, and engineering gives rise to several issues:

– What is the role of energy in physics, chemistry, and biology?
– How can different forms of energy be measured and how can they be converted?
– What information is contained in an economy's energy balance?
– What is the relationship between primary, final, and useful energy?
– How does the energy balance relate to an economy's national accounts?
– Why does a comprehensive measurement of a country's energy requirements call for input-output analysis?

The variables used in this chapter are:

E	Energy (in energy units)
F_j	Final demand for goods and services of sector j
CER	Cumulated energy requirement
P	Pressure
ϑ	Temperature
V	Volume
X_i	Gross production of sector i
X_{ij}	Energy supply from sector i to sector j
ω	Fuel efficiency factor

2.1   **Energy and the Natural Sciences**

This section presents an overview of energy-related terminology and the role of energy in several scientific disciplines. It further highlights the many ways in which energy can be defined.

2.1.1   **Physics**

From the standpoint of physics, energy is defined as the ability to accomplish work (mechanical energy). The unit of measurement is the joule (1 J $= 1$ kg m^2/s^2). One joule represents the work required to lift a body with a mass of 102 g $\times$ 1 m. This amount of work is needed to overcome the Earth's gravitational force, resulting from the acceleration g $= 9.807$ m/s^2 caused by the Earth (measured at the norm location in Paris, France). In physics, force is equal to mass (kg) times its acceleration (m/s^2), measured in Newton (N),

$$1\text{N} = 1\,\text{kg m/s}^2. \tag{2.1}$$

Mechanical energy can exist as potential energy (e.g. water stored in a mountain reservoir) or as kinetic energy (e.g. a rotating turbine). The work performed per unit of time is called power and is measured in watts (W) or kilowatts (kW),

$$1\text{ kW} = 1000\,\frac{\text{J}}{\text{s}} = 1000 \cdot \frac{\text{kg m}^2}{\text{s}^3}. \tag{2.2}$$

A kilowatt hour (kWh) is the energy quantity released by a device working with a power of one kilowatt (kW) operating for one hour (h). This energy can be converted into joules (J) or megajoules (MJ) as follows,

$$1\text{ kWh} = 3600\text{ kWs} = 3.6 \cdot 10^6 \text{J} = 3.6\text{ MJ}. \tag{2.3}$$

A kilowatt year (kWa) is equal to $365 \cdot 24 = 8760$ kWh or $31.54 \cdot 10^9$ J, respectively.

For thermal energy, the pertinent unit of measurement is the calorie (cal). A calorie equals the energy required to heat water with a mass of 1 g from 14.5 to 15.5 °C. In comparison, the melting heat of (frozen) water is 80 cal/g, while the boiling heat is 539 cal/g.

The relationship between mechanical and thermal energy was discovered by the Scottish physicist James Joule. It is governed by the principle of energy conservation. He discovered that mechanical energy can be completely converted into heat (but not *vice versa*) which was one of the first principles of energy conservation. The conversion factor, the so-called heat equivalent of mechanical energy, is

$$1 \text{ cal} = 4.187 \text{ kJ or } 1 \text{ kJ} = 0.2366 \text{ cal.} \tag{2.4}$$

In the twentieth century, more principles of energy conservation were discovered, such as the principle of equivalence between energy and mass (as expressed in the formula of Albert Einstein $E = mc^2$) and the quantum law of radiant energy (radiation law of Max Planck $e = h\nu$ with Planck's constant h and the frequency of radiation ν).

The physical knowledge of energy can be summarized by the two laws of thermodynamics. The first law of thermodynamics states that in closed systems, the total amount of energy is constant. The following forms of energy can be distinguished.
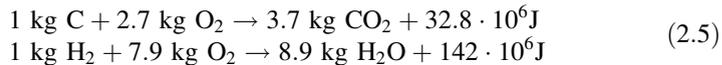
– Mechanical energy: energy capable of performing work, also called exergy, among others orderly kinetic energy;
– Chemical energy: bond energy of molecules (Coulomb force);
– Electrical energy: energy of electromagnetic fields;
– Thermal energy: kinetic energy of atoms and molecules;
– Radiant energy: energy through radiation (if energy in form of photons impacts matter, the energy is absorbed or reflected; the absorbed energy can be further transformed into internal heat or transformed in chemical processes, e.g. photosynthesis);
– Nuclear energy: energy of mass (so-called mass defect).

According to the first law of thermodynamics and contrary to common language, energy can neither be created nor consumed but only transformed. For example, there are processes such as those for transforming the chemical energy stored in fossil fuels into kinetic or thermal energy. What is consumed therefore is the energy source. The share of the stored energy that can be transformed into work (rather than dissipated heat) is called exergy, while the share that cannot be transformed into work is called anergy.

The second law of thermodynamics states that the energy capable of performing work gradually decreases in a closed system (law of the increase of entropy). Rather than being based on macroscopic deterministic relationships, the second law of thermodynamics is derived from probabilistic information (so-called statistical mechanics) about microscopic details. More precisely, the second law of thermodynamics reflects the high degree of freedom in thermodynamic systems with its many atoms or molecules. However, it is applicable only to closed systems (Nicolis and Prigogine 1977). Thermodynamically, the globe is an open system in which entropy can decrease, for example through the storage of solar radiation in fossil energy sources.

