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I. Introduction: the historic significance of water-mills

For almost two millennia, water power, in the form of the vertical water-wheel, provided the principal source of mechanical energy in the economies of the regions comprising modern-day Europe.[1] To be sure, in view of the essentially agrarian character of these economies for most of this long period, animal power – humans, oxen, horses, and mules – collectively provided

[1] Horizontal water-wheels are ignored in this study, for reasons given in the following studies. See T.S. Reynolds, *Stronger than a Hundred Men: A History of the Vertical Water Wheel.,* Baltimore-London 1983, p. 7: contending that horizontal water-wheels were largely confined to peasant agriculture, employed in the single-task of grinding grain; and that they were wasteful of water resources, while providing no more power (or less) than donkey- or horse-driven flour mills. See also his discussion of these wheels on pp. 103-09, in which he also contends (p. 107) that 'technological superiority alone cannot explain the all-but-complete dominance assumed by the vertical water-wheel in much of western Europe, and that 'the incorporation of the watermill into the manorial system, as Usher suggests, probably provides the best explanation' for the supremacy of the vertical water-wheel. See also A.P. Usher, *A History of Mechanical Inventions*, London 1954 (2nd revised edn.), pp. 180-182; and R. Holt, *The Mills of Medieval England*, Oxford 1988, pp. 118-119: contending that, although horizontal mills were evidently almost as ubiquitous as vertical mills in pre-Conquest England (and Ireland), they disappeared soon or sometime thereafter; for no evidence of their existence can be found in the manorial accounts that commence in the thirteenth century. He also believes that feudal landlords, seeking to exercise monopoly powers over milling, 'favoured the more powerful vertical mill'. Nevertheless, as he also notes, horizontal mills were widely used elsewhere, especially in peasant societies with weaker landlords: in Italy, southern France, and Spain. See J. Muendel, *The Distribution of the Mills in the Florentine Countryside during the Late Middle Ages*, in *Pathways to Medieval Peasants*, ed. J.A. Raftis, Toronto 1981, pp. 87-99; and J. Muendel, *The Horizontal Mills of Pistoia*, in "Technology and Culture", 15, 1974, pp. 194-225; and B. Blaine, *Mills*, in *Dictionary of the Middle Ages*, ed. J. Strayer, et al, I-XIII, New York 1982-89, VIII, 1987, pp. 388-395.

a much greater quantity of energy.[2] Indeed the magnitude of that contribution from animal power grows even more if we add the transportation sector, which, of course, was also vitally dependent on wind power, in the form of sailing ships.

Yet for industry and industrial development, albeit by far the smallest sector of the European economy well into the early-modern era, water-powered mills clearly provided by far the predominant 'prime mover': any apparatus that converts natural sources of energy into mechanical power to operate some form of machinery. Its application there, though long a limited one, came to have enormous historical significance. Thus Joel Mokyr, inspired by Lynn White, has recently observed that 'medieval Europe was perhaps the first society to build an economy on nonhuman power',[3] certainly non-animal power. Terry Reynolds, the leading technological historian of the watermill has also contended that: 'if there was a single key element distinguishing western European technology from the technologies of Islam, Byzantium, India, or even China after around 1200 [CE], it was the West's extensive commitment to and use of water power'.[4]

Providing good quantitative evidence to justify this assertion is, however, virtually impossible before the nineteenth century. Therefore we must rely on basically qualitative evidence and inductive logic to test this assertion, at least within the European context itself from early medieval times, and to seek answers to the following questions: how and why did water power contribute to European industrial development; why was it the industrial prime-mover for so many centuries; and what were the often severe limitations on its application and its potential? That would then lead us to ask why revolutionary new methods of power came to be required for modern European industrialization. Let us note at the very outset, however, that the modern 'Industrial Revolution' commenced in the eighteenth century with the application of water-power.

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[2] See in particular, J. LANGDON, *The Economics of Horses and Oxen in Medieval England*, in "Agricultural History Review", 30, 1982, pp. 31-40; IDEM, *Horses, Oxen, and Technological Innovation, 1066 to 1500*, Cambridge 1986; IDEM, *Water-mills and Windmills in the West Midlands, 1086-1500*, in "Economic History Review", 2nd ser., 44, August 1991, pp. 424-444. See n. 17 below.

[3] J. MOKYR, *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford-New York 1990, p. 35; L. WHITE, *Medieval Technology and Social Change*, Oxford 1962, pp. 79-90, 129-134.

[4] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., p. 5. For an alternative view, see n. 120. For the ancient Roman and then Islamic words, see TH. SCHIØLER, *Roman and Islamic Water-Lifting Wheels*, Odense 1973 (Acta Historica Scientiarum Naturalium et Medicinalium, Biblioteca Universitatis Hausiensis, 28).

II. Ancient origins and original uses of the water-mill

European precocity, or relative advancements in employing this technology, may be all the more surprising if the origins of water-powered machinery are to be found in Asia. The renowned Joseph Needham cited some texts that ambiguously suggested that water-wheels were used in fourth-century BCE India; but his bold interpretations have since found no support from other historians.[5] The next earliest text, dating from c. 200 BCE, with somewhat more credible (or plausible) evidence for the use of an apparent overshot water-wheel (see below), is found in Arabic manuscript copies of the treatise *Pneumatica* by the Greek scientist Philo of Byzantium. But his wheel was designed only to produce whistling sounds, and its depiction is most likely an Arabic addition from a thousand years later.[6]

More convincing references may be found in other Greek manuscripts of the following century. The earliest or first acceptably documented use of mechanical water-power is found in the *Geographica* by Strabo (64 BCE - 23 CE): a water-mill *(hydralatea)* at Cabeira, in northern Asia minor (the Kingdom of Pontus), built between 120 and 65 BCE. Even better, if somewhat later, descriptions of undershot vertical water-wheels are presented in *De rerum naturae* by the philosopher Lucretius (96-55 BCE) and in the treatise *De architectura libri decem* by Marcus Vitruvius Pollio (ca. 25 BCE).[7] These are *noria*-type water

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[5] J. NEEDHAM, *Science and Civilization in China*, I-IV, Cambridge 1965, IV/2, p. 361. The chief criticism comes from TH. SCHIØLER, *Roman and Islamic Water-Lifting Wheels,* cit., pp. 88-89, whose reading of the texts indicates that some hand-powered water-lifting device was used, rather than a true water-wheel. The *noria* was a vertical water-wheel, powered by the flow of water against its blades, but without any machinery; instead pots or buckets were attached to its outer time. See also T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., p. 14 (and p. 13, fig 104 for the noria).

[6] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 15-16, and fig. 1-7; TH. SCHIØLER, *Roman and Islamic Water-Lifting Wheels*, cit., pp. 61, 65-66, 163. He notes that other water-powered devices in this manuscript are all of indisputable Islamic origin; and that the vertical chain drive is highly improbable, in driving the lower rather than upper wheel. Furthermore, the first confirmed depiction of the more sophisticated overshot wheel comes from six centuries after Philo.

[7] For this and the following see: T.S. REYNOLDS, *History of the Vertical Water Wheel*, pp. 16-18, 353; TH. SCHIØLER, *Roman and Islamic Water-Lifting Wheels*, cit., p. 158-162; R.J. FORBES, *Studies in Ancient Technology*, I-II, Leiden 1955, vol. II, pp. 78-79; IDEM, *Power*, in *A History of Technology*, ed. CH. SINGER, et al, I-II, Oxford 1956, vol. II, pp. 589-590; J. GIMPEL, *The Medieval Machine: the Industrial Revolution of the Middle Ages*, New York 1976, pp. 1-12; A.P. USHER, *History of Mechanical Inventions*, cit., pp. 163-165; S. LILLEY, *Men, Machines, and History: the Story of Tools and Machines in Relation to Social Progress,* London 1965, pp. 38-39. The latter three also cite a poem of Antipater of Thessalonica (c. 85 BCE): 'Cease from grinding-, ye women who toil at the mill; For Demeter has ordered the Nymphs to perform the work of your hands, and they,

wheels: without hydraulic machinery but with water-filled buckets fitted to the wheel's rim. In this same century BCE we possess our first extant archaeological evidence for a vertical undershot wheel, at Venafro, in southern Roman Italy (near Pompeii).[8] Curiously enough the first credible, if not fully substantiated, evidence for the use of water power in ancient China comes from the same period (though the power may have come from horizontal or vertical water wheels, or even from a water-lever).[9] In the West, according to Reynolds, the earliest genuine undershot water-wheel with hydraulic machinery was a subsequent adaptation of *noria* wheels. It was probably first used in Roman Asia Minor or adjacent Syria, within the same first century BCE (perhaps ca. 65 BCE), employing rotary millstones used in hand-powered grain querns and Hellenistic gearing mechanisms (both dating from about the third century BCE).

Evidently the potential uses and productivity gains from using such machines were not widely appreciated, if at all. Vitruvius himself indicated that they were 'rarely employed'. In the following century, the first CE, the only significant literary evidence for their application (apart from Talmudic complaints about supposed use during the Sabbath) comes from the famed *Historiae naturalis* by Pliny the Elder (Gaius Plinius Secundus, 23-79 CE). But, in the following century, the almost equally famed historian Suetonius (Gaius Suetonius Tranquillus, 76-160 CE) makes no mention of them at all; and, for the third century CE, only archeological evidence can be found to indicate their use. But then, at the beginning of the fourth century, Diocletian's Edict of 301 CE does list water mills, and at a value significantly higher than those for animal, let alone hand, mills.[10] During the fifth and sixth centuries, the wa-

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leaping down on the top of the wheel, turn its axle, which with revolving spokes, turns the heavy concave Nysarian millstones…'

[8] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 18, 36-37 (Fig 1-13), 353, citing L. JACONO, *La ruota idraulica di Venafro*, in "L'ingegnere", 12, 1938, pp. 850-853. But the earliest pictorial representation of a vertical undershot water-wheel is a mosaic in the Great Palace of Byzantium, dating from the fifth century CE, provided in T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., fig 1-8, p. 19. For the earliest depiction of the overshot wheel, see n. 26 below.

[9] J. NEEDHAM, *Science and Civilization*, cit., IV/2, pp. 370, 392. The official history of the Han dynasty, *Hou Han Shu*, refers to the use of water-powered bellows for iron-casting used by the prefect of Nanyang c. 31 CE. But see also T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 12 (Fig. 1-3), 18, 26-30, 353; he believes it was a water-lever: a pivoted beam with a water-holding compartment (bucket) on one end and a hammer on the other, rising when filled with water, and descending with force as the water drained out. The transition to genuine vertical water-wheels in China may have been as late as c. 200 CE.

[10] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 30-31; R.J. FORBES, *Studies in Ancient Technology*, cit., II, p. 87. In Diocletian's edict, the water-mill was valued at 2,000 *denarii*,

ter wheel spread rapidly, littering the map of western Europe, to become its major source of mechanical power.[11]

Reynolds has himself speculated on various reasons why diffusion of these mills took almost five centuries to become widespread: in particular, why such diffusion was so slow before the fourth century CE and why it became so much more rapid thereafter, at least in those areas with accessible water resources. There may well be merit in his primary reasons: a Graeco-Roman cultural heritage that was hostile to interference with nature and the Aristotelian 'natural order'. Furthermore, in an age whose cultural values esteemed the role of quality, most people could not perceive that this innovation produced any such improvements in what was the only significant use of water-mills in the later Roman Empire: milling wheat into flour. Evidently such flour was inferior to that produced by hand querns.[12] Nor did any such market-oriented concepts involving productivity gains and profitable investments find much favour in Graeco-Roman society. Obviously construction of such mills required considerable capital in an age when capital was costly and labour cheap. During the first centuries BCE and CE, the Roman Empire, at its apogee, had such a large population, abundant supply of slaves, and ample labour force that investment of capital in labour-saving machinery made little sense: economic, social, political, or cultural. One oft cited example is the earliest known conception of steam-power: Hero of Alexandria's steam turbine (c. 60-70 CE), but one never applied, given that any related tasks could be so well performed by slaves.[13] And yet the reasons for employing slave-labour, so long as slaves were abundant, were often more cultural than purely economic.

For most economic historians, however, the most convincing argument for the later diffusion of water-mills was the subsequent and very radical alteration in the ratios of labour to land and labour to capital. First, thanks indeed to the very successes of the Empire in Pax Romana, the supply of

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the donkey mill, at 1,250 *den.*; the horse mill at 1,500 *den.*; and the handmill at only 250 *den.*; i.e., at 12.5 percent of the value of watermills.

[11] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 31-32, 356, notes a passage from Procopius's *De bello Gothico*, 5:19, 19-27, in which he describes an attempt by the invading Goths in 536-37 to starve Rome (under general Belisarius) into submission by cutting the water aqueducts, thereby halting the operation of its water-driven flour mills; Belisarius responded by creating floating boat-mills on the Tiber.

[12] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 30-35.

[13] F. KLEMM, *A History of Western Technology*, Cambridge, Mass., 1964 (trans. D.W. Singer), pp. 35-38, citing Hero's *Pressure Machines* (p. 383); A.G. DRACHMAN, *The Classical Civilizations*, in *Technology in Western Civilization*, I, *The Emergence of Modern Industrial Society,* eds. M. KRANZBERG, C. PURSELL, London 1967, pp. 51-55; S. LILLEY, *Men, Machines, and History,* cit., pp. 35-37.

slaves, furnished chiefly from the ranks of captives in military campaigns, began to diminish, and then finally disappeared, as the status of the dwindling remainder was elevated into much more valuable and better treated serfs.[14] If the vastly reduced dependence on slave labour in the early-medieval economy was certainly a principal factor promoting the use of water power, the second and complementary factor was a continuous and widespread fall in the Empire's population (from the reign of Marcus Aurelius, 121-80 CE), with a combination of falling birth rates and rising mortalities, from various diseases.[15] Certainly labour scarcity had become acute by the fifth century CE; and at the nadir of the demographic decline in the tenth century, western Europe contained no more than half of the inhabitants – probably only 40 million or less – that had lived in this region at the apogee of the Roman Empire.[16]

One significant indicator of that diffusion of water-power can be found in England, just a century later, in the Domesday Book of William the Conqueror (1086): for over 3,000 locations, it records 6,082 watermills, which, according to one estimate, provided perhaps 30 per cent of eleventh-century England's energy requirements.[17] Yet the subsequent reversal in the land:labour ratio, with a very rapid growth in western Europe's population, which more than doubled by 1300, in no way impeded and probably promoted a much more rapid diffusion of water-mills, through the concomitant economic development. Manorial, urban, and other records indicate that the most rapid growth in construction of new watermills took place between the

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[14] M. BLOCH, *La société féodale*, I-II, Oslo 1940, republished in English translation as *Feudal Society*, by L.A. MANYON, London 1961, chapters 4, 11-14, 18-22; M. BLOCH, *The Rise of Dependent Cultivation and Seigniorial Institutions*, in *The Cambridge Economic History of Europe*, I, *The Agrarian Life of the Middle Ages*, eds. J.H. CLAPHAM, E. POWER, Cambridge University Press 1941, pp. 224-277; reprinted without change in the second edition, ed. M.M. POSTAN, Cambridge 1966, pp. 235-289. See also n. 15.

[15] See also T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit, pp. 44-45, who cites, as early as the fourth century, a treatise of the Roman writer Palladius (*De re rustica*) , recommending construction of water-mills because of current labour shortages. J. MOKYR, in *The Lever of Riches*, cit., pp. 194-195, noting that slave labour is not necessarily cheap labour, when their cost of maintenance is measured against low output, nevertheless admits that 'dismissing slavery altogether as a factor seems premature', if only in terms of cultural factors (since slave regimes required coercion while adapting technological changes requires co-operation).

