ENERGY IN HISTORY

Paolo Malanima
National Research Council (Italy), Institute of Studies on Mediterranean Societies Naples, Italy

Keywords: energy consumption, energy-environment, resources, energy systems, organic vegetable economies, organic fossil economies, energy-history.

Contents

1. Introduction
2. Definition and Concepts
3. Pre-modern Organic Vegetable Economies
4. Modern Organic Fossil Economies
5. Conclusion

Glossary
Bibliography
Biographical Sketch

Summary

The topic of energy is of central interest today. Debates and analyses on the future availability of energy carriers, their prices, the role of energy consumption in economic growth and its environmental impact are developing daily. In general the perspective on the past is limited, perhaps extending back to 1973 at the most. Scholarly literature provides little information on the consumption of energy sources by past societies before and sometimes after the beginning of the 20th century. However, in the case of energy, a long-term view can be useful in order to clarify contemporary trends and provide perspectives on the likely impact of policy decisions and developments.

In the following analysis the topic of energy and environment will be discussed from the viewpoint of economics, with a long-term historical perspective. After a brief introduction, Section 2 will examine some definitions and concepts, useful when dealing with energy and the role of energy within the economy. Section 3 will focus on the relationship between man and energy in early human societies. Section 4 will discuss perspectives on future options and changes in energy and the environment from the early modern age to the present day. In the Conclusion general estimates will be proposed of past energy consumption on the whole.

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 part in the 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 something less than 10 percent 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 have 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 life. Material underpinnings to economic success are not to be underrated, in their view. Energy is also a central concern since it supported human exploitation of the environment and its heavy transformation in the last two centuries.

2. Definitions and concepts

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 can be exploited. In both cases effects such as movement, heat or light reveal the presence of what we call energy from about 200 years. The analysis of energy in history requires some preliminary definition in order to avoid misunderstanding.

In physics energy is defined as the ability of bodies to perform work. Since work is the product of force by distance, then energy includes any movement of some material body in space together with the potential energy deriving from its position. When referring to the interrelationship between humans and the environment, the definition is more limited. 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 position in space*. Solar heat is of decisive importance for the existence of life. It is a free source of energy and thus 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 warmth, 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 not a source of mechanical power for men when consumed by wild animals in a forest. 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 considering energy and do not include daily food consumption or fodder as main energy carriers. 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 such as the fuel utilized to drive cars or machines today. When looking at energy within the economy in a historical perspective, we use the word energy with a wider meaning than in everyday life. 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.

2.2. Energy and production

Technical progress mainly consisted in the introduction of changes in natural resources so as to exploit some indirect effects of these changes, today defined as energy. In this long history, the main developments were supported by 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 (Figure 1).

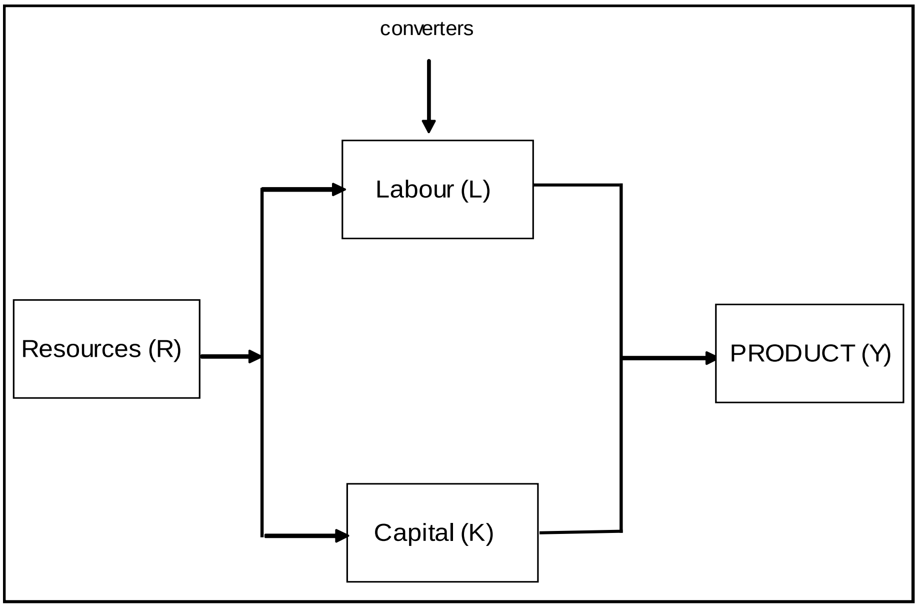

Figure 1. Natural resources, converters of energy, product.