2.1.2   Chemistry

The chemical view of energy is connected to the physical principles of energy conversion. However, its focus is more on the outcome of specific energy conversion processes. A particularly important chemical transformation process is combustion (oxidation). The result of this (so-called exothermic) process is molecules with lower bond energy (known as Coulomb force) compared to the bond energy of the original molecules. Examples of these transformation processes are the combustion of carbon (C atom) and hydrogen (H atom),

$$
\begin{aligned}
1 \text{ kg C} + 2.7 \text{ kg O}_2 &\rightarrow 3.7 \text{ kg CO}_2 + 32.8 \cdot 10^6 \text{J} \\
1 \text{ kg H}_2 + 7.9 \text{ kg O}_2 &\rightarrow 8.9 \text{ kg H}_2\text{O} + 142 \cdot 10^6 \text{J}
\end{aligned}
\tag{2.5}
$$

While hydrogen reacts with oxygen and burns producing water vapor, the combustion of carbon-based fuels with oxygen leads to the formation of carbon dioxide (CO_2) in a (stoichiometric) ratio of 3.7 kg CO_2 per kg carbon. In these combustion processes, energy (measured in joule J) is released.

Vice versa, many chemical processes only take place if energy is added (so-called endothermic processes). This includes the opposite reactions of combustion processes, e.g. when producing hydrogen. Electrolysis of hydrogen requires energy in the form of electricity. Regarding the steam reforming of natural gas (methane CH_4) to hydrogen, the following chemical reaction takes place,

$$
1 \text{ kg CH}_4 + 2.2 \text{ kg H}_2\text{O} + 15.8 \cdot 10^6 \text{J} \rightarrow 2.7 \text{ kg CO}_2 + 0.5 \text{ kg H}_2.
\tag{2.6}
$$
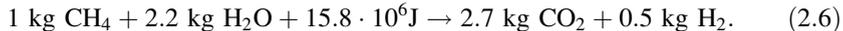
Therefore, the production of 1 kg H_2 through steam reforming calls for an energy input of $31.6 \cdot 10^6$ J and releases 5.4 kg CO_2.

2.1.3   Biology

From a biological perspective, energy transformation is closely linked to photosynthesis and cell respiration. In photosynthesis, solar radiation (energy in the form of photons) is used to break up carbon dioxide and water molecules (CO_2 and H_2O), as well as to transform them into hydrocarbon compounds (e.g. carbohydrates) with higher bond energy through the release of oxygen. In this process, chlorophyll acts as the catalyst.

In the case of cell respiration, chemical energy of organic hydrocarbon compounds is transformed in a combustion process involving oxygen. Energy flows in the living human body serve as a quantitative example. The metabolic rate of a human body at rest is approximately 80 watt (W), 20 W of which is accounted for by human brain. At normal everyday physical activity, the total metabolic rate is 100–120 W. Because this average is in use during 24 h per day, a daily energy intake of 2.4–2.9 kWh (or 2000–2500 kcal, respectively) is necessary. In addition, humans can perform physical labor with 100 W for a few hours. In

Table 2.1   Metabolic rate for continuous physical labor, humans vs. work animals

	Metabolic rate for physical labor
Human body in rest	0 W
Physical labor of a human	ca. 100 W
Physical labor of a mule	ca. 250 W
Physical labor of a bullock	ca. 400 W
Physical labor of a horse	ca. 600 W

Source: Erdmann and Zweifel (2008, p. 19)

Table 2.2   Conversion table (based on IEA data)

	MJ	kcal	kWh	toe	bbl	tce
1 MJ	1	238.8	0.2778	$23.88\,E^{-06}$	$175\,E^{-06}$	$34.14\,E^{-06}$
1 kcal	0.0042	1	0.00116	$0.1\,E^{-06}$	$0.73\,E^{-06}$	$0.143\,E^{-06}$
1 kWh	3.6	860	1	$86\,E^{-06}$	$630\,E^{-06}$	$123\,E^{-06}$
1 toe	41,880	$10\,E^{+06}$	11,630	1	7.33	1.430
1 bbl	5713	$1.36\,E^{+6}$	1587	0.1364	1	0.195
1 tce	29,290	$6.995\,E^{+6}$	8136	0.6995	5.127	1

this case, the required energy intake increases by at least 0.5 kWh for every hour of physical labor.

According to Table 2.1, mules, bullocks, and horses have a higher capacity for physical labor than humans. This is why they have been very valuable to mankind for many millennia. Before the industrial revolution, an estimated 30% of agriculturally usable surfaces in Central Europe were used for supplying energy to pack and draught animals.

The figures cited can be used to calculate the biological energy needed for maintaining a world population of about 7.4 bn humans. The required annual quantity of energy amounts to some $0.74 \cdot 10^{12}$ kWh per year or 910 mn tons of crude oil equivalent (toe, see Table 2.2). For comparison, current oil consumption is about 35 bn bbl or 3.63 bn toe annually, i.e. the fourfold of the energy needed for nutrition (see IEA 2016). This energy is provided through food in the form of high-grade biomass, which is obtained from about 5 bn toe of biomass per year harvested worldwide through farming and fishing.

2.2   Engineering and Energy

Being available in several forms, energy can be measured in different units. In energy engineering, focus is on the development, construction, and operation of equipment and devices designed to transform energy. The need to measure their performance has resulted in statistical concepts and information that are indispensable for energy economics.

2.2.1 Energy Units

What is considered as an energy source from an engineering standpoint depends on the technical knowledge about how to make use of its energy content, as well as on the (economic and social) willingness to make use of it. For instance, uranium oxide (U_3O_8) has only become an energy source with the invention of the controlled fission of uranium isotopes ^{235}U.

