ENERGY, POWER AND GROWTH
in the High Middle Ages

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Historians agree that the long period between the 9th and the 14th century could actually be defined as a period of growth in Europe. Population rose, urbanisation spread both thanks to the formation of new centres and increase in numbers of inhabitants of the old ones, technical knowledge improved and institutional changes supported this material progress of the European world. Yet it is much harder to specify the character of this phase of growth. Was it an epoch of mere rise in population, without any improvement in the standard of living, or an age of true economic rise even in per capita terms? The first form of growth is ordinarily defined as *extensive* growth, while the second as *intensive* growth. Since any form of extensive or intensive growth must be supported by a rise in the endowment with energy, then it is reasonable to wonder whether new energy sources began to be exploited or if exploitation of the old ones improved.

Sections 1 and 2 of the present article will be devoted to the increase in population and urbanisation. Since increase in urbanisation implies some rise in labour productivity and then some form of intensive growth, I will examine in section 3 the sources of energy of past agrarian civilisations and then, in section 4, the information on the specific sources of energy exploited by medieval European populations. Section 5 will be devoted to power exploitation and section 6 to the influence of climate on the endowment with energy in the period under examination. The path I will follow is then from the evidence on growth provided by data on population and urbanisation to the changes in the energy basis of the medieval population.

1. *The European population*

While in the 7th–8th centuries density of population in the continent was low indeed, 5 or less inhabitants per km^2, in the following three-four centuries the number and size of inhabited areas increased and new centres of population multiplied, cities became more populous, deserted regions, especially in the east and north of the continent, began to be inhabited. Yet quantitative figures on population for this age are almost entirely lacking; with the exception of scattered information in few medieval censuses of land-ownerships (the polyptics) and evidence on the birth of new centres and spread of population towards uninhabited areas. Any quantitative attempt at estimating European population at the beginning of the phase of growth cannot but proceed from the population level around 1300, when more reliable information is available, going back to previous epochs through plausible rates of increase. This is the method followed in the column 7 of Table 1,[1] while in the other columns data are reported proposed by historians and demographers on the European population between 1000[2] and 1500.

Table 1. Data on the European population between 1000 and 1500 (000).

	1	**2**	**3**	**4**	**5**	**6**	**7**
	Urlanis	**Mc Evedy-Jones**	**Biraben***	**Russell**	**Le Bras**	**Maddison**	**Malanima**
1000	56,400	36,000	43,000	38,500	43,000	39,200	47,000
1300	78,700	79,000	86,000	73,500	87,000		93,600
1400	78,100	60,000	65,000	50,000			67,800
1500	100,400	81,000	84,000	81,800	84,000	87,700	84,800

Sources:

1. B.T. Urlanis, *Rost Naselenie v Europe*, Moscow 1941.

2. C. Mc Evedy, R. Jones, *Atlas of World Population History*, New York 1978.

3. J.-N. Biraben, *Essai sur l'évolution du nombre des hommes*, „Population", 34 (1969), pp. 13-25.

4. J.C. Russell, *European Population 500-1500*, in C.M. Cipolla (ed.), *The Fontana Economic History of Europe,* Glasgow-London 1973, I, pp. 25-70.

5. H. Le Bras, *La popolazione*, in P. Anderson, M. Aymard, P. Bairoch, W. Barberis, C. Ginzburg (eds.), *Storia d'Europa*, I, Torino 1993, pp. 71-130.

6. A. Maddison, *Contours of the World Economy, 1-2030 AD. Essays in Macro-Economic History*, Oxford 2007.

7. P. Malanima, *Pre-modern European Economy. One Thousand Years (10th-19th Centuries),* Leiden-Boston 2009 and text.

* All Russia is included and not only the European part.

We see that the range between the lowest and highest estimate in about 1000, 36-56 million, is higher than 50 percent. If we exclude, however, the outlying figure proposed by Urlanis,[3] the range shrinks to 30 percent. For 1300 a re-

[1] Assuming the yearly per cent rise of 2.3 per thousand, plausible in the case of pre-modern economies.

[2] The information collected in the following Table 1 starts from 1000. This is, however, only a chronological simplification deriving from our ignorance about the starting period of the medieval demographic growth.

[3] Let's consider that that by Urlanis is by far the earliest estimate.

markable difference still exists between the highest (94 million) and the lowest figures (73 million), although the range is lower: 20 percent. Any estimate, however, suggests a remarkable rise in population during the period here under examination, until the top reached around 1300. The demographic level then attained will be overtaken only in the 18th century.

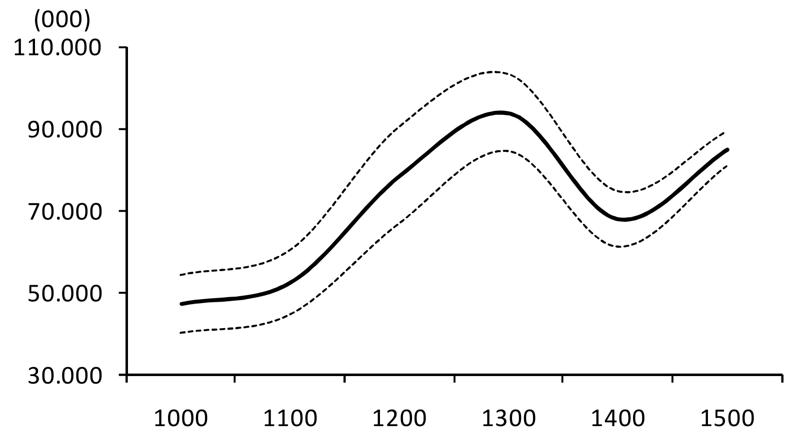

Figure 1. European population and range of uncertainty of our estimates from 1000 until 1500 (000).
Sources: the same of Table 1, col. 7. The dashed curves draw the range of uncertainty of our figures, diminishing from the beginning to the end of our series. The interpolation of the figures for 1100 and 1200 is done through a logistic curve.

