Energy Consumption and Energy Crisis in the Roman World

Paolo Malanima

The energy system of the ancient Mediterranean civilisations was the same as that of all agrarian societies between the 5th millennium B.C. and the 19th century, and the level of per head consumption of energy was the same too. This system was based on food, firewood, and fodder for working animals. Despite the increase in useful knowledge and the extensive development of the agrarian energy basis, supported by a favourable climatic phase, this system was finally unable to support the increasing population. Per capita availability of energy began to diminish. An unfavourable climatic phase, from the 2nd century A.D., contributed to this decline.

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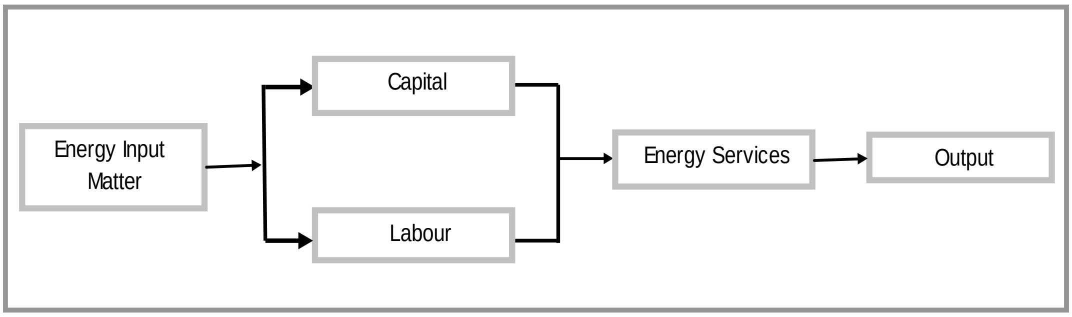
Economic development has been supported, over the last two centuries, by a technical revolution in the use of power and energy. The introduction of *modern machines*, able to deliver huge quantities of work per unit of time on the one hand and the availability of cheap *fossil energy sources* on the other, have enormously increased productive capacity. Both changes were the *necessary* although not *sufficient* conditions for the notable discontinuity in the economic history of the human populations and were the main determinants of a huge increase of output. The scarce availability both of mechanical power and energy set a limit to the growth potential of previous agricultural economies from the 5th millennium B.C. until the start of modern growth two centuries ago and was the direct determinant of phases of decline or collapse.

The purpose of the present paper is to focus on energy consumption in the early Roman Empire; and, in particular, to identify the energy sources (§ 1-2), to quantify their exploitation (§ 3-4), and their constraints to the growth potential (§ 5-6). The last sections (§ 7-8) will be devoted to the dynamics of the ancient energy systems, that is the innovations in the technical exploitation of energy and its availability. The Appendix will present the procedure followed in the quantification of energy consumption in the Roman Empire and discuss alternative estimates.

1. *The energy flow*

The following diagram represents a production function from the viewpoint of energy consumption (Figure 1).

Figure 1. The flow from energy and matter to output.



Energy and matter are environmental resources exploited by the two production factors of any economy, labour and capital, thanks to technology, that is the accumulation of useful knowledge regarding the properties of both natural materials and environmental forces. Any production process is nothing but a combination of matter and energy by means of the available technical knowledge.

2. *The input of energy*

Often it is not completely clear what actually were the sources of energy in past agrarian civilisations.[1] The consequence is that any quantification becomes imprecise or, indeed, quite impossible. Although certainty is unattainable on the subject, a plausible order of magnitude is not out of reach.[2]

Three were the main inputs of energy in pre-modern agrarian civilisations from about 5000 B.C. until 1800 A.D.: *food, firewood* and *fodder for working animals*.[3]

Food has been the primary source of energy since the beginning of the human species. A second source, *firewood*, began to be exploited as fuel between 1,000,000 and 500,000 years ago. From then until the Industrial Revolution it was the main provider of heat.[4] The third source, *fodder for draft animals*, began to supply mechanical work in the agricultural civilisations between 5000 and 4000 B.C., that is since the exploitation of animal power on a wide scale in agriculture and transportation. These were still the main energy carriers of the ancient Mediterranean civilization. The discovery of fire on the one hand and the exploitation of draft animals on the other, marked two main changes in the history of technology. The most recent change has been the spread of thermal machines over the last two centuries.

Food consumption has not changed so very much during the long history of mankind, at least in term of calories. Even in the case of the ancient Greek and Roman civilisations, we can assume a daily average consumption of 2-3,000 calories;[5] as recent estimates indicate. Although within a wide geographic area such as the Roman Empire differences in diet were remarkable, the intake of calories was similar.[6]

Regional variations in firewood consumption were much wider and depended on two main variables: temperature and industrial demand. In Mediterranean civilisations the amount of 1 kg. of wood (that is about 3,000 kcal.) per head per day can be assumed as the lower margin of a likely range, given the relatively high temperature in this area of the world. Calculations of industrial consumption by metallurgy and other industries suggest that another half kg. may be added to this daily amount; at least in regions with a widespread industrial activity. Differences in firewood consumption certainly existed within the Roman civilisation and derived from the regional differences in temperature and industrial development. A range between 1 and 2 kg., that is between 3,000 and 6,000 calo-

[1] Here I refer to the energy sources with a cost (often an opportunity cost). Solar light is important for our survival, but is free and then excluded from our calculations. The same holds true for the vegetation of a forest, when not exploited by the humans. Water and wind power, when exploited through mills and sails (expensive to build), is included, while it is excluded when not exploited for some productive activity. See, however, the Appendix for more information on the subject.

[2] I have discussed this topic in greater depth in Malanima (forthcoming). See the following Appendix on the quantification of energy consumption in the early Roman Empire.