[16] See R. LOPEZ, *The Birth of Europe*, New York 1967, pp. 25-30, 51-58, 108-20, contending in fact that 'Europe' itself was really born in this depopulated, depressed era; J.C. RUSSELL, *Late Ancient and Medieval Population*, Philadelphia 1958.

[17] H.C. DARBY, *Domesday England*, Cambridge 1977, p. 61; R. HOLT, *Mills*, cit., pp. 5-16; T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 51-52, citing older if better known figure of 5,624 mills. For energy requirements, see J. MOKYR, *Lever of Riches*, cit., p. 38.

mid-twelfth and mid-thirteenth centuries.[18] Holt estimates that, by 1300, the number of watermills in England grown by about 65 percent, to over 10,000 (plus about 2,000 windmills), which was the medieval maximum; and the second half of the fourteenth century, following the Black Death, and other debilitating demographic factors, reducing England's population by 40 - 50 per cent, 'would see a precipitate fall' in the number of watermills.[19]

Thus neither demographic nor purely economic factors can fully explain the diffusion of watermills (and then their declining numbers). Two very powerful social forces in the development of medieval western Europe also bore a major responsibility for the construction of so many watermills: the Church, and most especially its monasteries; and feudal-manorial lords, who sought to exploit increased rents (profits) from their tenants by requiring them to use their seigniorial mills (*banalités*).[20] These social-institutional factors, along with more obvious water-based geographic factors, help to explain why water-power became so much more highly diffused within western Christian Europe than within the Muslim world, or even the Byzantine Empire, by the twelfth century.[21] Although water-mills had certainly, by that era, become important for many industrial uses within China, its predominant agricultural economy, based on rice – which requires no milling, while millet and other grains were distinctly secondary -- may explain why water power still played a lesser role there than in Europe.

III. The changing technology of water-mills: undershot wheels

By early-modern times, the chief economic significance of fully-evolved water-mills, in powering labour-saving machinery, was well expressed, in 1540, by the Italian mining engineer Vannoccio Biringuccio: who contended that 'the lifting power of a [water] wheel is much stronger and more certain than

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18 T.S. Reynolds, *History of the Vertical Water Wheel*, cit., pp. 52-53.

19 R. Holt, *Mills of Medieval England*, cit., pp. 107-116.

20 See note 1 above (on the role of feudal power in the victory of the vertical waterwheel).

21 See T.S. Reynolds, *History of the Vertical Water Wheel*, cit., pp. 119-121, and also for other political, social, cultural factors. In the Muslim world the relative insufficiency of water was, however, offset by the use of irrigation canals; but water mills remained far less frequent and were almost entirely confined to milling flour and raising water. For the Byzantine world, T.S. Reynolds cites a letter, dated 1444 CE, from the Greek Cardinal Bessarion to Constantine Paleologos, despot of Byzantine Morea, urging the latter to adopt western advances in technology, especially mill-based machines, strongly indicating that water-mills were used far more widely in the West than in the East. See his source, A.G. Keller, *A Byzantine Admirer of Western Progress: Cardinal Bessarion*, in "Cambridge Historical Journal", 11, 1955, pp. 343-348.

that of a hundred men', a phrase that Reynolds used in the title of his aforementioned book. For the first known vertical water-wheel, at Venafro (see above, p. 3), Reynolds has provided a rather more modest estimate of its potential power at 1 -2 horsepower (though others have suggested it had 3 hp). Even so, a small water-mill with just 2 hp was sufficient to liberate anywhere from 30 to 60 persons (women more likely than men) from the laborious and wearisome task of grinding grain into flour.[22]

As indicated earlier, the undershot wheel was certainly the first form to be used, historically. As the very name indicates, it was driven directly by the flow of the water underneath the wheel, acting on paddles or flat radial blades fixed to its circumference. The power that such wheels could generate was a function of two elements: the volume or weight of the water flowing against the wheel's blade per minute, and the 'head' or 'fall' of the water – the speed or impulse of the water acting against the blades. Thus a swift flow could compensate for a small volume of water, to produce the requisite amount of power. Although any wheel could be placed directly on any convenient stream or river, its most desirable location – both in terms of opportunity cost (to avoid monopolizing a given water site) and efficiency – was in an artificially constructed mill-race designed to produce an unvarying volume of water at fairly high speeds, above 1.5 metres per second. Such devices, of course added to the capital costs of building such water-wheels, especially if the mill races also required the use of dams, reservoirs, and/or aqueducts.

In that ideal form, such vertical undershot wheels had a typical efficiency of 15 to 30 per cent (in converting potential water power into mechanical power). Placed vertically in the water flow the wheel employed a tapered horizontal axle (tapered for the ball bearings) that was attached to two sets of gears, in the form of racheted (toothed) disks: a vertical gear, turning with the wheel itself, which drove the horizontal gear, which in turn rotated the upper of two millstones (used in pairs to grind the grain poured through the hole in the centre). In later water-mills, the horizontal gear-wheel was made smaller than the vertical, so that the millstone would rotate more rapidly than the wheel itself. Some evidence suggests that the Roman and early medieval water-wheels used the opposite form of step-down gearing (i.e., with a larger horizontal gear) so that millstones turned more slowly. Furthermore, as the archaeological remains of the Venafro water-mill indicate, the late-Roman and early medieval water-wheels may have also been deficient in having hubs

22 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., p. 5, citing *The 'Pirotechnica' of Vannoccio Birunguccio*, trans. and ed. by C. SMITH, M. GNUDI, Cambridge, Mass., 1966, p. 22. See also pp. 3-5; and R. HOLT, *Mills*, cit., pp. 122-136.

and wheel-rims that were overly large and heavy, so much so that they impeded rotation and water-exit. Reynolds speculates that such technical design problems, and the time necessary to remedy them, may have been another factor hindering the diffusion of the water-mill.[23]

Other major problems lay in coping with frequent seasonal variations in the water-flows of rivers and streams, which could either swamp the mills or leave them with insufficient water. One remedy was to use floating or boat-mills, often anchored to bridges. An even more effective and related solution, first recorded in the later twelfth century, was the bridge-mill itself: in which the entire watermill (with wheel, gears, millstone) was built into the superstructure. Some variants used large iron suspension chains to adjust the wheel to changing river flows. But the most effective form of the vertical water-wheel used on such variable rivers was the combination of the hydro-power dam and power-canal or mill-race. Not only did they ensure a more regular flow of water, by storing and then channelling the required amount of water, but they could also be so constructed and used to increase the 'fall' or 'head' of water available at the mill-site, certainly in hilly regions. The other key advantage was the ability to divert the water-flow, via the mill-race, to more convenient and economically suitable locations, i.e., closer to where the power was required and/or with lower opportunity costs for the mill-site. As can be best documented for medieval England, the use of hydropower dams and millraces permitted the further spread of watermills from swift upland streams to tributaries of larger rivers; and then by the thirteenth century, to the lower, more navigable, and usually more slowly flowing parts of England's major rivers, especially in the lowland, eastern regions (and thus without disrupting navigation). Although some historians believe that the hydropower dam mills evolved from bridge-mills, there is evidence for their possible use in tenth-century England (Hertfordshire), and more certainly near Augsburg, in Bavaria, c.1000, and thus before the first recorded use of bridge mills.[24]

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23 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 18-19, 35-44; R. HOLT, *Mills of Medieval England*, cit., pp. 117-144. Rimless wheels permit far faster and more efficient exit of the water flow; but rims may have been useful in stabilizing the wheels.

24 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 54-68. He contends (p. 59) that the earliest evidence for a bridge-mill comes from Muslim Cordoba, c. 1150 (geographical treatise of al-Idrisi); and for Moulin-du-Pont, in the Côte d'Or region of France, c. 1175; R. HOLT, *Mills*, cit., pp. 122-136. Another if less significant innovation in mill technology was the adoption of tidal canals, especially in Italy – first appearing around Venice, as early as 1044; but space limitations preclude further discussion of such mills.

IV. THE CHANGING TECHNOLOGY OF WATER-MILLS: OVERSHOT WHEELS

As important as these innovations in medieval mill technology indisputably were, even more important – and from an earlier age – was the creation of the overshot water-wheel, whose use almost always required aqueducts. It came to be the most efficient and practical when used as well with a combination of hydro-power dams and millraces (power canals). As the name suggests, the requisite water was delivered, and usually by an elevated aqueduct, to the very top of the wheel, where it was poured into inclined buckets or other receptacles fixed into the rim-circumference of the wheel. Thus the wheel's rotation resulted from the weight of the water contained in these buckets, rather than from the speed of the flowing water. The water then poured out of these buckets as the wheel reached the bottom of the revolution (when the buckets were fully upside down), to be refilled at the top of the revolution. If well constructed, the medieval overshot wheel was more than twice as powerful as the undershot wheel: i.e., its efficiency ranged from 50 to 70 percent of the potential force of the water, as it struck the wheel, while requiring only about one-quarter as much water as undershot wheels. Its *relative* efficiency was even greater in areas with slower moving streams and rivers, provided, of course, that suitable hydro-power dams, storage ponds, and mill races could also be constructed to project the water over the wheels with a sufficiently forceful 'head' or 'fall'. Most overshot wheels required a much larger capital investment than that for vertical water-wheels, but one fully justified by the much greater gains in efficiency and power.[25]

The first introduction of overshot wheels, evidently first used in western Europe, cannot be precisely ascertained. The earliest documented evidence comes from Christian wall-paintings in Roman catacombs of the third century CE; and less conclusive archaeological evidence, from this same era, or the early fourth century, was found at Barbegal, near Arles, in southern Roman Gaul, in the form of possibly terraced overshot wheels. Much more conclusive archaeological evidence for an overshot wheel, employing an aqueduct, has been documented for the Agora, near the Valorian Wall, in fifth-century Athens.[26] In England, the earliest evidence for the overshot wheel is

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[25] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 10-14, 24-25, 36-41, 105-107. The statement in Frances and J. GIES, *Cathedral, Forge, and Waterwheel: Technology and Invention in the Middle Ages*, New York 1994, p. 106, to the effect that overshot wheels could produce 'as much as forty to sixty' hp, is based on a misreading of Reynolds, confusing his percentage efficiencies with horsepower.

[26] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 19 (fig. 1-9: Roman catacombs) and pp. 36-42 (fig. 1-15: Athenian Agora; fig. 1-16,17: Barbegal). He estimates that the

its very accurate depiction in the famous Luttrell Psalter of 1338; and archeological evidence from the mid-fourteenth century indicates that a water-mill at Batsford in East Sussex used an overshot wheel.[27] About this same time (c.1350) appeared the German treatise now known as the *Dresdener Bildhandschrift des Sachenspiegels*, which contains a crude drawing of an overshot wheel.[28] Nevertheless, after examining all of the available illustrations and iconographical evidence, A. P. Usher concluded that overshot wheels were much less common than undershot wheels until the early sixteenth century. Reynolds confirms that view, while suggesting that diffusion of overshot wheels was highly dependent upon the construction of more and more hydro-power dams, storage ponds, and power-canals to provide water power in the requisite form.[29]

V. ECONOMIC GAINS FROM WATER POWER: CONSERVING ON LABOUR, CAPITAL, AND LAND

If the economic benefits of watermills in economizing on labour are obvious, indeed self-evident, less evident are the economies it provided in terms of conserving capital and land. Of course, in medieval and early-modern Europe, the chief form of capital in its agrarian and transport sectors was livestock. If, in that economy, such mills had instead been powered by horses – and indeed quite a few grain mills were -- then European flour production, especially in feeding the tremendous growth in population from the tenth to early fourteenth centuries, and again during the sixteenth and early seventeenth centuries, would have required some commensurate expansion in the supply of horses, or their diversion way from the agricultural and transport sectors. And the former in turn would have required an increased use of scarce pasture/meadow lands and in arable production of fodder crops to feed them. A modern parallel is the mechanization of American agriculture, which, according to one economic historian, provided a savings of about 25 percent of total harvested production, i.e., in not having to feed the draft

Athenian mill had 2-4 hp (double that of the Venafro undershot wheel) and that Barbegal mills had 4-8 hp. See J. GIES, *Cathedral, Forge, and Waterwheel*, pp. 33-35; J. GIMPEL, *Medieval Machine*, cit., pp. 7-10.

27 R. HOLT, *Mills*, cit., pp. 99-100, 126-131; for Batsford, citing: O. BEDWIN, *The Excavation of Batsford Mill, Warbleton, East Essex, 1978*, in "Medieval Archaeology", 24, 1980, p. 194.

28 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 98-103 (fig. 2-37), also with reproductions of the Luttrell Psalter (fig. 2-38) and of the overshot wheel in Conrad Kyser's *Bellifortis* of c.1405 (fig. 2-39).

29 A.P. USHER, *History of Mechanical Inventions*, cit., pp. 169-170; T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 97-103.

animals displaced by tractors and other such machinery.[30] Finally, water-mills conserved on capital, in comparison with the alternatives. For the growth of the western medieval economy – if it had succeeded in growing as much without water mills – would have required a far greater number of animal-powered mills, just in grinding the same quantity of grain.

VI. Other industrial applications of water power: rotary and reciprocal power

Rotary power: in food processing, metal-working, paper-making, tanning, and mining

For many centuries, and perhaps for a millennium, the watermill was used virtually exclusively for grinding grain into flour. Its next application was in the closely allied fields of brewing: to pulverize barley malt into beer mash; and the first document for such beer-mills date from ninth century France (in Picardy, 861 CE). Also using almost precisely the same technology as in flour-milling, water mills soon thereafter – by the eleventh century – came to be used in producing olive oil. But since the requisite task involved crushing rather than grinding the olive seeds, such mills used an 'edge-roller' in the form of vertically placed stones connected by a short axle to the mill's drive shaft, whose vertical rotation forced the crushing-stone to follow a circular path. Such 'edge-roller' mills were soon employed for very similar tasks: in crushing mustard and poppy seeds (also for oil), sugar (Norman Sicily, 1176), and various dyes (though only from the later fourteenth century). But perhaps the most important use of such mills was in tanning: by crushing oak-bark into very small pieces to facilitate the leaching process that produced tannin. First documented at Charement (near Paris) in 1138, tanning-mills had become quite widespread by the thirteenth century.[31]

Certainly by this time, rotary water-mills were being used to facilitate various tasks in metal-working, but using carborundum (carbon-silicon) grindstones rather than millstones: for polishing and/or sharpening cutlery, swords, other blades. The earliest documented cutlery mill is again to be found in northern France, at Evereux (Normandy), in 1204. Rotary water-mills were also used, though rather later, for cutting metals: by passing (or forcing) the metal through a pair or revolving cylinders to produce either

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[30] See http://www.eh.net/bookreviews/reviewer.php (EH.Net 28 November 2001), for D. Gale Johnson's review of: V. Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*, Cambridge, MA: MIT Press, 2001. It is estimated that draft animals utilized a quarter of all the harvested output of American agriculture in the 1920s.