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

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

Labour (*L*) and capital (*K*), the inputs of any productive process of useful goods and services (*Y*), can be better defined, from the viewpoint of energy, as *converters* able to extract from matter the energy exploited in order to transform materials into commodities. The progress of technical knowledge embodied in *A*, plays a central role in the production function. In one sense, energy is the main input; that is to say, the main input is that part of matter transformed into energy by the converters, that is by workers (*L*), who metabolize food; natural resources (*R*), which convert a part of the matter used as food and firewood into biomass, through solar radiation; and capital (*K*), which transforms some materials such as 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 of those already existing (*micro-inventions*) 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. In the previous diagram, it is the result of the ratio between the final product and the part of the matter transformed into energy by the converters. It is a measure of the efficiency of the energy converters from a technical viewpoint.

2.3. Energy and history

At the end of the 20th century, per capita energy consumption, on a world scale, was about 50,000 kilocalories per day; that is 76 Gigajoules per year, including traditional sources. About 80 percent of this consumption was represented by *organic fossil sources*; coal, oil and natural gas. Nuclear energy represented 6 percent and hydroelectricity 2 percent. This 8 percent was the non organic contribution to the energy balance. The remaining 12 percent consisted of biomass, i.e. *organic vegetable sources* (Table 1). If the part of waste utilized in order to produce energy is excluded, the rest of this 12 percent was composed of food for men and working animals, today a marginal source of power, and firewood, an important item of consumption only in relatively backward countries.

Table 1. Daily and yearly consumption of energy per capita worldwide around 2000 (kilocalories, Toe and %).

Sources	**Kcal per c. per day**	**Toe per c. 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

This composition of the energy balance reveals the strata of a long history of technical conquests. 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, we will track the history of energy consumption from the most remote stratum (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.

From the viewpoint of energy, the long history of mankind could be divided into two main epochs:

- the 5-10 million years from the birth of the human species until the early modern age, that is about 5 centuries ago, and
- 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, 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 source. 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.

Although the energy system prevailing today is apparently different from the 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.*

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

3. Pre-modern organic vegetable economies

At the end of the 18th century there were three main economic sources of energy. According to the age of the discovery and exploitation of these three sources, three ages can be distinguished in the distant past. 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 mills.

3.1. The first epoch: food

Since the birth of the human species some 7 to 10 million years ago, and then for some 85-90 percent 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 1,500-2,000 Calories 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 20 percent of the input of energy, that is 300-400 Calories, 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 output of these far ancestors consisted in collecting and transporting this original input of energy.

3.2. The second epoch: fire

The transition to the use of fire started the second phase of human technology and represented the main conquest in the history of energy. The first evidence of fire being used by humans refers to several different regions of the world and can be dated between one million and 500,000 years ago. Fire was a conquest of independent groups of humans in several parts of the world. Its use spread slowly. Firewood became the main source of energy for several millennia. In this case, as in the case of food, an estimate of the level of energy consumption by our distant ancestors can be only 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, and between 3-4,000 and 30-40,000 Calories. A daily consumption of less than 1 kg per capita could be assumed for the humans living in relatively warm climates of the African continent, where man was born. When humans spread from Africa towards the other continents, their firewood consumption rose considerably. Fire could be used for heating, cooking, producing light, and for protection against other animals. Although, with fire, Calories per head drastically increased from 2,000 to 3-4,000 per day or more, that is 5-6 Gigajoules per year, the efficiency in its use was very low. An open-air fire can supply man no more than 5 percent of its Calories, that is no more than 2-300. Useful energy exploited by the population from food and fire did not exceed 500-700 Calories.

3.3. The third epoch: 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. However, observing this evolution in per capita terms, the perspective is different. While the population increased rapidly, 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, agriculture progressed towards Europe at the speed of 1 km per year. Within 3,000 years, agriculture reached Northern Europe, while, 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.

New development in the agricultural transition took place during a second phase: from about 5000 years until 3000 BC. 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. Mans' 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 Calories -- among the men who employed him, human consumption may have increased by 20-50 percent or more, according to the ratio between working animals and men; which is not easy to define for these distant epochs. Only about 15 percent of this input represented, however, useful energy, that is energy converted into work.

During this age, several innovations allowed a more efficient utilization of man's 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 provided through the photosynthesis of vegetables. Labour productivity rose markedly. Even though some changes in the agricultural energy system also took place in the following centuries, generally technical progress was modest. Water and windmills, invented respectively 3 centuries BC (as recent research suggests) and in the 7^{th} century AD, 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 percent.

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 man and the 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, vegetables can 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 percent, is transformed into phytomass by the vegetable species. Of this 1 percent, only an insignificant part, could be utilized by men 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 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, which suffered a cold climate, was characterized by 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 1840, was again a period of economic hardship and popula-

tion stability or slow increase. It is common knowledge that present day energy systems heavily influence the environment and climate. Until a few centuries ago the opposite was true.

3. *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 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 8-12,000 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.