Accordingly, there is a multitude of energy sources. In order to compare them, it is necessary to convert their specific energy contents into a common energy unit. While the joule (J) is the base unit for energy of the International System of Units (SI for *Système International d'Unités* in French) and the appropriate unit in physics, several industry-specific energy units are in use. Some of the more common are:

- Tons of coal equivalent (1 tce = 29.3 GJ);
- Tons of oil equivalent (1 toe = 41.87 GJ);
- Barrels of crude oil (1 bbl = 159 l crude oil): 1 bbl is equivalent to 5.7 GJ (approximation: 1 bbl = 50/365 toe);
- Standard cubic meter of natural gas (at a temperature of 0 °C and a pressure of 1.013 bar, 1 m^3 natural gas = 36.43 MJ);
- British Thermal Unit (BTU): 1 BTU represents the energy required to heat 1 lb of water by 1°F (1 BTU = 1055 J). For larger energy quantities there are the British therm (thm), with 1 thm = 10^5 BTU = 105.5·10^6 J = 29.31 kWh and the quad unit (1 quadrillion BTU) with 1 quad = 10^{15} BTU.

Instead of decimal powers, the following symbols are often used:
exa (E) 10^{18}
peta (P) 10^{15} femo (f) 10^{-15}
tera (T) 10^{12} pico (p) 10^{-12}
giga (G) 10^{9} nano (n) 10^{-9}
mega (M) 10^{6} micro (μ) 10^{-6}
kilo (k) 10^{3} milli (m) 10^{-3}

Table 2.2 shows some basic conversion factors between these units. Its first three rows and columns represent energy units that are based on definitions in physics. The units in the last three rows and columns are derived from fossil energy sources that occur in nature. Because of the different properties of geological deposits, reference is made to tons of oil equivalent (toe) instead of tons of oil, and tons of coal equivalents (tce) instead of tons of coal.

The conversion factors exhibited in Table 2.2 are based on lower heating values (H_i). The lower heating value is the quantity of energy that is released during a complete combustion, net of the energy needed for the condensation of the steam contained in the exhaust gas (so-called condensate enthalpy), assuming an exhaust gas temperature of 25 °C. By way of contrast, the upper heating value (H_s) includes the energy contained in the condensate enthalpy. The difference between these two values depends on the water content in the exhaust gas and ranges between 5 and 30%, depending on the energy source. The usable energy of a combustion process is

Table 2.3 Energy conversion processes (examples)

Output Input	Mechanical energy	Thermal energy	Chemical energy	Electricity	Radiation
Mechanical energy	–	Frictional heat	–	Hydropower turbine	–
Thermal energy	Heat engine	–	Thermo-chemistry	Electrical generator	–
Chemical energy	Combustion engine	Boiler	–	Fuel cell	Gas lamp
Electricity	Electric engine	Induction heater	Electrolysis	–	Electric bulb
Radiation	Laser	Microwave oven	Solar chemistry	Photovoltaic	–
Nuclear energy	–	Nuclear reactor	–	–	Radioactivity

Fig. 2.1 Principle of a steam engine
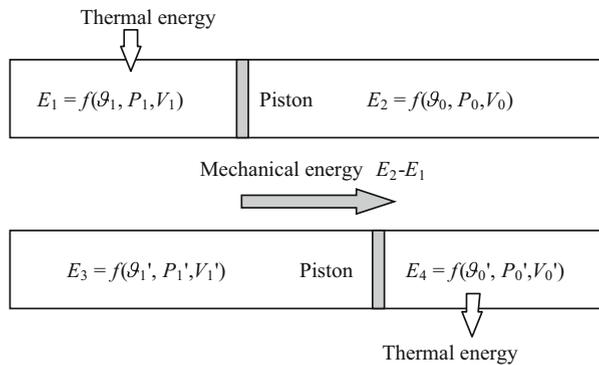
generally indicated by the lower heating value, which is used in most energy statistics. Exceptions are the energy statistics of the United States and those of the natural gas sector, where upper heating values are traditionally used.

2.2.2   Energy Conversion

There are many technical processes for the conversion of energy, some of which are listed in Table 2.3. In order to perform work, energy needs to be available in so-called transient form. For example, a temperature differential is necessary to convert thermal into mechanical energy. A wide variety of energy in transient form occurs in nature, such as rivers, wind, and geothermal heat. Fossil as well as nuclear energy sources, in contrast, are only capable of performing work after one or more conversion processes. In the course of these conversion processes, part of the energy content turns into heat rather than work.

The thermodynamics of energy conversion can be explained using the example of a steam engine (see Fig. 2.1). Water or another medium is heated in the left

chamber through the combustion of a fossil fuel. There, the increase in temperature causes pressure to increase (assuming that the volume in the chamber remains constant). This follows from the equation of state (here simplified for an ideal gas),

$$\frac{P \; V}{\vartheta} = \text{constant} \tag{2.7}$$

with pressure P (measured in Pascal), volume V (measured in cubic meter), and temperature ϑ (measured in Kelvin, where 1 K = –273 °C). The piston moves to the right until pressure in the two chambers is equalized. This movement amounts to a release of mechanical energy (top of Fig. 2.1). In modern heat engines, the equalization of pressure drives a turbine, which is subject to a smaller loss of exergy caused by friction than a piston.

The potential to convert the energy in the left chamber into mechanical energy is exhausted as soon as pressure and counter-pressure are equalized by the movement of the piston. Equivalently, the temperature in the heated chamber adjusts to the temperature on the other side. An excess of energy $E_4 > E_2$ (in the guise of heat) is created in the process of the decompression on the other side of the piston (the turbine, respectively). This excess thermal energy needs to be dissipated to permit continuous operation of the heat engine. In large thermal power plants, cooling towers are used for this purpose.