2. *Urbanisation*

Since in pre-modern societies per capita income underwent modest changes and was hardly higher than the level of subsistence, population growth implied always increase in gross output. Rise in urbanisation witnesses, instead, rise in labour productivity and per capita GDP: workers in the primary sector must be able to support not only themselves, but also a share of population not employed in agricultural production.

A comparison of urbanisation in 1300 with urbanisation some centuries earlier is not easy, given the scarcity or lack of information on urban population before the 14th century (Table 2). Historians have often stressed, however, increase in the number and population of the urban centres as a landmark of the medieval European civilisation and information on specific cities seems to support this opinion. The results of a recent estimate of the western European centres with more than 10,000 inhabitants indicate that these doubled from 74 around 1000 to 156 around 1300. In the same period, the urbanisation rate would have risen from 5.8 per cent to 6.5: a modest increase indeed.[4] The rise is higher if the value for 1300 is compared to that in 900, when urbanisation in western Europe has been estimated 3.5 per cent.[5] If we consider as cities the centres with more than 10,000 inhabitants, in 1300 Europe (as a whole and not only western Europe, as in the previous estimate) 210 cities could be counted and the urbanisation rate was about 5 per cent.[6] The most urbanised regions were Italy and Flanders, with 18 per cent of the population living in towns of more than 10,000 inhabitants. Spain, as well, boasted a high level of urbanisation (12 per cent). In some regions, such as Scandinavia, Scotland and The Netherlands no city reached the threshold of 10,000 inhabitants.

Table 2. Extent of the European regions (000), density of population and urbanisation rate in 1300 (towns with over 10,000 inhabitants).

	1300 urbanisation
Scandinavia	0.0
England (Wales)	4.0
Scotland	0.0
Ireland	0.8
Netherlands	0.0
Belgium	18.8
France	5.2
Italy	18.0
Spain	12.1
Portugal	3.6
Switzerland	3.0
Austria (Czech., Hung.)	0.6
Germany	3.4
Poland	1.0
Balkans	5.2
Russia (European)	2.1
EUROPE	5.3
EUROPE (without Russia)	5.4

Source: P. Malanima, *Pre-modern European Economy* and Id., *Decline or Growth? European Cities and Rural Economies, 1300-1600*, in M. Cerman, E. Landsteiner (eds.), *Zwischen Land und Stadt,* "Jahrbuch für Geschichte des ländlichen Raumes", 6 (2009), pp. 18-44.
Note: the urbanisation rate of Italy actually refers only to the centre and north.

[4] P. Bairoch, *Cities and Economic Development from the Dawn of History to the Present*, Chicago 1988.
[5] M. Bosker, E. Buringh, J.L. Van Zanden, *From Baghdad to London. The Dynamics of Urban Growth in Europe and the Arab World, 800-1800* (forthcoming; provisional draft).
[6] P. Malanima, *Pre-modern European Economy*; Id., *Decline or Growth? European Cities and Rural Economies, 1300-1600.*

3. *Energy sources of past agricultural civilisations*

Today the daily consumption of energy on the world scale is 50,000 kilocalories per capita. In Europe it is notably higher: 150,000 kilocalories. At the beginning of modern growth, in the first decades of the 19th century, however, about 10 times less energy was consumed: 5,000 kilocalories per capita per day on the world scale and 15,000 in Europe.[7] Despite the growing exploitation of coal, energy consumption in Europe was still based on the three traditional carriers of any agricultural society: food first of all, then firewood and fodder for working animals. Food had been the original source of energy since the beginning of the human species. The second source had been firewood, discovered between one million and half million years ago. The third source, fodder for working animals, began to be exploited on a wide scale by agricultural civilisations between 5,000 and 4,000 years B.C., at the time of the taming of animals and their exploitation in agricultural labour and transport. Food and fodder were, so to speak, the fuels of animate, biological converters. Their joint contribution was equal to that of wood: about 50 per cent in southern Europe and less in the north, where firewood represented a higher share of the overall consumption. These were also the main sources of mechanical energy, since, through their metabolism, they provided almost the totality of work power.

Water and wind were the only non organic sources of energy. At the beginning of the 19th century, the contribution of water exploited by watermills, and wind, utilized both by sailships, boats and mills, to the overall energy consumption was modest indeed. Even though we assume that watermills, windmills and sails, whose number and power are known for several European countries, functioned all day long and their contribution to consumed energy is divided among the population, the result seldom exceeds 1-3 percent of the total energy consumption.[8] We will see, however, that in terms of power water and wind play a more important role.[9]

All these forms of energy are reproducible and will in all likelihood remain so for some 5 billion years, that is for as long as the sun's rays will continue to reach the Earth. These are organic vegetable sources, while fossil sources are organic mineral.[10] They may effectively be considered as inexhaustible sources. In the long run their availability could be assumed as endless. Yet in the short run it is hard to increase their exploitation. Sunlight can be employed more advantageously by increasing the number of cultivated areas, managing woodland with

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[7] I examined the topic of energy consumption in pre-modern Europe in P. Malanima, *Energia e crescita nell'Europa preindustriale*, Roma 1996.
[8] Malanima, *Pre-modern European Economy*, chap. II.
[9] In section 5.
[10] As defined by E.A. Wrigley, *Continuity, Chance and Change. The Character of the Industrial Revolution in England*, Cambridge 1988.

greater efficiency and harnessing more effectively the power of the wind and water. These are, however, slow processes which increase human strength only in the long term. It is easy, by contrast, to extract ever larger quantities of crude oil or coal. Although growth existed before modern times, the increase of production in those pre-modern epochs met with difficulties in energy availability that were virtually impossible to overcome in the short-term. The availabilbity of energy has always been a main constraint for the agricultural pre-modern economies, medieval included.