[3] I have examined the transitions among energy systems in greater depth in Malanima 2010.

[4] Perlès 1977; Goudsblom 1992.

[5] Here I use the terms of kilocalorie (kcal.) or calorie as synonyms, although they are not. Actually, a kilocalorie (the correct unit of measure when we speak of food or heat) is 1,000 calories.

[6] On the topic, regarding the Roman Empire, see Jongman 2007b.

ries per head per day, seems plausible.[7] When taking into account the high temperatures in the Southern Mediterranean and the regions with poor industrial activity, a lower estimate of firewood consumption of about 3,000 kcal. per head per day, that is 1 kg., seems reasonable. A consumption of 6,000 kcal, equivalent to 2 kg. of wood, could have actually been reached in cold regions, on the mountains, or in regions with rigid temperatures.[8]

As to the contribution by draft animals to the energy balance, an estimate can be based on the ratio between their consumption of fodder (expressed in some energy measure) and population. We follow, in this case, the same procedure we use today to establish the average consumption of oil in a country: that is, dividing the oil consumed among the population. The only difference being that in pre-modern agrarian civilisations, we are mainly dealing with biological converters and that their fuel is food intake. From the available information on the size of ancient working animals[9] and the draft animals-population ratio,[10] we then estimate how much energy was consumed per head dividing the calories of fodder intake by the population. The range of a plausible consumption is 1,000-2,000 kcal. per head per day.

The only energy carriers not provided by the land through photosynthesis in the ancient agricultural civilisations were wind, used to drive sailing ships, and water, exploited for mills as from the 3rd century B.C.[11] An estimate of the consumption of the energy of wind and water is difficult to make. We know, however, for the early Modern Age, that their contribution to the energy balance hardly represented more than 1 percent of the total energy consumed. It seems plausible to assume that watermills and sailing ships were not more numerous in the Roman Empire than in medieval and early modern Europe. In mere quantitative terms, the role of wind and water in pre-modern agrarian societies was negligible, although they were very important from the technological viewpoint. Actually, sailing ships and watermills were the only engines whose mechanical work did not derive from the digestion of food.[12] Together these engines provided 100 percent of the mechanical energy by non-biological converters.

3. *A quantification*

Table 1 presents a likely consumption range for the ancient Mediterranean civilisation in the age of the early Roman Empire, that is the 1st century and the first half of the 2nd, up until the Antonine Plague. As we see, energy consumption is comprised between 6,000 and 11,000 kcal. per capita per day (or 9.2-18.4 Gigajoules per year). We see also that half of consumption consisted of food for humans and draft animals, the other half of firewood.

Table 1. Energy consumption in the early Roman Empire (in Gj. per capita per year and kcal. per capita per day).

[7] The article by Harris 2011 is important for the quantification of firewood consumption .

[8] See the lower energy consumption proposed by Smil 2010, reported in the Appendix to this paper.

[9] On the topic see in particular Kron 2000, 2002, 2004. See also Ward-Perkins 2005, Ch. VII and Fig. 7.3.

[10] This ratio is hard to establish for ancient economies. See, however, the Appendix.

[11] Wilson 2002 and 2008 and Lo Cascio, Malanima 2008.

[12] Technical change in maritime technology was continuous and certainly contributed to enhance the exploitation of wind power, although, in mere quantitative terms, the energy consumed by sailing ships remained modest. See now, on changes in maritime technology, Harris, Jara (eds.) 2011.

	Gj/year		Kcal/day		%	
Sources of energy	***Minimum***	***Maximum***	***Minimum***	***Maximum***	***Minimum***	***Maximum***
Food for humans	3.1	4.6	2,000	3,000	33	27
Fuel	4.6	9.2	3,000	6,000	50	55
Fodder for animals	1.5	3.0	1,000	2,000	17	18
Total	**9.2**	**16.8**	**6,000**	**11,000**	**100**	**100**

Sources: see text and Appendix.

Today World energy consumption is 50,000 kcal. per capita per day or 76.5 gigajoules (Gj.) per year. In Europe it is notably higher: 100,000 kcal. per day (153 Gj. per year). At the beginning of modern growth, in the early decades of the 19th century, World average consumption per capita was 7-10,000 kcal. per day (10-15 Gj. per year) and the European 15,000 kcal. per day (23 Gj. per year).[13] Around 1850, consumption per head of the three main sources of energy (food, firewood and fodder) in Northern Mediterranean countries (Portugal, Spain, France, Italy) ranged between 11,500 and 13,500 kcal. per day.[14] A Mediterranean average including Northern Africa and the Near East (for which we have no data until 1970) would be certainly lower.[15] Thus, a plausible result is that per capita energy consumption in the ancient Roman world was 5-6 times less than the World average in 2000 and 10 times less than the European average at the same date. It was also a little lower than that of the Northern Mediterranean countries at the beginning of industrialisation, but only because the ancient Roman civilisation included many Southern regions, where the consumption of firewood was certainly lower than in the Mediterranean countries of Europe at the start of industrialisation.

It is hard to specify the impact of the production of energy on the environment in the early Roman Empire. If we assume that food production required half a hectare per capita,[16] firewood half a hectare of forest and fodder for draft animals another half hectare, then per capita requirement was 1.5 hectares. This estimate is nothing but a plausible average (based mainly on late medieval-early modern European examples, where the productivity of fields, meadows and forests was quite similar to that in Roman antiquity).