Evidently, the usable mechanical energy converted by such a heat engine is substantially lower than the amount of energy contained in the fuel. An inverse measure of technical conversion losses is the efficiency factor,

$$\omega = \frac{\text{useful energy output}}{\text{energy input}}. \tag{2.8}$$

Maximum mechanic efficiency of an ideal steam engine with an input temperature ϑ_1 and a discharge temperature ϑ_0 (measured in Kelvin) is given by the so-called Carnot efficiency,

$$\omega_{\text{max}} = \frac{\vartheta_1 - \vartheta_0}{\vartheta_1} = 1 - \frac{\vartheta_0}{\vartheta_1} \; (\text{Kelvin equation}). \tag{2.9}$$

In reality, efficiencies are below their theoretical maximum values because of friction, heat loss to the environment, plastic deformation, and other thermodynamic irreversibilities. For example, a combined cycle gas turbine (CCGT) with an input temperature of $\vartheta_1 = 1230$°C and a discharge temperature of $\vartheta_0 = 20$°C has a theoretical fuel efficiency of $\omega = 80\%$. Currently, actual fuel efficiency is about 60%.

The traditional goal of energy engineering has been to attain the highest possible efficiency in the provision of energy. Of course, the thermodynamic laws and constraints cannot be transcended.
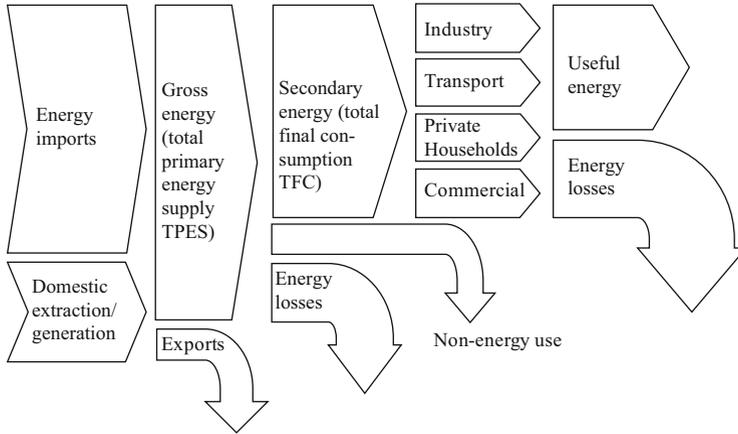
Fig. 2.2 Energy flow chart

2.3   Energy Balance

To obtain a quantitative overview of a country's energy economy, one makes use of the information made available by statistical offices, business associations, energy companies, and research institutions. A particularly important data source is the energy balance, which provides a comprehensive overview of a country's flows of energy.[1] The energy balance documents the overall supply and use of the different energy sources during a given period of observation.

Energy flow charts are often used to illustrate an energy balance. A simplified example of an energy-importing country is shown in Fig. 2.2. The widths of the arrows reflect the country's energy structure. The terms used as well as their interpretation are explained below.

2.3.1   Gross Energy (Primary Energy)

The available gross energy of a country consists of domestic energy sources plus energy imports minus exports. Sometimes, the expression 'total primary energy supply' (TPES) is used, although this is not entirely correct. Primary energy consists of those energy sources that have not undergone any transformation process, e.g. crude oil or coal. In contrast, energy sources that have undergone at least one transformation process are called secondary energy. Due to growing

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[1]In the context of accounting and economics, the term 'balance' is used for stock quantities. Energy balances however represent aggregated flows per period, typically a year. Their equivalent in accounting is the income statement.

imports of secondary energies such as gasoline or electricity, the expression 'total primary energy supply' is becoming increasingly inaccurate.

After subtraction of conversion and transportation losses as well as non-energetic uses from gross energy, one obtains total final energy consumption (TFC). Total final energy consumption amounts to the energy delivered to end users for energy purposes. In industrialized countries, it traditionally equals commercial energy sold by energy companies. However, end users might also have access to non-commercial energy, e.g. from self-collected firewood or solar collectors. Because of the difficulties of measurement, most data regarding non-commercial energy are estimates.

Table 2.4 shows the basic structure of an energy balance, using the European Union as an example. The table consists of three matrices. The upper section contains domestic gross energy supply by origin and energy source. Nuclear fuels are traditionally classified as a domestic energy source even though most of them are imported. The reason for this international convention is that nuclear fuels are usually stored within the country over a period of several years. From a supply policy perspective, nuclear fuels can therefore be considered equivalent to a domestic energy source.

The middle section of the energy balance shows how the available domestic supply of gross energy is transformed into secondary energy. The columns again report the primary energy sources, whereas the rows list the transformation technologies. Negative entries reflect energy inputs, positive ones, outputs after transformation. Therefore, horizontal summation results in energy loss attributable to the corresponding transformation technology (see the last column). The third row explicitly reports statistical differences originating from inconsistencies in the data sources. Furthermore, the two rows towards the bottom in the middle section exhibit the energy industry's own use of energy and its losses (e.g. due to transportation), respectively.

The row entitled 'total final consumption' (TFC) results from the vertical summation of the two upper sections of the energy balance. Comparing this row with the Total Primary Energy Supply (TPES), one can deduce the energy 'lost' in transformation and transportation processes. In the case of the European Union (see Table 2.4), about 70% of primary energy is available to final consumers.

However, statements of this type must be interpreted with great care. While assessing final energy provided by nuclear, hydro, wind, or solar power plants is rather straightforward, statistically specifying their primary energy supply is challenging. There are three main approaches to deduce primary energy supply from final energy.