In case of extensive growth, the total consumption of energy has to increase. Naturally the increase has to be higher whenever growth is intensive. In this last case, in fact, not only energy consumption has to support demographic increase, but also the higher standard of living of the growing population. Now, we have just seen that during the 3-4 centuries of medieval growth, population doubled, increasing by about 50 million. If we optimistically assume that energy in form of food for the population, feed for the working animals and wood, required 2 hectares, including arables (with fallow land), forests and meadows (to feed working animals), then the exploitable surface in order to meet the needs of 50 million inhabitants was 1 million km^2, that is 10 per cent of the whole extent of Europe.[11] Any calculation of this kind is only a rough approximation. Naturally the need of forest was much higher in cold, northern Europe than the south. Also whenever we refer to arable soil, the required amount of land to support a person differed as land productivity was diverse in different regions. Because the dry European agriculture needed working animals, the demand for land was inevitably greater. In any case a massive effort was required in order to support the doubling of the population. Excluding Russia and excluding lands where survival was impossible as in the case of high mountains, we can estimate that medieval demographic growth had to be supported by the colonisation of one third of the total extent of the continent in order to keep energy consumption per head stable.

The question is: what changes did occur in the energy basis during medieval growth to meet this increase in the number of inhabitants?

4. *Energy in the high Middle Ages*

We can only speculate about the level energy consumption during the high Middle Ages. Deviations in food consumption from the average of 2-3,000 kilocalories per day cannot be too great. Information relating to the early modern centuries suggests, furthermore, that a technical ratio existed in Europe between

[11] I presented an estimate of the extent of land necessary to provide the energy in pre-modern Europe in P. Malanima, *The Energy Basis for Early Modern Growth 1650-1820*, in M. Prak (ed.) *Early Modern Capitalism. Economic and Social Change in Europe, 1400-1800*, London and New York 2000, pp. 51-68.

working animals and population: an ox or horse every 4-7 people.[12] Since, taking into account their size, any medieval draft animal needed about 20,000 kilocalories in fodder per day, then a European inhabitant had to avail himself of a further 2,800-5,000 kilocalories in oder to feed the animal. Considering a draft or transport animal as a machine, we merely divide its daily fodder consumption by the people which owned it. Variations in firewood consumption were sharp in different European regions. While in the south 1 kg, or 3,500 kilocalories per head, could be enough, in the extreme north any inhabitant had to consume 5 kg or more, including the industrial uses of fuel.

Thus the energy balance of medieval Europeans can be synthesized by the following equation:

$$c = \frac{F_h}{N} + \frac{F_a}{N} + \frac{F_i}{N} + \frac{W}{N} \quad (1)$$

where *c* is per capita consumption of energy, F_h, F_a, F_i and *W*, respectively the total consumption of food for humans, fodder for working animals, firewood and both water and wind-power, and *N* population.

It is important to specify that only a small part of the whole energy input was converted into useful energy, that is mechanical work or heat that people could actually exploit. If we divide this useful energy (E_u) by the total energy input (E_i), and multiply by 100, the result, that is the efficiency in the exploitation of energy, is 15-20 per cent in pre-modern agrarian societies, while today, in our modern economies, it is about 30 per cent:[13]

$$\eta = \frac{E_u}{E_t} \quad (2)$$

From 80 to 85 percent of the input of energy was lost in pre-modern biological economies. In our mechanical economies the loss is lower: around 70 percent.

Arables. Medieval colonisation came about over a period of time from the 10^{th} century to the 14^{th}. The boundaries of farming shifted and woodland regions were cultivated for the first time. Particularly important was the settlement of eastern European regions, beyond the Elba river, by German peasants, which occurred from the 12^{th} century onwards.[14] A veritable migration took place. Thousands and thousands of German settlers flooded into Eastern Europe. The Euro-

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[12] A. Kander, P. Warde, Energy Availability from Livestock and Agricultural Productivity in Europe, c. 1800-1913: a New Comparison, "Economic History Review", 64/1: 1-29. See also the figures proposed in P. Malanima, *Energia e crescita.*

[13] P. Malanima, *Pre-modern European Economy*, chap. II.

[14] H. Aubin, *Medieval Agrarian Society in Its Prime: The Lands East of the Elbe*, in M.M. Postan (ed.), *Cambridge Economic History of Europe,* I, Cambridge 1966, pp. 449-506.

pean border was pushed further east and thousands of farming villages were created.

On the basis of European and non-European examples, an elasticity of woodland to population rise of -0.6 has been recently estimated, which means that an increase of 10 percent in population implies a reduction of woodland by 6 percent.[15] Using this elasticity coefficient, we can estimate that, during the centuries of the medieval European demographic rise, forests diminished by 30 per cent. Arable lands replaced these forests.

Firewood. During the later centuries of Roman civilisation, forests had been cut down in many densely inhabited areas of the Mediterranean.[16] Following the fall of the Roman Empire in the west, population declined in the Mediterranean regions and consequently forests grew up again. There were less than 30 million people living in Europe in the 8th century, with demographic density at below 3 inhabitants per kmq.[17]

From the 10th century onwards demographic growth began to intensify in Europe thus forcing forests to be cut back.[18] As the demand for food gradually increased, farming families, monasteries, and landowners cleared gaps in the thick forests in order to gain land for agriculture. Cultivated lands extended north, south and to the east, where German settlers searched for land to cultivate.