[31] T.S. Reynolds, *History of the Vertical Water Wheel*, cit., pp. 69-77; A.P. Usher, *Mechanical Inventions*, cit., pp. 184-186.

sheets, or rods, or bars. The earliest documented cutting-mills are found only in and from the fifteenth century, in northern France (Raveau: 1443); then in Germany (1532); but not in England before the very late sixteenth century. Evidently similarly-designed mills were also being used for cutting timber and wood; and though the first fully documented example of a wood lathe is dated 1590, some evidence suggests that they were being used in late-medieval Dauphiné.[32]

Reciprocal power: cams and crankshafts in saw-milling and metallurgy (forges and smelters)

Other contemporary applications or innovations in the use of water-power, and especially in metallurgy, necessarily involved a radical transformation in the mill's own machinery: in order to convert the natural rotary power of the water-wheel into reciprocal power. The solution to that problem was found first in the cam and then in the crankshaft. The cam was evidently first conceived in the ancient world, by Hero and other Alexandrian Greek theoreticians. It was simply a small projection fixed to the axle of the water-wheel designed to lift mallets or pounders, in the form of vertical stamps or trip-hammers; but it did not receive a fully practical application until the creation of the fulling mill in the cloth industry (see below, pp. 23), perhaps as early as the tenth century. As the water-wheel rotated, the cams came into contact with similar cam-projections on the heavy hammer's vertical shaft, thus lifting them away from the shaft (as the wheel continued to rotate), and allowing them, by the simple force of gravity, to fall with considerable force on the object to be pounded or hammered. Recumbent trip-hammers worked in the same fashion, except that the hammer's shaft was pivoted horizontally rather than vertically. After fulling, its next major industrial purpose was in paper-making: hydraulic trip-hammers to beat rags into pulp, first documented at Xativa, near Valencia (Spain), in 1238; and in Italy, at Fabriano, in 1268. Such water-powered paper mills became very widespread in France and the Low Countries during the fourteenth and in Germany by the fifteenth.[33]

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32 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 76-77.

33 J. GIMPEL, *Medieval Machine*, cit., pp. 14-16; S. LILLEY, *Men, Machines, and History*, cit., pp. 46-48, 59-60; and T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 79-83, who states that the first documented use was at Fabriano, in 1276. B. BLAINE, *Mills*, cit., p. 393, however, states that water-powered forge-hammers were known in Bavaria as early as 1028 (but not noted or accepted by other authorities). There is some conjectural if doubtful evidence for the use of water-powered trip-hammers in brewing (for pounding malt into beer mash) at St. Gall, c. 820 (accepted by *ibid.*, p. 392). For England, see R. HOLT, *Mills of Medieval England*, cit., pp. 149-152. For fulling mills, see below pp. 23-38.

The more efficient alternative to the cam, in producing reciprocal power, was the crankshaft, possibly known in ancient China but not effectively employed in the West until the very late Middle Ages, when indeed many cam-operated systems were replaced with crank-shafts.[34] The crankshaft is, of course, that part of the axle or driving shaft bent into a right angle; and as such is just as effective in converting reciprocal power into rotary power as in its original use, in producing reciprocal power. One of its earliest and most important uses was in the hydraulic saw-mill, which used the rotary power of the wheel itself to feed the log or timber into the saw, and then reciprocal power, with cams or crankshafts, to operate the saw itself, in cutting back and forth. Normandy provides the first documented example of a hydraulic saw mill, in 1204 (though earlier mills may have been used to cut stone and marble). Well known is a drawing by Villard de Honnecourt, c1235, depicting such a mill using both rotary and reciprocal power.[35]

The Central European mining boom: mining and smelting silver-copper ores

Undoubtedly the most important application of rotary water-power for the industrial and economic development of early-modern Europe was in powering drainage pumps for silver mining, from about the mid fifteenth century, and one to which Reynolds gives only passing attention. By the 1450s, much of western Europe was suffering from a veritable 'bullion famine', in terms of a relative scarcity of both gold and silver for coinage. Evidence for such a scarcity can be seen, first, in the very low mint outputs – or indeed mint closures for lack of bullion – that are well documented for England, the Low Countries, France, and Germany.[36] But even more impressive

[34] See an extensive discussion in L. WHITE, *Medieval Technology*, cit., pp. 103-118. While noting its appearance in the West in the ninth century, he dates its first effective applications to the fifteenth century, particularly in the form of the carpenter's brace (Flanders, c.1420), p. 112.

[35] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 88-92; and fig. 2-28, citing *Sketchbook of Villard de Honnecourt*, ed. TH. BOWIE, Bloomington 1959, p. 129 and plate 59; see also J. GIMPEL, *Medieval Machine*, cit., pp. 130-132.

[36] J. DAY, *The Great Bullion Famine of the Fifteenth Century*, in "Past and Present", 79, May 1978, pp. 1-54; reprinted in IDEM, *The Medieval Market Economy*, Oxford 1987, pp. 1-54; IDEM, *The Question of Monetary Contraction in Late Medieval Europe*, in "Nordisk Numismatisk Arsskrift", 1981: special issue, *Coinage and Monetary Circulation in the Baltic Area, c. 1350 -c.1500*, ed. J. STEEN JENSEN, pp. 12-29; reprinted in J. DAY, *Medieval Market Economy*, cit., pp. 55-71; P. SPUFFORD, *Money and Its Use in Medieval Europe*, Cambridge 1988, Part III: 'The Late Middle Ages,' pp. 267-396; and in particular, chapter 15: 'The Bullion-Famines of the Later Middle Ages', pp. 339-362; J. MUNRO, 'Bullion Flows and Monetary Contraction in Late-Medieval England and the Low Countries', in John F. Richards, ed., *Precious Metals in the Later Medieval and Early Modern Worlds* (Durham, N.C., 1983), pp. 97-158; reprinted in J. MUNRO, *Bullion Flows and Monetary Poli-*

proof can be found in the behaviour of prices, falling money-of-account prices based on the silver penny in most western currencies: that is, a sharp deflation that reached its nadir in the 1460s.[37]

Those lower silver-based prices correspondingly meant a higher purchasing power and thus value of silver per gram (or ounce); and such a rise in the metal's purchasing power clearly provided the economic incentive to seek out the twin technological innovations that produced a veritable silver mining boom in South Germany and Central Europe from the 1460s. After several centuries of intensive silver-mining, with no technological advances beyond those devised by the Romans, the most accessible seams had become depleted; and in still operating mines, diminishing returns had raised marginal costs. Furthermore, since the best or potentially the richest silver-loads were found in mountainous regions, with high water-flows, the corollary and major problem that had brought so much European silver mining to a virtual halt by the 1440s, preventing access to deeper lying seams, was flooding.[38] One

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cies in England and the Low Countries, 1350 – 1500, London 1992 (Variorum Reprints), no. VI; H. MISKIMIN, *Money and Power in Fifteenth-Century France*, New Haven-London 1984, pp. 127-138 (annual mint outputs). See my review article: J. MUNRO, *Political Muscle in an Age of Monetary Famine: A Review*, in "Revue belge de philologie et d'histoire", 64, 1986, pp. 741-46; J. DAY, H. BERTAND, *Les frappes de monnaies en France et en Europe aux XIV^e-XV^e siècles*, in *Rythmes de la production monétaire, de l'antiquité à nos jours*, eds. G. DEPEYROT, T. HACKENS, GH. MOUCHARTE, Louvain-la-Neuve 1987, pp. 537-577.

37 See: J. MUNRO, *Mint Outputs, Money, and Prices in Late-Medieval England and the Low Countries*, in *Münzprägung, Geldumlauf und Wechselkurse/ Minting, Monetary Circulation and Exchange Rates*, eds. E. VAN CAUWENBERGHE, F. IRSIGLER, *Trierer Historische Forschungen*, VII, Trier 1984, pp. 31-122; J. MUNRO, *Deflation and the Petty Coinage Problem in the Late-Medieval Economy: the Case of Flanders, 1334-1484*, in "Explorations in Economic History", 25, October 1988, pp. 387-423; reprinted in J. MUNRO, *Bullion Flows,* no. VIII; IDEM, *The Central European Mining Boom, Mint Outputs, and Prices in the Low Countries and England, 1450-1550*, in *Money, Coins, and Commerce: Essays in the Monetary History of Asia and Europe from Antiquity to Modern Times*, ed. E. VAN CAUWENBERGHE, Leuven 1991, pp. 119-183; P. NIGHTINGALE, *Monetary Contraction and Mercantile Credit in Later Medieval England*, in "Economic History Review", 2nd ser., 43, November 1990, pp. 560-575; H. VAN DER WEE, *Prices and Wages as Development Variables: A Comparison between England and the Southern Netherlands, 1400-1700*, In "Actae Historia Neerlandicae", 10, 1978, pp. 58-78; reprinted in IDEM, *The Low Countries in the Early Modern World*, London 1993 (Variorum), pp. 58-78. Having a common base period of 1451-75 = 100, the quinquennial composite price indices for Flanders, Brabant, and England fell as follows: the Flemish, 36.9 per cent from 1436-40 to 1461-65; the Brabantine, 27.4, from 1436-40 to 1461-65; and the English, 20.5 , from 1436-40 to 1456-60 (rising somewhat, in the next quinquennium, with the English coinage debasement of 1464-65).

38 See J.U. NEF, *Silver Production in Central Europe, 1450-1618*, in "Journal of Political Economy", 49, 1941, pp. 575-591; IDEM, *Mining and Metallurgy in Medieval Civilization*, in *Cambridge Economic History of Europe*, ed. M.M. POSTAN, II, Cambridge 1952, pp. 456-469; reissued in *The Cambridge Economic History of Europe,* eds. M.M. POSTAN, E. MILLER, II, *Trade and Industry in the*

only partially effective solution, possibly in use in Moravia and Silesia by the later fourteenth century, was water–powered chain-of-bucket pumps, which literally lifted buckets of water from the mine shaft.[39]

But the far more effective solution, dating from about the mid-fifteenth century, and one that truly permitted the mining boom, was the water-powered suction piston pump. Placed at various levels of the mine shaft, these pumps used piston rods to expel and thus to create a vacuum within the pump. Such a vacuum thus permitted the atmospheric pressure (101.325 pascal at sea level) outside the piston chamber to force the water up the pump to the next level of the mine-shaft, where the next piston pump similarly pumped the water to the higher levels.[40] The famous 1556 treatise *De re metallica* by the German engineer Georg Bauer (better known as Georgius Agricola) depicts a triple action piston pump, operated by an overshot wheel; and also, an overshot wheel that powered a ventilating fan, using wooden paddles fixed into a cylinder rotated by the water.[41] Added to these devices were adits

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Middle Ages, revised edn., Cambridge 1987, pp. 696-734; D. KOVACEVIC, *Les mines d'or et d'argent en Serbie et en Bosnie médiévales*, in "Annales: E.S.C.", 15, 1960, pp. 248-58; S. CIRKOVIC, *The Production of Gold, Silver, and Copper in the Central Parts of the Balkans from the 13th to the 16th Century*, in *Precious Metals in the Age of Expansion*, ed. H. KELLENBENZ, Stuttgart 1981, pp. 41-69; PH. BRAUNSTEIN, *Innovations in Mining and Metal Production in Europe in the Late Middle Ages*, in "Journal of European Economic History", 12, 1983, pp. 573-591; E. WESTERMANN, *Zur Silber- und Kupferproduktion Mitteleuropas vom 15. bis zum frühen 17. Jahrhundert: über Bedeutung und Rangfolge der Reviere von Schwaz, Mansfeld und Neusohl*, in "Der Anschnitt: Zeitschrift für Kunst und Kultur im Bergbau", 38, May-June 1986, pp. 187-211; IDEM, *Über Wirkungen des europäischen Ausgriffs nach Übersee auf den europäischen Silber- und Kupfermarkt des 16. Jahrhunderts*, in *Columbus: Tradition und Neuerung*, ed. A. REESE, Idstein 1992 (Forschen-Lehren-Lernen: Beiträge aus dem Fachbereich IV –Sozialwissenschaften- der Pädagogischen Hochschule Heidelberg, Vol. 5), pp. 52-69; J. MUNRO, *Central European Mining Boom*, cit., pp. 119-183; IDEM, *The Monetary Origins of the "Price Revolution" Before the Influx of Spanish-American Treasure: The South German Silver-Copper Trades, Merchant-Banking, and Venetian Commerce, 1470-1540*, in *Global Connections and Monetary History, 1470-1800,* ed. R. VON GLAHN, D. FLYNN, London forthcoming (Ashgate Publishing),.

[39] T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., p. 7, citing an unpublished doctoral dissertation: B. BLAINE, *The Application of Water-Power to Industry during the Middle Ages*, University of California 1966; and also IDEM, *The Enigmatic Water-Mill*, in *On Pre-Modern Technology and Science*, ed. B. HALL, D. WEST, Malibu 1976, pp. 163-176; and B. BLAINE, *Mills*, cit., pp. 388-395 (n. 1 above).

[40] See sources cited in note 38 (especially those of Nef and Braunstein). In imperial terms: 14.667 lb. per square inch = 1031.2 grams per cm^2 (vs 1013.25 millibars or dynes per square centimetre).

[41] See GEORGIUS AGRICOLA, *De re metallica*, translated from the 1556 Latin edition by H. HOOVER, L.H. HOOVER, New York 1950, pp. 183-199, 206; and T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 77-79, figs. 2-17, 18, and 19; S. LILLEY, *Men, Machines, and History*, cit., pp. 72-80, figs. 15, 17, 18; J. MOKYR, *Lever of Riches*, cit., pp. 62-64, 67 (fig. 19). Note that

drilled into the mountain sides (sloping downwards) to drain off excess water; and together these devices permitted far deeper shafts to be constructed to reach previously inaccessible but often rich ore seams.

The complementary and necessary part of this dual technological revolution was one in chemical engineering: the so-called *Seigerhütten* process, which utilized lead in smelting argentiferous cupric ores. Indeed, the largest and most widespread silver lodes in medieval Central Europe were those mixed with copper, previously inseparable from the silver. Sometime during the early to mid fifteenth century, metallurgical engineers in Nürnberg observed that when lead was added to the ore in the smelter, it combined with the silver, leaving the copper as a precipitate. Then the previously known methods of lead-silver separation – for lead melts at a lower temperature than silver – were applied to extract the silver. The first documented application of this technique is found in a licence granted to an engineer named Johannes Funcken, by the office of the duke of Saxony, in 1450. Even for this process, water-power was important: in operating the hydraulic machinery to power the smelter's bellows, a topic to be considered in greater detail below.[42]

From the 1460s, the subsequent silver-copper mining boom – in Saxony itself, the Austrian Tyrol, Thuringia, Bohemia, Hungary – increased Europe's silver supplies at least five-fold, by the time it reached its peak in the 1540s – when more cheaply produced silver was becoming available from the Spanish Americas. At the same time, the by-product of this mining boom also greatly increased Europe's supply of copper, itself a monetary metal (since all coins, gold and silver, were alloyed with some copper, for hardening), but even more important as the major military metal, for cast bronze artillery (a technique developed from casting church bells).[43]

The Central European mining boom may have been the single most important economic phenomenon in resuscitating the overland, transcontinental trade routes, between Italy, and the Low Countries; and together they provided the major stimulus for Europe's recovery from the late-medieval economic contraction (sometimes known more dramatically as the 'Great Depression'). Subsequently, as I have argued elsewhere, it also provided the fundamental origins for the later, sixteenth-century Price Revolution, through the vast increases in mined silver production, even if the actual

these pumps used cams, or angled-projections, fixed to the axle of the water wheel; and they are discussed in more detail below, on pp. 26-27.

[42] See sources cited in nn. 38-39.

[43] See sources cited in n. 38 and 41 above, 44-45 below.

European-wide inflation did not really commence until about 1515.[44] Furthermore, this ever growing flow of silver – much of which initially went to Venice, but then, from c.1515, chiefly to Antwerp and the Brabant Fairs -- also supplied the key initial ingredients in Europe's new trans-Oceanic commerce inaugurated by Portugal, which allowed the Portuguese to acquire, directly by sea, the East Indies' spices and other Asian goods, which were marketed throughout Europe via the new Antwerp spice staple (from 1501).[45]

Metallurgy: the application of water-powered machinery to forges, furnaces, and smelters.