– The substitution principle: One derives primary energy supply from final energy assuming that it was transformed in a typical conventional thermal plant. Often, the average fuel efficiency of installed thermal capacities (for electricity usually around 35–40%) is used to derive a primary energy supply.
– The efficiency principle: Here, one uses the actual efficiency of the respective transformation technology to derive the primary energy supply from the final

Table 2.4 Energy balance of the European Union 2011

(mn toe)	Coal	Crude oil	Oil prod.	Gas	Nuclear	Hydro	Wind, PV, etc.	Biomass	Electricity	Heat	Total
Production	167.4	84.2	–	140.1	236.4	26.4	27.7	121.9	–	0.8	804.9
Imports	143.9	585	310.9	353.6	–	–	–	11.4	27.2	–	1432
Exports	–26.0	–52.7	–295.7	–83.8	–	–	–	–4.7	–27.1	–	–490
Stock changes	0.2	5.5	2.3	–8.5	–	–	–	–0.1	–	–	–0.6
TPES	285.6	622.0	–74.9	401.5	236.4	26.4	27.7	128.4	–	0.8	1654

(mn toe)	Coal	Crude oil	Oil prod.	Gas	Nuclear	Hydro	Wind, PV, etc.	Biomass	Electricity	Heat	Total
TPES	285.6	622.0	–74.9	401.5	236.4	26.4	27.7	128.4	–	0.8	1654
Transfers	–	15.5	–12.8	–	–	–	–	–	–	–	2.7
Statistical diff.	–1.1	1.4	–3.0	0.5	–	–	–	0.1	0.1	0.3	–1.7
Power plants	–146.5	–	–9.5	–65.3	–233.4	–26.4	–24.9	–19.8	221.3	–0.2	–304.6
CHP plants	–66.6	–	–10.5	–60.5	–3.0	–	–	–23.8	58.2	43.3	–62.9
Heat plants	–4.6	–	–0.8	–8.2	–	–	–0.1	–5.5	–0.1	14.8	–4.5
Oil refineries	–	–650.0	644.7	–	–	–	–	–	–	–	–5.3
Coal transform.	–19.3	–	–1.5	–	–	–	–	–	–	–	–20.9
Other transform.	–0.2	15.2	–15.6	–0.4	–	–	–	–0.2	–	–0.4	–1.5
Own use	–5.4	–	–35.7	–14.4	–	–	–	–0.2	–24.2	–5.7	–85.6
Losses	–0.9	–	–	–3.5	–	–	–	–	–17.3	–4.1	–25.9
TFC	40.2	4.6	480.5	249.6	–	–	2.7	79.1	238.0	48.8	1143.5

(mn toe)	Coal	Crude oil	Oil prod.	Gas	Nuclear	Hydro	Wind, PV, etc.	Biomass	Electricity	Heat	Total
TFC	40.2	4.6	480.5	249.6	–	–	2.7	79.1	238.0	48.8	1143.5
Industry	26.3	2.1	29.4	82.8	–	–	–	24.5	88.8	15.3	269.1
Transport	–	–	293.8	2.9	–	–	–	13.9	5.8	–	316.4
Residential	9.6	–	37.3	101.5	–	–	2.0	35.9	69.1	20.3	275.7
Commercial	1.7	–	17.5	41.7	–	–	0.5	1.9	69.2	8.2	140.7
Agriculture	1.1	–	14.1	3.5	–	–	0.1	1.6	4.2	0.3	24.9
Non-specified	0.1	–	1.9	3.3	–	–	0.2	1.3	1.0	4.7	12.5
Non-energy use	1.3	2.5	86.5	13.9	–	–	–	–	–	–	104.2

TPES Total primary energy supply, *TFC* Total final consumption, *PV* Photovoltaic, *CHP* Combined heat and power. Source: International Energy Agency IEA

energy (e.g. up to 36% for nuclear power, approximately 80% for hydro pump storage, 10–25% for photovoltaic systems, and up to 55% for wind turbines).
– The fictive efficiency factor principle: According to this principle, electricity from renewables and from imported power is treated as a primary energy source. Thus, an efficiency factor of 100% is implicitly assumed. As a consequence, the share of renewable energies in total primary energy supply (TPES) is underestimated.

The three approaches lead to very different estimates of total primary energy supply, limiting the comparability of energy balances between countries or covering different time periods. For detailed analysis, it is absolutely necessary to check the approach used.

2.3.2   Final Energy Consumption

The lower part of the energy balance (see Table 2.4) indicates total final energy consumption (TFC) by consumer group, e.g. industry, transportation, commercial, and residential consumers. Also, non-energy uses are singled out in the bottom row. Note that this classification differs from that used in national accounts and other sources of macroeconomic data (see Table 2.8). An example is fuel consumption for road transportation, which should be allocated to business (passenger and freight traffic) and private households, respectively for national accounting. Energy balances fail to make this distinction because filling stations do not differentiate between their customers.

2.3.3   Data Sources

There is an abundance of publicly available energy statistics (particularly on the internet). A recognized data source for primary energy supply by individual countries and world regions is the annual BP Statistical Review of World Energy, published by the British Petroleum group. In addition, the International Energy Agency (IEA), the American Department of Energy (DOE) and the statistical office of the European Union (Eurostat) publish statistical material regarding the international energy economy, e.g. the development of energy prices. Information about the consumption of non-commercial energy can be found in the annual World Development Report of the World Bank.

