Mechanical Energy and Water Power in Europe
A Long Stability?

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A big change in the ability to perform work, that is, mechanical energy, took place only 200 years ago through the transition often referred to as Modern Growth.[1] The central technical changes which supported Modern Growth consisted in:

- the possibility of doing work through machines able to transform thermal energy into mechanical work in order to produce goods and services;
- the possibility to feed these machines by means of mineral materials, that is, fossil fuels.

Of these two transformations the second is often mentioned as the most important. Certainly it was an important lever of riches in the age of Modern Growth. It was the first, however, that actually marked the passage from the *biological economies* of the past, whose main converters of energy were human and animal bodies, to the *machine economies*, whose main converters are inanimate devices fed by means of mineral sources of energy. Although both features of the modern energy system had already been known since Antiquity, the real combination of these two ingredients of our economic life took place thanks to modern technological advances and stronger interactions between knowledge and production. It marked a turning point in the economic history of civilizations. Machines fed by mineral carriers and mechanical work produced through the heat of mineral sources of energy actually opened a new age, hard to merely imagine before.

[1] Malanima, 2006a.

The dependence of Modern Growth on the technological transition from the *biological energy system* to the *machine energy system* stands out whenever we try to figure out the real possibilities of economic development without these two big changes.

Energy consumption per capita per day was about 15,000 kcal in Europe in 1750, with a population of 111 million (Russia excluded),[2] and a little less than 40,000 in 1900, when the inhabitants were 295 million. It is now 150,000, with a population of 523 million in the continent. A simple calculation can show that, if the energy system had been based, during the following 250 years, on the same sources exploited in 1750 and if its efficiency had been the same, the need for soil would have grown in Europe to more than 3 times the entire surface – Alps and Pyrenees included - in 1900 and to 25 times the whole extent in the year 2000 (Table 1).

Table 1. Hectares of soil theoretically needed by the European population to meet energy requirements in 1750, 1900 and 2000, with the same energy carriers as in 1750, and the same efficiency (Europe without Russia).

	Per c. Mj* Per day	**Per c. Toe per year***	**European Population (millions)**	**Soil per c. (ha)**	**Total soil (10^3 ha)**
1750	63-84	0.55-0.73	111	1.75	194,250
1900	157.3	1.37	295	4.50	1,330,000
2000	593.7	5.18	523	19.86	10,387,000

* Mj: Megajoules; Toe: Tons Oil Equivalent (1 Toe = 10^7 kcal).

Sources: Malanima, 2003 and 2006a.

No doubt, possibilities of making this old biological energy system more productive existed. The productivity of land and peasant labour could, in fact, be raised. A big advance in agricultural productivity occurred, however, ultimately only in the age of chemical fertilizers and tractors. Both technologies were based on the changes brought about by the transformation of the energy system and could not take place without them.

It is worth noticing that already C.M. Cipolla,[3] some decades ago, and A. Wrigley,[4] more recently, stressed the vegetable basis of past agrarian civilizations as

[2] Russia excluded. The same for 1900 and 2000.
[3] Cipolla, 1962.
[4] Wrigley, 1988; and the essays collected in Wrigley, 2004.

the main obstacle towards the economic progress of these past agrarian civilizations. Since the metabolism of this system depended on soil availability, which is limited, the multiplication of men resulted in decreasing labour productivity, less and less supported by natural resources and animals, and, as a consequence, in decreasing energy for any converter to translate into motion and work. More favourable institutions, a keener division of labour, the improvement of tools and implements could displace the existing limits, but not completely remove them within the dominating past energy system. Only the passage to the new, modern system, starting in the 19th century, opened to the agricultural civilizations new potentialities of growth.

What is then the position of water power against this background? With water power exploitation through mills and water devices we are still prior to the big transformation and not within it. No doubt, water technologies introduced since Antiquity were means to exploit a non-biological source of energy and made available to men a noteworthy addition of energy. Undoubtedly, they significantly contributed to the evolution of power technology. However, neither in quantitative nor qualitative terms did they set the foundations to the abovementioned transformation. The path towards economic modernization was different and did not cross the ancient and widely trodden one of mechanical water power. It was based on the combination of heat and mechanical work. Water and wind engines were not a real introduction into the new age of the machines.