In Europe, from the 13th century onwards, the attack to woodlands by the population began to be seen as dangerous, and, by the end of the century, the first laws appeared, attempting to limit the felling of forests. According to the Domesday Book of 1086, 15 per cent of the land surface of England was woodland. Over the next two centuries between one third and half of this area had been cleared.[19]

Wood was not only necessary for building and heating, but also for use in many industries. Wood and charcoal were used in breweries, potteries, salt refineries, dye-works, bakeries, and distilleries but above all for working metals. The ratio between charcoal used and iron obtained was 16 to 1. According to another calculation one needed to process 200 kg of minerals and burn 25 square metres of wood to obtain 50 kg of iron.[20]

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[15] O. Saito, *Forest History and the Great Divergence: China, Japan and the West Compared*, “Journal of Global History”, 4 (2009), pp. 379-404.

[16] See the overview by W. Harris, *Bois et déboisement dans la Méditerranée antique*, “Annales HSS” (2011), pp. 105-40.

[17] Ch. Higounet, *Les forêts de l’Europe occidentale du Ve siècle à l’an mil*, in *XIII settimana di studi del Centro italiano di studi sull’alto Medioevo (Spoleto 1965)*, Spoleto 1966, pp. 343-99.

[18] J.O. Kaplan, K.M. Krumhardt, N. Zimmermann. *The Prehistoric and Preindustrial Deforest ation of Europe*, “Quaternary Science Reviews”, 28, (2009), pp. 3016-34.

[19] E.A. Wrigley, *The Transition to an Advanced Organic Economy: Half a Millennium of English Agriculture*, “Economic History Review”, II s., LIX, 3, (2006), p. 439, n. 18 (on the basis of O. Rackam).

[20] R.F. Tylecote, *Metallurgy in Archaeology*, London 1962, pp. 190-1; R.F. Tylecote, *Furnaces, Crucibles, and Slags*, in T.A. Wertime, J.D. Muhly (eds.), *The Coming of the Age of Iron*, New Haven

It has been previously seen that rising population implied a reduction of forests of about 30 percent. We know that, at the end of the 19th century, woodlands represented 30 percent of the whole surface of the continent and that the strong demographic rise from the end of the 17th century meant a remarkable decline in the extent of woodland areas. If, as already recalled, the high medieval decline of woods was about 30 per cent and at the beginning of demographic growth forests presumably covered 70-80 percent,[21] then in the 14th century they extented across 40-50 per cent of the entire surface of the continent.

Other fuels: Coal was almost unknown in the ancient world; with the exception of England, where its exploitation was remarkable.[22] Already widely utilised in medieval China,[23] its exploitation in Europe is documented for the 13th century. We know that it was extracted at that time in England, Scotland and in the Netherlands, around Aachen, in Franche-Comté, near Lyon, in Forez and in Anjou.[24] Limited quantities were transported by sea and therefore consumed in places some distance from the mines. In the 13th century coal from Northumberland was transported not only to London, but also to the Netherlands.[25] Peat, another fossil fuel, which had formed over the centuries in areas of marshland, was already employed when the Romans reached the Dutch plains. During the 11th–12th century its use spread with the population.

In the 15th century coal and peat were widely used around Lièges and near Newcastle. In urbanised, therefore deforested, areas such as Flanders, such quantities of peat were used as to exhaust the peat fields. Further supplies were sought elsewhere, to the north of Antwerp and near Utrecht.[26]

Draft animals. From the 8th century onwards, animal power began to be employed to a much greater extent on the European continent. It has been calculated that, as a result of this progress, 70 percent of the available mechanical energy in 11th-century England was provided by working animals (still mostly oxen at that time) and only the remaining 30 per cent by human muscle power or

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and London 1980, p. 183; J. Schneider, *Fer et sidérurgie dans l'économie européenne du XI^e^ au XVII^e^ siècle*", "Actes du colloque international "Le fer à travers les âges" , Nancy, Annales de l'Est (1956), p. 125.

21 C.H. Higounet, *Les forêts de l'Europe occidentale du V^e^ siècle à l'an mil*.

22 A.H.V. Smith, *Provenance of Coals from Roman Sites in England and Wales*, "Britannia" (1997), 28, pp. 297-324. See also P. Malanima, *Energy Consumption and Energy Crisis in the Roman World* (forthcoming).

23 M. Elvin, *The Pattern of the Chinese Past*, Stanford 1973, p. 85; and above all R.M. Hartwell, *A Cycle of Economic Change in Imperial China: Coal and Iron in North-East China, 750-1350*, "Journal of the Economic and Social History of the Orient", X (1967), pp. 478-92.

24 J. Nef, *Mining and Metallurgy in Medieval Civilization*, in M.M. Postan, P. Mathias (eds.), *Cambridge Economic History of Europe*, II, Cambridge 1952, pp. 691-761.

25 M. Postan, *The Trade of Medieval Europe: the North*, in M.M. Postan, P. Mathias (eds.), *Cambridge Economic History of Europe*, II, Cambridge 1952, pp. 240-304.

26 J.W. De Zeeuw, *Peat and the Dutch Golden Age. The Historical Meaning of Energy-Attainability,* "A.A.G. Bijdragen", 21 (1978), pp. 3-32.

by water mills.[27] Even assuming a more modest increase in the use of horses outside England, we can, nonetheless, suppose a rise in the availability of energy per capita in the high medieval centuries.