4. Modern organic fossil economies

At the start of modern growth around 1800, world scale energy availability was about 5-6,000 kilocalories per capita per day, that is 6-7 Gigajoules per year. The main sources were those already seen, that is food, firewood and fodder for working animals. Water and wind were the only non organic sources. In 1800, throughout Western Europe, the energy balance per head was 20 Gigajoules per year, that is 13,000 Calories 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 Gigajoules per year (10,000 Calories per day), in Scandinavia it was 45 (30,000 Calories per day). In pre-modern Europe, the main energy carrier was firewood. It represented 50 percent in the South and more than 70 percent in the northern regions, followed by fodder for working animals and food for the population.

In Europe, energy consumption was higher than in other agricultural civilisations, both in Asia and 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;
2. in the dry European agriculture, the utilisation of animals in agriculture and transportation was much widespread than elsewhere. In both China and America, the presence of animals in agriculture was far more modest. In pre-modern centuries, probably only in India was animal power exploited to the same extent as in Europe.

4.1. The start of 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. 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*. 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. 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, as 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 have a wide impact 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 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 2).

Table 2. Share of coal production in England and the rest of Europe from 1800 until 1870 (%).

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

The proportion of coal consumed in England was 12 percent of the total energy consumption in 1560, 20 percent in 1600, and 50 percent in 1700. Its consumption from 1560 until 1900 reveals an almost stable rate of growth, as a graph in log scale shows (Figure 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.

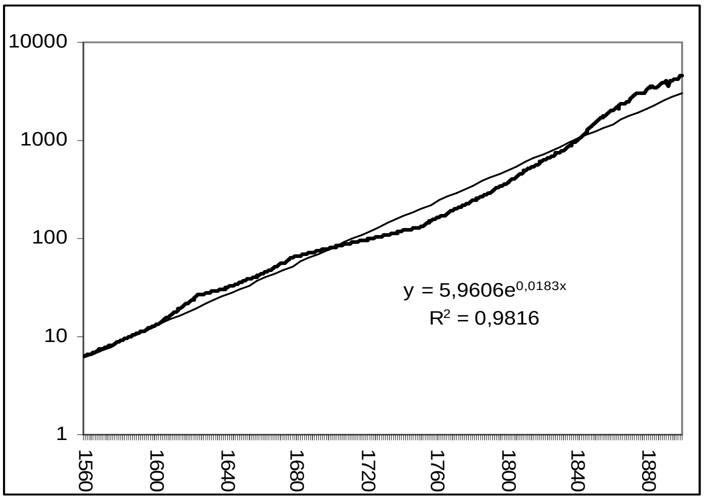

Figure 2. Coal consumption in England & Wales 1560-1900 (in Petajoules; log scale).

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 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 onwards. Land per capita outside Europe was also diminishing. The European population growth was part of a much greater 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 were 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 men and animals; apart from wind and water (whose mechanical work, in any case, was not a 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. In his opinion they would replace both the force of animals and that of water and wind. This is precisely what has 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 of energy consumption;
- the process of substitution of energy carriers;
- the geography of energy production;
- the price of energy;
- the relationship energy-economy.

4.2. The trend of energy consumption

Energy consumption per head diminished in Europe during the 18th century, whilst from 1800 until 2005 it rose considerably more than population: 7-fold from 1800 until 2000, that is from 23 Gigajoules to 155 (Figure 3). Since contemporaneously population increased 3.8 times, total energy consumption registered a 26-fold increase (Table 3).

Table 3. Energy consumption in Europe from 1800 until 2000 in kcal per capita per day, in Toe per year, European population and total energy consumption in Mtoe.

	kcal. per c. per day	Toe per c. per year	Traditional sources %	Rate of growth (%)	European population	Total Mtoe
1800	15,000	0,55	87		189	104
1830	15,150	0,55	80	0,09	234	129
1900	37,590	1,37	25	1,31	422	578
1950	47,430	1,73	15	0,47	548	948
1970	89,560	3,27	5	3,23	656	2,145
1989	101,057	3.7	5	0.63	720	2,680
2000	101,882	3.7	5	0.07	728	2,707

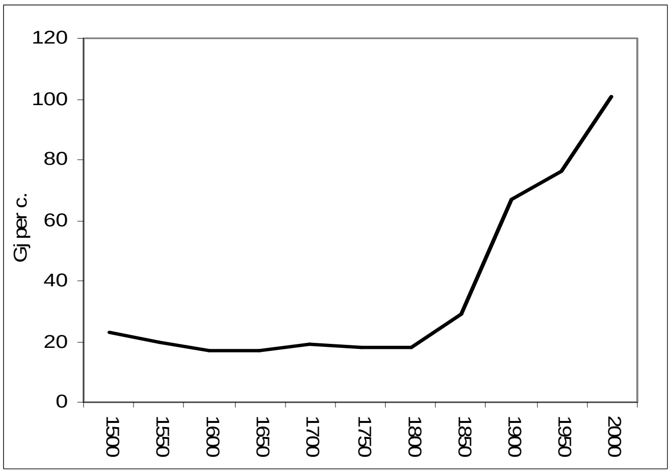

Figure 3. Per capita energy consumption of traditional and modern carriers in Europe 1500-2000 (Gj)(decadal values).