The purpose of energy balances is to obtain information on the structure and the development of technical energy systems. As an example, Table 2.5 shows figures on global primary energy supply, which have been calculated according to the substitution principle. In the 1950s, coal was still the most important energy source. Currently, crude oil dominates the global energy system, but its share is declining in favor of coal. The shares of natural gas, hydropower, and nuclear energy are mostly

Table 2.5 Global commercial primary energy supply

	1950		1975		2000		2013	
	(mn toe)	(%)	(mn toe)	(%)	(mn toe)	(%)	(mn toe)	(%)
Mineral oil	500	27	2290	44	3519	39	4185	33
Coal	1120	61	1640	18	2157	24	3827	30
Natural gas	180	10	930	32	2217	25	3020	24
Hydropower	30	2	300	6	617	7	859	7
Nuclear power	–	–	20	0	585	6	563	4
Renewables[a]	–	–	–	–	–	–	279	2
Total	1830	100	5180	5180	9015	100	12,730	100

[a]Without noncommercial energy. Sources: Darmstadter et al. (1971, p. 10) and BP (2014)

stable. While non-commercial sources such as firewood and dung are still important in developing countries, they are not included in Table 2.5.

2.3.4 Useful Energy (Net Energy) and Energy Services

From both the engineering and the economic perspective, final energy is an intermediary good. It is used by energy-converting devices, machines, and facilities to perform useful function. The main purpose of final energy is the utility it creates, such as

– heat (e.g. space heating, hot water, high and low-temperature process heat);
– work (e.g. transportation, information and communication, cooling);
– light (e.g. lighting, laser technology);
– chemically bound energy (e.g. electrolysis, reduction processes in batteries).

For obtaining utility from final energy, end users operate boilers, motors, lighting systems, air conditioners, furnaces, etc., generally on their own account. Just like in any other conversion process, operation of these devices goes along with losses, particularly in the form of unused heat. The statistical recording of these losses is difficult because there is no stringent definition of useful energy (also called net energy). An example is the measurement of heat provided by a central heating system. Should this heat be measured at the exit of the burner or at the radiator? While the heat distribution losses are included in the first case, they are excluded in the second.

The term 'energy service' takes the concept of useful energy even further. The idea is that it is not the warm radiator or hot water that is ultimately demanded but rather a pleasantly heated room or a well-formed piece of steel. These examples show that not only the technology matters (e.g. thermal insulation standard, optimized design of engine performance), but also the behavior of the final energy user. An example is a short and intense instead of a long and moderate airing of a

room which might ultimately lead to the same level of utility for the consumer but with lower energy consumption.

Traditional energy balances do not include useful energy and energy services because the appropriate figures cannot be observed on market. However, according to estimates, significant conversion losses occur at final energy users. From a macroeconomic point of view, the share of primary energy in useful energy and energy services is estimated to lie between 10 and 20%. If it were possible to further minimize the conversion losses along the entire value chain linking primary energy sources to energy services, total energy expenditure would significantly decrease with an unchanged level of energy services. Additionally, energy-related environmental damages and greenhouse gas emissions would also be mitigated.

2.4 Cumulated Energy Requirement

The cumulated energy requirement (CER) of goods and services is defined as the sum of the total primary energy amount required for the production (CER_P), the use (CER_U), and the disposal (CER_D) over the entire lifetime of the product (so-called life-cycle assessment):

$$CER = CER_P + CER_U + CER_D. \qquad (2.10)$$

The cumulated energy requirement is used as an indicator for the assessment of measures to reduce the energy consumption of buildings, vehicles, and appliances. Reductions in energy consumption during the use of an appliance could e.g. be cancelled by an increase in the process of its production. Countervailing developments of this type need to be considered when assessing energy-saving measures.

Other instances are solar and wind power plants. While their operation requires almost no energy, their construction does. The energy payback time is defined as the operating time of a plant needed to recover the energy amount for their construction and disposal. The harvesting factor, or 'energy returned on energy invested', respectively, indicates how often a plant recovers the CER during its lifetime.

The CER concept is also helpful for an in-depth assessment of a country's technical energy flows. While its energy balance documents immediate energy flows within its confines, it does not account for the energy used in the production of imported goods (so-called 'gray energy'; see Spreng 1988). Countries with high energy prices tend to outsource the production of energy-intensive goods, resulting in a decrease in their primary energy demand but without an effect on its global amount. It is the calculation of the CER that makes such facts transparent.

In general, there are two different methods to calculate the CER, process chain analysis and energy input-output analysis. Process chain analysis is a detailed assessment of energy inputs at each stage, from production to disposal of a good (see Frischknecht et al. 1994). This method is relatively simple to apply if the necessary data is available. Table 2.6 shows an example using the results of the

Table 2.6   Cumulated energy requirement (CER) in 2012

	CER (non-renewable) (kWh prim./kWh final)	CO_2 equivalent (g/kWh)
Heating oil extra light	1.13	311
Natural gas H	1.14	247
Liquid gas (ethane, butane)	1.13	272
Hard coal	1.08	439
Lignite	1.21	452
Power mix (Germany)	2.22	607

Source: GEMIS Version 4.8 (GEMIS 2014)

GEMIS model developed by IWU Darmstadt (Fritsche et al. 1999). According to this model, the supply of 1 kWh of heating oil requires 1.13 kWh of primary energy, while the supply of 1 kWh of electricity requires about 2.22 kWh of primary energy (in the case of Germany). The third column of Table 2.6 indicates the greenhouse gas emissions (in CO_2 equivalents).

However, it is impossible to take all of the economic interdependencies in the production of a good into account in this way. At some point, process chain analysis must stop, resulting in errors which can be avoided using the method of energy input-output analysis.