From an even earlier era, water-power had already proved itself to be of great importance in a related field of metallurgy: in producing iron, arguably the most important metal in the medieval economy. Prior to the applications of new forms of hydraulic machinery, the long-traditional, indeed ancient methods, of 'iron-winning' involved the use of charcoal-fired 'bloomery' furnaces to extract usable iron from its ferric-oxide ore: so that the carbon in the charcoal fuel – an absolutely pure form of fuel (unlike highly contaminated coal) – would combine with the oxygen in the ore to liberate the iron, releasing carbon dioxide, and leaving a viscous or sponge-like mass of carbonised iron known as a 'bloom'.[46] The next stage in producing purified iron required extensive hammering or pounding of the 'bloom' in another charcoal-fired forgery, with very large amounts of both fuel and labour, to burn off or oxidize the carbon, sulphur, silicon, and other impurities. The initial application

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[44] See J. MUNRO, *Central European Mining Boom*, cit., pp. 119-83; and IDEM, *Monetary Origins of the Price Revolution*, cit.. In Table 3 in this publication, I have estimated that, just from those mines with extant records, total annual outputs of silver rose from 12,973.44 kg in 1471-75 to a peak of 55,703.84 kg per year in 1536-40, amounts that Prof. Ekkehard Westermann regard as most likely well below the true or actual aggregate silver outputs. See also sources in n. 38 above.

[45] See H. VAN DER WEE, TH. PEETERS, *Un modèle dynamique de croissance interseculaire du XII^e XVIII^e siècles*, in "Annales E.S.C.", 15, 1970, pp. 100-128; and a further elaboration of these views in H. VAN DER WEE, *Structural Changes in European Long-Distance Trade, and Particularly in the Re-export Trade from South to North, 1350-1750*, in *The Rise of Merchant Empires: Long-Distance Trade in the Early Modern World, 1350-1750,* ed. J. TRACY, Cambridge 1990, pp. 14-33; J. MUNRO, *The 'New Institutional Economics' and the Changing Fortunes of Fairs in Medieval and Early Modern Europe: the Textile Trades, Warfare, and Transaction Costs*, in "Vierteljahrschrift für Sozial- und Wirtschaftsgeschichte", 88, 2001, 1, pp. 1-47; and IDEM, *Monetary Origins of the Price Revolution*, cit.; and also IDEM, Patterns of Trade, Money, and Credit, in *Handbook of European History in the Later Middle Ages, Renaissance and Reformation, 1400 - 1600*, eds. J. TRACY, TH. BRADY JR., H. OBERMAN, I, *Structures and Assertions*, Leiden 1994, pp. 147-195.

[46] The formula for this chemical reaction combining ferric oxide (Fe_2O_3), carbon (charcoal), and oxygen, to liberate iron, along with carbon dioxide, is: $3C + 2Fe_2O_3 \rightarrow 4Fe + 3CO_2$

of water-power, in the form of the hydraulic trip-hammers, greatly reduced both the labour and fuel inputs in iron-refining. Some perhaps doubtful evidence suggests that such hydraulic trip-hammers may have been employed in southern Germany, Scandinavia, France, as early as the eleventh or twelfth centuries. Certainly they had become widespread by the later thirteenth and early fourteenth centuries.[47] Equally significant was the somewhat later application of water-mills to power air-bellows that were designed to fan charcoal-based fires in the forge to much higher temperature levels. The first concrete evidence for such hydraulic bellows can be found at a monastic iron foundry at Trent, in northern Italy, in 1214.

Even more momentous, at the dawn of the modern era, was the subsequent application of such water-powered bellows in brick-kiln furnaces, of radically new design, almost nine metres high, known as blast-furnaces or smelters. The far higher temperatures, reaching about 1000° C, and combustion achieved with the air-blast from the water-powered bellows, rapidly liberated the iron from its ferric-oxide ore, while also forcing the iron itself to absorb some carbon (about three per cent) from the charcoal fuel. The absorption of carbon in turn reduced the melting point to this temperature (while pure iron becomes molten at the much higher temperature of 1535° C.), allowing the iron product to be poured or 'cast' into moulds.[48] The earliest documented evidence for such a water-powered blast smelter is for Liège, in the eastern Low Countries (on the Meuse), in 1384; and by the later fifteenth century these blast-smelters had become fairly widespread in France, Germany, and finally England (by 1496, in the Weald district).[49]

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47 See also B. GILLE, *Le moulin à fer et le haut-fourneau*, in "Métalaux et civilisations", 1, 1946, pp. 89-94; and IDEM, *Les origines du moulin à fer*, in *Revue d'histoire de la sidérugie*, 1, 1960-63, pp. 23-32; A.R. HALL, *Early Modern Technology, to 1600*, in *Technology*, cit., I, pp. 88-94; J. GIES, *Cathedral, Forge, and Water-Wheel*, cit., pp. 200-203; S. LILLEY, *Men, Machines, and History*, cit., p. 61; B. BLAINE, *Mills*, p. 393.

48 See J. MOKYR, *Lever of Riches*, cit., pp. 48-49; T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 86-87; see in particular, fig. 2-24, of a fifteenth-century hammer forge, and fig. 2-25, a drawing by Taccola illustrating a forge bellows, activated by an overshot wheel with cams, dated c.1449; and sources cited in nn. 47, 49.

49 For this and the following see J. NEF, *The Rise of the British Coal Industry*, I-II, London 1923; IDEM, *The Progress of Technology and the Growth of Large-Scale Industry in Great Britain, 1540-1640*, in "Economic History Review", 1st ser. 5, 1934, 1, reprinted in *Essays in Economic History*, ed. E.M. CARUS-WILSON, I-III, London 1954-62, I, pp. 88-107; and TH.S. ASHTON, *Iron and Steel in the Industrial Revolution,* London 1924; and more recently, H. CLEERE, D. CROSSLEY, *The Iron Industry of the Weald,* Leicester 1985; J. HATCHER, *The History of the British Coal Industry*, I, *Before 1700: Towards the Age of Coal,* Oxford 1993, pp. 31-55, 422-425; R. HOLT, *Mills of Medieval England*, cit., pp. 150-152.

This veritable 'industrial revolution' in iron manufacturing – a term better justified than for the earlier one in textiles (see below) – created the new metal 'cast' iron; but it also necessarily introduced a two-stage process for making fully refined or malleable iron. Cast iron, having a very high carbon content, was as hard as steel, and was useful for pre-shaped moulded pans, pipes, and machinery parts. But it was also very brittle, subject to cracking or shattering under stress; and thus cast-iron cannon were much inferior and certainly more dangerous to use than were cast-bronze cannons. Most of the metal then demanded in early-modern Europe was in fact still in the form of completely purified and much softer iron known as malleable or wrought iron. When used as an input for this purpose, the product of the blast smelter, known from its shape as 'pig iron', was taken to a refinery forge, also called a chafery, which used a charcoal fuel and water-powered tilt-hammers to subject the pig to successive poundings at red-hot but not molten heat, in order to decarburize and purify the iron.

Ashton's 'tyranny of wood and water'

Although the chief beneficiaries of this new water-powered technology in metallurgy were probably Russia and Sweden,[50] who became the world's leading producers of bar iron in the seventeenth and eighteenth centuries, much more attention has been devoted (especially by Anglophone historians) to its supposed role, albeit a contributory role, in the growth of England's industrial economy in the Tudor-Stuart era. Though England was then hardly the 'economic backwater' so often portrayed in the past, the introduction of the blast-smelter certainly did transform its metallurgical sector. The relative success of this of this water-powered industrial revolution in metallurgy for England can be seen in statistics (or estimates) of pig iron outputs: rising from a decennial mean of 1,200 metric tonnes in 1530-39 (with six blast smelters) to a seventeenth-century peak decennial mean of 23,000 tonnes in 1650-59 (with 86 smelters, down from the peak number of 89 in 1600-09).[51]

This apparent industrial ceiling and apparent industrial stagnation for another century, until the 1760s, inspired Thomas Ashton to justify the need for the subsequent 'industrial revolution' in metallurgy, by what he called the 'tyranny of wood and water'. His views were fully upheld by the American historian John Nef, famed for his theses concerning the prior, if admittedly far less

[50] See I. BLANCHARD, *Russian Railway Construction and the Urals Charcoal Iron and Steel Industry, 1851-1914*, in "The Economic History Review", 2nd ser., 53, 2000, 1, pp. 107-126.

[51] See the statistical sources in the more complete citation in note 53 below, especially those of Hammersley, Hyde, and Riden.

significant 'industrial revolution' of the Tudor-Stuart era (c.1540-1640): one based on a new coal-burning furnace technology, but one that could not be applied to iron manufacturing until coal fuels were finally purified into the form of coke.[52] Over the past forty years, their views have provoked a strenuous debate in the economic history literature, in which their opponents have focussed almost entirely on the 'tyranny of wood' (charcoal fuels), while virtually ignoring the question of water-power.[53] This is no place to rehearse let alone settle this debate, though it may be noted that all of the recently compiled statistics on steeply rising prices for wood and wood-charcoal, and those on the rising imports of Swedish bar iron (as proportions of total consumption), for the late sixteenth, seventeenth and eighteenth centuries, lend more support to the views of Ashton and Nef than to those of their chief critics.[54]

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[52] See note 49 above.

[53] G. HAMMERSLEY, *The Crown Woods and their Exploitation in the Sixteenth and Seventeenth Centuries*, in "Bulletin of the Institute of Historical Research, University of London", 30, 1957, pp. 154-159; M. FLINN, *The Growth of the English Iron Industry, 1660-1760*, in "Economic History Review", 2nd ser., 11, 1958, pp. 144-153; M. FLINN, *Timber and the Advance of Technology: A Reconsideration*, in "Annals of Science", 15, 1959, pp. 109-120; G. HAMMERSLEY, *The Charcoal Iron Industry and its Fuel, 1540-1750*, in "Economic History Review", 2nd ser., 26, 1973, pp. 593-613; D.C. COLEMAN, *Industry in Tudor and Stuart England,* London 1975, pp. 35-49; G. HAMMERSLEY, *The State and the English Iron Industry in the Sixteenth and Seventeenth Centuries*, in *Trade, Government, and Economy in Pre-Industrial England: Essays Presented to F. J. Fisher,* eds. D. COLEMAN, A.H. JOHN, London 1976, pp. 166-186; PH. RIDEN, *The Output of the British Iron Industry Before 1870*, in "Economic History Review", 2nd ser., 30, 1977, pp. 442-459; CH.K. HYDE, *Technological Change and the British Iron Industry, 1700-1870,* Princeton 1977, especially chapter 1, pp. 7-22; also chapter 3, pp. 42-52. [Modifies Ashton and Nef.]. The critics are at least justified in asserting that the English iron industry did not experience any significant absolute decline and that its pig iron outputs recovered to a decennial mean of 23,000 tonnes in 1690-9 and then rose to another decennial mean peak of 28,000 tonnes in 1720-29, declining thereafter.

[54] For statistics on wood, charcoal, coal, and industrial prices see: J.E. THOROLD ROGERS, *History of Agriculture and Prices in England From the Year After the Oxford Parliament (1259) to the Commencement of the Continental War (1793)*, I-VII, Oxford 1866-92, IV, (*1401-1582*), pp. 383-387; V, (*1583-1702*), pp. 398-402; W. BEVERIDGE, *Prices and Wages in England*, I, *The Mercantile Era,* London 1939; reissued 1965; P. BOWDEN, *Agricultural Prices: Statistical Appendix*, in *Agrarian History of England and Wales*, ed. J. THIRSK, IV, *1500-1640,* Cambridge 1967, Table XIII, p. 862; 'Basket of Consumables' and general industrial price index: E.H. PHELPS BROWN, SH. HOPKINS, *Seven Centuries of the Prices of Consumables*, in "Economica", 23, Nov. 1956, pp 296-314; reprinted in *Essays in Economic History*, ed. E.M. CARUS-WILSON, II, London 1962, pp. 194-195; and in E.H. PHELPS BROWN, S.V. HOPKINS, *A Perspective on Wage and Prices*, London 1981, pp. 13-59. For statistics on relative charcoal prices and on Swedish iron imports, defending Ashton and Nef, see, B. THOMAS, *Was There an Energy Crisis in Great Britain in the 17th Century?*, in "Explorations in Economic History", 23, April 1986, pp. 124-152. See sources in nn. 53-54.

The arguments concerning the supposed 'tyranny of water' can be briefly summarized under three headings, which in turn may explain why the early-modern English iron industry was, in their view, so scattered, badly located, and small scale. First, according to the Ashton-Nef thesis, the freely available sites for water power, or those with reasonably low opportunity costs, often forced iron industrialists to build smelters and finery forges in otherwise disadvantageous locations, in terms of access to labour, iron ores, and markets. The second problem was that the available sources of water power were often insufficient because of winter freezing (during this somewhat colder era) or summer droughts, sometimes severe enough to shut down smelters or forges for weeks at a time. Third, in early-modern England, the supplies of both water power and charcoal (from accessible trees) were rarely sufficient to justify the side-by-side operations of both smelters and forges, which might have reduced the industry's internal transportation and transaction costs. Furthermore, the available supplies of both wood-charcoal fuel and water power in general could not permit the greatly enlarged scale, industrial concentrations, and optimum locations that were permitted by the subsequent integration of smelting and refining based upon the use of coke fuels and coal-fired steam power throughout the entire range of production. Even though the early eighteenth-century English iron industry had achieved some renewed growth, with greater scale economies than suggested by the Ashton-Nef thesis, nevertheless many other historians have also argued that the great achievement of the Industrial Revolution in metallurgy was the creation of a fully-integrated, very large-scale and concentrated iron industry – concentrated around coal fields, and integrated by the use of coal throughout, in coke fuels and coal-fired steam power.

The true industrial revolution in iron manufacturing did not begin in 1710-12, with Abraham Darby's high-cost coke-fired blast smelter, but rather in 1760, with John Smeaton's water-powered piston bellows (Carron Ironworks of Edinburgh), which produced a far more powerful blast, with the requisite economies in coke fuels. Arguably, however, an even more important breakthrough was the application of James Watt's steam engine to Wilkinson's piston-operated blast smelter in Shropshire, in the revolutionary year of 1776. The statistics on the output of pig iron from the mid eighteenth century also provide some justification for the term 'industrial revolution' over the ensuing century: outputs rising from a decennial mean of 29,500 tonnes in 1750-59 to one 122,000 tonnes in 1790-99 and then to one of 3,106,000 tonnes in 1850-59.[55] But of course such developments are well beyond the scope of this study.

VII. The application of water-power to textile manufacturing: fulling mills in the woollen cloth industry

As noted earlier, the first industrial application of water-power, beyond its original and for centuries sole use, was in fulling woollen cloths, which long remained a foremost industrial use. The earliest documented fulling mills are all in tenth-century Italy: in Abruzzo (962), Parma (973), and Verona (985). In northern Europe, the first known fulling mill was established at Argentan, Normandy, in 1086.[56] Fulling was also the only process in manufacturing woollen or worsted textiles to be so mechanized before the fifteenth-century introduction of gig-mills for nap-raising (see below pp. 42), and indeed the only important process, before the eighteenth-century Industrial Revolution.

The techniques and economics of foot-fulling:

The true significance of the fulling mill – and the limitations on its use – can be appreciated only by understanding the nature of fulling itself, which is virtually never explained in any published studies on technology, and the human-powered techniques that it was designed to replace. Fulling was the most crucial process in manufacturing the true, heavy-weight woollen cloths, to give such cloths the luxury qualities that justified their very high price, especially in terms of the cloth's requisite density, weight, and durability. Indeed, fulling was necessary simply to ensure that the woven woollen cloth did not fall apart shortly after being worn. All of those requirements for fulling

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55 See sources in nn. 53-54.