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 growth was instead remarkable until the First World War. 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 (Figure 4).

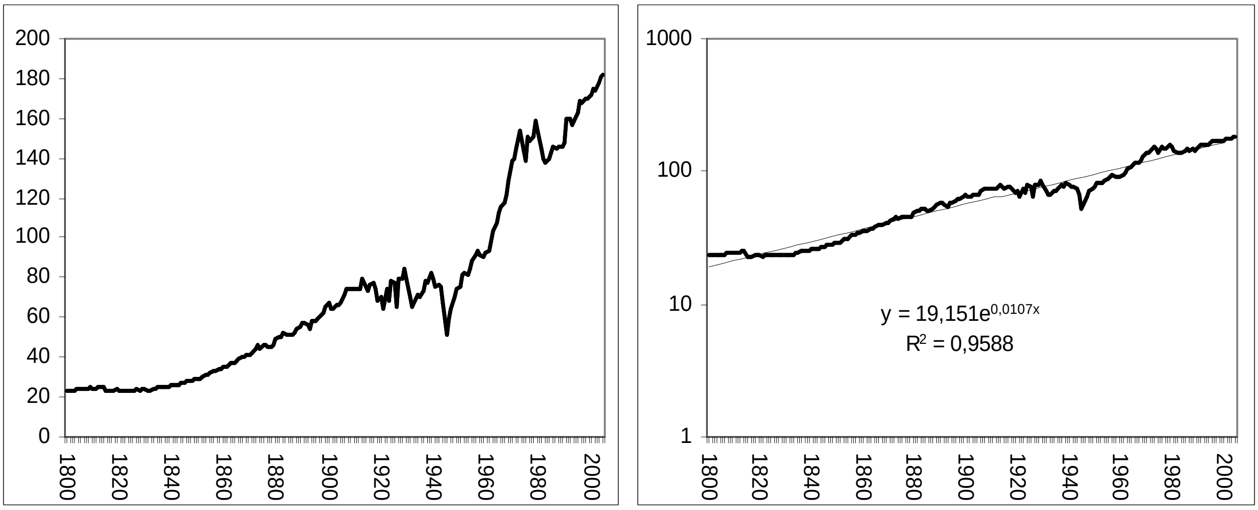

Figure 4. Per c. energy consumption in Europe 1800-2005 (Gj) (with log vertical axis on the right).

On the World scale, the rise of per capita consumption has been 6 times within the two centuries from 1850 to 2000. Since population growth was 4.8-fold, the aggregate rise was 25 times (Table 4). We see that modern or commercial sources overcame traditional sources, or the phytomass, in the last decades of the 19th century, or the epoch of the second industrial revolution.

Table 4. World energy consumption from 1800 until 2000 in kcal per capita per day, in Toe per year, World population and total in Mtoe.

	kcal. per c. per day	Toe per c. per year	Traditional sources %	Rate of growth (%)	World population	Total Mtoe
1850	9,500	0.3	80		1,241	430
1880	12,300	0.4	50	0.86	1,330	597
1900	17,500	0.6	45	1.75	1,634	1,044
1950	25,600	0.9	30	0.76	2,530	2,364
1970	41,380	1.5	20	2.40	3,637	5,493
1985	41,100	1.5	20	-0.04	4,815	7,223
2000	50,400	1.8	15	1.35	6,000	11,038

4.3. Transitions and substitutions

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 95 percent in 1800 to 45 in 1900 and only 15 in 2000. 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 percent of the overall consumption. Their share decreased to 25 percent in 1900 and was only 5 percent in 2000.

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 percent. Wood consumption was, in relative terms, already insignificant in 1900, while coal equalled about 80 percent. 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, 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 (Figure 5).

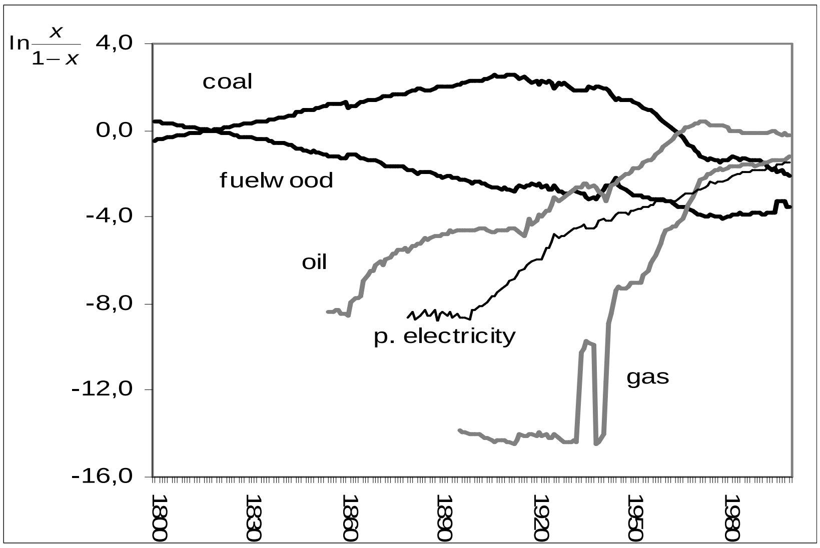

Figure 5. Shares of any fuel on the total fuel consumption in Europe 1800-2000 (ln).
Note: x, on the vertical axis, refers to the share (%) of an energy carrier on the total of the 5 energy carriers.