2.5   Energy Input-Output Analysis

Input-output analysis is based on the division of the national economy into economic sectors. The goods and services that are exchanged between these sectors are summarized in input-output tables. The sectors are defined by homogeneous product groups (so-called functional differentiation), in contrast to national accounts, where they are defined institutionally.[2]

Table 2.7 contains a greatly simplified example of an input-output table with five sectors, two of which are energy sectors. Here, transactions are valued at production cost net of value-added taxes and excise duties such as taxes on mineral oil or tobacco. Imports are valued at cif-prices (including cost, insurance, and freight), exports, at fob-prices (free on board). Trading margins are registered as an output of the service sector.

The rows of an input-output table show the value of a sector's deliveries to economic sectors (so-called first quadrant or intermediate consumption matrix) and to final consumers.[3] For example, companies producing oil, gas, and coal had sales of 0.09 monetary units (MU) to other companies in the same sector and of 0.07 MU

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[2]In an institutional differentiation of sectors, companies are consolidated into sectors following their main focus of economic activity.

[3]Final consumption consists of private consumption, public consumption and investment, exports, and stock changes.

to electricity generators. However, the largest demand came from final consumers with 5.72 MU, bringing the total of deliveries (so-called gross output) to 13.10 MU.

The columns show the cost of production factors of each sector consisting of purchases from economic sectors (again shown in the first quadrant or intermediate consumption matrix) and primary inputs.[4] Companies producing oil, gas, and coal bought 0.07 MU of it from other companies in the same sector but only 0.01 MU from electricity generators. Of course, imports loom large with 8.16 MU, while wages and salaries paid for the purchase of labor amount to a mere 0.83 MU. In total, inputs amount to 13.10 MU.

Note that for every sector, the sum of its row entries (sales revenues) is equal by definition to the sum of its column entries (expenditures and profits), reflecting equality of the two sides of a company's income statement.

Input-output tables are published by statistical offices in regular or irregular intervals, usually with a delay of several years. For the European Union, Eurostat is in charge, for the United States, the Bureau of Economic Analysis of the Department of Commerce (BEA).

The cells printed in bold of Table 2.7 relate to the economy's energy sector. If they are in energy rather than monetary units, the table becomes an energy input-output table (see the example shown in Table 2.8). Its source is the energy balance, transposed and structured to conform to the division of the economy in sectors. Average prices of the energy supplied to the other sectors and for final consumption can be calculated by dividing the sales revenues of the monetary input-output table by the corresponding energy flows of the energy input-output table.

Input-output tables can be used as a basis for input-output models. The most important variant is associated with the Russian economist and Nobel laureate Wassily Leontief (1970). With N sectors, total output of each sector X_i (the gross output of sector $i = 1,\ldots, N$ in monetary units) can be expressed by the following core equation of the Leontief input-output model,

$$X_i = \sum_{j=1}^{N} X_{ij} + F_i, (i = 1 \ldots, N), \tag{2.11}$$

where X_{ij} represents deliveries from sector i to sector j and F_i final demand for goods or services in sector i.

The linear Leontief input-output model is based on the assumption that relationships between the sector inputs X_{ij} and outputs X_i are constant, at least in the short term. These constant relationships are expressed by input coefficients,

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[4]Primary inputs consist of imports, cost of capital (depreciation, interests, and profits), cost for labor (wages and salaries, including surcharges for social security), and indirect taxes (excluding subsidies).

Table 2.7 Sample input-output table of a country (in monetary units)

	Oil, gas, coal	Electricity	Agriculture	Industry	Services	Final demand F_i	Output X_i
Oil, gas, coal	**0.09**	**0.07**	**0.18**	**2.86**	**4.18**	**5.72**	**13.10**
Electricity	**0.01**	**0.28**	**0.09**	**1.18**	**2.22**	**3.67**	**7.45**
Agriculture	0.00	0.00	0.90	11.54	1.33	3.31	17.08
Industry, constr.	0.01	0.61	3.82	45.08	26.02	143.42	218.96
Services	0.06	0.82	1.98	20.01	38.48	159.62	220.97
Imports	**8.16**	**1.24**	1.29	62.15	15.18		88.02
Depreciations	0.98	1.26	2.98	11.23	17.26		33.71
Interest, profits	0.26	0.62	3.07	9.49	32.92		46.40
Wages, salaries	0.83	1.25	3.51	44.89	72.72		123.20
Indirect taxes/subsidies	2.70	1.30	-0.74	10.53	10.66		24.50
Input X_j	13.10	7.45	17.08	218.96	220.97	315.74	793.30

Table 2.8 Sample energy input-output table of a country (in energy units)

	Oil, gas	Electricity	Agriculture	Industry	Services	Final consumption F_i	Output X_i
Oil, gas	8.2	4.7	11.6	157.3	149.6	206.2	537.6
Electricity	0.6	20.6	3.1	56.4	46.2	130.4	257.3
Imports	571.1	56.1					627.2

$$a_{ij} := \frac{X_{ij}}{X_j} = \text{const.}, (i, j = 1, \dots, N). \tag{2.12}$$

Thus, the ratio of inputs to outputs in production is predetermined and fixed by the prevailing technology. In this case, the production function is of fixed proportions or Leontief type. The input coefficients a_{ij} represent the average production technology characterizing sector j during the period of observation. Substitution processes between inputs driven e.g. by changing input prices or new technologies, are not taken into consideration in Eq. (2.12). Possibilities to relax this very restrictive assumption are discussed at the end of this section.