56 P. Malanima, *The First European Textile Machine*, in "Textile History", 17, 1986, pp. 115-128; L. White, *Medieval Technology*, cit., p. 83, cites a possible fulling mill in Tuscany, from 983 CE. See T.S. Reynolds, *History of the Vertical Water Wheel*, cit., pp. 82-83, who states that the earliest documented fulling mill is the one at Lodi, near Milan, in 1008 CE; see also fig. 2-22 (for the fulling mill depicted by Vittoria Zonca, in *Novo teatro di machine et edificii per varie et sicure operationi*, Padua 1607, reissued as a reprint (Acuto: Aedes Acutenses, 1969). For the previous literature on early fulling mills see: E. Kilburn Scott, *Early Cloth Fulling and Its Machinery*, in "The Newcomen Society Transactions", 12, 1931-32; A. Rupert Hall, N.C. Russell, *What About the Fulling Mill?*, in "History of Technology", 6, 1981; R. Van Uytven, *De volmollen: motor van de omwenteling in de industrielle mentaliteit*, in "Tijdschrift van de kring der alumni van de wetenschappelijke stichtigen", 38, 1968, pp. 61-76, republished in translation as *The Fulling Mill: Dynamic of the Revolution in Industrial Attitudes*, in "Acta Historiae Neerlandica", 5, 1971, pp. 1-14.

cloths, at least for the true woollens, were determined by the nature of the particular wool fibres used in their manufacture: those from very costly wools, with short, curly, fine, and certainly weak fibres.[57] Such wools were initially prepared by a rigorous cleansing with hot alkaline water, lye, and stale urine, in order to remove the natural lanolin and other natural greases, dirt, and other foreign matter that constituted about 20 percent of the raw wools' weight. Then these wools had to be thoroughly re-greased or oiled (with butter, olive oil) to prevent any damage or entanglement of their curly fibres from the ensuing combing or carding, spinning, and weaving processes; and indeed yarns serving as warps on the loom also had to be 'sized' with a flour-based mixture.

Removed from the loom, the woven cloth, typically about 30 metres long and 2.5 metres wide, was placed it in a large stone or wooden vat filled with an emulsion of warm water, urine, and 'fuller's earth': a chemical mixture composed of various hydrous aluminum silicates, usually *kaolinite* ($Al_2O_3Si_2O_4.2H_20$). In the traditional, human-powered process, two (or three) male fullers then trod upon the immersed cloth for a period of three to five days (depending on the season, weather, and the quality of the cloth), to achieve three objectives. The first was to remove all the grease and cleanse the cloth, aided by the ammonia in the urine, which enhanced the scouring and bleaching properties of fuller's earth and combined with the grease to form a cleansing soap.[58] At the same time, the combination of heat, intensive pressure, and chemicals effected the remaining two objectives: to force the short, scaly, curly wool fibres to interlace, mat and felt together, thus providing the fabric's requisite cohesion and durability; and thus also to shrink the cloth quite drastically, reducing its area by more than 50 percent, largely accounting for the cloth's very heavy weight. Indeed the best luxury woollens weighed about three times as much as did

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[57] See J. MUNRO, *Wool-Price Schedules and the Qualities of English Wools in the Later Middle Ages, ca. 1270-1499*, in "Textile History", 9, 1978, pp. 118-169; reprinted in IDEM, *Textiles, Towns, and Trade: Essays in the Economic History of Late-Medieval England and the Low Countries*, Aldershot 1994 (Variorum Collected Studies series CS 442).

[58] Most drapery guild ordinances (certainly the Flemish and Dutch) banned the use of urine; but such repeated prohibitions, along with those prohibiting herring fat, suggest their common use. See J. MUNRO, *Textile Technology*, in *Dictionary of the Middle Ages*, cit., XI, *Scandinavian Languages to Textiles, Islamic,* New York 1988, pp. 693-711; reprinted in IDEM, *Textiles, Towns, and Trade*, cit.; and IDEM, *Industrial Entrepreneurship in the Late-Medieval Low Countries: Urban Draperies, Fullers, and the Art of Survival*, in *Entrepreneurship and the Transformation of the Economy (10th - 20th Centuries): Essays in Honour of Herman Van der Wee*, eds. P. KLEP, E. VAN CAUWENBERGHE, Leuven 1994, pp. 377-388; and J. MUNRO, *Medieval Woollens: Textiles, Textile Technology, and Industrial Organization, c. 1000-1500*, in *The Cambridge History of Western Textiles,* ed. D. JENKINS, Cambridge 2003, pp. 204-10.

contemporary – and modern – worsted fabrics.[59] The fullers hung the fulled cloth by hooks on a tentering frame, to remove all the wrinkles and to ensure even dimensions throughout its length. Then they engaged in a preliminary raising of the cloth's nap (loose fibres), using hand-teasels, a form of thistle (teasels or teazles: *Dipsacus fullonum*). The cloth was then delivered to the shearers, who subjected it to a repeated combination of nap-raising and shearing, of the fibres so raised. The end result of both fulling and finishing was a cloth whose weave-design had been totally obliterated and whose texture was as soft and fine as silk. Indeed the prices of fully finished fine woollens, especially the vivid kermes-dyed scarlets, also rivalled those of silk.[60]

Working about 210 to 240 days a year – up to 14 hours in the summer and about 8 hours in the winter months – a team of fullers (two journeyman and a master) could process about 30 to 35 full-length woollens (21 metres) a year. Their output of cheaper, small woollens was obviously much higher, because such cloths required no more than two days' fulling; and only about a

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[59] See J. MUNRO, Medieval Woollens, cit., Table 5:8, p. 316. According to drapery guild ordinances, the Bruges *bellaert* (1458), was 30.0 metres on the loom; the Ghent *dickedinnen* (1456, 1462, 1546), 29.750 m; the Leuven *oppersten zegel* (1519) was 29.885 m; the Armentières *oultreffin* (1510), 29.40 m; the Haubourdin *oultreffin* (1539), also 29.40 m; the Mechelen *gulden aeren* (1544) was even longer, 33.072m. High grade woollen 'short cloths' from Suffolk and Essex, whose final dimensions were regulated by statute (1552), were 22.56 m when finished; and we may deduce that they were slightly longer on the loom. In 1458, the Bruges fullers' ordinance for *bellaert* woollens stipulated that the overall shrinkage from this compression and felting had to be at least 56 percent (from 172 to 75 square ells): in length, from 43 to 30 ells (30m to 21m); and in width, from 4.0 to 2.5 ells (2.8m to 1.75m). See *Collection des keuren ou statuts de tous les métiers de Bruges*, eds. O.DELEPIERRE, M.F. WILLEMS, Ghent 1842, p. 58. The better known Ghent *dickedinnen*-broadcloths of the fifteenth and sixteenth centuries (1456, 1462, 1546) underwent a very similar shrinkage, of 54 percent, from 75.49m² to 34.91m²: in length, from 29.75 m to 21.00 m; in width, from 2.5375 m. to 1.663 m.. In both, and indeed in all such woollens, the width underwent greater shrinkage than the length (37.5 percent vs 30.2 percent), because the warps were more tightly spun than the wefts. Late-medieval fine woollens, from Ghent, Leuven, Mechelen, Armentières, and East Anglia, ranging in size from 21.00 to 22.56 metres in length, and from 1.400 to 1.723 metres in width (from 29.400 m² to 37.095 m² in weight. Per square metre of cloth, the weights ranged from 633.77 g (Ghent) to 820.50 g (Armentières). In contrast, pure worsted says from Essex weighed only 141.19 g per m²; those from Bergue-St. Winoc in Flanders, 260.35 g per square metre; and Honschoote serge-type says, 322.42 g m².

[60] J. MUNRO, *Industrial Protectionism in Medieval Flanders: Urban or National?*, in *The Medieval City,* eds. H. MISKIMIN, D. HERLIHY, A.L. UDOVITCH, New Haven-London 1977, pp. 229-268; and J. MUNRO, *The Medieval Scarlet and the Economics of Sartorial Splendour*, in *Cloth and Clothing in Medieval Europe: Essays in Memory of Professor E. M. Carus-Wilson*, eds. N.B. HARTE, K.G. PONTING, London 1983 (Pasold Studies in Textile History No. 2), pp. 13-70; both reprinted in J. MUNRO, *Textiles, Towns, and Trade*, cit.

day's fulling, for most serge-type and semi-worsted fabrics, with worsted warps and woollen wefts. That was more for scouring and cleansing than for any real compression and felting. True worsteds, with coarse, strong, long-stapled yarns in both warp and weft, did not require any fulling, in terms of felting and compression, except a cursory fulling for cleansing; and they were fully finished once woven, leaving distinctly visible weave patterns.[61]

The fulling mill in England and Carus-Wilson's 'industrial revolution' thesis

The introduction of the fulling-mill reduced this arduous, immensely laborious and time-consuming task for the true woollens to just a matter of hours, generally a day for most cloths, perhaps a day and a half for some, and with just one man to operate the mill.[62] As indicated earlier, the water-wheel used cams on its axle to convert rotary into reciprocal power: in order to operate two large, very heavy oaken trip-hammers. As the water-wheel revolved, these cams rotated a smaller drum with wooden cam-tappets protruding from each side; and as the wheel and its drum ascended, the cam-tappets raised the first trip hammer, as they came into contact with similar grooved-projections on the hammer. When the wheel began its descent, the cams passed by the trip-hammer's projections, thereby releasing the hammer to fall with immense force into the fulling trough below; then the cams on the revolving drum made contact with the cams on the second trip hammer, to repeat this process, pounding the cloth up to forty times a minute.

The significance of this innovation was highlighted, for generations of economic historians to come, in 1941, when England's most renowned historian of the cloth industry, the late Eleanora Carus-Wilson, published a seminar article with the intriguing title: 'An Industrial Revolution of the Thirteenth Century'.[63] Of course, as just noted, its introduction in western Europe came al-

[61] See nn. 58-60 above.

[62] See n. 58.

[63] E.M. CARUS-WILSON, *An Industrial Revolution of the Thirteenth Century*, in "Economic History Review", 1st series, 11, 1941, reprinted in her *Medieval Merchant Venturers: Collected Studies,* London 1954, pp. 183-211. Her views were repeated in her essay, *The Woollen Industry*, in *Cambridge Economic History of Europe*, II, *Trade and Industry in the Middle Ages,* eds. M.M. POSTAN, E.E. RICH, Cambridge 1952, pp. 372-428; reissued with minor revisions in the 2nd edition, ed. M.M. POSTAN, E. MILLER, Cambridge 1987, pp. 614-690. See also: E.M. CARUS-WILSON, *Evidences of Industrial Growth on Some Fifteenth-Century Manors*, in "Economic History Review", 2nd ser., 12, 1959, pp. 190-205; reprinted in *Essays in Economic History*, II, ed. E.M. CARUS-WILSON, London 1962, pp. 151-167; and E.M. CARUS-WILSON, *Wiltshire: The Woollen Industry Before 1550*, in *The Victoria History of the Counties of England: A History of Wiltshire*, ed. E. CRITTALL, IV, London 1959, pp. 115-147.

most three centuries earlier; and even in England, fulling mills can be found from the later twelfth century: at Paxton in Huntingdonshire in 1173; and in 1185, mills of the Knights Templar at Newsham in Yorkshire and Barton in Gloucestershire (Cotswolds). But undoubtedly the period of the greatest and most extensive diffusion, even into the flat, lowlands of eastern England, was during the thirteenth and early fourteenth centuries.[64]

In Carus-Wilson's view the fulling mill was responsible for three profound transformations in the industrial and commercial history of later-medieval northern Europe: the rise of a fundamentally new and vibrant English cloth industry in western England, especially in the predominantly rural, highland regions of the West Country; the consequent decline, by the early fourteenth century, of the old traditional urban cloth industry in the lowland, eastern seaboard towns of England (from York to London), which had never been a serious competitive threat to the current industrial leader in textiles, in the Flemish towns across the Channel; and finally the ultimate victory, during the fifteenth century, of this new rural, water-power-based English cloth industry over its Flemish and other continental rivals.

Naturally such a dramatically-presented, far reaching *grande thèse* was bound to provoke hostile reaction. In launching the first major attack, Edward Miller argued that, since the fulling processes accounted for no more than '7-12 percent of the cost of the main manufacturing processes', mechanized fulling could not possibly have effected any such industrial revolution.[65] Furthermore, while agreeing with Carus-Wilson that manorial lords had promoted the growth of a rural cloth industry by investing in fulling mills, he also contended that they would have exploited their monopoly powers over their cloth-working tenants by charging high fees that would have eliminated

[64] See nn 58-63 above, 65 below; and R. HOLT, *Mills*, cit., pp. 152-54; J. GIMPEL, *Medieval Machine*, cit., pp. 15-16; R.V. LENNARD, *Early English Fulling Mills: Additional Examples*, in "Economic History Review", 1st series, 17, 1947, pp. 342-343; R.A. PELHAM, *Fulling Mills*, London 1958 (Society for the Protection of Ancient Buildings, no. 5); J. LANGDON, *Water-mills and Windmills*, cit., pp. 424-444.

[65] E. MILLER, *The Fortunes of the English Textile Industry in the Thirteenth Century*, in "Economic History Review", 2nd ser. 18 (1965), 64-82; and then E. MILLER, J. HATCHER, *Medieval England: Towns, Commerce and Crafts, 1086-1348,* London 1995, pp. 93-127; but their Table 2.1, on p. 96, provides data to indicate that fulling and finishing together accounted for 16 per cent of manufacturing costs at Beaulieu Abbey (1270) and 20 per cent at Laleham (1294-95). See also T.H. LLOYD, *Some Costs of Cloth Manufacture in Thirteenth-Century England*, in "Textile Industry", 1, 1968-70, pp. 332-336. These data do not indicate, however, whether the fulling was undertaken by a water-mill or by the fullers' feet.

any cost advantage of fulling-mills.[66] Pursuing similar arguments, but in a far more trenchant manner, Anthony Bridbury noted that the very era of this supposed 'industrial revolution' was one in which England was reaching its maximum medieval population, so that the use of fulling-mills to displace foot-fullers would likely have raised, not lowered, production costs, by substituting costly capital for cheap labour, especially in the densely populated Midlands.[67] Finally, and most recently, Richard Holt, in his 1988 monograph on *The Mills of Medieval England*, firmly denied that the water-mill brought about any 'industrial revolution' in this era; and furthermore, he supplied evidence from hundreds of manorial accounts in this region to show that landlords's profits from grain mills virtually always exceeded those from fulling mills, and by a wide margin.[68]

Most of Carus-Wilson's critics have, however, agreed that by the later thirteenth century, rural sites did provide other advantages, far more important in their view than mechanized fulling, for textile manufacturing that fully explain the industrial 'decay' of the old traditional eastern seaboard towns. For rural industrial sites offered not only freedom from urban guild restrictions, guild fees and taxes, but presumably also a much cheaper labour supply, especially for the combing, carding, spinning, and weaving processes, which, according to Miller, accounted for 70 to 90 percent of the value-added labour costs.[69] Most of these critics also contend that such a cost-cutting flight to the countryside became an all the more necessary defence against a supposed influx of 'cheaper' Flemish cloths.[70]

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[66] Cf. E.M. CARUS-WILSON, *Industrial Revolution*, cit., pp. 199, 201: 'the [manorial lords] insisted also that all cloth made on the manor must be brought to the manorial mill and there fulled by the new mechanical method.…'

[67] A.R. BRIDBURY, *Medieval English Clothmaking: An Economic Survey*, London 1982 (Pasold Studies in Textile History), pp. 16-26.