It is not our purpose to present here new empirical knowledge on the spreading of water power in ancient or Medieval or early Modern Europe. More modestly, our purpose is to specify the relative importance of the water devices within the past biological energy system (§ 1); to investigate their role in Medieval and early Modern Europe (§ 2); and to recall the recent improvements in our knowledge on water technology in the ancient Roman world (§ 3). Going back in time from the 19th century until the Roman Republican age, we will discover that a real rise of water technology, in per capita terms, is dubious over the 1800 years preceding modern growth. A long stability seems more convincing than a progressive path.

1. *Water power within the past biological energy regime*

Research on traditional energy carriers in pre-modern Europe has progressed fast in recent times. It is now possible to specify much better than 20 years ago the relative quantitative importance of the main energy carriers to human beings and also to estimate per capita energy consumption.

We here take into account only economic, that is costly, sources of energy.[5] Free sources, such as sun light, are disregarded. In the late 18th century, three were the main carriers of energy in Europe and Mediterranean. The most important in quantitative terms was firewood. Its contribution to the total energy balance was about 50 percent in the regions of Mediterranean Europe such as Italy and Spain.[6] Data on this kind of consumption do not allow the desirable precision. Few doubts, however, exist on the magnitude of their contribution. Wood was by far the main source of thermal energy. Coal (although important in England) represented a negligible addition to the European average. The second and third sources of energy were food for men and feed for working animals. Here working animals are merely considered as animate machines whose consumption is divided among the people exploiting their energy. Food and fodder were, so to say, the fuels of these animate, biological converters. Food for men and fodder for working animals played almost the same role and their contribution was comparable to that of wood: about 50 percent. They were the main sources of mechanical energy, since, through their metabolism, they were the basis of any kind of work.

And water power? Some calculations are to the point. From our late Medieval-early Modern documentary sources, we know that seldom an ordinary water-mill exceeded the power of 3 HP. This engine was then able to perform the work of 3 HP per unit time. Often the power was lower: around 2 HP or less. As a comparison, we can remember that the ordinary Watt steam engines in 1800 had 10 times this power. Let’s make some calculations supposing a power of 2 HP. If a water-mill with a power of 2 HP worked 12 hours a day, its daily energy consumption, in order to grind grain, produced by the falling water of a stream was 24 HPh (HPh being a measure of the consumed energy, while HP is a measure of power). The mechanical work performed in 12 hours was then 24 HPh. Since 1 HPh is equal to 736 Watthours, 24 HPh correspond to 17,986 Watthours or 15,475 kcal. This is then the energy developed by a water-mill working half a day. An HP could grind about 0.15

[5] The methods to estimate tradional sources of energy are widely explained in Malanima, 2006b.
[6] Gales, Kander, Malanima, Rubio (forthcoming).

quintals of grain per hour.[7] In the famous big water-mills in Barbegal, at the mouth of the Rhone, in the 2nd century A.D. any pair of stones could grind 0.24 quintals, as far as we know.[8] It was a big mill. We have information on big water-mills in late Medieval-early Modern Europe. Their power could even reach 20-30 HP. Most were, however, small water-mills endowed with 2-3 HP; able then to transform 3.5-5 quintals cereals into flour in 12 hours. The diameter of their wheels ordinarily did not exceed 3 metres.

Now, the power of a man turning a hand-driven mill hardly reaches 50 W and for relatively short periods of time: in our case no more than 6 hours per day. Totally, then, the energy spent could not exceed 300 Wh per day. The result is that, in a day of work, a modest horizontal mill could substitute 50-60 men at the best; in most cases something like 30-40. A horse, whose power was 300 W, could do in 6 hours, the work of 6 slaves. A more powerful mill -3 HP-, endowed with a vertical overshot wheel, could substitute about 100 men, as Vannoccio Biringuccio maintained in the 16th century.[9]

The mechanical contribution of a water-mill to the energy availability in traditional societies, is, however, relatively modest when we compare it to human and animal energy consumption in terms of food and fodder; even more, if the comparison is with total energy consumption, firewood included. The mechanical energy produced by a water-mill with the power of 2 HP is equal to about 15,000 kcal (64,749 kj), and since in a day a man consumes 3,000 kcal, consumption of gravitational energy by a water-mill is 5 times the food energy consumption of a man. A working animal consumed fodder for about 20-25,000 kcal a day. Energy consumption by this animate machine is higher than that by a water-mill. We have to take into account, however, that, while the yield of a mill is high – that is the transformation into mechanical, useful work, is about 70 percent or more of the gravitational water energy falling on a vertical wheel - the yield of an animal body is low: 10 percent for working animals and a little more - 20 percent - for a man. Useful energy is then about 2-2,500 kcal for an animal and 5-600 for a man. A lot of energy is util-