Using the input coefficients a_{ij}, gross production X_i of sector i is given by

$$X_i = \sum_{J=1}^{N} a_{ij} \cdot X_j + F_i, (i = 1, \dots, N). \tag{2.13}$$

In this way, the inter-sectoral production relationships can be represented by a system of linear equations. In matrix form, one has

$$\begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_N \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{N1} & a_{N2} & \dots & a_{NN} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_N \end{pmatrix} + \begin{pmatrix} F_1 \\ F_2 \\ \dots \\ F_N \end{pmatrix} \tag{2.14}$$

This equation system can be solved for the gross production values X_i knowing that total input equals total output for each sector and that the corresponding matrix below is always invertible. The solution is given by another linear equation system of equations,

$$\begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_N \end{pmatrix} = \begin{pmatrix} 1 - a_{11} & -a_{12} & \dots & -a_{1N} \\ -a_{21} & 1 - a_{22} & \dots & -a_{2N} \\ \dots & \dots & \dots & \dots \\ -a_{N1} & -a_{N2} & \dots & 1 - a_{NN} \end{pmatrix}^{-1} \cdot \begin{pmatrix} F_1 \\ F_2 \\ \dots \\ F_N \end{pmatrix} \tag{2.15}$$

or in elementary form,

$$X_i = \sum_{j=1}^{N} f_{ij} \cdot F_j, (i = 1, \dots, N). \tag{2.16}$$

The coefficients f_{ij} (elements of the inverted matrix in Eq. (2.15)) are called Leontief multipliers. They indicate by how many monetary units (MU) gross production of sector i needs to expand if final demand of sector j increases by one MU.

The Leontief multipliers pertaining to the input-output Table 2.7 are given in Table 2.9. Note that the values on the diagonal all exceed 1. For instance, if power

Table 2.9 Leontief multipliers corresponding to the input-output Table 2.7

	Oil, gas	Electricity	Agriculture	Industry	Services
Oil, gas, coal	1.007	0.015	0.019	0.021	0.026
Electricity	0.001	1.041	0.010	0.009	0.014
Agriculture	0.000	0.008	1.075	0.074	0.018
Industry, constr.	0.002	0.133	0.332	1.304	0.190
Services	0.006	0.155	0.189	0.156	1.236
Total	1.016	1.352	1.625	1.564	1.484

generators are to produce one extra MU worth of electricity, they trigger an extra demand of 1.041 MU worth of electricity in their own sector because they have to e.g. employ more workers who in turn use more electricity. Moreover, they call on additional inputs provided by the service sector, which adds another 0.155 MU worth of power. The sum of column entries indicates that if the country's demand for electricity increases by one MU, national production of electricity must increase by the equivalent of 1.352 MU.

Using the input-output table, the energy requirements of products and services can be estimated. First, direct energy coefficients e_{kj} are calculated from the energy input-output table for all M energy sectors,

$$e_{kj} = \frac{\text{energy supply from sector } k \text{ to sector } j}{\text{gross produktion of sector } j}, (k = 1, \ldots, M; j = 1, \ldots, N). \tag{2.17}$$

Summation of e_{kj} over the M energy sectors yields e_j, which indicates how much energy sector j (in energy units) uses directly per MU of its gross production,

$$e_j = \sum_{k=1}^{M} e_{kj}, (j = 1, \ldots, N). \tag{2.18}$$

In addition to these direct energy supplies to sector j, there are indirect ones from the non-energy sectors. Total (direct and indirect) supplies $\hat{e}_{kj}$ from sector k to sector j can be determined with the help of Leontief multipliers,

$$\widehat{e}_{kj} = \sum_{i=1}^{N} e_{ki} \cdot f_{ij}, (k = 1 \ldots, M; j = 1 \ldots, N). \tag{2.19}$$

The total value of direct and indirect energy requirements of sector j per MU of gross production can be obtained by summing $\hat{e}_{kj}$ over all M energy sectors,

$$\widehat{e}_j = \sum_{k=1}^{M} \widehat{e}_{kj}, (j = 1\ldots, N). \qquad (2.20)$$

Up to this point, the energy requirements of non-energy imports (known as gray energy) and the energy contained in the depreciation of capital have been neglected. Both can be estimated using data from input-output tables. In order to estimate the gray energy, consider the row 'imports' (in MU) of Table 2.7. To deduce the energy requirements for these imported goods, the cumulated energy requirement (CER) needs to be calculated from the input-output tables of the corresponding exporting countries. In practice, these estimates are limited to the most important countries of origin.

The energy content of used-up capital can be derived from the row 'depreciation' of Table 2.7. Here, the assumption is made that the energy directly and indirectly required for the production of capital goods needs to be accounted for only when they are depreciated. The correct approach would be an estimation using input-output tables of past years.

Despite the elegance of the input-output model, the assumption of fixed proportions in production according to Eq. (2.12) presents a serious shortcoming. It can be neglected when calculating the CER for a particular year. However, for other energy economic purposes, a dynamic input-output table may be necessary. In this case, the sectoral consistency condition must absolutely be satisfied which states that the sum of sectoral inputs (in MU) is equal to the sum of sectoral outputs (in MU). Generally, there are two different ways to satisfy this condition:

– The input coefficients can be adjusted over time according to specific changes in sectoral production processes. For example, nuclear power plants may be substituted by gas-fired ones. For determining the macroeconomic consequences of this substitution, one has to first define the cost structure of the two types of power plant as two column vectors in the input-output table. From this, the changed cost structure of the electricity sector can be simulated, using exogenously given shares of nuclear and gas-fired plants in electricity production.
– Input coefficients can also be made flexible using economic models, with changes in the relative prices of inputs serving as an explanatory variable. These prices depend on the sectoral development of wages and productivities as well as changes in indirect taxes and import prices. The first empirical study adopting this approach was the Hudson-Jorgenson model for the United States (Hudson and Jorgenson 1974). Later studies are referred to as computable general equilibrium (CGE) models (see Shoven and Whalley 1992).

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