[68] R. HOLT, *Mills of Medieval England,* cit., p. 158: 'it is perfectly clear that a power revolution did not occur in medieval England;' and that 'corn mills alone were generally worth building because flour was the only commodity that was always, everywhere, in demand'. See also T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 82-83, 113-114; L. SYSON, *British Water-Mills*, London 1965, pp. 76-82.

[69] E. MILLER, *English Textile Industry*, cit., pp. 72-74, 77; E. MILLER, J. HATCHER, *Medieval England*, cit., pp. 107-114, 120-127; and especially 95, Table 2.1. They estimated that spinning accounted for 40-50 per cent of manufacturing costs, and weaving for 30-40 per cent; and presumably the spinning-cost estimates including wool-preparation, combing (warps), and carding (wefts).

[70] See E. MILLER, *English Textile Industry*, cit., pp. 74-81; E. MILLER, J. HATCHER, *Medieval England*, cit., pp. 107-124. For similar views, see P.D.A. HARVEY, *The English Trade in Wool and Cloth, 1150-1250: Some Problems and Suggestions*, in *Produzione, commercio e consumo dei panni di lana (nei secoli XXI - XVIII)*, ed. M. SPALLANZANI, Florence 1976 (Istituto internazionale di storia

The only critic to deny that the old, traditional urban cloth industry then faced a genuine 'industrial crisis' or that rural clothmaking had any such advantages was the iconoclastic Anthony Bridbury. For once I have found myself at least partly in agreement with his views, especially in his use of data long ago supplied by Harold Gray, in finding that urban cloth production continued to account for more than half of the cloths exported abroad, until the very late fifteenth century.[71] Much of this production, however, did take place in very different towns, some to be sure in newer centres in East Anglia, though more in western England.

I myself also found (though Bridbury did not) that many of these newer rising clothmaking towns also used water-powered fulling mills, either within or just outside the town walls: in Bristol, Salisbury, Gloucester, Worcester, Exeter (possibly), Colchester, and then many small towns along the Colne and Stour rivers, the boundary between Suffolk and Essex in East Anglia.[72]

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economica 'F. Datini' Prato, Series II), pp. 369-376; A. WOODGER, *The Eclipse of the Burel Weaver: Some Technological Developments in the Thirteenth Century*, in "Textile History", 12, 1981, pp. 59-76. While Harvey's article has much merit, little confidence can be placed in Woodger's paper. For my response to these views see nn. 95, 112 below.

[71] See A.R. BRIDBURY, *Economic Growth: England in the Later Middle Ages*, London 1962, pp. 52-82; IDEM, *English Clothmaking,* pp. 27-36, 62-85; and H.L. GRAY, *The Production and Exportation of English Woollens in the Fourteenth Century*, in "English Historical Review", 39, 1924, pp. 13-55. An attack on Gray's data was offered in: E.M. CARUS-WILSON, *The Aulnage Accounts: A Criticism*, in "Economic History Review", 1st ser., 2, 1929, pp. 114-123; reprinted in E.M. CARUS-WILSON, *Medieval Merchant Venturers: Collected Studies*, London 1954, pp. 279-291; but Bridbury effectively refutes her arguments (which, if valid for the late fifteenth century, are not for the fourteenth). For further evidence of urban cloth production and urban prosperity in this era, see J.N. BARTLETT, *The Expansion and Decline of York in the Later Middle Ages*, in "Economic History Review", 2nd ser., 12, 1959-60, pp. 17-33; H. SWANSON, *The Illusion of Economic Structure: Craft Guilds in Late Medieval English Towns*, in "Past & Present", 121, November 1988, pp. 29-48; H. SWANSON, *Medieval Artisans: An Urban Class in Late Medieval England*, I-II, Oxford 1989; D.J. KEENE, *Survey of Medieval Winchester*, Oxford 1985 (Winchester Studies no. 2), I, pp. 299-316; IDEM, *Textile Manufacture: The Textile Industry*, in *Object and Economy in Medieval Winchester*, ed. M. BIDDLE, Oxford 1990 (Winchester Studies, vol. VII.ii), pp. 200-240; D.J. KEENE, *Textile Terms and Occupations in Medieval Winchester*, in "Ler História", 30, 1996, pp. 135-147.

[72] See the Bristol fullers' ordinances in *The Little Red Book of Bristol*, ed. F. BICKLEY, I-II, Bristol 1900, II, pp. 10-12 (1346), 15-16 (1381), 75-79 (1406); for Salisbury (Wiltshire) and Gloucester, see G. RAMSAY, *The Wiltshire Woollen Industry in the Sixteenth and Seventeenth Centuries*, London 1965, pp. 18-20; for Worcester, see GREAT BRITAIN, RECORD COMMISSION, *Statutes of the Realm*, I-VI, London 1810-22, III, pp. 459-460: 25 Hen VIII c. 18, 1533-34. Exeter is the only one in this list for which fulling-mills have not yet been documented; but for its cloth industry, see M. KOWALESKI, *Local Markets and Regional Trade in Medieval Exeter*, Cambridge-New York 1995. See also K.G. PONTING, *The Woollen Industry of South-West England: An Industrial, Economic, and Technical Survey*, Bath-New York 1971, pp. 15-16. For a verification of the location of fulling-mills in Suffolk and Essex, especially the small towns, see the map published in Pel-

Furthermore, some of the old traditional eastern-seaboard textile towns also achieved a recovery and 'come back' during the later fourteenth century, in particular, York – by far the most successful (until the very late fifteenth century) – Winchester, London, Lincoln, and Leicester.[73] In so doing, the drapers or clothiers of most of these older cloth towns also resorted to fulling-mills, though chiefly in adjacent rural sites.[74] The most interesting case is that of

ham, *Fulling Mills*, cit., which shows 11 such mills (and two more in Norfolk). See nn. 78-81. For the cloth industry in East Anglia, see R.BRITNELL, *Growth and Decline in Colchester, 1300-1525*, Cambridge 1986, pp. 13-21, 76-78; M. GERVERS, *The Textile Industry in Essex in the Late 12th and 13th Centuries: A Study Based on Occupational Names in Charter Sources*, in "Essex Archaeology and History: The Transactions of the Essex Society for Archaeology and History", 3rd series, 20, 1989, pp. 48-49, 69.

73 See also H. SWANSON, *Craft Guilds*, cit., pp. 29-48; IDEM, *Medieval Artisans*, cit., pp. 26-44; J.N. BARTLETT, *Decline of York*, cit., pp. 17-33; M. SELLERS, *The Textile Industries*, in *The Victoria History of the Counties of England: A History of the County of York*, ed. W. PAGE, I-III, London 1907-13, II, pp. 406-429.

74 See nn. 71-72 above and 75-77 below; and for York ordinances permitting fulling just outside the town, see *York Memorandum Book*, ed. M. SELLERS, I-II, London 1911-14 (Surtees Society nos. cxx and cxxv), I, pp. 70-72: *ordinacio fullaris* (c.1390); but see also II, pp. 206-207, for an ordinance of 5 March 1464, by which the town government, seeking to alleviate the recent decline of the urban cloth industry, prohibited anyone within the franchise of York to deliver cloths for fulling to 'any foreyn walker [fuller] to full or to wirk,' with no mention of mills. See also H. SWANSON, *Medieval Artisans*, cit., pp. 41-42 (though emphasising rural advantages for fulling). For Lincoln, see an ordinance issued between 1297 and 1337 requiring fulling-stocks rather than vats, in *English Gilds: Original Ordinances of the Fourteenth and Fifteenth Centuries*, ed. L.T. SMITH, London 1870 (Early English Text Society no. 40), pp. 179-180. For London, see the 1298 ordinance concerning fulling mills outside the city: a ban limited only to fullers, weavers, dyers, but not drapers, last referred to in 1314; drapers were clearly permitted to full their own cloths in Stratford mills; subsequent bans were issued only for fulling hats and caps at the mills. See ed. H.TH. RILEY, *Munimenta Gildhallae Londoniensis: Liber Albus*, *Liber Custumarum*, *et Liber Horn*, I-IV, London 1859-62, I, pp. 127-129; *Calendar of Letter-Books of the City of London at the Guildhall*, ed. R. SHARPE, London 1899-1912, *Letter Book C*, pp. 51-52 (1298); pp. 52-53 (1314); *Letter Book D*, pp. 239-40 (1311). In July 1362, the London civic government issued an ordinance for the 'mistery of Hurers' to require that all caps, hats, and bonnets be fulled and felted by hand only; and on 2 August and 17 September 1376 the Mayor and Aldermen of London forbade any Hurer to full caps at any water-powered fulling mills -- and specifically 'in the mills of Wandlesworth, Oldeford, Stratford, and Enefeld, where the Fullers full their cloths.' *Letter Book H*, p. 36 (July 1362), p. 37 (Aug. 1376), pp. 47-48 (Sept. 1376); see also *Letter Book K*, p. 220 for the Hurers' petition to have this ordinance properly enforced, on 20 November 1437. In 1482-83, Parliament enacted a statute prohibiting anyone in England from fulling hats, bonnets, and caps 'in fulling mills,' for 'in the said mills the said huers [hats] and caps be broken and deceitfully wrought and in no wise by the mean of any Mill may be faithfully made.' *Statutes of the Realm*, cit., II, pp. 473-474, 22 Edwardi IV c. 5. But such bans were never applied to woollen cloths. For an alternative view of some of these bans, see E.M. CARUS-WILSON, *Industrial Revolution*, cit., pp. 194-209; E.M. CARUS-WILSON, *Woollen Industry*, cit., pp. 409-413 (pp. 667-73 in the 1987 edn).

Winchester, in southern Hampshire, which achieved a brief recovery from the mid fourteenth century, though declining once more in the fifteenth. In the 1360s, the bishop of Winchester built a new fulling mill just outside the city, adjacent to a long established civic fulling mill (dating from the 1220s), at Prior's Barton; and its revenues more than doubled between 1370 and 1406, when it was 'farmed' to a Winchester clothier, who subsequently converted the episcopal mill at Durn's Gate into yet another fulling mill (joining another that the city had built in 1402).[75] Furthermore, urban fullers themselves came to operate four of Winchester's fulling mills, which, in Derek Keene's view, 'strengthened the urban industry rather than promoting its migration into the countryside.'[76]

Such evidence therefore, also seems to challenge Carus-Wilson's contention that primary reason why the newer, vibrant English cloth industry came to be concentrated in the hilly, rural West Country and adjacent regions, was that only such regions offered adequate sites for fulling mills: with the very fast-flowing streams to provide more efficient power for undershot water-wheels.[77] That historians can document the existence of thousands of manorial grain mills in the eastern lowland Midlands is, however, not necessarily relevant, because grains mills employ simple rotary mechanisms, while fulling mills necessarily must use the more complicated and more power-consuming reciprocal machinery.[78] The evident disadvantage of the far slower-moving rivers in eastern, lowland England in operating fulling mills might have been overcome with the admittedly costly use of hydro-power dams, and mill-races, especially efficacious for overshot wheels; but, as noted earlier, there is little evidence of any widespread use of such overshot wheels before the sixteenth century – while there is much evidence for fulling mills in these re-

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75 D.J. KEENE, *Medieval Winchester*, cit., I, pp. 304-307; II, pp. 1050-1052, no. 972; II, pp. 1082-1083, no. 1057; IDEM, *Textile Manufacture*, cit., pp. 208-210; IDEM, *Textile Terms*, cit., pp. 40-41. Fulling mill revenues had risen from £7 3s. 0d. sterling in 1370-71 to £16 0s. 0d. in 1400-01.

76 *Ibid.*, p. 141 (quotation); D.J. KEENE, *Medieval Winchester*, cit., I, pp. 302-309; II, pp. 1050-1052, doc. no. 972; II, pp. 1082-1083, doc. no. 1057; D.J. KEENE, *Textile Manufacture*, cit., pp. 208-212.

77 E.M. CARUS-WILSON, *Industrial Revolution*, cit., pp. 183-210 (1954 edn. with some new additions); see E. MILLER, *English Textile Industry*, cit., p. 72.

78 R. HOLT, *Mills*, cit., p. 157, also denying that mills in the south-west, with swifter streams, were any more profitable; but for contrary evidence, see nn. 75-76. The comprehensive map in Pelham, *Fulling Mills*, cit., reprinted in Bridbury, *Medieval English Clothmaking,* p. 18, demonstrates that the very regions cited by Carus-Wilson, for offering the best locations for fulling-mills -- namely the south-west and the north, were the very regions that contained the overwhelming majority of fulling-mill sites.

gions.[79] Another argument that Carus-Wilson might have used (and is perhaps implicit in her publications) is that the much more sparsely settled upland and chiefly pastoral sites of the West Country's fulling mills evidently had much lower opportunity costs, and thus rentals, in comparison with sites in densely populated and grain-producing eastern England, and other parts of the Midlands, with many more competing uses for water.

In any event, if the proof is in the pudding, the indisputable fact is that mechanized fulling became widespread throughout most of the late-medieval English cloth industry, as well as in many continental draperies. Clearly within later-medieval England itself, the majority of those cloth artisans using fulling mills were not servile tenants compelled to do so by oppressive manorial lords exercising their *banalités*. No mill-owner and no clothier or draper, fuller, or other textile entrepreneurs would have invested in and utilized fulling mills unless there had been a clear cost advantage in doing so. Indeed, Carus-Wilson's critics (especially Edward Miller) have been quite unfair and quite misguided in doing so, because the later-medieval, early modern cloth industries of Florence and the Low Countries do offer quite precise data on this issue. They clearly indicate that, first, foot-fulling accounted for about 20 percent of the draper's value-added manufacturing costs; and second that mechanized fulling provided a productivity and cost gain of about 70 per cent over foot fulling – so that mechanized fulling (and tentering together) accounted for only five percent of the entrepreneur's value-added production costs.[80] Using evidence from different sources, Raymond Van Uytven also calculated that the resort to fulling mills in sixteenth-century Brabant similarly provided a 3.3 fold productivity-gain – which is rather more modest than Walter Endrei's undocumented assertion that it provided a 35-fold productiv-

[79] See above pp. 11 and n. 27.