In the early Middle Ages horse power was little used and, as in ancient times, the horse was still considered a war machine. Horses were not exploited in agriculture and were expensive, owned only by rich people. In Anglo-Saxon documents of 7th century England, for example, the horse is never mentioned as a working animal.[28] In early 9th-century France only the ox appears as a working animal in the fields, whereas the horse is employed exclusively for the transportation of people and goods.[29]

The exploitation of horse power was most intense in northern Europe and particularly in England and The Netherlands. Certainly the wider exploitation of animal power was an important support to the colonisation of northern Europe during the high Middle Ages and was, as suggested, the cause of the changing demographic balance between the south and the north. Europe was becoming more and more continental and ever less Mediterranean[30].

Water and wind. Until a few decades ago, the opinion prevailed that the water mill, although an ancient invention, was definitely a medieval "innovation". It was commonly believed that water mills, after enjoying a short-lived period of technological development in the late Roman Empire, rapidly declined and almost disappeared in the early Middle Ages. Only from the 9th-10th centuries onward did mills spread again thanks to the initiative of monasteries and feudal lords. The span of time between the 9th century and the 12th century is usually regarded as a period of rapid progress in water technology. Mills began to be used not only to grind cereals, but also for many different kinds of industrial work. Around the time of the Domesday Book, in the late 11th century, the population-waterwheels ratio had already reached the level it was to maintain for the following centuries until the beginning of economic modernization[31]. In their important studies, both M. Bloch[32] and L. White[33] support this notion of technological progress in the Middle Ages. Some scholars argued that an indus-

[27] J. Langdon, *Horses, Oxen and Technological Innovation. The Use of Draught Animals in English Farming from 1066-1500*, Cambridge 1986, p. 20. In this estimate only mechanical energy is included. See also J. Langdon, *The Use of Animal Power from 1200 to 1800*, in S. Cavaciocchi (ed.), *Economia e energia Secc. XIII-XVIII*, Firenze 2003, pp. 213-21. See also P. Vigneron, *Le cheval dans l'antiquitè gréco-romaine*, Nancy 1968, R. Lefebvre De Noëttes, *L'attelage. Le cheval de selle à travers les âges. Contribution à l'histoire de l'esclavage*, Paris, I, 1931; A.G. Haudricourt, M. J-B. Delamarre, *L'homme et la charrue à travers le monde*, Paris 1955.
[28] Langdon, *Horses, Oxen and Technological Innovation*, p. 26.
[29] C. Parain, *The Evolution of Agricultural Techniques*, in M.M. Postan (ed.), *Cambridge Economic History of Europe,* I, Cambridge 1966.
[30] Russell, *European Population 500-1500*.
[31] M.T. Hogden, *Domesday Water Mills*, "Antiquity", XIII (1939), pp. 261-79.
[32] M. Bloch, *Avênement et conquète du moulin à eau*, "Annales d'histoire économique et sociale", VII (1935), pp. 538-63.
[33] L. White Jr., *Medieval Technology and Social Change*, Oxford 1962.

trial revolution had taken place in the central centuries of the Middle Ages and that this revolution had been supported by the rise in energy availability.[34]

As landmarks of this revolution the following novelties have often been quoted. The spread and eventually the prevailing of the overshot vertical mill, much more efficient than the old horizontal water mill, is often credited as having opened a new phase in the history of water technology. Because of its higher power yield, the vertical wheel found application in many different industrial sectors.[35] Amongst the new industrial applications for water were the fulling mill, water-powered suction pumps in the mines, hydro-powered bellows and the blast-smelter in metallurgy, paper mills, silk-throwing mills. As we go back in time, however, we find out that these innovations (except the last two) are only apparently such. In many cases, recent archaeological investigations indicate that they were already employed in ancient times. We have furthermore to stress that the addition of new power from the water-mill was relatively limited.

Wind was used for mills and sails. The wind-mill supposedly originates from Asia. The first evidence we possess refers to the 7^{th} century AD.[36] Whatever the origins really were, windmills were long known in Europe as Persian mills. Thus were they mentioned in one of the first, if not the first, account of windmills in Europe: the *Book of King Ruggero*, written in 1154 by the Arabian geographer al-Idrisi. In Sicily, al-Idrisi wrote, in Calatubo, near Erice, on the extreme southwest point of the island, "exists a quarry where they cut stone for the use of mills driven by water and for those called <<Persan>>"[37].

The regions in which wind power played a more important role were the great plains of northern and western Europe, where the winds are constant and there are no mountains; from northern France, to Holland, Denmark and then inland as far as Poland and Russia. In any case windmills only became important engines after the medieval growth and their contribution to the energy balance during the high and late Middle Ages was negligible.

Whilst the use of wind power for milling was an innovation of considerable economic influence, the modifications in the use of the wind for navigation were

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[34] B. Gille, *Le moulin à eau, une révolution technique médiévale*, "Techniques et civilisations", III (1954), pp. 1-15.; E. Carus-Wilson, *Medieval Merchant Venturers*, London 1954.

[35] See especially J.H. Munro, *Industrial Energy from Water-Mills in the European Economy, 5^{th} to 18^{th} Centuries: the Limitations of Power*, in S. Cavaciocchi (ed.), *Economia e energia Secc. XIII-XVIII*, Istituto Internazionale di Storia economica "F. Datini", Firenze 2003, pp. 223-69, who summarizes many previous works on this subject.

[36] R.J. Forbes, *Power*, in Ch. Singer, E. J. Holmyard, A.R. Hall, T.I. Williams (eds.), *A History of Technology*, New York-London 1956, II, pp. 589-628.