Electricity is 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 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 percent of energy in Europe. In 2005 it was 13.6 percent, thanks especially to the nuclearisation of the French energy system. Since the share of primary electricity in the continent was 17.2 percent, the other sources of primary electricity 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 5).

Table 5. World consumption of primary commercial energy (in Mtoe per year).

	Coal	**%**	**Oil**	**%**	**Nat. Gas**	**%**	**Electr. (prim.)**	**%**	**Total**
1700	3	*100.0*							3
1750	5	*100.0*							5
1800	11	*100.0*							11
1850	48	*100.0*							48
1900	506	*94.8*	20	*3.7*	7	*1.3*	1	*0.2*	534
1950	971	*58.7*	497	*30.1*	156	*9.4*	29	*1.8*	1,653
1973	1,563	*29.1*	2,688	*50.0*	989	*18.4*	131	*2.4*	5,371
1987	2,249	*31.7*	2,968	*41.8*	1,550	*21.8*	332	*4.7*	7,099
2005	2.892	*25.4*	4,000	*35.0*	2,354	*20.6*	2,182	*19.0*	11,428

4.4. The geography of energy

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 presence of fossil sources of energy more or less coincided. At the middle of the century, 90 percent of fossil energy was still produced in Europe and 10 percent in the United States (Table 6). Things changed during the 20th century, when oil began to play a central role in the energy systems of the developed countries, and especially in the second half. After the World War II, Europe produced 35-40 percent 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 registered only 4 percent in 1950, in 1973 it had grown to about 50 percent. At the end of the century, a little less than 50 percent 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 price increases.

Table 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	0	1.72	9.99	23.11
Africa	0	0	0.12	1.24	5.83

Oceania	0	0	0.82	0.73	1.95
	100	100	100	100	100

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. 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 percent of the total; that of centrally planned economies 20 percent and that of the developing countries 30 percent. At the end of the second millennium, 25 percent of the world population – 1.5 billion --, the population, that is, of the developed economies, consumed 7,920 toe, i.e.75 percent of the world consumption in one year, while 75 percent of the population – 4.5 billion – consumed 2,340 toe, or 25 percent of the whole. With about 4.9 toe per year, an inhabitant of the most advanced economies consumed on average 9 times more commercial energy than an inhabitant of the poorest countries – only 0.54 toes --. So strong differences did not exist before modern growth. Only differences in climate and not in wealth could then imply remarkable disparities in consumption. The existing differences among countries can be clarified through the consumption of electricity, a proxy of energy consumption on the whole (Table 7).

Table 7. Per capita consumption of electricity in the World in 1992 (in Kwh).

World		**2,188**
Africa		**476**
Centre	163	
East	136	
North	663	
South	3,605	
West	112	
America		**5,765**
Northern America	12,734	
Latin America	1,462	
Southern America	1,593	
Asia		**924**
Eastern Asia	1,424	
Southern Asia	335	
South-East Asia	415	
South-West Asia	1,845	
Europe		**5,729**
Eastern Europe	5,025	
Western Europe	6,371	
Oceania		**7,098**

4.5. The energy price

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 since the age of spread of this new carrier, after 1861, we notice that, after a couple of decades of high prices, there was a downward curve until the 1973 crisis (Figure 6).

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 common movement of energy prices on the whole. Data on energy prices for the periods both before and after the introduction of the new fossil carriers, suggest 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.

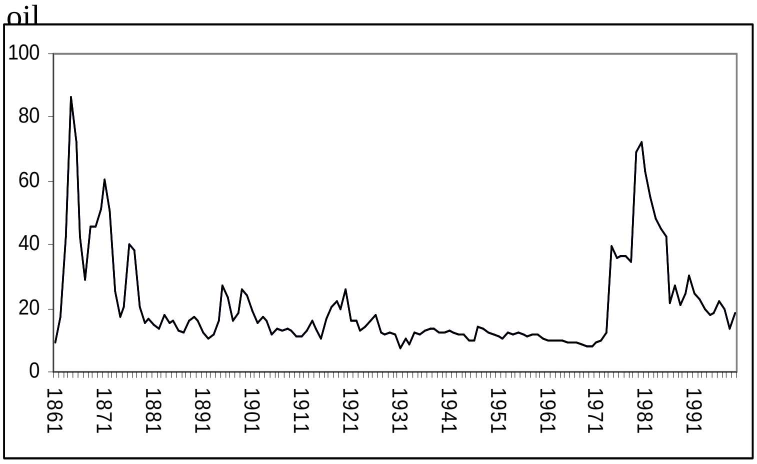

Figure 6. Oil prices US 1999 dollars per barrel 1861-2000.