[80] In Leiden and Leuven, in manufacturing high-quality woollens from English wools during 1430s, foot-fulling accounted for 19.8 per cent of the pre-finishing 'value-added' costs: 46d. *groot* Flemish, out of a total of 232.1d (£0.967 *groot*, with £3.094 for the wool, and 214.1d or £0.982 for the dyes, dyeing, and dressing, for a total cost of £4.953 *groot* for a Leuven broadcloth, vs. £4.450 *groot* for a pair of Leiden *voirwollen halvelaken*). In the Medici's Florentine drapery of 1556-58, water-powered fulling (including burling, scouring, and tentering) cost 0.987 florin or 5.1 per cent of the total pre-finishing manufacturing costs of 19.463 florins for a woollen broadcloth whose final price was 43.334 florins (with 12.977 florins for the Spanish wools = 30.0 per cent of the price). See *Bronnen tot de geschiedenis van de leidsche textielnijverheid, 1333-1795*, ed. N. POSTHUMUS, I-VI, The Hague 1910-22, I, *De middeleeuwen*: *passim;* STADSARCHIEF LEUVEN, no. 5058 (1434-35) and no. 5072 (1442-43); R. DE ROOVER, *A Florentine Cloth Firm of Cloth Manufacturers: Management of a Sixteenth-Century Business*, in "Speculum", 16, 1941, pp. 32-33; reprinted in his *Business, Banking, and Economic Thought in Late Medieval and Early Modern Europe: Selected Studies of Raymond De Roover*, ed. J. KIRSHNER, Chicago 1974, pp. 118.

ity gain![81] To be sure, a 1359 fuller's tariff for Aire-sur-Lys (Artois) offered only a 25 percent cost-advantage in mill-fulling over foot-fulling per cloth; but the stipulated rate for the former may conceal a large economic rent for that particular mill-owner.[82]

Fulling mills and foot fulling on the continent: the Low Countries and northern France

Not only in Artois but elsewhere in northwestern France and in the adjacent southern Low Countries – especially in Normandy, Hainaut, the Liège region (the Vesdre), and Brabant – water-powered fulling mills can be found during the thirteenth and early fourteenth centuries, the very era when this region had become predominant in European export-oriented textile production.[83] To be sure, none has been found in Flanders itself during this period. To explain that deficiency – and one that, in her opinion, doomed the Flemish cloth industry to extinction – Carus-Wilson put forth two reasons. First, she asserted that 'Flanders like Lincolnshire is a land of windmills, not watermills,' without bothering to explain why wind-mills could not have been so used for fulling.[84] In any event, she was completely mistaken, because watermills were widely used throughout medieval Flanders and in the adjacent the southern Low Countries. Furthermore, if the *drie steden* – the three great medieval textile towns of Ghent, Ypres, and Bruges – evidently did not employ them for fulling, their governments certainly operated many water-powered grain mills, which supplied significant annual revenues.[85] There was no com-

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[81] R. VAN UYTVEN, *The Fulling Mill*, cit., pp. 1-14; IDEM, *Technique, productivité, et production au moyen âge: le cas de la draperie urbaine aux Pays-Bas*, in *Produttività e tecnologia nei secoli XII-XVII*, ed. S. MARIOTTI, Florence 1981, pp. 285-286; W. ENDREI, *Changements dans la productivité de l'industrie lainière au moyen âge*, in "Annales: E.S.C.", 26, 1971, pp. 1296-1298. See also J. MUNRO, *Textile Technology*, cit., pp. 705-707; and J. MUNRO, *Industrial Entrepreneurship*, cit., pp. 377-388; and J. MUNRO, *Medieval Woollens*, cit., pp. 206-07.

[82] *Recueil de documents relatifs à l'histoire de l'industrie drapière en Flandre*, Ire partie: *des origines à l'époque bourguignonne*, eds. G. ESPINAS, H. PIRENNE, I-IV, Brussels 1906-1924 (Commission Royale d'Histoire), I, pp. 28-32, no. 10 (1358); 36-37, no. 13 (1359); 38-39, no. 15 (1377).

[83] M.A. ARNOULD, *Les moulins en Hainaut au Moyen Age*, in *Produttività e tecnologia*, cit., pp. 183-199; IDEM, *A la recontre des moulins*, in *Moulins en Hainaut*, ed. J.-M. CAUCHIES, Brussels 1987, pp. 27-32; R. VAN UYTVEN, *Fulling Mills*, cit., pp. 1-14, and other sources in nn. 76-77. For a fulling mill at Saint-Omer in 1280, see *Recueil de documents*, cit., III, p. 243, no. 651.

[84] See E.M. CARUS-WILSON, [put in italics]1952 edn., p. 413; but in the 2nd edition (1987), p. 674, she amended that to say that Flanders was 'on the whole a land of windmills,' in response to Van Uytven's evidence on fulling mills.

[85] Examples of water mills in: Bruges, 1292: 'ad molendinum ad aquam', in STADSARCHIEF BRUGGE, *Stadsrekening* 1291-92; account published in *De Rekeningen van de stad Brugge (1280-1319)*, I, *1280 – 1302*, eds. C. WYFFELS, J. DE SMET, Brussels 1965; Bruges, 1352: 'ter Watermuelene ten Wijgaerde', in SAB, *Stadsrekening* 1351-52; Ghent, 1334: 'vanden viere [4] wa-

pelling technological reason why these mills could not have been adapted for fulling, as they were in the eastern lowland towns of late-medieval England.

Her second reason might seem more compelling: supposed prohibitions by the urban cloth guilds, 'which were not less conservative than those in England, and very much more powerful'.[86] Her argument is, however, invalid for three reasons. First, during the medieval heyday of this region's textile industries, up to the Battle of Kortrijk in 1302, the textile *ambachten* lacked any official status and had been powerless to prevent the great capitalist drapers, who had dominated all the major Flemish towns, from employing fulling mills, had they wished to do so. Second, when the aftermath of the urban militia's victory at Kortrijk enabled the cloth guilds to obtain virtual independence, to enter the aldermanic ranks of the towns governments, and then to exert strong influence over industrial regulation in all the leading Flemish towns, nevertheless their governments never issued any such prohibitions.[87] While the cloth guilds did succeed in imposing their guild *keuren* on the draperies of not only the traditional *drie steden* but also on the *nouvelles draperies* of the smaller towns (Kortrijk, Wervik, Comines, etc.), those industrial regulations contain no references to fulling mills – not even the most extensive set, those of Ypres, which, from the mid-fourteenth century, faced severe competition from nearby *nouvelles draperies* in the Leie river valley. Subsequently, though not before the sixteenth century, some of them did employ fulling mills.[88]

Third, during much of this later medieval era, the fullers guilds in the Flemish towns (and indeed in those of Brabant and Holland) were subservi-

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termolne ter Braembruggen boven den temmerwerke', in Stadsarchief Ghent, Stadsrekening 1333-34, reeks no. 400:3(5), fo. 140ro: account published in *Gentsche Stads- en Baljuwsrekeningen, 1280 – 1336*, ed. J. VUYLSTEKE, Ghent 1900, p. 910; Ypres, 1310: 'des moulins a ewe' and in 1325: 'des molins à yauwe à le porte de Messines', in *Comptes de la ville d'Ypres de 1267 à 1329*, eds. G. DES MAREZ, E. DE SAGHER, I-II, Brussels 1909-13, I, p. 294, no. 21 (1309-10): 426-27, no. 36 (1324-25); Ypres, 1406: receipts from the 'watermuelen ter Meesenpoorte, £35 10s 0d *parisis'*, in ALGEMEEN RIJKSARCHIEF BELGIË, *Rekenkamer*, reg. no. 38,635: Stadsrekening, July - Sept. 1406, fo. 2ro.

[86] E.M. CARUS-WILSON, *Woollen Industry*, cit., p. 413 (1952 edn.); modified in 1987 edn., p. 674.

[87] G. ESPINAS, *La vie urbaine de Douai au moyen âge*, I-IV, Paris 1913; IDEM, *La draperie dans la Flandre française au moyen âge*, I-II, Paris 1923; IDEM, *Les origines du capitalisme*, I, *Sire Jehan Boinebroke, patricien et drapier Douaisien (? - 1286 env.)*, Lille 1933 (Bibliothèque de la société d'histoire de droit des pays flamands, picards, et wallons); D. NICHOLAS, *Medieval Flanders,* London 1992, pp. 173-246, 273-316; IDEM, *Town and Countryside: Social, Economic, and Political Tensions in Fourteenth-Century Flanders*, Bruges 1971; IDEM, *The Metamorphosis of a Medieval City: Ghent in the Age of the Arteveldes, 1302 – 1390*, Lincoln 1987, pp. 135-177.

[88] *Recueil de documents,* cit., III, doc. no. 778, pp. 568-585.

ent to the weavers' guilds, whose masters were the major industrial entrepreneurs (and now often in alliance with cloth merchants); and in Ghent the fullers' guild was expelled from the town government in the early 1360s.[89] In the drapery towns of neighbouring Brabant and Holland, the fullers had even less influence with urban governments that merchants and merchant-drapers so strongly dominated; and in Leiden the mercantile *gerecht* brutally suppressed several fullers' strikes and rebellions during the fifteenth century.[90] The often bloodier labour strife between the weavers and fullers guilds in the late-medieval Flemish towns is even more famous. The fullers constituted the only set of wage-earning employees who enjoyed some degree of guild protection and bargaining power, in seeking wage increases. Their weaver-draper employers were generally unwilling to countenance such wage increases, when, as just noted, the fullers' wages already accounted for 20 percent of their value-added production costs, and wage increases could cost them profits or produce losses. Hence the obvious question: why did these weaver-drapers fail to adopt fulling mills, if that would have reduced production costs, avoided long-time destructive strife, and countered the competitive threat from the expanding English cloth trade?

The answer can be found in understanding the reasons why Leuven, a leading drapery town in Brabant, and draperies in Normandy and elsewhere

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89 H. VAN WERVEKE, [put in italics]*De economische en sociale gevolgen van de muntpolitiek der graven van Vlaanderen (1337-1433)*, in "Annales de la Société d'Emulation de Bruges", 74, 1931, pp. 1-15; IDEM, *De koopman-ondernemer en de ondernemer in de Vlaamsche lakennijverheid van de middeleeuwen*, Antwerp 1946 (Medelingen van de koninklijke Vlaamse academie voor wetenschappen, letteren, en schone kunsten van Belgie, Klasse der letteren, no. VIII); D. NICHOLAS, *Metamorphosis of a Medieval City,* cit., pp. 135-177, 235-262; IDEM, *Medieval Flanders*, cit., pp. 242-246; J. MUNRO, *Industrial Entrepreneurship*, cit., pp. 377-388. See also the next note.

90 See documents on Leiden's fullers' strikes in: N. POSTHUMUS, *Bronnen tot de geschiedenis van de leidsche textielnijverheid,* cit., I, pp. 136-143, nos. 121-30; 179-182, nos. 154-59; 224-240, nos. 187-90; 253-254, no. 215; 342-347, nos. 279-82; 616-663, nos. 506-36 [for the years 1435-80]; and also IDEM, *Geschiedenis van de Leidsche lakenindustrie*, I-III, The Hague 1908-1939, I, *De Middeleeuwen, veertiende tot zestiende eeuw* (1908), pp. 308-355, 362-367; K. SPADING, *Streikkämpfe des Vorproletariats in der holländischen Tuchstadt Leiden im 15.Jahrhundert*, in "Wissenschaftliche Zeitschrift der Ernst-Moritz-Arndt Universität Greifswald, Gesellschafts- und sprachwiss. Reihe", 18, 1969, pp. 171-175; M. BOONE, H. BRAND, W. PREVENIER, *Revendications salariales et conjoncture économique: les salaires de foulons à Gand et à Leyde au XVᵉ siècle*, in *Studia Historica Oeconomica: Liber Amicorum Herman Van der Wee*, ed. E. AERTS, B. HENAU, P. JANSSENS, R. VAN UYTVEN, Leuven 1993, pp. 59-74; M. BOONE, H. BRAND, *Vollersproeren en collectieve actie in Gent en Leiden in de 14e en 15e eeuw*, in "Tijdschrift voor sociale geschiedenis", 19, May 1993, 2, pp. 168-192; J. MUNRO, *Industrial Entrepreneurship*, cit., pp. 377-388. For Mechelen, see M. G. Willemsen, *La grève des foulons et des tisserands en 1524-1525 et le règlement général de la draperie malinoise de 1544*, in "Bulletin du cercle archéologique de Malines", 20, 1910, pp. 1-115.

had decided to abandon their own fulling mills sometime during the early fourteenth century. In Van Uytven's view, Leuven itself did so because its drapery had 'switched over' to the production of luxury woollens production for export markets.[91] Evidently the same was true of many draperies in Normandy, where, during the later Middle Ages, only a few fulling mills were retained, principally for *les gros draps bureaux, de grosses et mauvaises laynes*.[92] In several recent publications, I have provided considerable evidence that, from the 1290s to the 1330s, the textile industries of northern France, the Low Countries, and England, once manufacturing a wide range of fabrics, chiefly for the populous Mediterranean markets, had all been forced to forsake export-oriented production of the relatively cheap and light fabrics – says, worsteds, biffes, douken, tiretaines, etc. – to concentrate more and more upon the production of the very high priced, heavy-weight luxury woollens.

The essential incentive or stimulus for this pronounced industrial transformation, from the 1290s, was a very sharp rise in the transportation, marketing, and other transactions costs in international trade; and that in turn was the consequence of widespread, very disruptive warfare throughout the entire Mediterranean basin, Italy especially, and central and north-western Europe (and leading into the Hundred Years' War, from 1336). Unable to set or even influence prices for the cheaper, light fabrics in Mediterranean markets (as 'price-takers'), northern producers found that rising costs made long distance trade in such textiles unprofitable and that only the very high priced ultra-luxury woollens, whose sales price they could determine (as 'price-makers'), could literally 'bear the freight' in late-medieval international trade. [93] One

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[91] R. VAN UYTVEN, *Fulling Mill*, cit., pp. 1-6; R. VAN UYTVEN, *Technique, productivity*, cit., pp. 283-294. For documents on the Leuven fulling mill in Sept. 1298, see F. PRIMS, *De eertse eeuw van de lakennijverheid te Antwerpen, 1226-1328*, in "Antwerpsche archievenblad", 2nd ser., 3, 1928, p. 148, doc. no. 8.

[92] Cited in M. MOLLAT, *La draperie normande*, in *Produzione, commercio e consumo dei panni di lana*, cit., p. 418. The *petites draperies* of Artois (Hesdin, St. Pol, Aire) and the Meuse Valley region (Huy, Liège, Verviers, Maastricht) that continued to use fulling mills evidently also produced only cheap fabrics for local or regional consumption. See *Recueil de documents,* cit., I, pp. 28-32, no. 10 (Aire, 1358); pp. 36-37, no. 13 (Aire, 1359); pp. 38-39, no. 15 (Aire, 1377); II, pp. 689-890, no. 582 (Hesdin-le-Vieux, 1340); pp. 699-700, no. 587 (Hesdin-le-Vieux, 1377); IV, pp. 69-70 (Hesdin-le-Vieux, 1379); III, pp. 336, no. 706 (Saint-Pol, 1383); G. ESPINAS, *La draperie dans la Flandre française au moyen âge*, I-II, Paris 1923, I, pp. 159-160; II, pp. 212-213, 742-746.

[93] J. MUNRO, *Urban Regulation and Monopolistic Competition in the Textile Industries of the Late-Medieval Low Countries*, in *Textiles of the Low Countries in European Economic History*, eds. E. AERTS, J. MUNRO, Leuven 1990 (Studies in Social and Economic History, Vol. 19), pp. 41-52; reprinted in J. MUNRO, *Textiles, Towns, and Trade*, cit.; J. MUNRO, *Industrial Transformations in the North-West European Textile Trades, c. 1290-c. 1340: Economic Progress or Economic Crisis?*, in *Before the Black Death: Studies in the 'Crisis' of the Early Fourteenth Century*, ed. B.M.S. CAMPBELL, Manchester-New

immediate consequence of those rising transaction costs, from as early as the 1290s, was the rapid decline of the Champagne Fairs, which, as Patrick Chorley has demonstrated, had earlier been heavily dependent on the international trade in cheaper textiles.[94] In my view, these adverse circumstances also explain the decline of England's eastern seaboard textile towns, which had been even more dependent than the Flemish on the export of cheaper textiles to the Mediterranean basin. The English draperies also took far longer to reorient their textile production, not until the 1360s, when Baltic markets for worsteds experienced similar difficulties. From that very decade the rapid expansion in exports of heavy-weight English woollens mirrors the sharp decline in worsted exports.[95]

Why then did the draperies in the later-medieval Low Countries, including the *nouvelles draperies*, refuse to follow their dreaded rival, the newly expanding English woollen-cloth industry, in using the fulling mill? The English cloth industry's chief cost advantage did not, in fact, lie in the fulling mill – important though it may have been – but in its low-cost, tax-free access to same very high quality wools used in the continental luxury draperies. The primary if not sole determinant in the manufacture of ultra- luxury quality broadcloths – in the Low Countries, Normandy, Italy, and Catalonia – was in fact the finer English wools (from the Welsh Marches and the Cotswolds), whose

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York 1991, pp. 110-148; reprinted in J. MUNRO, *Textiles, Towns, and Trade*, cit.; IDEM, *The Origins of the English 'New Draperies': The Resurrection of an Old Flemish Industry, 1270-1570*, in *The New Draperies in the Low Countries and England, 1300-1800*, ed. N.B. HARTE, Oxford-New York 1997 (Pasold Studies in Textile History no. 10), pp. 35-127; J. MUNRO, *The Low Countries' Export Trade in Textiles with the Mediterranean Basin, 1200-1600: A Cost-Benefit Analysis of Comparative Advantages in Overland and Maritime Trade Routes*, in "The International Journal of Maritime History", 11, 1999, 2 pp. 1-30. See also the next note.