In around 165 A.D., the Roman Empire measured 3,800,000 km^2.[17] Accepting the previous calculations regarding consumption and soil per head, to provide energy for the 70 million inhabitants living in the Empire 1,050,000 km^2 were necessary, which is 25-30 percent of the total. If we assume a population of 100 million, plausible as well for the middle of the 2nd century A.D., the need of soil to support energy production becomes 1,500,000 km^2, which is 40 percent of the Empire. If we exclude the mountains (lands more than 600 metres high), which in the Mediterranean regions cover 20-25 percent of the total area and were hard to exploit, the extent of the agrarian soil in the Roman Empire becomes about 3,000,000 km^2. In this case, according to the two previous population estimates the share covered by fields, exploitable woods and meadows becomes respectively 33 and 50 percent of the total area. These shares naturally rise if we subtract from the total extent not only the mountains, but also hilly lands hard to cultivate, marshes, lakes and urban areas.

[13] Malanima 1996 and 2010.
[14] Kander, Malanima, Warde forthcoming.
[15] For these countries the series elaborated by IEA (International Energy Agency) start only from the 1970s.
[16] Fallow land is not included.
[17] I take both the extent of the Empire and the inhabitants from Scheidel 2010, p. 48.

4. *Efficiency and energy intensity*

Only a share of energy input is actually transformed into useful energy (or energy services, that is mechanical work 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 percent of the input of energy becomes actual mechanical work, light or useful heat. In past agricultural civilisations, the efficiency was much lower. The ratio between useful mechanical work and input of energy into biological converters, such as humans and working animals, is around 15-20 percent. 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 percent. Overall, the efficiency of a vegetable energy system based on biological converters, such as that of the ancient civilizations, was around 15 per cent at the most: that is 1,000-1,500 kcal. were transformed into useful mechanical work or heat; the rest was lost. Thermal machines are much more efficient than biological converters such as animals and humans.

Another measure of the efficiency in the use of energy is the ratio between the energy input and output. It represents the energy intensity, or the quantity of energy we need to produce a unit of output (*Y*), that is GDP:

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

This ratio depends on the efficiency of the converters, but, contrary to the previous ratio, it also depends on the structure of the production, that is the relative importance of the different sectors and subsectors within the economy. Some sectors (e.g. industry and especially heavy industry) consume much more energy per unit of output than others (e.g. some services). If there is a change in the relative importance of any specific sector, energy intensity changes as well, even without any change in the thermodynamic efficiency of the converters. It is apparent that the impact of energy use on the environment depends both on the amount of energy exploitation and on energy intensity; higher intensity implying a higher impact on the environment. In past agricultural civilizations, for any unit of GDP (e.g. 1 dollar), the expense of energy was higher than today. Around 2000, in Western Europe, energy intensity was 7-8 Megajoules per dollar.[18] In past agrarian economies it was at least twice as much, since mechanical converters of energy are more efficient than biological converters. In 1800 Western Europe, that is before the start of industrialization, it was 12-14 Megajoules per dollar. Assuming that in the early Roman Empire energy intensity the same as in pre-

[18] International 1990 Geary-Khamis dollars Purchasing Parity Power.

modern European societies, the level of per capita GDP would be about 1,000 dollars (1990 intern. $ Purchasing Parity Power).[19]

5. *The energy constraints*

Vegetable energy carriers, such as those exploited in past pre-modern civilisations, are reproducible. The sun's energy enables a continuous flow of exploitable phytomass and the circulation of water and wind. Although the availability of these carriers was and is endless,[20] and the energy system based on them was and is sustainable, their increase was hard and time consuming. A large part of working time in pre-modern economies was aimed at providing energy. All in all, the expense for energy (food, firewood and fodder) could represent 60-70 percent of the average income.

Since all sources of energy came from the soil and soil is not endless, the consequence during epochs of demographic rise was a fall in soil per worker and then decreasing returns to labour. The main change taking place from the start of modern growth has been the elimination of the dependence of the energy system on the soil's constraint. When demand increases, it is much easier to provide coal, oil or natural gas, than the vegetable carriers utilized in past agrarian economies. Since in pre-modern organic vegetable energy systems, the transformation of the Sun's radiation by plants into phytomass, thanks to photosynthesis, was central and climatic conditions can heavily influence the output of energy, climatic phases marked the past history of mankind. Short-term deviations from the average temperature or precipitations resulted in dramatic increases or falls in energy availability: the well-known years of plenty and the frequent famines of the agricultural economies. Long-run changes were much less felt or were even unnoticed. Paleoclimatologists show, however, that these long-term phases influenced agricultural production, thus the overall availability of energy, and, consequently, total output and population trends.

The second important constraint of all pre-modern energy systems was the low power of the converters, which resulted in a low working capacity per unit of time. The high standard of living of modern societies is the result of the higher output per unit of time or higher labour productivity. The power of a man in everyday work is the same as a 40-watt lamp, or 0.05-0.07 Horse Power (HP). The power of a horse is 15-20 times higher. In pre-modern civilizations, the most powerful engines were watermills, producing about 3 HP, and sailing ships, which could even reach 50 HP.[21] 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 kilowatts) is equal to the power of 2,000 people and that the power of a big generating electric station (800 megawatts) is the same as that of 20 million people. The electric power of a medium sized nation such as Italy in 2000 equals 80,000 megawatts, which is the same power as that 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.

While the adoption of new energy carriers in the past two centuries has greatly expanded the *quantity* of energy at our disposal, an equally key development has been new technology (machinery) able to concentrate large amounts of

[19] See on the topic Lo Cascio, Malanima 2009 and forthcoming.
[20] Actually, it is not endless. In any case, Sun's light will still reach the Earth for 5 billion years.
[21] I neglect here the employment of power for military purposes. A catapult was an ingenious concentration of power.