4.6. Energy and economy

When dealing with energy, both energy input into the economic system and the share of total energy actually available as mechanical work and heat are of interest. 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, the result, that is, of the ratio of useful energy to total energy input:

$$\eta = \frac{E_u}{E_t}$$

where η is the efficiency of conversion, E_u is useful energy and E_t is total energy input. When we compute the amount of useful energy in traditional societies, we have to calculate the total input of energy together with the efficiency of the converters used (human and animal bodies, fireplaces, wind, water engines, and ships). 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:

	%
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.

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*), which is energy (*E*) employed in order to produce a unit of product (*Y*) (Figure 7). 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.

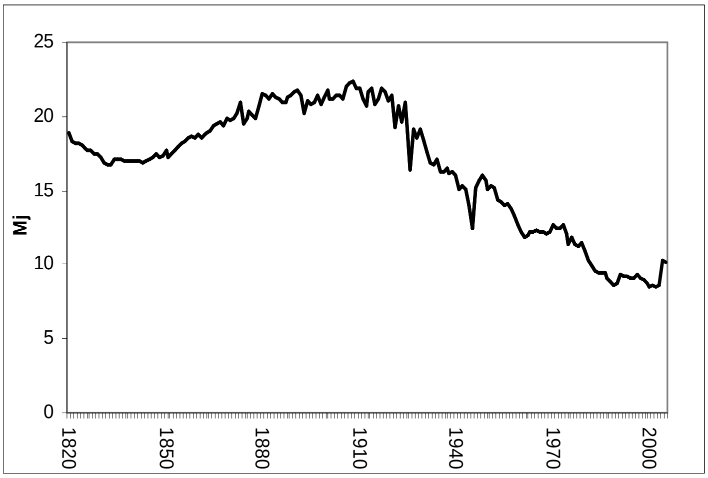

Figure 7. Energy intensity in Europe between 1820-2005 (Mj/GDP).

A decline in energy intensity occurred in the second half of the 20th century in almost all world economies; although the differences are still remarkable (Table 8).

Table 8. Energy intensity in different economies 1950-1990 (in Toe per 1000 dollars 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

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

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 reciprocal of energy intensity, that is the *productivity of energy* (*Y/E*):

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

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:

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

In our case, we have:

$$1.54 = 1.10 + 0.44$$

The conclusion is that, from 1820 until 2000, the annual rate of growth of per capita GDP was 1.54 percent, 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 8 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). The difference between the interpolating exponential curves was filled through the rise in the efficiency of energy use.

The introduction of new machines and more efficient engines was responsible for the leap in the productivity of energy. After all, the efficiency of a biological converter such as the human or animal body is no higher than 15-20 percent, while a thermal machine can reach the yield of 35 percent. From the last decades of the 19^{th} century, electricity contributed significantly to efficiency, together with the development of new devices which entered production plants and homes. Between 1867 and 1914, the introduction of electricity, steam and water turbines, and the internal combustion engine (together with inexpensive steel, aluminium, explosives, synthetic fertilizers and electronic components), marked a technical watershed in recent economic history.

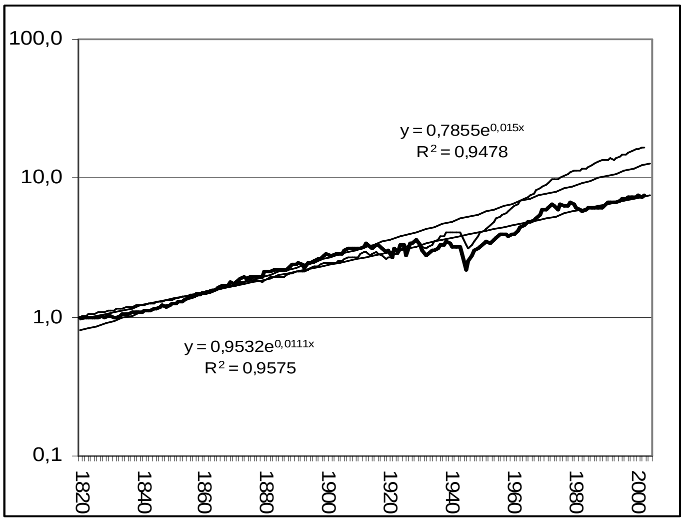

Figure 8. Per capita GDP and per capita energy consumption (the thick curve) in Western Europe 1820-2003 (1820=1) (the interpolating curves are exponential curves -- resulting in a straight line on a log scale).

