Energy in History

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Chapter 1
Energy in History

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Abstract The topic of energy is of central interest today. Although a long-term view can be useful in order to clarify contemporary trends and future perspectives, scholarly literature provides little information on the consumption of energy sources by past societies, before the beginning of the 20th century. In the following analysis, the topic of energy will be discussed from the viewpoint of economics, with a long-term historical perspective. After a brief introduction in Sects. 1.1 and 1.2 will examine some definitions and concepts, useful when dealing with energy and the role of energy within the economy. Section 1.3 will focus on the relationship between humans and energy in pre-modern societies. Section 1.4 will discuss the energy transition, that is changes in energy and environment from the early modern age to the present day. In the Conclusion (Sect. 1.5) general estimates will be proposed of past energy consumption on the whole.

1.1 Introduction

Scholars disagree about the role of energy within the economy. An optimistic view is shared by many economists. Their opinion is that raw materials played virtually no role in the modern development of the economy, as growth depended and continues to depend on knowledge, technical progress and capital. The contribution of natural resources to past and present growth is almost non-existent; and energy is a natural resource. After all energy represents today—they say—something less than 10 % of aggregate demand in the advanced economies.

Scholars with interest in environmental changes support the opposite view on the role of material goods and nature in the economy. Environment and natural materials played an important function in the development of human societies and in history on the whole. Energy in particular is of central importance in economic

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life and is also a central concern, given the heavy impact of energy consumption on the environment, especially in the last two centuries. Material underpinnings to economic success are not to be underrated, in their opinion.[1]

1.2 Definitions and Concepts

1.2.1 An Economic Definition

In daily life we have direct contact with matter, but not with energy. Matter can be touched, its form described and it is to be found underfoot as well as around us. With energy it is different. Its indirect effects are only perceived deriving from changes either in the *structure,* that is the molecular or atomic *composition* of matter, or in its *location* in space, such as in the case of a stream of water or wind, whose potential energy we can exploit. In both cases effects such as movement, heat or light reveal the presence of what we call energy from about 200 years.

In physics energy is defined as the ability of bodies to perform work.[2] Since work is the result of force by distance, then energy includes any movement of some material body in space together with the potential energy deriving from its position. Heat as well is the result of the movement of the components of matter. When dealing with the economy and then with the interrelationship between humans and the environment, our definition must be a little different. We could define energy in economic terms as *the capacity of performing work, useful for human beings, thanks to changes introduced with some cost or effort in the structure of the matter or its location in space*. Solar heat is of primary importance for the existence of life. The definition of energy in physics includes it. Since it is a free source of energy, it is not included in our economic definition; whereas the capture of solar rays by means of some mechanism in order to heat water or produce electric power is included. In the first case solar heat is not an economic resource, while it is in the second. The formation of biomass in a forest is a transformation of the Sun's energy by the plants through photosynthesis and is not included in this definition either. On the other hand, firewood is included, which is a part of forest biomass used by human beings for heating, cooking and melting metals. Food is a source of energy in economic terms, since its consumption enables the performance of useful work and its production implies some cost. Food for animals is only exploitable, and then it is an economic resource, when metabolised by those animals utilized by humans for agricultural work. It is their fuel, and, since the power of the working animals is exploited by the people, its calories have to be divided among the consumers (such as the fuel of our cars today is divided among the population and is part of their per capita consumption). When consumed by wild animals in a forest, however, these

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[1] On these topics see the first two chapters of Kander et al. (2013) chaps. 1 and 2.

[2] Useful the discussion of the definitions of energy in Kostic (2004, 527–538) (2007).

calories are not a source of mechanical power for humans and then are not included in our calculation of past energy consumption. Both fossil fuels used today and uranium are also energy carriers. They were not until a quite recent epoch, since they were not utilized in order to produce economic goods and services.

Although the definition of energy in physics is much wider than in economics, the definition here proposed is much wider than the ordinary meaning of the term energy. Many people immediately think of modern sources, when speaking of energy, and do not include daily food consumption. It is well known that working animals played a central role in pre-modern agricultural economies, but their feed is not considered as a main source of energy for humans. The lack of a clear definition, common to most contributions devoted to the history of energy, prevents from the possibility of calculating energy consumption in past societies.

1.2.2 Energy and Production

In the long history of technology, main developments consisted in the increasing knowledge about the possibility of "extracting" energy from the input of natural resources. The production process and the role of energy can be represented by the following diagram (Fig. 1.1).

The diagram can be seen as an illustration of the ordinary production function:

$$Y = AF(L, R, K).$$

Labour (*L*) and capital (*K*), the factors of any productive process of useful goods and services (*Y*), can be better defined, from the viewpoint of energy, as *converters* able to extract energy from resources (*R*) in order to transform materials into commodities. Y is in fact a function (*F*) of the converters. The progress of technical knowledge embodied in *A*, plays a central role in the production function. In one

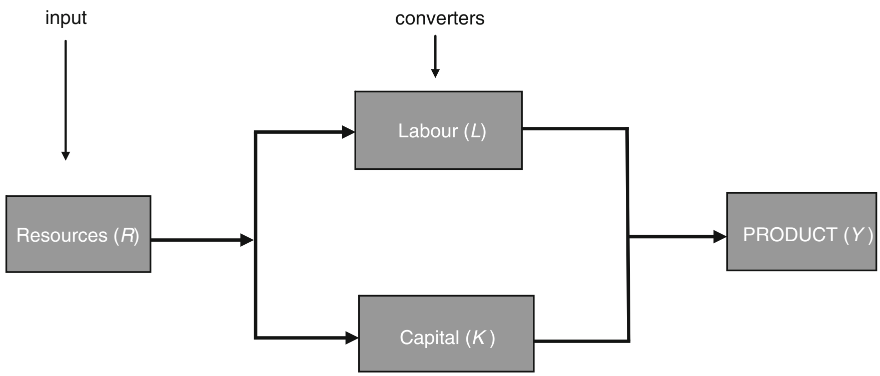

Fig. 1.1 Natural resources, converters of energy, product

sense, energy is the main input; that is to say, the main input is that part of matter (resources R) transformed by the converters, that is by workers (L), who metabolize food, and capital (K), which transforms some materials such as firewood, coal, oil, gas and electricity into mechanical work, heat and light.

The increase in productivity of energy, as a consequence both of discoveries of new sources and technologies (*macro-inventions*) or improvements in the exploitation of those already existing (*micro-inventions*)[3] can be represented by the following ratio:

$$\pi = \frac{Y}{E}$$

where Y is output (in value) and E is the total input of energy in physical terms (in Calories or joules or any other energy measure). The formula represents the productivity of energy, that is the product generated by the unit of energy. It is the reciprocal of the better known energy intensity (i), or the energy we need to produce an unit of GDP:

$$i = \frac{E}{Y}$$

In the previous diagram, energy productivity is the result of the ratio between the final product (in money) and the input of matter (food, coal, oil…) transformed into energy by the converters (in kcal, joules…). It is a measure of the efficiency of the energy converters from a technical viewpoint. The result is also conditioned by changes in the structure of the product. The increasing importance of less energy intensive sectors can result in an increase in energy productivity (or decline in energy intensity) even without any technical change.

1.2.3 Energy and History

At the end of the 20th century, per capita energy consumption, on a world scale, was about 50,000 kcal per day; that is 76 GJ per year, including traditional sources. About 80 % of this consumption was represented by *organic fossil sources*; coal, oil and natural gas. Nuclear energy represented 6 % and hydroelectricity 2 %. This 8 % was the *non organic* contribution to the energy balance. The remaining 12 % consisted of biomass, i.e. *organic vegetable sources* (Table 1.1). If the waste utilized in order to produce energy is excluded, the rest of this 12 % was composed of food for humans and working animals (today a marginal source of power), and firewood, an important item of consumption only in developing countries.