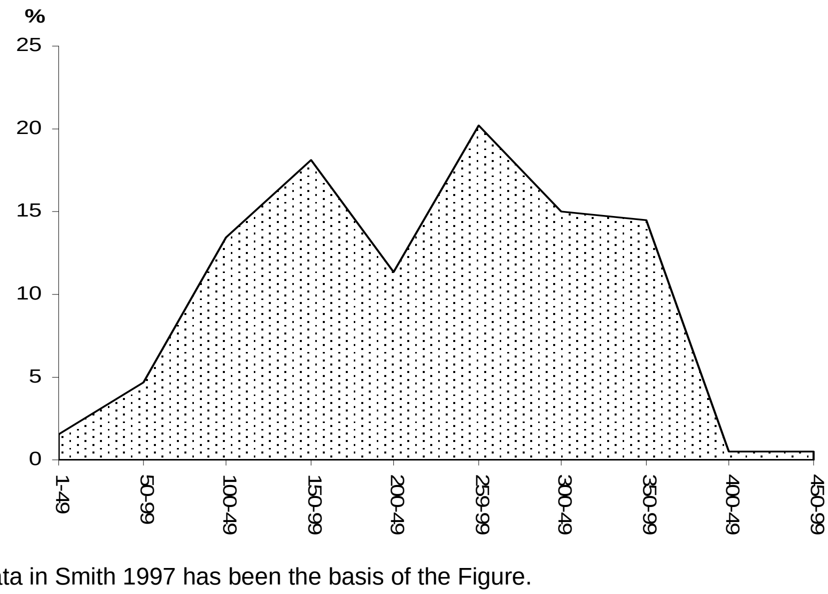
work in particular locations in order to carry out specific tasks. This *concentration of work* allows humans to accomplish tasks that were barely imaginable just a few lifetimes ago. It was the first step toward a new control of the natural forces at a level inconceivable in past agrarian civilisations.

6. *Innovations*

The progress of technology in the ancient Mediterranean world did not reveal interruptions or declines.[22] We cannot but agree on the fact that "the use of machines was more widespread in ancient Greece and Rome, together with ancient China, than in any other civilization until certainly the 12th or perhaps the 14th century A.D. in Western Europe".[23] On the other hand, looking at the problem of technical innovation from the viewpoint of energy, Roman technology consisted primarily, as J-P. Vernant wrote, "in the application of the human and animal force through a variety of tools, and not in the utilisation of the forces of nature through the use of machines".[24] There is no doubt that the introduction of new tools made human work more efficient, although the increase in efficiency was modest indeed; at least from the viewpoint of energy and power.

As suggested by A. Bresson, in the 1st century A.D.,[25] Hero's work demonstrates the knowledge of all the main elements for constructing a steam engine, such as the conversion from rotatory to alternating movement, the cylinder and piston, non-return valves and gearings: "the main technical elements embodied in the Newcomen engine were, if not in function at least well known in the Hellenistic age".[26] We can wonder, however, how widespread this knowledge actually was. With the exception of Hero's work, no other mention of the use of steam is available in ancient literary texts or archaeological remains.

Figure 2. Dated remains of coal in England 1-500 A.D. (% of the total dated remains every 50 years).



Source: data in Smith 1997 has been the basis of the Figure.

[22] Greene 2000; Schneider 2007.
[23] Wilson 2008, p. 362.
[24] Vernant 1957, p. 207.
[25] Described in *Pneumatica* 2.11.
[26] Bresson 2006, p. 72.

We know that in England coal began to be used on a wide scale from the 1st century A.D. both for domestic usage and for the melting of metals. Coal has been recovered from 70 archaeological sites in England and Wales. Its chemical analysis has allowed these remains to be dated (Figure 2).[27] Although we cannot quantify the level of consumption, we can specify the chronology of its exploitation. When the Romans conquered England, coal was already exploited. Its utilization spread and attained a maximum level from the 2nd until the 4th century. At least until the 5th century A.D., coal continued to be used on a wide scale. Later it almost disappeared.

Coal, however, is very unevenly distributed across the globe, and, apart from Australia, is almost entirely found in a few parts of the Northern hemisphere, that is, North America, North-Western and Eastern Europe, Russia and China. The centres of the ancient civilisations and especially the Mediterranean regions are not comprised in the geography of coal. The high price of firewood on the one hand and the lack of coal on the other did not allow the transition towards a new energy system in a Mediterranean civilisation.[28]

7. *An energy crisis: population and stature*

It is still hard to quantify the rise in population during the millennium spanned by the ancient Mediterranean civilisations. While historians do not agree on the figures, they do agree, on the trend of population. In 800 B.C., some 20 million people lived around the Mediterranean Sea, whereas in 150 A.D. the population of the Roman Empire numbered 70 million[29], although the estimate of 100 million could be equally plausible. Such a level of population was again attained by the European continent (without Russia), only in the early Modern centuries. Although a calculation of the carrying capacity of the Mediterranean world is risky, the estimates proposed above regarding the extent of land able to support the population in energy sources do suggest that the rising population put pressure on resources.

Figure 3. Length of the femur (mm.) of cohorts born between A.D. 1 and A.D. 450.

[27] The decline of the curve in Figure 2 coincides with economic decline in Britain. See the trend of the British economy described by Ward-Perkins 2005, Ch. V.
[28] Bresson 2006, p. 77.
[29] Scheidel 2007, p. 47.

Source: Jongman (2007a), based on data collection by Geertje M. Klein Goldewijk (research still in progress).