[7] Makkai, 1981, p. 179 writes of an average of 20 kg per hour in the case of more powerful mills in the late Middle Ages.
[8] Brun (forthcoming).
[9] Biringuccio, 1914. From the work by Biringuccio Reynolds, 1983, derived the title of his book. See the calculations in Reynolds, p. 22.

ized by these biological machines only to survive, just for their metabolism. The inanimate machines nowadays are much more efficient: usually more than 30 percent of the energy of our cars is transformed into useful work (the transportation, that is, of men or commodities). The biological mechanical energy system in the past was less efficient, under 15 percent. If we add the thermal energy of firewood the total yield diminishes, since traditional fireplaces were very poor converters of energy into useful heating. The dispersion of heat that simply increased entropy was much higher in the past than today.

For the 19th century, estimates of energy consumption in some European countries are now available. Before the introduction of coal, daily energy consumption – both mechanical and thermal energy - in Mediterranean countries such as Italy and Spain, was around 10,000 kcal (41,185 kj) per capita. In Northern European regions such as Sweden and The Netherlands it was at least twice as much.[10] Mechanical energy was half the total consumption in Spain and Italy and about one third or less in the North. Within this consumption, water represented less than 1 percent. Its contribution was similar to that of wind power by sails and windmills (with the exception of Holland, where wind consumption was traditionally much higher). It increases if the comparison is only with mechanical energy. It does not exceed, in any case, 2 percent.

2. *Water power in late Medieval and early Modern Europe*

Many new contributions have been recently published on Medieval and early Modern water technology. They have increased our knowledge of the European technological evolution; much less they say about the quantitative importance of mills and water engines within the economy over time. In our perspective, it is useful to recall, from these studies, the use of water in many industrial technologies and the long-term evolution of water exploitation.

On the basis of recent contributions on the subject, it is possible to sum up the main changes in Medieval water technology. The expansion and finally the dominance of the overshot vertical mill, much more efficient than the old horizontal water-mill -which continued to characterize the rural world- is perhaps the main feature

[10] Gales, Kander, Malanima, Rubio (forthcoming).

of this new phase of water technology.[11] Thanks to its higher power, the vertical wheel began to advance in many different industrial sectors. The innovation of the cam, whose existence, until a few years ago, was dated back to the 10th century,[12] allowed the conversion from rotary to alternate motion, which was the very basis of any further progress in the use of hydropower. The fulling mill, water-powered suction pumps in the mines, hydro-powered bellows in metallurgy, the blast-smelter in the same industry, the working of paper, silk-throwing mills are but a few of the new applications of water in industry. Going back in time, we can see, however, that these novelties are actually supposed novelties. In many cases their existence has been singled out in previous periods by recent archaeological investigations.

Often, reading about these new techniques and their expansion we could imagine that, in quantitative terms, water-power exploitation underwent significant progress in late Medieval and early Modern Europe. At the same time, however, population was growing as well. Regarding the ratio population-water devices in Europe from the late Middle Ages until the 19th century modernisation, the quantitative proposals by L. Makkai and F. Braudel,[13] worked out some decades ago, have not been replaced by new estimates. Both historians maintained that, from the 11th and 12th centuries until the beginning of the 19th, the ratio men – water-mills, not only to grind cereals but for any industrial use, more or less stagnated. Water-mills grew in number from the late Middle Ages to the 19th century at the same rate as the population. There was, however, a likely increase in the power of wheels over the centuries from an average of 2 HP (1,491 W) to 3 (2,237 W), and hence a very modest rise in per capita HP in the long term (Table 2).

Table 2. Per capita power from water wheels in 1200 and 1800 (HP).

	Average power per wheel (HP)	**Inhabitants per water wheel**	**Per capita HP**
1200	2	250	0.008
1800	3	250	0.012

Source: Makkai, 1981.