[3] For the terms “micro-” and “macro-inventions” see Mokyr (1990).

Table 1.1 Daily and yearly per capita consumption of energy worldwide around 2000 (kcal, Toe and %)

	Sources	kcal per capita per day	Toe per capita per year	(%)
3	Non organic	4,000	0.15	8
2	Organic fossil	40,000	1.47	80
1	Organic vegetable	6,000	0.22	12
		50,000	1.84	100

Source IEA, *World Energy Outlook 2010*, OECD/IEA, Annex A, Tables for Scenario Projections
Note Organic Vegetable food, firewood and feed for working animals; *Organic Fossil* coal, oil, natural gas; *Non organic* nuclear, wind, hydro, photovoltaic. Toe = ton oil equivalent = 10 million kcal

This composition of the energy balance reveals the strata of a long history of technical conquests.[4] The history of energy technology is nothing else than the chronological analysis of our present energy balance, in order to single out the various ways of extracting energy from matter to produce heat, movement, light, work etc. Following Table 1.1, we will track the history of energy consumption from the most remote layer (1) that is *Organic vegetable sources*, to the development of *Organic fossil sources*, the intermediate stratum (2), and subsequently to the progressing *Non organic sources* (3), which will be the basis of our future energy systems.[5]

From the viewpoint of energy, the long history of mankind could be divided into two main epochs (corresponding to the first two lines of Table 1.1):

- *First epoch* the about 5–7 million years from the birth of the human species until the early modern age, that is about 5 centuries ago, and
- *Second epoch* the recent history of the last 500 years, which has witnessed a fast acceleration in the pace of energy consumption.

In the first long epoch, energy sources were represented by *food for humans*, *fodder for animals* and *firewood*, that is biomass, with a small addition of *water* and *wind power*. The second epoch witnesses the rapid partial replacement of the old sources by *fossil carriers*, which became and still are the main energy sources. While in the first epoch energy was scarce, expensive and environmental changes heavily influenced its availability, during recent history energy has been plentiful, its price relatively low and the influence of the energy consumption on the environment considerable.

4 Still important on the big changes in the history of energy is the book by Cipolla (1962).

5 “Organic economies” is the expression used by Wrigley (1988). With reference to the history of energy, the same term of “organic” had been used before by Cottrell (2009), See also Wrigley (2010).

Here is a synthetic view of the sources characterizing these two main epochs:

First epoch	Second epoch
Food	Coal
Firewood	Oil
Fodder (for working animals)	Primary electricity
Water power	Natural gas
Wind power	Nuclear power

Although the energy system prevailing today is apparently different from the simple digestion of food (the first energy source), or from the burning of firewood by our primitive ancestors, it is based on the same principle, which is the oxidation of Carbon compounds by breaking their chemical ties. Since Carbon compounds are defined in chemistry as organic compounds and organic chemistry is the chemistry of organic compounds, we could define all the energy systems which have existed until today as organic and the economies based on those organic sources as *organic economies*. Coal, oil and natural gas, the basic sources oxidized today in order to bring about organized, that is mechanical, work, heating or light are carbon compounds such as bread or firewood. The difference between pre-modern and modern energy systems depends on the fact that, until the recent energy transition, organic vegetable sources were exploited, whilst from then on organic fossil energy sources became the basis of our economy. Since organic vegetable sources of energy were transformed into work by biological converters (animals) and fossil sources are transformed by mechanical converters (machines), we are able to distinguish past economies according to the system of energy they employed and the prevailing kind of converters in:

1. *organic vegetable economies* or *biological economies*;
2. *organic fossil economies* or *mechanical economies*.[6]

Given the importance of energy in human history, changes in the use of this main input mark the evolution of humans in relation to their environment much more than changes in the use of those materials, such as stone and metals, ordinarily utilized by the historians to distinguish the main epochs of human history.

[6] In chemistry "organic" refers to Carbon compounds. The term has been used by F. Cottrell and A. Wrigley (see the previous footnote) to distinguish past agricultural economies (whose base was an organic energy system) from modern economies (based on mineral fossil sources). However, fossil fuels are also organic compounds. To avoid misunderstandings I think it useful to distinguish "Past agricultural organic vegetable economies" from "Modern organic fossil economies".

1.3 Pre-modern Organic Vegetable Economies

At the end of the 18th century three were the main economic sources of energy; corresponding to three different kinds of biomass. According to the age of the discovery and exploitation of these three sources, three ages can be distinguished in the distant past (that is in the First epoch identified in Sect. 1.2.3). The original source was *food*, the second was *firewood* and the third was *fodder for working animals*. A relatively small contribution came from two other carriers: *falling water*, the potential energy of which was exploited by watermills; and *wind*, utilized both by sailboats, and, much later, mills.

1.3.1 The First Age: Food

Since the birth of the human species some 5–7 million years ago, and then for some 85–90 % of human history, food was the only source of energy. In this long period, the only transformation of matter in order to engender movement and heat was the metabolism of organic material either produced spontaneously by plants and vegetation or converted into meat by some other animal consumed by humans as food. Although nothing certain can be said about energy consumption per head at that time, given the stature and physical structure of these early humans, consumption per day of about 2,000 Cal could be plausible. Their own body was the early machine used by humans. An animal body is not very efficient in the conversion of energy. Only 15–20 % of the input of energy, that is 300–400 Cal, is transformed into work, while the rest is utilized in order to support the metabolism and dispersed in the environment as heat and waste. The economic output of these far ancestors consisted in collecting, transporting and consuming this original input of energy.

1.3.2 The Second Age: Fire

The use of fire has been the main conquest in the history of energy.[7] The first evidence of fire being used by humans refers to several different regions of the world and can be dated between 1 million and 500,000 years ago. Fire was a conquest of independent groups of humans in several parts of the world and the main source of energy for several millennia. Its use spread slowly. In this case, as in the case of food, an estimate of the level of energy consumption by our distant ancestors can only be speculative. As far as is known for much more recent ages, the level of firewood consumption in different regions in pre-modern times may have varied from 1 kg per head per day to 10 in cold climates, that is between

[7] On the discovery of fire see particularly Perlès (1977) and Goudsblom (1992).

3,000–4,000 and 30,000–40,000 Cal. A daily consumption of about 1 kg per capita could be assumed for the humans living in relatively warm climates. In northern regions firewood consumption was considerably higher. Fire could be used for heating, cooking, lighting, and for protection against wild animals. Although, with fire, Calories per head drastically increased from 2,000 to 3,000–4,000 per day or more, that is 5–6 GJ per year, the efficiency in its use was very low. The useful energy exploited by the population did not exceed 5 % of its Calories, the rest being lost in the air.

1.3.3 The Third Age: Agriculture

During the Mesolithic, the end of glaciations and the rise in temperature enabled humans to increase the cultivation of vegetables and particularly cereals. The overall availability of energy in the form of food increased dramatically and supported the growth of population. In per capita terms, the perspective is different. Since population increased rapidly in the agricultural regions of the World, availability of food per head did not increase. A diet based on cereals represented a deterioration, as is witnessed by the decrease in stature following the spread of agriculture. Agriculture, as the main human activity, progressed quite slowly, if we compare the diffusion of this technological conquest to the following ones. From the Near East, where primarily developed 10,000 years ago, agriculture progressed towards Europe at the speed of 1 km per year. Within 3,000 years, agriculture reached northern Europe. At the same time, the new economic system was spreading from northern China and central America, the regions of the world where agriculture independently developed at the same time or a little later than in the Near East.