4.7. Energy in the future

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 has shown. In any case, the consequences of changes in the environment on humans and their societies, due to climatic changes in particular, were much greater than those produced on the environment by human activities. 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 when biomass was the main energy carrier.

In the last 200 years, changes have come about. The 60-70-fold growth of energy consumption and the higher emissions by fossil fuels have 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 sources, although. Remarkable differences, however, exist among them: natural gas is much less polluting than coal. The likely effect of such gases on climate has been known for a long time. According to most paleoclimatologists the rise in temperature during the last century, and especially in the last decades, 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 of the last decades 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. CO_2 emissions increased from 18,500 million of metric tons in 1980 to almost 30,000 million in 2006: a 60 percent rise in less than 30 years. On the other hand, attempts at the reduction of CO_2 emissions in order to stabilize or reduce 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 the future of mankind). The rise of new non polluting sources of energy is slower than it was hoped at the end of the past century.

After a few years forecasts in energy consumption always prove to be inaccurate. 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 today per capita consumption on a global scale is around 50,000 Calories per day and that about 12 percent is made up of organic vegetable sources – the old heritage of past agricultural societies -- and 80 percent of organic fossil sources – the more recent heritage of modern growth --. Only a relatively narrow residual amount is represented by photovoltaic, wind, water and nuclear energy. These are the sources of our non-organic future. It is known, that 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.

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. However, the level of technical and scientific knowledge, which is the main foundation of modern growth, reserves a better prospect for future generations. In any case, with the relatively near exhaustion of fossil sources, a replacement of these organic carriers by means of other organic carriers will no longer be possible. Our past has been organic. Our future will not be so.

5. Conclusion

The long history of energy consumption until today as recounted above can be thus summarized (Table 9):

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

These data on energy consumption are, naturally, speculative, but not implausible.

Table 9. Energy systems, their duration, daily consumption (in Cal.) and yearly consumption (in Gj).

Energy Systems	Duration (years)	Per c. Energy per day (Cal)	Per c. Energy per year (Gj)
1. *Food*	$7 \cdot 10^6$	2,000	3
2. *Fire*	$5 \cdot 10^5$	4,000	7
3. *Agriculture*	$1 \cdot 10^4$	5-6,000	8
4. *Fossil Fuels*	$5 \cdot 10^2$	37,000	56.5

Calculations of the number of humans to have lived 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 the hypothesis of 100 billion humans from 1 million years ago until today, we must add at least 20-30 billion people, assuming that is, that our species was born 7-10 million years ago, such as the paleologists are nowadays inclined to believe. If the amount of people ever born from the origins numbers some 120-30 billion, today 5 percent of our species is alive, and 18 percent of the total population has lived in the age of fossil fuels, which can be established as beginning around 1600. This negligible part of the population, during the 0.01 percent of time since the beginning of the species, consumed about 80 percent of the energy ever consumed by humans. If the more recent period between 1700 and 2000 is observed, humans consumed 32 percent of the whole wealth in fossil fuels. Consumption of coal was negligible in the 18th century 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 percent was remaining (although these estimates are generally speculative) (Table 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.

Table 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

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". 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 6.5 billion human beings, alive at the start of the 21st century, are still increasing and contribute, day by day, to intensify this passage of energy through the thin biological envelope of the Earth.

Glossary

Calorie : kilocalorie or Calorie (with capital C) is a measure of energy and corresponds to the quantity of heat necessary to increase the temperature of 1 kg of water from 14.5 °C to 15.5.

Commercial energy : modern, fossil, energy sources; distinguished from the traditional sources.

Energy efficiency : the ratio between useful energy (in the form of heat or movement) and the total energy input: E_u/E_i.

Energy Intensity : the ratio between the total energy consumption in a country (in an energy measure) and the product of the same country (in money): E/Y.

Energy productivity : the ratio between the output of a country (in money) and total energy consumption in the same country (in an energy measure): Y/E (which is the reciprocal of energy intensity, that is $1/E/Y$).

Joule : the measure of work and energy. 1 Gigajoule= 238,846 kilocalories.

Kilowatthour (kwh) : a measure corresponding to 860.42 Calories or 3,600 Kjoules (1 kj=1,000 joules).

Organic : in chemistry a Carbon compound. The term was originally used by A. Wrigley 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. Past agricultural organic vegetable economies can thus be distinguished from modern organic fossil economies.

Photovoltaic : refers to the application of solar cells for energy by converting sunlight directly into electricity.

Power : defined as the maximum of energy liberated in the unit of time by a biological or technical engine.

Primary energy : energy carriers as they are produced (not yet transformed by human intervention).

Secondary energy : sources transformed by means of primary sources (such as electricity).

Toe : ton oil equivalent. It corresponds to 10 million kilocalories. 1 Mtoe = 1 million Toe.

Useful energy : a share of total input of energy corresponding to the part transformed into work or light or useful heat.