[11] See especially Munro, 2003, who resumes a lot of previous works on the topic.
[12] The problem is discussed in Malanima, 1986 and 1988 and Ludwig, 1994. We come back to the problem of the cam in the following pages.

We know, however, that per capita power from water did rise during the first wave of the 19th century industrialization or proto-industrialization, but only for a relatively short period, to be replaced by steam and mechanical mills in the 20th century.[14]

It is hardly necessary to remember the constraints limiting the possibilities of water power progress. The localization of the mill is dictated by the existence of flowing water. To exploit water's gravitational energy, the carrying capacity of the flow must be high and the slope must be high as well. Water flow has to be ruled and the regulation is far from easy in many physical contexts. The basic material of a mill, wood, can not undergo heavy stress. The energy produced must be consumed on the spot and only for some kinds of works. The exploitation of water-power is, furthermore, constrained by the climate, ice and dryness being powerful obstacles to the activity of the mill. Once attained a ratio population-mills, it is almost impossible to proceed further. Versailles waterworks in the 17th century are credited with a power of 75 HP; but a simple Watt's steam engine used as ship propeller could reach 1,500 HP at the middle of the 19th century and 8-12,000 50 years later.[15]

Going back in time it is possible now to set these developments in a wider context.

3. *Water power in the early Middle Ages and Roman Era*

Until some decades ago the opinion prevailed that the water-mill, although an ancient invention, was, however, definitely a medieval innovation, according to the Schumpeterian meaning of the word innovation. In fact, after a short advance in the late Roman empire, rapidly coming to an end, it almost disappeared in the early Middle Ages. Only from the 9th-10th centuries did mills begin to be more intensively built thanks to the initiative of monasteries and feudal lords. The centuries between the 9th and the 12th were seen as a period of fast progress in water technology. Mills began to be utilized not only to grind cereals, but also for many different kinds of industrial work. At the time of the Doomsday Book, in the late 11th century, the ratio

[13] Braudel, 1979, Chap. V; Makkai, 1981, p. 178 (on which is based the following Table 2).
[14] See the still useful (on the usage of water power in the first phase of the industrialization) Landes, 1969, passim.

men-waterwheels was already the one prevailing in the following centuries and until the start of economic modernization.[16] Both M. Bloch[17] and L. White[18] supported this idea of a technological medieval progress with their important works. A kind of industrial revolution had already taken place in the central medieval centuries, according to several scholars.[19]

We know that this progress was, at least partially, the effect of the increasing volume of documents and the rise of population. We can question the actual rise of water-power in this period (and, even more, of the ratio water-power – men). It is likely to have been merely the continuation of a previous progress: so some scholars begin to guess. Summing up the recent advances in our knowledge on Medieval water power, J.H. Munro has recently written that "during the 5th and 6th centuries, the water wheel spread rapidly, littering the map of western Europe, to become its major source of mechanical power".[20] It seems then that the Medieval water revolution was actually the continuation of an earlier phase. On the other hand, it does not seem that the 5th century was really the start of something new. Looking back in time we discover that the 5th century advance was already well rooted in a previous phase of water power expansion.

In these last years, in fact, our knowledge about the use and the spread of mechanical water devices in Antiquity has been progressing fast. We now know that all the devices, which were to be exploited in late Medieval-early Modern Europe to grind grains, were already in use in the late Republican Roman world. Hand querns were the only tools to grind cereals in early Republican Rome. From the 3rd century B.C. onwards, however, both the animal mills, usually put in motion by donkeys, and also by slaves, and water-mills were used.[21] The horizontal water-mill differed very little from the animal-driven mills. Both archaeological remains and hints in the literary sources attest the existence of the vertical mill, whose mechanics were more complex since the transmission of motion to the upper stone was not direct. A lantern gear was used to this purpose , through which the motion was transmitted from

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15 Cook, 1976, p. 29.
16 Hogden, 1939.
17 Bloch, 1963.
18 White Jr., 1962.
19 Gille, 1959; Carus-Wilson, 1954.
20 Munro, 2003, pp. 226-27.
21 Lewis, 1997.

one shaft to another. The vertical mill, on the other hand, could be distinguished according to the kind of wheel, over- or under-shot, fed by the falling water.[22] The archaeological remains suggest a prevalence of the technologically more complex vertical water-mills in the late ancient Roman world, although the possibility exists that the simpler horizontal–wheeled hydraulic mills, probably more numerous in rural areas, disappeared faster than the urban and more complex ones.