A new development in the agricultural transition took place during a second phase: from about 5,000 years until 3000 BCE. The period can be considered as a true revolution. The fundamental change was represented by the taming of animals, (oxen, donkeys, horses and camels), and their utilization in agriculture and transportation. Humans' energy endowment was rising. If we consider a working animal as a machine and divide his daily input of energy as food—about 20,000 Cal—among the humans who employed him, consumption per head may have increased by 20–50 % or more, according to the ratio between working animals and human beings; which is not easy to define for these distant epochs. Only about 15 % of this input represented, however, useful energy, that is energy converted into work.

During this age, several innovations allowed a more efficient utilization of humans' power, fuels and animals; e.g. the wheel, the working of metals, pottery, the plough, and the sail. The sail was previously used, but it only spread widely during this revolutionary epoch. The use of wind was the first example of the utilization of a non-organic source of energy, not generated by the photosynthesis of vegetables. Labour productivity rose markedly. Even though some changes in the agricultural energy system also took place in the following centuries, technical progress was modest on the whole. Water and windmills, invented respectively 3 centuries BCE (as recent research suggests) and in the 7th century CE, were the main innovations in the energy basis of the agrarian civilisations. Although important from a technological viewpoint, these changes added very little in terms of energy availability: ordinarily no more than 1–2 %.[8]

1.3.4 Main Features of the Organic Vegetable Economies

Although several important differences exist among the three ages of our organic vegetable past, there are also some analogies; especially when dealing with the relationship between humans and environment. The dependence of this energy system on soil implies several constraints to the possibilities of economic development.

1. *Reproducible sources* Vegetable energy carriers are reproducible. They are based on solar radiation and since the Sun has existed for 4.5 billion years and will continue to exist for 5 billion years, vegetable materials may be considered as an endless source of energy. Organic vegetable economies have been sustainable since solar energy allowed a continuous flow of exploitable biomass. However, only a negligible part of solar radiation reaching the Earth, less than 1 %, is transformed into phytomass by the vegetable species. Of this 1 %, only an insignificant part is utilized by humans and working animals. On the other hand, increase in the exploitation of phytomass was far from easy. The availability of more vegetable sources implied extension of the arables and pastures and the gathering of firewood, which was difficult to transport over long distances. The ways of utilizing the phytomass were also in conflict, since more arables implied less pastures and woods. Thus, while the availability of these carriers was endless, their exploitation was hard and time consuming. The production of phytomass was, furthermore, subject to climatic changes both in the short and long run and heavily influenced by temperature changes and weather variations. Long-term climatic changes could also raise or diminish the extent of cultivation and wood productivity. Past organic vegetable economies, based on reproducible sources of energy, were the economies of poverty and famine.
2. *Climate and energy* Given that, in pre-modern organic vegetable energy systems, transformation of the Sun's radiation into biomass by means of photosynthesis was fundamental and since the heat of the Sun is not constant on Earth, the energy basis—phytomass—of any human activity was subject to changes. Climatic phases have thus marked the history of mankind. The availability of phytomass deeply varied and strongly influenced human economies. Glaciations caused a decline in available energy and therefore in the

[8] On the quantification of water and wind power see Malanima (1996).

number of humans and the evolution of their settlements. The end of the glaciations provoked changes in the main human activities; from hunting and gathering to agriculture. Agricultural civilizations were also deeply influenced by climatic variations. While warm periods were favourable to the spread of cultivations and the multiplication of mankind, cold epochs corresponded to demographic declines. Roman civilisation flourished in a warm period and was accompanied by population rise, while the early Middle Ages, characterized by a cold climate, was an epoch of demographic decline. The so-called warm Medieval Climatic Optimum coincided with worldwide population increase, between 900 and about 1270, while the following Little Ice Age, from 1270 until 1820, was again a period of economic hardship and population stability or slow increase. While present day energy systems heavily influence the environment and climate, until a few centuries ago the opposite was true.

3. *Efficiency and energy intensity* Only a part of energy input is actually transformed into useful energy (or energy services, that is mechanical work, light and useful heat). How great this share is depends on the efficiency of the converters of energy, that is labour (L) and capital goods (K). The thermodynamic efficiency (η) of the system of energy can be represented through the following ratio between the energy services (Eu) and the total input of energy (Ei):

$$\eta = \frac{Eu}{Ei}$$

Today, in our developed economies, this ratio is about 0.35; that is 35 % of the input of energy becomes actual mechanical work, light or useful heat. In past agricultural civilizations, the efficiency was much lower. A plausible calculation is easier for the past, when biological converters prevailed, than for the present. Today, in fact, the variety of machines, with diverse yields, make hard any estimate. The ratio between useful mechanical work and input of energy into biological converters, such as humans and working animals, is around 15–20 %.[9] Part of the intake of energy in the form of food is not digested and is expelled as waste, whilst the main part is utilized as metabolic energy in order to repair the cells, digest and preserve body heat. A human being or animal consumes even when inactive. The use of firewood is even less efficient. The greater part of the heat is dispersed without any benefit for those who burn the wood. Its yield is about 5–10 %. Overall, the efficiency of a vegetable energy system based on biological converters, such as that of ancient civilizations, was around 15 % at the most: that is 1,000–1,500 kcal. were transformed into useful mechanical work or useful heat; the rest was lost. Thermal machines are much more efficient than biological converters such as animals and humans.

4 *Low Power* Power is defined as the maximum of energy liberated in a second by a biological or technical engine. In the economies of the past another

[9] See the useful Herman (2007).

consequence of the usage of biomass converted into work was the low level of power attainable. The power of a man using a tool is about 0.05 horsepower (HP). That of a horse or donkey can be 10 times higher. A watermill can provide 3–5 HP, while a windmill can reach 8–10 HP. As a comparison, a steam engine could attain 8,000–12,000 HP around 1900, while a nuclear plant can reach 2 million HP. The conquest of power meant an incredible advance in the possibility of harnessing the forces and materials of the environment. To clarify this central point about the differences between past and modern energy systems, we must remember that the power of an average car (80 kW) is today equal to the power of 2,000 people and that the power of a large power station generating electricity (800 mW) is the same as that of 20 million people. The electric power of a medium sized nation of 40–60 million inhabitants, some 80,000 mW, equals the power of 2 billion people. Today, a nuclear plant or a nuclear bomb can concentrate millions of HP, or the work of many generations of humans and draft animals, into a small space and a fraction of time. This *concentration of work* allows humans to accomplish tasks that were barely imaginable just a few lifetimes ago.

1.4 Modern Organic Fossil Economies

At the start of modern growth around 1800, on the world scale, energy consumption was about 8,000–9,000 kcal per capita per day, that is 13 GJ per year.[10] The main sources were those already seen, that is different kinds of biomass (food, firewood and fodder). Water and wind were the only non organic sources. In 1800, throughout western Europe, the energy balance per head was 20 GJ per year, that is 13,000 Cal per day, excluding coal, which was then widely used only in England. On the continent, many differences existed in the levels of energy consumption. While in Mediterranean countries it was about 15 GJ per year (10,000 Cal per day), in Scandinavia it was 45 (30,000 Cal per day). In pre-modern Europe, the main energy carrier was firewood. It represented 50 % in the south and more than 70 % in the northern regions, followed by fodder for working animals and food for the population.[11]

In Europe, energy consumption was higher than in other agricultural civilisations, both in Asia and southern America, for two reasons:

1. the European civilisation was the most northern agrarian civilisation and, since temperature was a main determinant of energy consumption, wood consumption was higher than in coeval agrarian economies;

[10] On the relationship Modern Growth—Energy see: Ayres and Warr (2009).

[11] See the estimates by Kander (2002) and Malanima (2006).