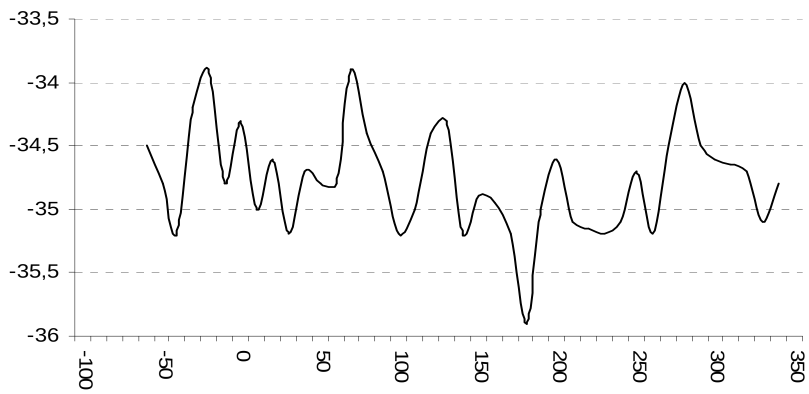
Information on changes in stature suggests that body size diminished in Western Europe from 150 A.D., after a period of rise (Figure 3). If stature is assumed as a good proxy for nutrition, that is input of calories, especially in the first years after birth, then data on stature suggests a worsening of the diet from the 2nd century A.D. onwards.[30] Probably it diminished later in Central and Northern Europe (e.g. Germany) than in the Mediterranean regions.[31]

8. *An energy crisis: climate*

For a long time the rising pressure of population was supported by rising temperatures in the Mediterranean and the whole of the Northern hemisphere, during the *Ancient Climatic Optimum.*[32] Historians agree on the existence of a Roman Warm Period.[33] Research on ice carrots from Greenland ice core allowed to specify changes in temperature from the 1st century B.C. (Figure 4). We can see that the two centuries B.C. were particularly favourable from a climatic viewpoint. Temperatures were high during that period and remained so until the middle of the 2nd century A.D. After 150 A.D. temperatures diminished remarkably. The middle of the 2nd century "witnesses the end of a warm period during which the ratio of the oxigen isotopes had attained levels which only in the 20th century would have been reached again".[34] The presence in the ice carrots of sulphur acids, dated between 153 and 162, reveals the influence of volcanic forcings on the fall in temperatures. Higher temperatures mean that the season for harvesting vegetables is longer; that land can be cultivated at higher altitudes and further North.[35] Soil per worker rises when teperatures are milder.

Much more is known about the evolution of climate in Central-Northern Europe, and the Northern regions of the Roman Empire, than in the Mediterranean.

Figure 4. Temperature variations from the Greenland glacier ice core 60 B.C.-350 A.D.

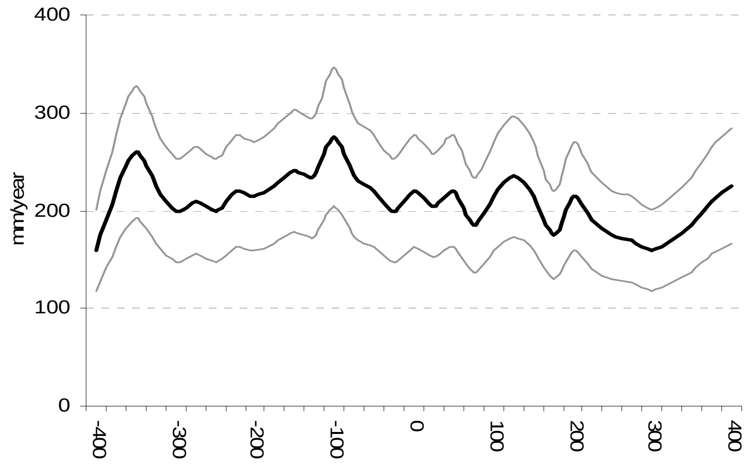


Source: Rossignol (forthcoming).

[30] Kron 2005, 2008.
[31] Koepke "Anthropometric Decline".
[32] Haas 2006, pp. 147 ff.
[33] Sallares 2007, p. 19. See also the long-term view in Blender, Fraedrich, Hunt 2006.
[34] Rossignol (forthcoming).
[35] See also Weinstein 2009.

Precipitations as well have been reconstructed for the region of Israel[36] and for Germany and Switzerland.[37] We know that these diminished and the climate became drier when the temperature was falling (Figure 5). In Central Europe, precipitations peaked in 100 B.C., but from then on diminished, reaching a minimum in A.D. 300 (100 millimetres less than in the second century B.C.). The climate became "increasingly dry".[38]

Figure 5. Intensity of precipitations between 400 B.C. and A.D. 400 (and range of error)(mm. per year).



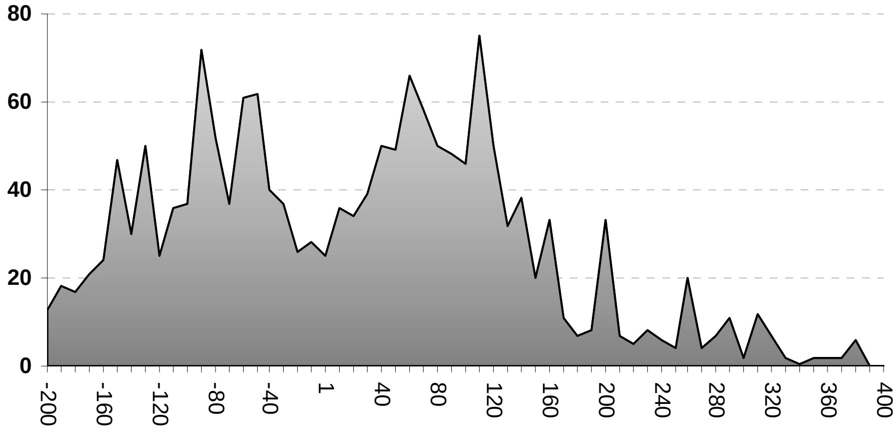
Source: Büntgen et al. 2011, p. 581.