[37] Idrisi, *Il libro di Re Ruggero*, in M.G. Stasolla (ed.), *Italia euro-mediterranea nel Medioevo: testimonianze di scrittori arabi*, Bologna 1983, p. 118. For the origins of the windmill see E.J. Kealey (1987), *Harvesting the Air. Windmill Pioneers in Twelfth-Century England*, Woolbridge, p. 69 and J. Langdon, *Water-mills and Windmills in the West Midlands, 1086-1500*", "Economic History Review", II s., XLIV (1991), p. 433 (n. 21) who criticises Kealey for his dates. See R.W. Unger, *The Ship in the Medieval Economy*, London-Montreal 1980, pp. 29 ff.

less important and only marginally concerned the use of energy.[38] Although the harnessing of wind power in navigation was not a real innovation, uninterrupted progress occurred in quantitative terms: increase in the number of sails on the seas implied a growth in the magnitude of energy exploited. For the second half of the 15th century the carrying capacity of the European fleet has been estimated between 200,000 and 350,000 tons.

5. *Power*

Together with the low availability of energy sources, another main 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, achieved using more powerful mechanical engines. The power of a man in everyday work is the same as a 40-watt lamp. The power of a horse is 15-20 times higher.

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 today equal to the power of 2,000 people and that the power of a large power station generating electricity (800 megawatts) is the same as that of 20 million people. The electric power of a medium sized nation of 40-60 million inhabitants, some 80,000 megawatts, equals the power of 2 billion people. Today, a nuclear plant or a nuclear bomb can concentrate millions of HP, or the work of many generations of humans and draft animals, into a small space and a fraction of time. This *concentration of work* allows humans to accomplish tasks that were barely imaginable just a few lifetimes ago.

Power is defined as the maximum of energy liberated in a second by a biological or technical engine. The power of a man using a tool is about 0.05 horsepower (HP). That of a horse or donkey can be 10-20 times higher (Table 3).

Table 3. Animal power (in HP).

	HP
Horse	1.00
Bullock-Ox	0.75
Mule	0.70
Cow	0.40
Donkey	0.40

Watermills generally provided 3-5 HP (although this power could be increased remarkably in particular cases), while a windmill can reach 8-10 HP. In

[38] See R.W. Unger, *The Ship in the Medieval Economy*, pp. 29 ff.

comparison, the very largest steam engines could attain 8-12,000 HP around 1900.[39] The conquest of power meant an incredible advance in the possibility of processing or manipulating the forces and materials of the environment (Table 4).[40]

Table 4. Chronological advances in power from traditional societies to the steam engine (in HP).

Man pulling a lever	0.05
Ox pulling a load	0.5
Donkey mill	0.5
Vertical water mill	3
Post windmill	8
Newcomen's steam engine	5
Watt's steam engine	40

Source: E. Cook, *Man, Energy, Society,* San Francisco 1976, p. 29.

As already remembered, the mechanical contribution of a water-mill to energy availability in traditional societies was relatively modest when we compare it to human and animal energy consumption from food and fodder; even more modest if the comparison is done with total energy consumption including firewood. The mechanical energy produced by a water-mill endowed with the power of 2 HP working 12 hours is equal to about 15,000 kcal (64,749 kj), and since in a day a worker 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 containing about 20-25,000 kcal a day, as we have seen. Energy consumption by this animate machine was higher than that by a water-mill. We also 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 per cent or more of the gravitational water energy falling on a vertical wheel -- the yield of an animal body is low, as we have seen: 10-15 per cent for working animals and a little more for a man. Useful energy is about 2-2,500 kcal for an animal and 5-600 for a man. The inanimate machines of today are much more efficient: usually more than 30 per cent of the energy of our cars is transformed into useful work (the transportation, that is, of people or commodities).

If in terms of energy consumption the contribution by a watermill is modest, in terms of power, or the capacity of doing work in the unit of time, a second, things are different. In the 11th and 12th centuries, the ratio of water-

[39] See Chapter 6.
[40] The values in the Table refer to averages and only suggest orders of magnitude.

mills to the population was around one mill to every 250-300 people;[41] which means that more or less every village had at least one mill. The same ratio of population to mills prevailed in early modern Europe until the end of the 18th century. From late medieval and early modern documentary sources, we know that an ordinary water-mill seldom exceeded the power of 3 HP. In nineteenth century more powerful mills were much more frequent. The contribution of water power in traditional economies is more apparent if we imagine a fairly typical medieval village of 300 people, each of whom consumes a little more than 2,000 kcal as food and works with some assistance from draught animals. The contribution, in terms of mechanical power, by a mill with the power of 3 HP would actually be substantial. Without it there may not be enough muscle power to grind the grain. In Table 5, we see a hypothetical quantification of the power, or the capacity to do mechanical work, for such a small village. We see that looking at the problem from the side of mechanical power, the existence of a mill represents a remarkable addition (10 percent) to the total power of the village. Vannoccio Biringuccio from Siena wrote in his *De la pirotechnia*, published in 1540, that a watermill could replace the mechanical work of 100 men.[42] We see also that any inhabitant of the village was endowed with 0.16 HP on the whole. Utilising this power 10 hours, we reach about 1.6 HPh (which is a measure of energy). This energy is equal to about 1,000 kcal or 0.0043 Gj. Assuming an efficiency of the energy system of 15 percent (plausible for the time as seen in section 4), 1,000 kcal per day per head imply an intake of energy of about 6,500 kcal (1,000/0.15) exploited by the biological and mechanical engines an average European inhabitant could use at that time to engender mechanical work (firewood is excluded as source of heat and not mechanical work).