2. in the dry European agriculture, the utilisation of animals in agriculture and transportation was more widespread than elsewhere. In both China and southern America, the presence of animals in agriculture was far more modest. In premodern centuries, probably only in India was animal power exploited to the same extent as in Europe.

1.4.1 The Start of the Energy Transition

Modern growth, from about 1820 until today, has marked a sharp rise both in the sources utilized and in the efficiency of their utilization.[12] We could define this change as an *energy transition.* It was an important support to the growth in the capacity to produce. Although not *sufficient condition* of modern growth, energy transition was a *necessary condition*.[13] Without this transition, modern growth could not occur. As has been seen, although some other deep changes occurred in the use of energy before the modern era, this last transition is often represented, for its rapidity and intensity, as the "transition" par excellence or the period that marked a break between past and present.

Fossil sources, coal, oil, natural gas, were also products of photosynthetic processes, such as food and firewood. Their formation had taken place in the Carboniferous era, some 300–350 million years ago. This underground forest had been mineralized or transformed into liquid fuel and gas in the course of several millennia.[14] In various parts of the world and in England and other northern European regions, coal was easily extracted. If by the start of the epoch of fossil fuels we refer to the period when they began to develop, the second half of the 16th century could be defined as the starting point. It was then that they began to be employed on a large scale by English manufacturers and for domestic use. If, instead, we want to single out the epoch when they began to play an important role on the European and non European economy, this age is the first half of the 19th century.

The existence of fossil fuels had been known in Europe since the times of ancient Rome. During the late Middle Ages, in those northern European regions where coal was easily available, its consumption spread, as its price was far lower than that of firewood. In China coal was also widely used in metallurgy during the late Middle Ages. From the second half of the 16th century, the use of coal increased in England, above all. The rising population and particularly that of London represented a strong stimulus towards the consumption of a much less expensive fuel than firewood. In the whole of England the production of coal increased 7–8 times between 1530 and 1630, thanks to the greater depth of the shafts and better drainage

[12] On this phase in the history of energy see the still useful article by Bairoch (1983) and particularly Kander et al. (2013). A brief, useful reconstruction is that provided by Grübler (2004).

[13] Malanima (2012).

[14] On the transition to fossil sources of energy, it is useful Sieferle (2001).

Table 1.2 Share of coal production in England and the rest of Europe 1800–1870 (%)

	England	Rest of Europe
1800	96	4
1830	79	21
1840	73	27
1850	73	27
1860	65	35
1870	58	42

Source Etemad and Luciani (1991, 256)

of the mines and by the 1620s it had become more important than wood as a provider of thermal energy. For a long period, England was by far the main producer of coal. Only at the end of the 19th century, was the rest of Europe able to compete with England (Table 1.2).

The share of coal on total energy consumed in England was 12 % in 1560, 20 % in 1600, and 50 % in 1700. Coal consumption from 1560 until 1900 shows an almost stable rate of growth (Fig. 1.2). In The Netherlands another fossil fuel, peat, began to be used on a wide scale from the 17th century onwards. It was an important support of the Dutch Golden Age, but did not cause such fundamental changes in the economy as coal in England.

One of the reasons for the transition to a new source of energy was the growth in population throughout the continent from the last decades of the 17th century onwards. While in 1650 the European population numbered 112 million, in 1800 it was already 189 million and in 1850 it was 288 million. The main converter of the organic vegetable energy system, land, was becoming scarcer. Energy consumption of traditional sources was diminishing in per capita terms, whereas food, fodder and above all firewood were becoming more expensive. The price of these sources increased across the whole continent from the second half of the 18th century

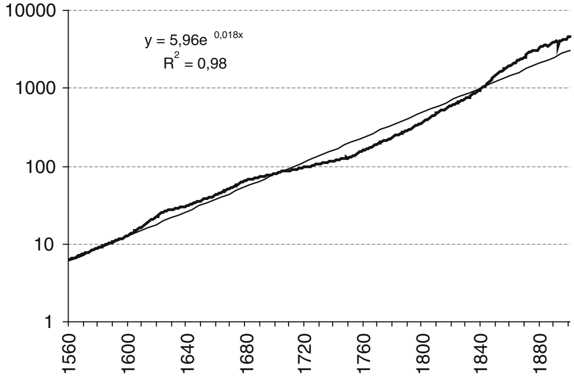

Fig. 1.2 Coal consumption in England and Wales 1560–1900 (in Petajoules; log scale). *Source* Warde (2007). *Note* you see in the diagram the formula of the exponential interpolating curve. 1 PJ = 1,000 billion KJ

onwards. Land per capita outside Europe was also diminishing.[15] The European population growth was part of the demographic transition taking place worldwide. World population rose from 600 million in 1650 to 1 billion in 1820.

The shift to new fuels represented one aspect of the energy transition then in act. It was not, however, the most important. The main technological change was the new utilisation of fuels, that is, the techniques designed to employ in a different way the heat of these organic sources. For about one million year, fuels had been utilized for heating, lighting and melting metals, while work, in economic terms, that is organized movement in order to produce commodities and services, was only provided by humans and animals; apart from wind and water (whose mechanical work, in any case, was not the conversion of a fuel). The only engines able to provide work were biological machines. The introduction of machines in order to convert heat into mechanical power was the main change in the energy system, comparable in importance to the discovery of fire. It was only during the 18th century, with the invention of the steam engine by Thomas Newcomen and James Watt, that the *Age of the Machines* really began. The fundamental technological obstacle that had for millennia limited the capacity of the economic systems to perform work, was only then overcome. In 1824, the French physicist Sadi Carnot clearly pointed out the great novelty represented by what he called the "machines à feu", the thermal machines.[16] In his opinion they would have replaced soon both the force of animals and that of water and wind. This is precisely what happened over the last two centuries. The age of machinery began with the steam engine and such energy transition resulted in great changes in:

- the volume and trend of energy consumption;
- the process of substitution of energy carriers;
- the geography of energy production;
- the price of energy;
- the relationship energy-economy;
- the relationship energy-environment.

The following sections are devoted to these changes.

1.4.2 The Volume and Trend of Energy Consumption

Energy consumption per head diminished in Europe during the 18th century, whilst from 1800 until 2000 it rose considerably: 5.8-fold from 1800 until 2000, that is from 23 to 134 GJ (Fig. 1.3).[17] Since at the same time population increased 3.5

[15] On the Malthusian constraints in pre-modern "organic" energy systems: Wrigley (1989). I examined the start of the energy transition in Malanima (2012). The path towards the modern economy.

[16] Carnot (1824).

[17] On energy consumption in Europe, see Bartoletto (2012).

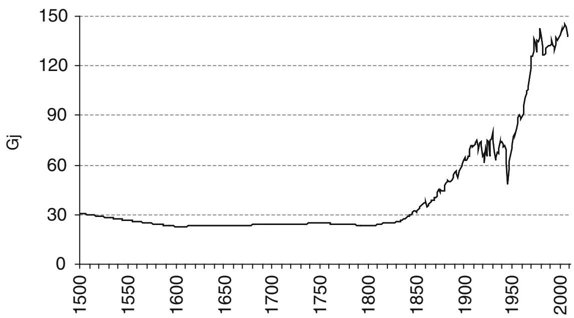

Fig. 1.3 Per capita energy consumption of traditional and modern carriers in western Europe 1500–2005 (GJ). *Source* Kander et al. (2013). *Note* 1 GJ = 1 million KJ = 0.0239 Toe

times, total energy consumption registered a 20-fold increase (Table 1.3). The global crisis of the first decade of the 21st century resulted in a fall of energy consumption.