Bibliography

Bairoch, P. (1983). Energy and Industrial Revolution: New Approaches. *Revue de l'énergie*, n. 356 [A stimulating perspective on the relationship between energy and modern growth].

Caracciolo, A. and R. Morelli (1996). *La cattura dell'energia. L'economia europea dalla protostoria al mondo moderno*. La Nuova Italia Scientifica, Roma [An overall reconstruction on the history of energy since the birth of the human species].

Cipolla, C.M. (1962). *The Economic History of World Population*. Harmondsworth, Penguin [A path-breaking book on two revolutions in the economy due to the adoption of new energy sources: the Agricultural (Neolithic) Revolution and the Industrial Revolution].

Cook, E. (1971). The Flow of Energy in an Industrial Society. *Scientific American*, 225, pp. 134-47 [The article deals above all with energy and the industrial world, in a long-term perspective].

Cook, E. (1976). *Man, Energy, Society*. San Francisco, Freeman [An overall reconstruction of energy and modern economy, also dealing with the developments of energy technology in past civilisations].

Etemad, B. and J. Luciani (1991). *World Energy Production 1800-1985*. Droz, Genève [A useful book with a reconstruction of global energy production during the last 2 centuries].

Goudsblom, J. (1992). *Fire and Civilization.* London Penguin [A stimulating analysis of the role of fire within past and present economies].

Kander, A. (2002). *Economic Growth, Energy Consumption and CO_2 Emissions in Sweden 1800-2000*, Lund, Lund University [A reconstruction of consumption of modern and traditional sources of energy and their relation with modern growth in Sweden].

Lee, R.B. and I. De Vore (eds.) (1968). *Man the Hunter*. Chicago, Aldine [An important book dealing with a remarkable step in the evolution of the economy and society].

Lotka, A. (1922). Contribution to the Energetics of Evolution. *Proceedings of the National Academy of Sciences*, VII, pp. 147-51 [A brief article on the trend of human economy and the role of energy].

Lotka, A. (1956). *Elements of Mathematical Biology*. New York, Dover Publications [1924] [In the mathematical perspective of biology by Lotka energy plays a central role in this still important book].

Malanima, P. (1996). *Energia e crescita nell'Europa pre-industriale*. La Nuova Italia Scientifica, Roma [A history of energy consumption in the European world before the Industrial Revolution].

Marchetti, C. (1977). Primary Energy Substitution Models: On the Interaction Between Energy and Society. *Technological Forecasting and Social Change*, 10, pp. 345-56 [An important article on the substitution process in the field of energy].

Mokyr, J. (1990). *The Lever of Riches. Technological Creativity and Economic Progress*. New York-Oxford, Oxford University Press [A history of technology and an analysis of the relationship technical development-economy].

Perlès, C. (1977). *Préhistoire du feu*. Paris, Masson [A well-documented reconstruction of a central change in the history of technology: the discovery of fire].

Pireddu, G. (1990). *L'energia nell'analisi economica*. Milano, F. Angeli [A research on the interrelationships energy-economy in the modern world].

Sieferle, R.P. (1982). *The Subterranean Forest. Energy Systems and the Industrial Revolution*. Cambridge, The White Horse Press, 2001 [An important reconstruction of the passage from pre-modern to modern energy systems].

Smil, V. (1994). *Energy in World history.* Westview Press, San Francisco-Oxford [One of the best histories of energy since the origin of the human species].

Warde, P. (2007), *Energy Consumption in England and Wales 1560-2000.* Napoli, ISSM-CNR [Useful for the reconstruction of energy consumption in England and for the methods of calculation of energy consumption in pre-modern economies].

Wrigley, E.A. (1988). *Continuity, Chance and Change. The Character of the Industrial Revolution in England*. Cambridge, Cambridge University Press [An important book on the role of energy in pre-modern English economy and an original view on energy in the pre-modern world in general].

Biographical sketch

Director of the Institute of Studies on Mediterranean Societies (ISSM) of the Italian National Research Council (CNR), Paolo Malanima received his education in Humanities at the Scuola Normale Superiore (Pisa) and University of Pisa; he has been Professor of Economic History and Economics at the University of Pisa and University <<Magna Graecia>> in Catanzaro. He is Co-President of the European School for Training in Economic and Social Historical Research (ESTER) (University of Utrecht) and member of the editorial board of the journals *Società e Storia* and *Rivista di Storia Economica*, corresponding editor of the *International Review of Social History* (dal 1993), member of Consejo di *Investigaciones de Historia Economica*. His research regards long-term economic history and the history of energy. His publication *Pre-Modern European Economy. One Thousand Years (10th–19th Centuries)* (Brill, Leiden-Boston, 2009; german translation as *Europäische Wirtschaftsgeschichte 10.-19. Jarhundert*, Wien, Böhlau, 2010), refers to both these areas of research.