Food intake diminished in the first two centuries of the Roman Empire while the extent of forests was shrinking to provide more fields for the rising population.[39] "By the end of the Republic, most of the areas of Italy that were accessible to Rome had lost most of their stands of tall trees, but except for some metal-working centres, most places had stabilized their fuel supplies. Patches of eroded land continued to multiply, however, all the way through the high-imperial period of prosperity".[40] In Spain, "climate deterioration" hampered "vegetation recovery after fire and exacerbate human impact (deforestation) in general".[41] In such cases, because of the need to meet the inelastic demand for food, the number of livestock and meadows diminish (although for ancient civilisation nothing certain can be said on the matter). Intensification occurred in agriculture and convertible husbandry spread to support the demographic rise at least in Italy.[42] In Europe, between 1500 and 1700, the 40 percent rise in population, from 80 to 120 million,[43] resulted in a 20 percent decrease in agricultural product per capita (that is energy, since the greater part of energy came from the fields).[44] In the case of the Roman empire, the decrease in per capita energy cannot be specified, due to the uncertainties regarding population. However, if we take the entire period from 200 B.C. to about A.D. 150, a decline between 10 and 20 percent per head does not seem implausible.

[36] Orland et al. 2008.
[37] Büntgen et al. 2011, p. 581.
[38] Schmidt, Gruhle 2003a and 2003b.
[39] See, however, the reconstruction by Kaplan et al. 2009. See also Ruddiman, Ellis 2009.
[40] Harris, 2011, p. 139.
[41] Kaal et al. 2011, p. 172.
[42] Forni, Marcone 2002
[43] Russia is included in these estimates of population.
[44] Kander, Malanima, Warde forthcoming.

We cannot say if the epidemics of smallpox, the Antonine Plague that is, that spread between 160 and 170 A.D., was actually connected with this energy crisis.[45] Certainly the ensuing decline in population reduced the demand of energy sources, as archaeological wood remains from Central Europe seem to suggest (Figure 6).

Figure 6. Estimates of forest clearance in Central Europe (Germany, North-Eastern France) from archaeological wood remains 200 B.C.-400 A.D. (decadal data; any point of the diagram represents the intensity of the felling).



Source: Büntgen et al. 2011, p. 580.

By themselves, neither population rise nor climatic changes are necessarily connected to phases of economic decline. Their coincidence can, however, deeply influence the economy and provoke destructuration and finally collapse. Overall for a civilisation as for a biological structure, the input of energy is the basis of its inner organisation and functioning and likewise, for an entire civilisation or a single living being, a reduction in the input of energy implies destructuration and decay.

Conclusion

The energy system of the ancient Mediterranean civilisations was the same as that of all agrarian societies. Despite the increase in useful knowledge and the extensive development of the agrarian energy basis, supported by a favourable climatic phase, this system was finally unable to support the increasing needs of the rising population. Per capita exploitation of energy began to diminish. An unfavourable climatic phase, beginning in the second half of the 2nd century A.D., heavily contributed to this decline. Economic decline was the result of a combination of these negative effects.

Much later, during the *Little Ice Age,* in the early modern centuries, the reaction to a similar crisis was a much wider use of coal.[46] This main change developed in England since the 16th century. Then, in the 18th century, the steam engine began to interact with the new, rising input of energy. This interaction initially began to involve the Central and Northern European regions and subsequently also the regions far from the centre of the great change then in act. The combination of changes in power and energy was the basis of Modern Growth.

[45] See especially Lo Cascio (ed.), *La Peste Antonina* (forthcoming).
[46] The topic is discussed in Malanima 2010 and 2011.

Such as in many other pre-modern civilisations, in the ancient Mediterranean civilisation, the structure of the energy system prevented from the possibility of following a similar path. Ancient growth found in its energy basis the main constraint to its further progress.

Appendix*

Estimates of energy consumption in the early Roman Empire

Table 1 presents a quantification of energy input per capita in the early Roman Empire (1st and 2nd centuries). A wider analysis of per capita energy consumption in the early Roman Empire is presented in Malanima (forthcoming). The topic of energy consumption in pre-modern economies is also discussed in Malanima 1996, 2006, 2009, 2010, 2011 (www.paolomalanima.it). Here I recall the way I followed to quantify energy consumption in the Roman world.

As seen (§ 2-3), sources of energy of pre-modern, agricultural economies are the following:

1. food;
2. fuel (almost always firewood);
3. fodder for working animals;
4. water and wind power.

1. Food

Food consumption has always been the most stable energy carrier ever exploited since the beginning of the human species. In the following diagram (Figure 7), I report the series presented by Jongman (2007b, p. 599), on calorie consumption in present day populations. Taking into account the age structure in Roman antiquity, with more young people than today, the range of 2-3,000 calories seems plausible. Considering yields per hectare, to cover the needs of a family of 5 people, about 5 hectares were necessary, including fallow lands. Thus a family needed between 2.5-3.3 hectares of cultivated land (excluding fallows): i.e. from half to two-thirds of a hectare per person (for data on yields, and soil per capita necessary to satisfy the food demand, see Forni, Marcone (eds.) 2002, on agriculture in Roman Italy).

Figure 7. Food consumption by modern populations according to age (kcal.)

Source: Jongman 2007b, p. 599.