Until about 1840, energy consumption per head did not increase in Europe, since the input of fossil fuels rose at the same rate as the population. From 1840 onwards until the First World War, growth was instead remarkable. After a period of stability between the two World Wars, a significant increase took place from the 1950s until the 1970s, followed by a slower rise. In the long run the growth witnesses an almost constant rate with brief deviations due to wars or epochs of fast economic rise (Fig. 1.4).

On the World scale, the rise of per capita consumption has been 5.7 times between 1850 and 2000. Since population growth was 5.8-fold, the aggregate rise

Table 1.3 Energy consumption in western Europe from 1800 until 2000 in kcal per capita per day, in Toe per capita per year, population and total energy consumption in Mtoe

	kcal per capita per day	Toe per capita per year	Traditional sources (%)	Rate of growth (%)	Population (000)	Total Mtoe
1800	15,300	0.56	77		96,950	54
1830	16,700	0.61	62	0.29	118,800	72
1900	42,000	1.53	20	1.32	194,800	299
1950	46,500	1.70	13	0.20	254,500	432
1970	82,200	3.00	7	2.85	293,700	880
1990	86,800	3.17	7	0.27	316,900	1,004
2000	90,700	3.31	8	0.44	327,400	1,084
2010	88,000	3.21	8	−0.30	336,000	1,079

Source Kander et al. (2013)

Note data refer to western Europe: Sweden, The Netherlands, Germany, France, Spain, Portugal, Italy. 1 Megatoe = 1 million Toe

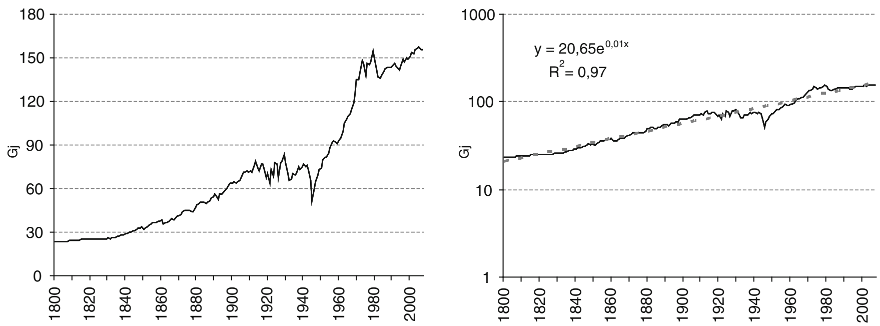

Fig. 1.4 Per capita energy consumption in western Europe 1800–2007 (GJ) (on the *right* log *vertical axis*, trend and the equation of the trend). *Source* Kander et al. (2013)

was 33 times (Table 1.4). We see that modern or commercial sources overcame traditional sources, or the phytomass, around 1900, or the epoch of the second industrial revolution.

1.4.3 The Process of Substitution

In organic vegetable economies any discovery of a new source was an addition to the balance of energy and not a substitution. With fossil sources it was different. Fossil sources replaced a large part of the traditional carriers, which lost their importance in relative and sometimes in absolute terms. While food consumption rose in aggregate and per capita terms, the power of working animals diminished and, in developed economies, totally disappeared. Firewood continued to represent an important share of energy consumption only in relatively backward areas. On the world scale, traditional sources of energy diminished from 98 % in 1800 to 50 in 1900 and only 14 in 2000–2010. In Europe the decline was still higher. England was the only important consumer of coal at the beginning of the 19th century. Traditional sources then represented the greater majority throughout the continent, that is almost 90 % of the overall consumption (when England is excluded). Their share decreased to 25 % in 1900 and was only 5 % in 2000 (always excluding England).

For several millennia changes in the energy system had been very slow. From 1800 transitions and substitutions began to dominate the picture. If we look at the fuels utilized in Europe from 1800 until 2000, we see that, in terms of Calories, firewood still dominated in 1800, while coal represented about 30 %. Wood consumption was, in relative terms, already relatively modest in 1900, while coal equalled about 80 %. Oil began to be used during the last decades of the 19th century and only in the 1960s exceeded coal. Natural gas spread from the 1970s on a large scale and only in the 1990s did it overtake coal; although its share was less than half that of oil. While coal dominated for a long period in the last half century,

Table 1.4 World energy consumption from 1800 until 2010 in kcal per capita per day, in Toe per year, world population and total in Mtoe

	kcal per capita per day	Toe per capita per year	Traditional sources (%)	Rate of growth (%)	World population (000,000)	Total Mtoe
1800	8,500	0.31	98		950	295
1850	9,800	0.36	88	0.30	1,180	425
1880	13,000	0.47	65	0.89	1,365	642
1900	18,400	0.67	50	1.77	1,560	1,045
1950	28,200	1.00	33	0.80	2,527	2,527
1970	45,900	1.67	20	2.56	3,691	6,164
1985	48,100	1.76	16	0.35	4,838	8,515
2000	49,000	1.79	14	0.11	6,077	10,878
2010	55,700	2.03	14	1.26	6,850	13,906

Sources on the World scale energy consumption and production can be assumed to be equal. Data on the production of modern sources of energy are from Etemad and Luciani (1991). The consumption of traditional energy carriers is based on plausible figures on the relative share of the modern sources (United Nations 1956) and Fernandes et al. (2007) and also the auxiliary material in http://onlinelibrary.wiley.com/doi/10.1029/2006GB002836/suppinfo on consumption of biofuels
Note 1 Megatoe = 1 million Toe

and although oil holds a central position, the picture is more varied and variety is ever increasing with the rising exploitation of solar power, wind, biomass and nuclear power as sources of primary electricity (Fig. 1.5).

Electricity is in any case a secondary energy source, a transformation, that is, of other sources. Even when electricity is generated by a water turbine, the primary source of power is represented by falling water, that is, by the change in its potential

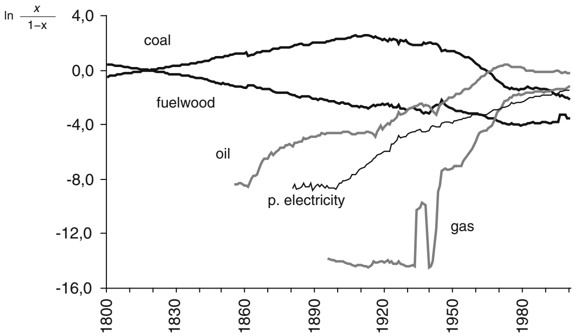

Fig. 1.5 Shares of any fuel on the total fuel consumption in Europe 1800–2000 (ln). *Sources* Kander et al. (2013). *Note* x, on the *vertical* axis, refers to the share of an energy carrier on the total of the 5 energy carriers minus the energy carrier x. I follow Marchetti (1977); although the results represented in the graph do not confirm those reached by Marchetti

energy. The same holds true for nuclear electricity, which began to develop from the late 1950s and whose primary source is the change in the atomic structure of uranium. Often, however, the expression "primary electricity" is used to single out that part of electricity not produced through fossil fuels. Today it includes solar, wind and geothermal electricity. Its share, in the form of hydroelectricity, has developed since the last decades of the 19th century. Nuclear power has been a remarkable addition since the 1970s. In 1971 it represented only 1 % of energy in Europe. In 2005 it was 13.6 %, thanks especially to the nuclearisation of the French energy system. Since the share of primary electricity in the continent was 17.2 % of primary electricity, the other sources were then negligible.

On the world scale, we find the same transition from coal to oil, to natural gas and to nuclear electricity, while photovoltaic, hydro and wind power progressed remarkably in the 1990s and the first decade of the third millennium (Table 1.5).