Table 5 . Estimate of the endowment with power in a small village of 300 inhabitants, with 60 draft animals and 1 watermill (in HP and %).

	HP each	Total HP	% on total HP
300 people	0.05	15	30
60 animals	0.5	30	60
1 watermill	3	3	10

6. *Climate and energy*

Could the above mentioned energy sources have represented the main support of medieval demographic growth and modest increase in the average in-

[41] L. Makkai, Productivité et exploitation des sources d'énergie (XIIe-XVIIe siècle)", in S. Mariotti (ed.), *Produttività e tecnologie nei secoli XII*-XVII, 1981, Istituto Internazionale di Storia Economica "Datini", Firenze 1981, pp. 165-81.

[42] V. Biringuccio, *De la pirotechnia,* A. Mieli (ed.), Bari 1914 [I ed. 1540]; T.S. Reynolds, *Stronger than a Hundred Men. A History of the Vertical Water Wheel*, Baltimore-London 1983 derived the title of his book from Biringuccio.

come? Some doubts remain. The widening of the arables to new areas, together with a wider exploitation of forests, meant the addition of new sources of energy to a rising population, but not a rise in energy consumption per capita. Probably animal power increased, with a keener exploitation of the horse's strength, and mills multiplied. In per capita terms, however, all this added very little to humans' working capacity. The rising population for 3-5 centuries, although at a very modest rate, is likely to meet in peasant economies fast decreasing returns due to the shrinking of the available sources of energy per head. Something still seems to miss in the framework of the medieval energy availability. When speaking of energy in pre-modern times, in fact, we often neglect the role played by climate and climatic changes. 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. While warm periods were favourable to the spread of cultivations and the multiplication of mankind, cold epochs were correlated with demographic declines. Roman civilisation flourished in a warm period and was accompanied by population rise. The so-called warm Medieval Climatic Optimum coincided with worldwide population increase, between 900 and 1300, while the following Little Ice Age was a period of economic hardship and population stability or slow increase.[43]

The recently elaborated series of annual temperatures in the northern hemisphere show a declining trend from the 3rd century A.D. onward.[44] Temperatures remained low until the beginning of the so-called Medieval Climatic Optimum, which lasted from the 9th century until 1250-1300[45]. It became possible to cultivate land located in cold regions and therefore feed an increasingly larger

[43] Two introductions to the topic of climate over very long periods are those of E. Le Roy Ladurie, *Histoire du climat depuis l'an mil*, Paris 1967, and M. Pinna, *La storia del clima. Variazioni climatiche e rapporto uomo-clima in età post-glaciale*, Roma 1984.

[44] On the temperature-economy relationship in the late Middle Ages, see B. Campbell, *Cause and Effect? Physical Shocks and Biological Hazard. The Crisis of the 14th Century Revisited*, in S. Cavaciocchi (ed.), *Le interazioni fra economia e ambiente biologico nell'Europa preindustriale*, Istituto Internazionale di Storia Economica, Firenze 2010; B. Campbell, *Nature as Historical Protagonist. Environment and Society in Pre-industrial England*, "Economic History Review", 63, 2 (2010), pp. 281-314.

[45] A general approach to climate in the past millennium is provided by R.S. Bradley, K.R. Briffa, J.E.Cole, M.K. Hughes, T.J. Osborn, *The Climate of the Last Millennium*, in K. Alverston, R.S. Bradley, T. Pedersen (eds.), *Paleoclimate, Global Change and the Future*, Berlin 2003, pp. 105-44, and by C. Pfister, *I cambiamenti climatici nella storia dell'Europa. Sviluppi e potenzialità della climatologia storica*, in L. Bonardi (ed.), *Che tempo faceva? Variazioni del clima e conseguenze sul popolamento umano. Fonti, metodologie e prospettive*, Milano 2003, pp. 15-59.

population (Figure 2).[46] Moreover, the higher temperature resulted in the formation of greater biomass for both men and working animals. The growth in population during the medieval period, and indeed of production, depended not only on the conscious efforts of man to harness new energy sources by means of new converters, but also on the variation in the availability of energy due to climatic phenomena.

Decadal data contribute to clarify the overal trend in the northern hemisphere (Figure 3).

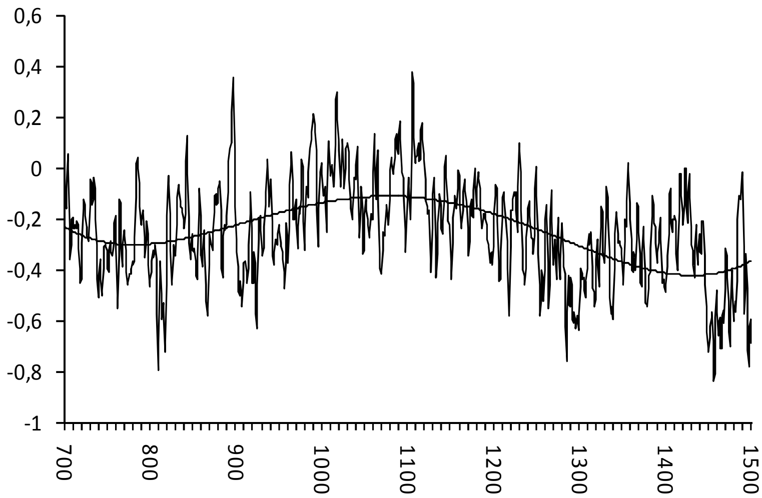
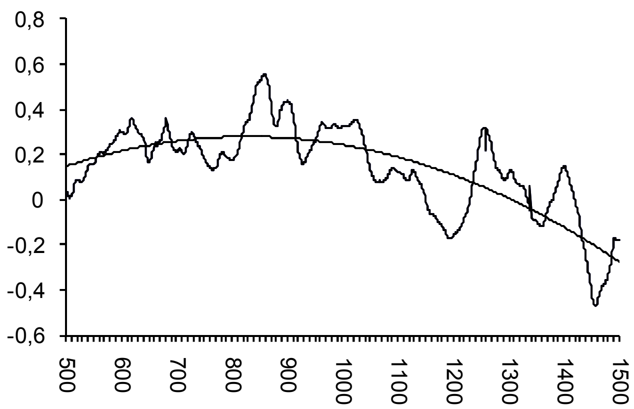