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2. Firewood

As said in § 3, firewood consumption depends on temperature and industrial use. One kg. of wood can be seen as the lowest possible level of consumption (as also stated by Harris 2011). Although hard to quantify, firewood consumption was low where temperatures were high and high where temperatures were low (see, for instance, data in Warde 2006, referring to early modern Europe). If, to simplify, we surmise that in a Mediterranean climate, each individual consumed 1 cubic metre of wood per year, that is 625 kg., including industrial uses as fuel (1.7 kg. per day), this amount of wood could be provided by the yearly growth of half a hectare of forest (Chierici 1911: 232-33). Assuming that the population of the Roman Empire in around 165 A.D. was 70 million inhabitants for an area of 3,800,000 km^2, and that every inhabitant consumed 1 cubic metre of firewood, then the total requirement was 70 million cubic metres. It could be provided by a wooded area of 350,000 km^2, or 9-10 percent of the total inhabited surface of the Empire (including wood from prunings). With a population of 100 million inhabitants, the wooded area rises to 500,000 km^2, or about 13 percent of the total. A city such as Rome, with 1 million inhabitants in the age of Augustus, needed 50 km^2 of forest to cover its needs.

As to industrial consumption, we can only provide some calculations from what we know about the output of metallurgy. Let us assume that iron production was between 80,000 and 160,000 tons per year (Harris 2011) and, at the lowest, a consumption level of 30 kg of firewood (transformed into charcoal) per kg. of iron (Smil 1994, pp. 144-56). Charcoal, known in Egypt as early as the 3rd millennium B.C., was widely used in Greek-Roman antiquity (Wikander 2008, p. 138). For the production of 80,000 tons of iron, the quantity of firewood would thus be 2,400,000 tons (converted into charcoal). In cubic metres, the requirement was 3,840,000 (assuming 625 kg. per cubic metre, and then dividing 2,400 million kg. by 625). With a yearly productivity of half a cubic metre per hectare of forest, in order to produce 3,840,000 cubic metres, 1,920,000 hectares or 19,200 km^2 were necessary. Assuming iron output being twice as high, the need amounts to 38,400 km^2 of forest. This area is only 5-10 percent of the total forest required by the population for heating and cooking. Fuels different from firewood represented a negligible share of the total. Thus, our estimate for a Southern Mediterranean civilization such as the Roman Empire is between 1 and 2 kg. of wood, that is 3,000-6,000 calories per capita per day.

3. Fodder

The estimate of fodder consumed by draft animals is more complex. From the viewpoint of energy, an ox or some other working animal is like a machine. It metabolizes vegetables to accomplish a task. In order to establish the average consumption in energy sources per head, the input of energy by a draft animal must be divided by the family members that exploit it. We know that improved fodder management and nutrition determined a remarkable increase in the size of animals during Greco-Roman antiquity. Ley farming and meadows supplied animals with better fodder than in the late Middle Ages and early Modern times (Kron 2000). Oxen were taller and heavier than in Medieval and early Modern Europe: about 400 kg instead of 2-300 (Kron 2002 and 2004).

We can establish a ratio between working animals and population in ancient Mediterranean civilisations from the technical relationship suggested by ancient agronomists between land and working animals. In the 1st century B.C., Varro recalls the opinions of Cato and Saserna about the need of a yoke for every 80-100 iugera (20-25 hectares)(*On agriculture* 1.21-22). Since a yoke is composed of two oxen, the relationship is therefore a working animal per 10-12.5 hectares. A century later, Columella tells of two yokes of oxen for a farm of 200 iugera (or 50 hectares)(*On agriculture* 2.12.1-7). Again we find a ratio similar to that suggested by Varro and relatively close to the animal-land ratio found in early Modern Europe. Since a peasant family required a farm of about 3-5 hectares to support its living (as shown in § 1 of this App.), we could divide among the 10-15 members of two average families endowed with a farm of 3-5 hectares each, the calories from fodder consumed by oxen (25-30,000 kcal per animal per day) and we would obtain the result of 1,700-3,000 kcal. per head. We would have to add to this estimate horses (on which see Vigneron 1968), mules, donkeys and camels, and we would also have to include urban inhabitants (excluded from the previous draft animals-peasant families ratio) in the denominator of our ratio. All things considered, a range of 1,000-2,000 calories per day per capita seems plausible.

4. Wind and Water

The only possibility of estimating the consumption of water and wind power is to start from power (work done per unit of time -1 second-). In the case of a large sailing ship, with a carrying capacity of 400 tons, a rare example in the ancient world, where the majority of sailing ships were below 100 tons (Greene 1986: 26 ff), a relationship existed between tonnage and power. The power of such a ship (400 tons) was about 50 HP (Malanima 2006). Assuming that this power was exploited fully for 24 hours and 365 days per year, energy per year would be 438,000 HPh (Horse Power hour is a measure of energy), that is, 770,000 kcal. per day. We would now need a plausible ratio between ships and boats on one hand and population on the other. Even assuming the ratio existing in early Modern Europe to be correct, the result would be less than 1 percent of the entire energy consumption per capita.

The watermill was the most powerful engine existing on land. Generally its power did not exceed 2-3 HP, although examples of big mills (Munro 2003) or the combination of several mills in powerful sets of engines are not lacking (Brun 2006; Wikander 1979, 2000 and 2008). The mechanical work produced by a watermill endowed with the power of 2 HP is about 64,749 kj. (15,000 kcal.) per day, and since a man consumes 2,550-3,000 kcal. per day as food, consumption of gravitational energy by a watermill is 6 times the energy consumption of food per capita. In late medieval and early modern Europe, a ratio existed between watermills and population: 1 watermill every 250 people. Otherwise stated, any small village of 50 families had its own mill. If we divide a mill's energy consumption by 250, the result is 60 kcal. Certainly, the use of mechanical energy to grind cereals was a remarkable achievement of ancient civilisation. Its contribution to the energy balance was, however, modest in mere quantitative terms. Although we do not know the inhabitant-watermill ratio in the ancient world, and even allowing for the existence of the same late medieval ratio, which seems too high for antiquity, as early as the first centuries of the Roman Empire, the result is that the contribution to the energy balance was indeed modest (Reynolds 1983; Lo Cascio, Malanima 2008).