Table 1.5 World consumption of primary commercial energy (in Mtoe per year)

	Coal	Oil	Natural gas	Primary electricity	Total
(MToe)					
1700	3				3
1750	5				5
1800	11				11
1850	48				48
1900	506	20	7	1	534
1950	971	497	156	29	1,653
1973	1,563	2,688	989	131	5,371
1987	2,249	2,968	1,550	332	7,099
2010	3,532	4,032	2,843	1,405	11,812
(%)					
1700	100				100
1750	100				100
1800	100				100
1850	100				100
1900	94.8	3.7	1.3	0.2	100
1950	58.7	30.1	9.4	1.8	100
1973	29.1	50.0	18.4	2.4	100
1987	31.7	41.8	21.8	4.7	100
2010	29.9	34.1	24.1	11.9	100

Sources Martin (1990) and BP (2012)
Note 1 Megatoe = 1 million Toe. Here consumption refers only to commercial sources of energy, while in Table 1.4 total consumption includes the traditional carriers as well

1.4.4 The Geography of Energy Production

At the beginning of the 19th century, commercial, that is fossil, energy production was still entirely localised in Europe and especially in the north and centre. Economic growth and availability of fossil sources of energy more or less coincided. At the middle of the century, 90 % of fossil energy was still produced in Europe and 10 % in the United States (Table 1.6). Things changed during the 20th century, and especially in the second half, when oil began to play a central role in the energy systems of the developed countries. After the World War 2, Europe produced 35–40 % of world commercial energy. In particular the European production of oil has always been negligible, despite an increase of North Sea oil exploitation in the 1980s and 1990s by Great Britain and Norway. If, as a whole, the energy deficit of developed countries was only 4 % in 1950, in 1973 it had grown to about 50 %. At the end of the century, a little less than 50 % of oil production was localised, in order of importance, in Saudi Arabia, the USA, the Russian Federation, Iran and Mexico. The concentration of oil production, which is the basic source of the energy system, in specific places, resulted in a higher vulnerability of energy provisioning of developed countries. This vulnerability clearly appeared in 1973 and 1979, when the oligopoly of the main energy producers, OPEC, limited oil production and resulted in fast and remarkable price increases.

At the end of the past millennium, considerable differences existed in energy consumption per country. The geography of energy consumption is similar to the geography of growth; while the geography of energy production is not. Countries with higher per capita GDP are higher consumers (Fig. 1.6).

Among rich and poor countries the range of commercial energy consumption per head is 40 to 1. While in Niger and Mali it is 0.2 toe per capita per year, in the USA it is 8 toe. In the 1980s, on the world scale, energy consumption of market developed economies was 50 % of the total; that of centrally planned economies 20 % and that of the developing countries 30 %. At the end of the second millennium, 25 % of the world population—1.5 billion, the population, that is, of the developed economies, consumed 7,920 toe, i.e.75 % of the world consumption in one year, while 75 % of the population—4.5 billion—consumed 2,340 toe, or 25 % of the whole. With about 4.9 toe per year, an inhabitant of the most advanced

Table 1.6 Total production of commercial energy per continent (%)

	1800	1850	1900	1950	1985
Europe	99.09	90.00	61.63	35.66	38.38
America	0.91	10.00	35.71	52.38	30.73
Asia	0.00	0.00	1.72	9.99	23.11
Africa	0.00	0.00	0.12	1.24	5.83
Oceania	0.00	0.00	0.82	0.73	1.95
	100	100	100	100	100

Source Etemad and Luciani (1991)

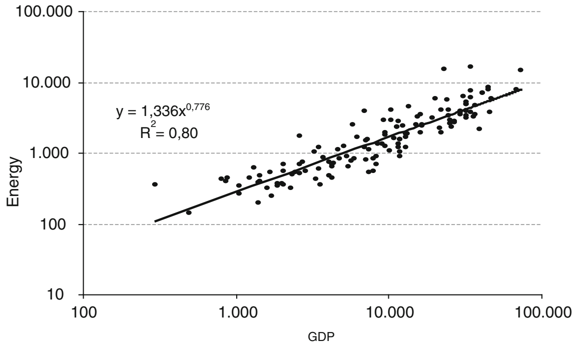

Fig. 1.6 Per capita energy consumption per country in 2009 (kg oil equivalent: koe) as a function of per capita GDP ($2005 PPP). *Source* World Bank (2011). *Note* the interpolation is drawn through a power regression, whose formula is represented in the graph. Ordinates and abscissae in log. 1 koe = 10,000 kcal

economies consumed on average 9 times more commercial energy than an inhabitant of the poorest countries—only 0.54 toe. So strong differences did not exist before modern growth. Only differences in climate and not in wealth could then imply remarkable disparities in consumption.

1.4.5 The Price of Energy

The spread of fossil fuels was fostered by their relatively low price in comparison with organic vegetable sources. During the second half of the 18th century and the first decades of the 19th, the initial progress of coal coincided with a period of rising prices of all organic vegetable sources of energy. For the same energetic content, fossil carriers were 2–3 times cheaper than the vegetable ones. If we take the curve of oil prices on the international markets, we notice that, after a couple of decades of high prices at the start of the use of oil, there was a downward curve until the 1973 crisis (Fig. 1.7).

In the 1950s and 1960s oil prices reached their lowest level. Although different sources have different prices, the trend in oil prices well represents the trend of energy prices on the whole. Data for the periods both before and after the introduction of the new fossil carriers, suggests that the fastest rate of the modern growth, occurring in the 1950s and 1960s, coincided with the lowest level of energy prices ever experienced, at least from when written information exists. On the other hand, the slower rate of growth of the world economy after 1973 depended, at least in part, on the higher price of energy and particularly oil.

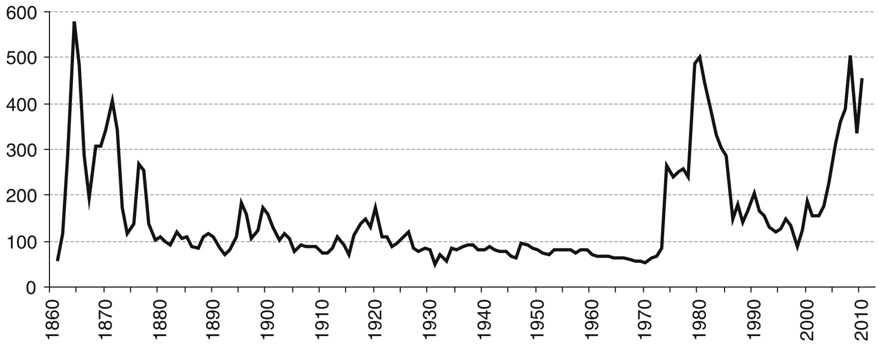

Fig. 1.7 Oil prices on the international market in 2008 euros per barrel 1861–2012. *Source* my calculations from data in https://opendata.socrata.com

1.4.6 Energy and Economy

When dealing with energy, we are interested both in the energy input into the economic system and the share of total energy actually available as mechanical work and heat. It is well known that energy cannot be created or destroyed, but only transformed (according to the first law of thermodynamics). On the other hand, it is also known that in any transformation there is a loss of *useful* energy: a large part of the energy that is consumed remains unavailable (according to the second law of thermodynamics). How great this amount is depends on the technical efficiency of the converter (as already seen in Sect. 1.3.4).

From 1800 on, not only were new fuels introduced on a wide scale, but equally important was the wider efficiency in their use. The conversion efficiency in different energy systems evolved through the following four main stages:[18]

	(%)
1. Subsistence agriculture	5
2. Advanced agriculture	15
3. Emerging industrial	25
4. Advanced industrial	35

As can be seen, modern growth implied not only a rise in the exploited energy, but also a rise in the efficiency of its exploitation. After all, machines are more efficient than animals as converters of energy.