Figure 2. Temperature in the northern hemisphere from 700 until 1500.
Source: A. Moberg, D.M. Sonechkin, K. Holmgren, N.M. Datsenko, W. Karlén, *Highly Variable Northern Hemisphere Temperatures Reconstructed from Low- and High-resolution Proxy Data*, "Nature", 433 (2005), No. 7026, pp. 613-17.



[46] M.E. Mann, *Medieval Climatic Optimum*, in *The Earth System: Physical and Chemical Dimensions of Global Environmental Change*, 1, in T. Munn (ed.), *Encyclopedia of Global Environmental Change*, Chichester 2002, pp. 514-16.

Figure 3. Temperature in the northern hemisphere from 500 until 1500.
Source: C. Lohele, *A 2000-Year Global Temperature Reconstruction Based on Non-Treering Proxies*, "Energy and Environment",18 (7-8) (2007), pp. 1049-58.

With the increasing density of population in northern Europe, the possibility of cultivating lands located at higher latitudes and located on the hills enabled the multiplication of harvests and firewood production, in order to feed more inhabitants and draft animals. It may be noted that temperatures in the Alps increased from the 8th century until the second half of the 13th century (Figure 4).

Although the presented figures of temperatures present many differences, several paleoclimatologists agree on the favourable climatic epoch during the high Middle Ages and the decline of temperature during the early Modern age: "Large-scale surface temperature reconstructions yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the "Medieval Warm Period") and a relatively cold period (or "Little Ice Age") centered around 1700".[47]

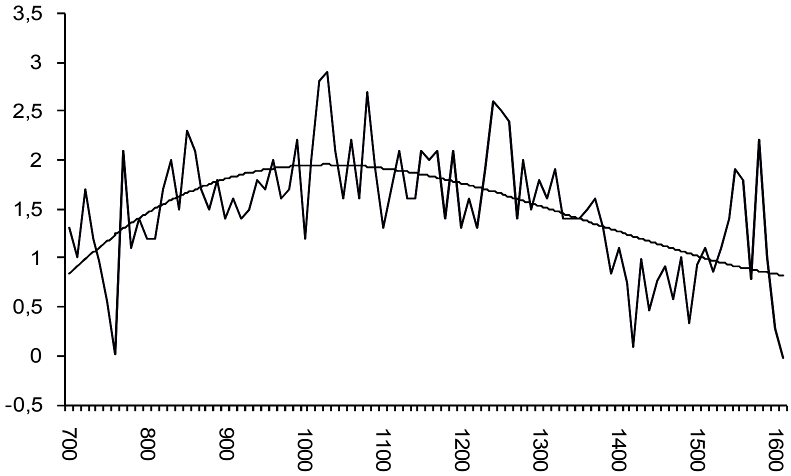


Figure 4. Temperature in the Alps from 700 until 1600.
Source: A. Mangin, C. Spötl, P. Verdes, *Reconstruction of Temperature in the Central Alps During the Past 2000 Years*, "Earth and Planetary Science Letters", 235 (2005), 3-4, pp. 741-51.

Many historians have suggested an interruption in the rise of population as from the beginning of the 14th century and again only a few decades after the end of the favourable climatic phase. We lack evidence about a relationship between climatic evolution and the Black Death. Recently, however, B. Campbell

[47] Committee on Surface Temperature Reconstructions for the Last 2,000 Years*, Surface Temperature Reconstructions for the Last 2,000 Years*, National Research Council, Washington 2006, p. 111.

suggested that the outburst of the plague, not long after the climatic change, might not be merely circumstantial.

Conclusion

The doubling of the European population between the 10th and the 14th centuries, together with the modest increase in urbanisation seem to suggest a cycle of both extensive and intensive growth prior to 1300. It was not until after a long period of approximately 3-4 centuries that the level of the European population reached in 1300 was exceeded. Only from the end of the 17th century onwards, with the start of the energy transition, did the European population begin to rise rapidly for about three centuries.

Medieval demographic rise implied a strong effort by the European populations in order to exploit more energy. The main feature of the pre-modern energy systems, that is the vegetable organic base, did not favour the easy rise in energy availability. Colonisation of new lands in the north and east increased the arables and allowed for the support of more inhabitants and draft animals. This increase of the energy basis occurred at the expense of the forests and implied the resort to mineral energy carriers such as coal and peat. Even allowing for the progress of cultivation and the exploitation of new sources, it seems that the mere extension of the arables would not explain periods of intensive growth that the rising urbanisation seems to suggest. In any case, growth in output per capita would hardly have been perceptible by the people of that time. Climatic changes played a decisive role in the energy availability. The end of the Medieval Climatic Optimum, in the last decades of the 13th century, contributed to favour (or even determined) the interruption of medieval growth in the central centuries of the Middle Ages. The European populations had to wait at least three centuries for a new epoch of growth; this time much faster than ever before.