Let us consider that previous calculations on mills and ships assume full-time work (24 hours per day), which is not plausible. Contributions to the energy balance assuming more realistic working time imply a reduction of the available energy per head.

The estimates by Ian Morris

Different estimates of energy consumption have been provided by Ian Morris (2010a and 2010b). According to Morris (2010a, p. 28), the sources to be taken into account for a calculation of energy consumption (including the ones used in modern economies) are the following:

"Food (whether consumed directly, given to animals that provide labour, or given to animals that are subsequently eaten);

Fuel (whether for cooking, heating, cooling, firing kilns and furnaces, or powering machines, and including wind and waterpower as well as wood, coal, oil, gas, and nuclear power);

Raw materials (whether for construction, metalwork, pot making, clothing or any other purpose)".

We can see that there is a similarity between this list and the sources taken into account in this paper. However: 1. I do not include feed "given to animals that are subsequently eaten", since it is already included in the 2-3,000 kcal. of food for humans (and it would be a duplication of the same source in our calculations). I include only feed for working animals; 2. it is not clear how Morris computes the contribution by wind and water power; 3. raw materials cannot be considered as energy carriers and are not included in my estimates (nor in those by modern statistical institutes for energy such as IEA (International Energy Agency) and EIA (US Energy Information Administration). Morris follows, however, Cook, 1971, who includes “vegetable fiber”, which brings “solar energy into the economy through photosynthesis” (p. 134). See also Cook, 1976 (pp. 51 ff. and 135). Raw materials, however, are not used as providers of energy. Firewood, is also generated by photosynthesis, hence when used as an energy carrier I include it in my calculations. When timber is used as raw material for construction, it is not included, despite being produced by photosynthesis. It is not an energy carrier, in this case.

The results by Morris are quite different from those presented in the previous pages. In the following Table 2 some data are reported from two series presented by Morris (2010b, p. 628).

Table 2. Energy consumption in advanced regions of the West and East according to I. Morris. 8000 B.C.-2000 A.D. (thousands of kcal. per capita per day).

	West (000)	***East (000)***
2000	230	104
1900	92	49
1800	38	36
1700	32	33
1500	27	30
1000	26	29.5
200 A.D.	30	26
1 A.D.	31	27
200 B.C.	27	24
8000	6	5

Source: Morris 2010b, p. 628.

Around 2000, the average world energy consumption was 50,000 calories per day. According to Morris' estimate, in 200 B.C. some parts of the World already exceeded this level even without fossil fuels.

In both works by Morris (2010a and 2010b), previous data (reported in Table 2) for the year 2000 actually refer to the most advanced countries in the West (USA) and in the East (Japan). In addition, data for previous years refer to “the most developed core within the West” (Morris 2010b: 42), whose borders, however, are not clearly defined. In any case, Morris' results are too high. In 1800, according to recent direct research, energy consumption in Western Europe (a highly developed part of the globe) was not 38,000 kcal. (as maintained by Morris), but about 15,000 (average for Sweden, Norway, The Netherlands, Germany, France, Spain, Portugal and Italy)(Kander, Malanima, Warde forthcoming and data published in Gales, Kander, Malanima, Rubio, 2007). In 1900, for the same countries of Western Europe, the average was 41,500 kcal. per day per capita, and not 92,000 (as in the previous Table 2). In England it was 95,000. Morris' estimate for 1900 is only plausible if by “West” we refer to England. As we see, data for the Roman Empire are also quite different from ours. Even if we take the most advanced part of the Roman Empire, Italy, in 1861, that is, the year of the Unification of the country, energy consumption per capita was 11-12,000 calories; -less than half the estimate proposed by Morris for the West (31,000) in 1 A.D.

Energy intensity represents the ratio between energy consumption and GDP. In Western Europe from 1800-20 it was 12-15 Megajoules per 1 dollar (1990 international Gery-Khamis dollars), when per capita GDP was 1,200 dollars (according to the series by Maddison 2007, in 1990 international Geary-Khamis dollars PPP). If we assume the very high estimate of 1,500 dollars for Roman Italy (taking into account that recent estimates hardly exceed 1,000 dollars, as shown in Lo Cascio, Malanima 2009 and Lo Cascio, Malanima forthcoming), the resulting estimate of energy intensity, taking Morris' estimate of 31,000 kcal. per head per day (and then 11,315,000 kcal. per year, or 47,342 Gigajoules), is 32 Mj. per dollar, and thus more than twice that ascertained in 1800 for Western Europe. With a GDP per capita of 1,000 dollrs in the early Roman Empire, the implied energy intensity becomes 47 Mj. per dollar. For a comparison, in 2000, World energy intensity was 11.5 Mj. per dollar (1990 Geary-Khamis int. dollars) and in Europe it was 5.5 Mj. per dollar.

Vaclav Smil (2010, pp. 107-13) proposed estimates of energy consumption in Ancient Rome that are far lower than those by Morris. Here is the comment by Morris on Smil's views: "Roman total energy capture would be somewhere between 4,600 and 7,700 kcal/cap/day [according, that is, to Smil's calculations]; if we assume that roughly 2,000 kcal/cap/day of this was food (which means ignoring the archaeological evidence for relatively high levels of expensive calories from meat, oil, and wine), that leaves just 2,600-5,700 kcal/cap/day to cover all other energy consumption. To justify this estimate, Smil suggests that Roman fuel use was just 180-200 kg. of wood equivalent per capita per year, or roughly 1,750-2,000 kcal/cap/day". Actually firewood consumption, in Smil's calculations, seems too low. On the whole, however, Smil's estimates are closer to mine than those by Morris.

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