[18] From Cook (1976, 135).

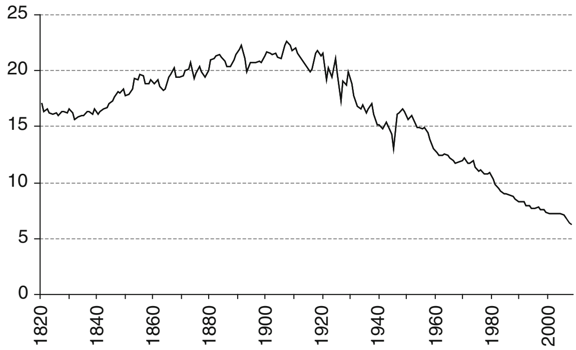

Fig. 1.8 Energy intensity in western Europe between 1820–2005 (per capita GJ (000)/per capita GDP in 1990 dollars PPP). *Source* Kander et al. (2013)

The advantages of machinery and technological change in terms of energy yield are easily visible if energy consumption (expressed in some energy measure) is divided by product (in money). The result of the ratio is the so called *energy intensity* (*E/Y*) (Fig. 1.8). The curve of energy intensity shows that, during the 19th century, some increase occurred in the energy/GDP ratio, due to the exploitation of coal by inefficient technologies especially in England, the main producer and consumer of coal. From 1900 on a remarkable decline took place. In the year 2000, the production of the same output required half the energy used some 200 years earlier.

A decline in energy intensity occurred in the second half of the 20th century in almost all world economies; although the differences were still remarkable (Table 1.7).

From 1820 until 2000, GDP per capita rose 16 times in western Europe, while energy input per head rose about 8-fold and efficiency in the use of energy doubled. A decomposition of per capita GDP proves to be useful in order to specify the relative importance of the input of energy and the efficiency of its exploitation. Per capita GDP (*Y/P*) can be represented as the result of energy consumption per capita (*E/P*) divided by the *productivity of energy* (*Y/E*):

Table 1.7 Energy intensity in different economies 1950–1990 (in Toe per $1,000 of GDP constant prices)

	OCDE	CPE	DC	OPEC
1950	0.55	1.70	0.23	0.10
1960	0.51	1.97	0.31	0.25
1970	0.52	1.66	0.38	0.22
1980	0.44	1.57	0.44	0.29
1990	0.36	1.39	0.46	0.44

Source elaboration of data from Pireddu (1990)

Note OCDE the organisation for cooperation and economic development; *CPE* centrally planned economies; *DC* developing countries; *OPEC* the organisation of the oil producer countries

$$\frac{Y}{P} = \frac{E}{P} \cdot \frac{Y}{E}$$

If we assume:

$\dot{y}$ as the rate of growth of *Y/P*;
$\dot{e}$ as the rate of growth of *E/P*; and
$\dot{\pi}$ as the rate of growth of *Y/E*;

we can specify the relative importance of *e* and π in the growth of *y*, during the period concerned; that is the years from 1820 until 2000. In fact:

$$\dot{y} = \dot{e} + \dot{\pi}$$

Our result is:

$$1.54 = 1.10 + 0.44$$

The conclusion is that, from 1820 until 2000, the annual rate of growth of per capita GDP was 1.54 %, and that *E/P* and *Y/E* grew respectively at the rates of 1.10 and 0.44 per year. The input of energy contributed more than the productivity of energy in the growth of per capita product. It was 2.5 times more important (1.10/0.44 = 2.5). Figure 1.9 shows that both per capita GDP and per capita energy consumption grew, in these last two centuries, with an almost constant and similar rate of increase. However, GDP per capita, (the higher curve) grew faster than energy (always per capita); as the interpolating exponential curves shows.

The introduction of new machines and more efficient engines was responsible for the leap in the productivity of energy. From the last decades of the 19th century, electricity contributed significantly to efficiency, together with the development of new devices which entered production plants and homes. Between 1860 and 1914, the introduction of electricity, steam and water turbines, and the internal

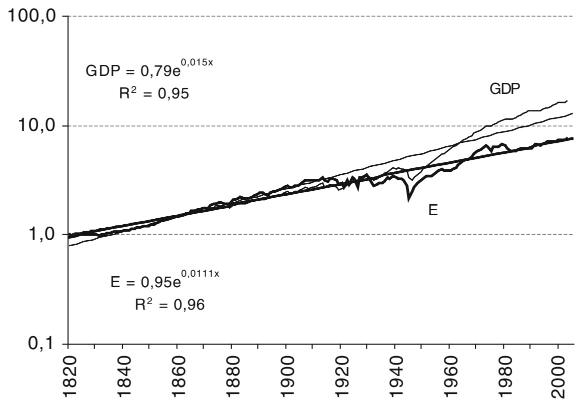

Fig. 1.9 Per capita energy consumption (the *thick curve*) and GDP per capita in western Europe 1820–2010 (1820 = 1) (exponential interpolating curves). *Source* Kander et al. (2013)

combustion engine (together with inexpensive steel, aluminium, explosives, synthetic fertilizers and electronic components), marked a technical watershed in recent economic history.

1.4.7 Energy and Environment

Among the different sources of energy, only the exploitation of wind, water and direct solar energy do not modify the environment since they do not cause a change in the molecular or atomic composition of matter. Whenever, by contrast, either the molecular or nuclear composition of matter is modified, even by the mere digestion of food, some change is introduced in the environment and some waste is produced. It is known that some environmental effects were produced by humans in past civilisations and that deforestation was not unknown in ancient economies. Lead in the atmosphere was notable in Roman antiquity due to melting metals, as the ice of Antarctica and Greenland has shown.[19] In any case, much heavier were the consequences of the environment on energy consumption by the humans than of human energy consumption on the environment. Both annual changes in temperature and rain, and long-term climatic cycles resulted in changes in the available energy, and subsequently in the level of the economic activity.

The 45–50-fold growth of energy consumption on the World scale, in the last 200 years, and the higher emissions by fossil fuels resulted in a dramatic rise in the level of gases in the atmosphere. Carbon dioxide (CO_2), water vapour, methane, nitrous oxide, and a few other gases are defined greenhouse gases. Their presence in the air has risen fast since the introduction and ever increasing use of coal and the other fossil carriers. Remarkable differences, however, exist among them: natural gas is much less polluting than oil, which is less polluting than coal. According to most paleo-climatologists the rise in temperature during the last century can be explained only as a consequence of the modern energy system and emissions of carbon dioxide into the atmosphere. Although the declining energy intensity from the 1990s results in a relatively lower impact of energy consumption on the environment, the fast rising energy consumption in absolute terms more than counterbalances the positive effect. On one hand, CO_2 emissions tend to decrease in relation with per capita GDP, since in rich countries energy intensity diminishes (Table 1.8). On the other hand, however, as a consequence of the high production per capita, per capita emissions in absolute values are much higher in rich than in poor countries. On the World scale, during the first decade of the third millennium, emissions averaged 4.5 tons per capita per year.

CO_2 emissions increased from 18,500 million of metric tons in 1980 to almost 30,000 million in 2006: a 60 % rise in less than 30 years. On the other hand, attempts at the reduction of CO_2 emissions in order to stabilize or reduce

[19] As stated by Rossignol and Durost (2007).