All these different kinds of devices to grind grain coexisted in the Roman period as they would also in late Medieval and early Modern Europe. The relative technological complexity of the several devices to grind cereals would suggest, however, in a chronological perspective, the passage from the hand querns to the horizontal mill geared by animals or men to the horizontal hydraulic mill and finally to the vertical mill under- and over-shot. Water and animal-driven mills coexisted for a long time. Let's recall that in 1869 in Italy, with a population of 26 million, there were 74,764 mills: a little more than half were water-powered and the rest animal-powered.[23]

We also know that "the bucket-chain, overshot wheel, and perhaps the noria and the saqiya drive", together with "animal-powered and water-powered lifting devices", were already in use probably in Alexandria in the mid-3rd century.[24] The well-known literary evidence on the existence of the hydraulic mill in the 1st century BC had been preceded by the long technological progress of water-powered mechanical devices. By 2005, 69 archaeological remains of water-mills, dating from the 1st century BC until the 5th AD, had been discovered[25] and most of them date back to the first two centuries of the Empire. It is important to note that these remains attest an advanced knowledge in the use of the hydraulic power. A relief on a sarcophagus recently discovered at Hierapolis of Phrygia and dating to the 3rd century AD shows that even the transformation of the rotation into an alternate motion, through the introduction of the cam, went back to Antiquity. It seems that the cam was already in use in 3rd-century-AD Hierapolis to put a marble saw into motion.[26] This new evidence removes the doubts cast in the past on the reliability of two

[22] Moritz, 1958.
[23] Malanima, 2006.
[24] Wilson, 2002.
[25] Brun (forthcoming).
[26] Ritti (forthcoming).

pieces of literary evidence dating back to Late Antiquity and apparently already showing the use of the cam (the Comment of Gregory of Nissa to the *Ecclesiastes* and some verses of the *Mosella* of Ausonius). The discovery of the cam, a central invention to adapt water energy to many different industrial processes (and primarily the fulling mill), has to be anticipated at least 6-7 centuries. In ore extraction and ore processing "the use of hydraulic technology in Roman mining of the I and II centuries AD remained unsurpassed until the 19th century".[27]

We know that in pre-modern agrarian economies the prices of manufactured goods - and technical engines are among these goods - tended to decline, while the prices of primary, agricultural goods rose. We can suppose that from the period of its first appearance to the age of Diocletian the cost of building a simple water-mill decreased. We know from Diocletian's *Edict on Prices* (A.D. 301) that the price of a water-mill was 2,000 denarii, one driven by animal force 1,250-1,500 and a slave-driven mill 250.[28] The investment in a water-mill corresponded to the wage (to which food was added) of 80 days of an agricultural labourer.[29] In these conditions, it was more and more convenient to invest in a water-mill. The advantages of a water-mill tended to rise and the comparison between the diverse forces to drive a mill – men, animals, water-power - was more and more favourable to water-driven engines.

In the 11th and 12th centuries the ratio water-mills/population was around 1 mill every 250-300 people;[30] which means that more or less any village had at least 1 mill. The same ratio population-mills prevailed in the early Modern Europe and until the end of the 18th century. Unfortunately, we have no Domesday Book for Antiquity. An answer to the question about the real expansion of water-power will remain, therefore, without any firm evidence. The Medieval ratio population/water-mills would imply only in Italy, at the end of the 1st century AD, within the current borders and with a population of 15 million, something like 30-50,000 water- and animal-driven mills. When we compare this figure to the existing archaeological remains of 69 water-mills within the Roman borders in the Roman Empire, it would seem to be at first sight too high. But we must take into account that the pace of the

[27] Wilson, 2002, p. 31.
[28] CITARE(15, 56-59 Giacchero)
[29] Brun (forthcoming).

discoveries of ancient mill structures has been enormously increasing in these last years, thanks to the growing ability of the archaeologists in recognizing them; moreover, we must consider also the evidence of the millstones probably coming from mill structures. Finally, we must also bear in mind that all the wooden structures of the mills were perishable and therefore we have no remains of them. The many new elements now available on ancient Roman technology do not perhaps allow a positive answer on the existence of so high a number of mills as 30-50,000 in Italy alone. They do not allow a negative one either!

[30] Makkai, 1981.

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