Table 1.8 Emissions of CO_2 in relation with GDP (kg/$2005 PPP) and population (tons/pop.) in 2005

GDP per capita in $2005 PPP	Level of income per capita	CO_2 kg/GDP ($2005 PPP)	CO_2 tons/population
		2005	2005
<995	Low	0.28	0.28
996–3,945	Lower middle	0.73	2.79
3,946–12,195	Upper middle	0.48	5.26
12,196 and >	High	0.37	12.49
	World	*0.49*	*4.63*

Source World Bank (2011)

concentration of gases in the atmosphere (as in the Kyoto protocol, enforced on February 16th 2005) imply heavy consequences for the economy in the short term (and people are always more interested in the immediate negative effects on the economy rather than in the long-run positive effects on future mankind). The rise of new non polluting sources of energy is slower than it was hoped at the end of the past century.

While in a first phase of the industrialisation the CO_2 increased emissions could have played a positive role in agriculture, contributing to the fertilisation of the soils, since carbon dioxide makes crops grow faster, there is no doubt that in more recent decades the negative effects were much heavier than the positive. Although a precise quantification of the social and economic costs is hard to provide, a likely estimate for the beginning of the new millennium is in the order of $20 per ton of carbon dioxide emitted in the atmosphere.[20] This cost would correspond to something like 0.5–5 % of GDP in advanced economic regions.

1.4.8 The Future of Energy

Forecasts of energy consumption always prove to be inaccurate.[21] Some general remarks on future developments are, however, possible. Humans have lived in organic economies since the birth of the human species, some 7–5 million years ago, until today. If humans continue to live and reproduce on the face of the Earth and enjoy the same levels of wealth we enjoy today or if they aim at increasing this wealth, our future will no longer be organic. We have seen that in about 2000–2010 per capita consumption on a global scale was around 50,000 Calories per day and that about 12 % was made up of organic vegetable sources—the old heritage of past agricultural societies—, while 80 % came from organic fossil sources—the more

[20] Nordhaus (2011).

[21] As stressed by Smil (2006).

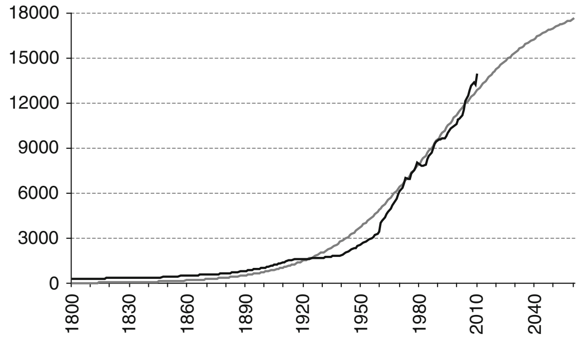

Fig. 1.10 World energy consumption (only modern sources) in Mtoe from 1800 until 2010 and prediction of future energy consumption until 2060 (*logistic curve*). *Source* see text. *Note* the coefficients of the *logistic curve* have been estimated through linear regression. The resulting equation is the following: with y = world consumption of modern sources; a = the lowest value; K the highest value; b the rate of growth; t time (starting with 1 in 1800)

recent heritage of modern growth. On a global scale, only a relatively narrow residual amount is represented by photovoltaic, wind, water and nuclear energy. These are the sources of our non-organic future. Fossil sources are diminishing and will disappear completely in one or two centuries. It is known that population rise is stabilizing, but that it will continue to grow for some decades, to reach at least 10 billion in the second half of this century. Per capita product is increasing rapidly in some countries, once poor, but now fast becoming rich. With a denser and richer world population, it will not be possible to devote land to the production of organic fuels or bio-fuels such as ethanol. Neither can we wish for the exploitation of new organic sources, with the consequences of their use inflicting such damage on the environment. A plausible trend of energy consumption in the future, drawn in Fig. 1.10 on the basis of the historical values of energy consumption in the last two centuries, suggests a relative decline of the rate of growth in the second half of the 21st century.

$$y = \frac{K}{1 + ae^{-bt}} = \frac{17.000}{1 + 3500e^{-0{,}042t}}.$$

Some environmentalists say that a decarbonisation of the economy is necessary. It will not only be necessary, but also unavoidable, in the future. More and more humans will have to learn how to deal with the non organic sources of energy, since an organic future will not be possible (or desirable). An alternative development is to return to the means of our ancestors of 3–4 centuries ago, when on a global scale, per capita consumption was one-tenth of that existing today. This means not only much less Carbon dioxide in the air, but also a smaller population and a much lower standard of living; which ultimately relies on the capacity to carry out useful work and then on energy.

Table 1.9 Energy systems, their duration, daily consumption (in kcal per capita) and yearly consumption (in GJ per capita)

Energy systems	Duration (years)	Per capita energy per day (kcal)	Per capita energy per year (GJ)
Food	7×10^6	2,000	3
Fire	5×10^5	4,000	7
Agriculture	1×10^4	5,000–6,000	8
Fossil Fuels	5×10^2	37,000	56.5

Source see text. See also, with different results, the estimates by Cook (1971)

1.5 Conclusion

The long history of energy consumption until today can be thus summarized (Table 1.9)[22]:

- the age when *food* was the only energy input extended over 5–7 million years and energy consumption per day could average about 2,000 Cal (that is 3 GJ per year);
- the age of *fire* (that is the epoch when fire was the only carrier except food) lasted some 1,000,000 years. Consumption can be established around 4,000–5,000 Cal per day or 6–8 GJ per year;
- the age of *agriculture* lasted some 10,000 years and World daily energy consumption per capita was about 5,000–6,000 Cal or 7–9 GJ per year;
- the age of *fossil fuels* lasted about 500 years and will finish this century or the next. Daily World consumption has been around 37,000 Cal or 56.5 GJ per year (according to a weighed average, based on population in the last two centuries).

The following data on energy consumption, although speculative, are not implausible.

Calculations of the number of humans since the origins are naturally uncertain and tentative depending on several assumptions; among which the epoch of the beginning of our species is of particular importance. If we accept that the hypothesis of 100 billion humans from 1 million years ago until today (an estimate proposed in the 1990s), is low and that our species was born 7–10 million years ago (such as the paleologists are nowadays inclined to believe), we must add at least 20–30 billion people. If the amount of people ever born from the origins numbers some 120–-130 billion, today 5 % of our species is alive, and 18 % of the total World population has lived in the age of fossil fuels, beginning around 1600. This negligible part of the population, during the 0.01 % of time since the beginning of the species, consumed about 80 % of the energy ever consumed by humans. If the more recent period between 1700 and 2000 is observed, humans consumed 32 % of the whole wealth in fossil fuels. Consumption of coal was negligible in the 18th century

[22] Both on past and future energy consumption see the useful reconstruction by Beretta (2007).

Table 1.10 Energy consumption of fossil fuels from 1700 until 2000 and estimate of the still existing commercial energy (millions Toe)

	Toe (millions)	(%)
Consumption 1700–2000	350,000	32
Estimated reserves in 2000	750,000	68
Total	1,100,000	100

Source see text

and described an exponential curve in the following two. According to recent estimates on the future availability of fossil fuels, around the year 2000 about 70 % was remaining (although these estimates are ordinarily speculative) (Table 1.10). In any case, this considerable wealth will not last long time (100–200 years according to different estimates), seen the high and rising levels of fuel consumption.

In an important article published in 1922, Alfred Lotka established a correlation between natural selection and energy consumption. "In the struggle for existence", he stated "the advantage must go to those organism whose energy-capturing devices are most efficient in directing available energy into channels favourable to the preservation of the species".[23] Since the organisms and species with superior capacity to capture energy will increase, the energy crossing the biological system will also tend to increase. There is a tendency, in natural history, towards a flow of more and more energy through the biological sphere. In trying to survive and enjoy better living standards any living being contributes, at the same time, to the rise in the flow of energy which crosses the biological system. The human beings alive at the start of the 21st century, and still increasing, will contribute, day by day, to intensify this passage of energy through the thin biological envelope of the Earth.

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