[94] P. CHORLEY, *The Cloth Exports of Flanders and Northern France During the Thirteenth Century: A Luxury Trade?*, in "Economic History Review", 2nd ser., 40, 1987, pp. 349-379; J. MUNRO, *The 'New Institutional Economics'*, cit.

[95] J. MUNRO, *The 'Industrial Crisis' of the English Textile Towns, 1290-1330*, in *Thirteenth-Century England:* VII, ed. M. PRESTWICH, R. BRITNELL, R. FRAME, Woodbridge 1999, pp. 103-141; J. MUNRO, *Anglo-Flemish Competition in the International Cloth Trade, 1340-1520*, in "Publication du centre européen d'études bourguignonnes", 35, 1995, pp. 37-60 [*Rencontres d'Oxford (septembre 1994): L'Angleterre et les pays bas bourguignonnes: relations et comparaisons, XVe-XVIe siècle*, ed. J.-M. CAUCHIES]; J. MUNRO, *The Symbiosis of Towns and Textiles: Urban Institutions and the Changing Fortunes of Cloth Manufacturing in the Low Countries and England, 1270-1570*, in "The Journal of Early Modern History: Contacts, Comparisons, Contrasts", 3, 1999, 1, pp. 1-74. Mean annual English cloth exports, just 5,491 pieces (24 yards by 1.75 yds) in 1351-60, rose from a mean of 13,122 pieces in 1351-60 to a peak of 39,150 pieces in 1391-1400, then fell to one of 27,580 in 1411-20, and then expanded to a new peak of 51,151 pieces in 1441-50; with a mid-century depression they fell to a nadir of 33,225 pieces in 161-70 and then rapidly expanded over the next 80 years, achieving their final peak of 126,623 pieces in 1451-40.

export was burdened with *specific* denizen duties (much higher for aliens) that amounted to 52 percent of the mean domestic price for better quality wools, by the early fifteenth century.[96] Contemporary evidence from various traditional draperies in the Low Countries indicate that these tax-burdened English wools accounted for as much as 76 percent of the value of woollens before finishing (dyeing and dressing: of 62.5 percent of the final price); and that industrial labour itself accounted for only 15 to 20 percent of the pre-finishing manufacturing costs.[97]

As noted earlier, even before the English cloth trade had become a discernible threat, the Low Countries' draperies (including the Dutch newcomer, at Leiden, from the 1360s), had decided that their sole path to industrial salvation lay in exporting fine woollens, while continuing to produce cheaper fabrics for domestic consumption. Because the Low Countries' draperies could not match English costs in producing woollen broadcloths, certainly not from the 1360s, and could compete only through offering demonstrably superior quality in craftsmanship, especially in the fulling and finishing processes, they thus chose to seek out a safe niche in the very upper end of the European luxury market.[98] In doing so, they were selling their finer woollens at prices about three to four times higher than the typical prices for English broadcloths (during the later fourteenth and fifteenth centuries). For that matter, the leading Flemish *nouvelles draperies* – those of Wervik, Kortrijk, Menen, Comines, and Armentières -- who came to thrive by selling cheaper imitations of the *drie steden*'s heavy-weight luxury woollens, were nevertheless selling them for two or three times the prices of English broadcloths.[99] Flem-

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[96] See J. MUNRO, *Wool Price Schedules*, cit., pp. 118-169; IDEM, *Industrial Protectionism in Medieval Flanders: Urban or National?*, in *The Medieval City*, eds. H. MISKIMIN, D. HERLIHY, A.L. UDOVITCH, New Haven-London 1977, Table 13.1, pp. 254-255, reprinted in J. MUNRO, *Textiles, Towns, and Trade*, cit.; IDEM, Industrial Entrepreneurship, pp. 377-388; IDEM, *Medieval Woollens*, cit., Table 1, p. 299; and the sources cited in nn. 58-60, 93, 95.

[97] See tables on cloth production in J. MUNRO, *Industrial Protectionism*, cit., Table 13.2, p. 256 (for Leuven 1434, 1445: 76.6 per cent and 55.1 per cent); IDEM, *Medieval Scarlet*, cit., Table 3.12, p. 52 (for Ypres, in 1501: 64.3 per cent).

[98] In 1363 the English crown made the newly acquired port of Calais the official and sole staple for the sale of wools to northern Europe, and granted quasi-monopoly powers to the Company of the Staple, to ensure that the full tax incidence was passed on to the foreign buyers rather than to the domestic wool growers. All of the statistical evidence indicates that the major drop in English wool sales and the output of the Flemish and Brabantine draperies date from this decade. See T.H. LLOYD, *The English Wool Trade in the Middle Ages*, Cambridge 1977; and sources cited in nn. 95-96; and also J. MUNRO, *Medieval Woollens*, cit., Tables 1-10, pp. 299-324.

[99] J. MUNRO, *Industrial Protectionism*, Tables 13.3, pp. 257-263; table 13.5, pp. 266-267; IDEM, *Medieval Scarlet*, cit., table 3.6-3.8, pp. 42-44; Table 3.11, pp. 48-51; IDEM, *Industrial Transforma-*

ish and Dutch archival sources for the 1430s further indicate that if mechanical fulling had been used instead, with the aforementioned productivity ratios, the drapers would have been able to reduce the wholesale price of their finer woollens by only three percent at best.[100].

That certainly would not have offered the Flemish draper any prospect of enhancing his profit margin, certainly not if using the fulling mill would have threatened his sales, indeed the likely loss of many customers in European cloth markets. For most drapers in the late-medieval Low Countries believed the contemporary opinions that the incessant pounding of those heavy oaken hammers damaged the textures cloths woven from the very fine, thin fibres, if not perhaps those of medium grade woollens, such as those that the English were then exporting. Even if these fears were exaggerated, the Low Countries' draperies and cloth merchants were clearly unwilling to risk debasing their reputations, and the validity of their cloth seals that still guaranteed them an ample supply of customers, by experimenting with fulling mills.[101] Indeed, contemporary Catalan records indicate that, while fulling-mills were widely used in the production of cheaper woollens in fifteenth-century Barcelona, foot-fulling was still mandatory for the finest quality woollens, also made exclusively from the very best English wools.[102]

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tions, cit., Appendix 4.1, pp. 143-48; IDEM, *New Draperies*, cit., table 1, p. 39-40; table 4, pp. 49-50; IDEM, *Medieval Woollens*, cit., Table 10, pp. 318-24.

100 A potential 75 per cent cost-saving from mechanized fulling of two *voirwollen halvelakenen* at Leiden in 1435 and 1449 (75 per cent of 46d) represents only 3.23 per cent of their price, £4 9s 0d *groot*; and only 2.73 per cent of the £7 0s 0d *groot* price for a Ghent *dickedinnen* in 1436. Fulling costs from *Bronnen leidsche textielnijverheid*, cit., I, pp. 136-139, nos. 121, 124. Prices from GEMEENTE ARCHIEF TE LEIDEN, *Diversche Rekeningen*, no. 999; ARCHIEF DER SECRETARIE VAN DE STAD, no. 522, fo. 92-3; STADSARCHIEF GENT, *Stadsrekening, Reeks* 400:15, fo. 15ro. See also J. MUNRO, *Industrial Entrepreneurship*, cit., pp. 377-385; IDEM, *Symbiosis of Towns and Textiles*, cit., pp. 1-74. See the following note.

101 On contemporary views about the impact of mechanical fulling on quality, see *Statutes of the Realm*, II, pp. 474-475 (22 Edwardi IV c. 15, 1482-83), and n. 74 above; M. MOLLAT, *La draperie normande*, cit., pp. 403-422; in particular with reference to the proposed fulling-mill at Louviers: 'on l'accusait de ruiner le renom acquis par la production de Louviers sur la plan international...' (p. 418); R. VAN UYTVEN, *Fulling Mills*, cit., pp. 1-14; and R. VAN UYTVEN, *Productivity*, cit., p. 285, citing a text of 1403, contrasting the superiority of foot-fulled cloths from Lormaye (Nogent-le-Roi) with mill-fulled cloths from Chartres. See also E.M. CARUS-WILSON, *Woollen Industry*, cit., (1987 edn), p. 675; H. SWANSON, *Medieval Artisans*, cit., pp. 41-42. On cloth seals, see W. ENDREI, G. EGAN, *The Sealing of Cloth in Europe, With Special Reference to the English Evidence*, in "Textile History", 13, Spring 1982, pp. 47-76.

102 See C. CARRERE, *Barcelone: centre économique à l'époque des difficultés, 1380-1462*, I-II, Paris 1967, I, pp. 448-452. As is well known, the Florentine cloth industry was using fulling mills along the Arno; but it is not clear whether they were in fact used for the higher-priced luxury cloths, or just the cheaper woollens produced for local and regional consumption.

Certainly evidence from the following century clearly indicates that there had been no other economic, physical, or institutional barriers to the establishment of fulling mills in the late-medieval Low Countries. For, from the early to mid-sixteenth century, when vastly changed circumstances in international trade – including the final victory of the English woollen cloth trade – once more encouraged the export of cheaper fabrics from the Low Countries, a number of the Flemish *nouvelles draperies* along the Leie valley – who had earlier steadfastly eschewed fulling mills – now adopted them for the production of their new fabrics: including bays and other semi-woollens.[103] So, during this same century, did many drapers in neighbouring Brabant, especially at Leuven (again) and Hasselt, in manufacturing similarly cheaper quasi-woollen fabrics.[104]. For England's own cloth industry, some evidence suggests that for its admittedly small sector devoted to producing scarlets and other very costly ultra-luxury woollens (in London and Salisbury), foot-fulling continued to be practised.[105]

VIII. GIG MILLS: FOR RAISING THE NAP ON WOOLLEN CLOTHS

Furthermore, the English cloth industry in general stoutly resisted another related invention of the early fifteenth century (first documented in 1435): the water-powered gig mill. It mechanised the napping processes in cloth finishing (teaselling, raising, rowing), by rapidly rotating metal cylinders containing compacted teasels across the front and back of the cloth, attached to a slowly moving leather belt (passing the cloth from one cylinder below to the other one above).[106] They were usually attached to or formed part of fulling mills, all the more so because, as noted earlier, the fullers usually

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[103] See Wervik's drapery *keure* of 1397, which also contains no references to fulling mills. *Recueil de documents relatifs à l'histoire de l'industrie drapière en Flandre*, IIe partie: *le sud-ouest de la Flandre depuis l'époque bourguignonne*, eds. H. DE SAGHER, et al., I-III, Brussels 1951-66, III, no. 554, pp. 452-478.

[104] R. VAN UYTVEN, *La draperie brabançonne et malinoise du XIIe au XVIIe siècles: grandeur éphemère et décadence*, in *Produzione, commercio e consumo dei panni di lana*, cit., pp. 85-97; R. VAN UYTVEN, *Fulling Mill*, cit., pp. 1-14; H. DE SAGHER, *Recueil de documents,* cit.. For changes in the international textile trade, see eds. E. AERTS, J. MUNRO, *Textiles of the Low Countries in European Economic History*, Leuven 1990 (Proceedings of the Tenth International Economic History Congress, Studies in Social and Economic History, Vol. 19); J. MUNRO, *Low Countries' Export Trade*, cit., pp. 1-30; IDEM, *The New Institutional Economics*, cit., pp. 1-47, especially tables 4-5; IDEM, *Patterns of Trade*, cit., pp. 163-180.

[105] See sources cited above in n. 95 and below in n. 109.

[106] E.M. CARUS-WILSON, *The Woollen Industry*, cit. (1952 edn), pp. 423-424, contending that a gig-mill was listed in the possessions of William Haynes, on his death in 1435. See: J. MUNRO, *Textile Technology*, cit., pp. 707-708;

commenced the finishing processes by engaging in 'wet-napping', with a preliminary teaselling. In the Parliament of 1463-64, a petitioner, in recommending various reforms of the cloth industry, demanded a ban on the use of all 'Gygmylles', contending that they were inflicting 'grete disceit ... in wirkyng of Woollen Cloth';[107] but the crown's response in the official statute enacted the following year merely required that all fullers, engaging in such 'wet-napping', 'shall exercise and use Taysels and no [wire] Cards'.[108] One may suspect that the real reason for the petitions was a fear of technological unemployment; for, according to a seventeenth-century report (1640), two men and a boy operating a gig-mill could perform the tasks done manually by eighteen men and six boys (reducing the total labour time from 100 hours to 12 hours, thus providing almost a 9:l gain in productivity).

But in view of the still declining population and labour scarcity in the 1460s, the more likely reason was indeed that expressed in the petition: a legitimate concern about impairing quality. Certainly many observers, then and later, believed that the gig-mill, by its very rapidity and rigidity, impaired the texture and weakened the fabric of cloth, and that the best quality was ensured by the much slower and more plastic actions of the hand-teaseller, undertaken discretely between repeated shearings.[109] Not until 1551-52 did Parliament itself officially ban the use of this machine, in a statute that similarly contended that 'the Draperie of this Realme ys wonderfullye empairyred

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[107] Great Britain, PARLIAMENT, *Rotuli parliamentorum ut et petitiones et placita in Parliamento*, I-VI, London 1767-77, V, pp. 502-503.

[108] Great Britain, *Statutes of the Realm*, cit., II, pp. 403: statute 4 Edward IV c. 1 (1464-65). The statute contended that such use of metal cards was 'deceitfully impairing the same Cloth'. The introduction to this statute complained that recently: 'the Workmanship of Cloth and Things requisite to the same is and hath been of such Fraud, Deceit, and Falsity that the said Cloths in other Lands and Countries be had in small Reputation'. The petitioner had also demanded a ban on such cards, as well as on gig mills. See the previous note.

[109] See E. Kerridge, *Textile Manufactures in Early-Modern England*, Manchester 1985, p. 173, contending that 'the use of the old gig mills was bad practice, for their wire teeth were much harsher than the hooked bracts of the fruiting heads of two-year-old king teasels'; and he cites a contemporary observer, who claimed that 'the heart of the thread is fretted and almost dissolved by the gig-mill, which maketh the cloth wear ill and quickly wear out'. See also K. PONTING, *Woollen Industry,* cit., pp. 24, 71-74; and a drawing of a fifteenth-century cloth-raising machine in *Leonardo da Vinci: Drawings of Textile Machines*, ed. K. PONTING, Leeds 1979, p. 68, no. 31. The late Kenneth Ponting, descended from generations of West Country clothiers, former editor of *Textile Industry*, and a personal friend, told me personally that producers of good quality and especially 'superfine' woollens insisted on the use of hand teasels into modern times.

and the Clothe deceitfully made, by reason of using the said Gigg Mill'.[110] Nevertheless, some use of gig mills can be documented throughout the sixteenth and following centuries, especially in Gloucestershire, though possibly they were confined to finishing cheaper quality woollens.[111]

The strong opposition to mechanical innovations to be found among so many medieval and even early-modern producers of luxury quality-woollens was not, however, restricted to just water-powered machinery. Guild regulations from various draperies in the Low Countries and France indicate bans as well on the use of both the spinning wheel and wire-cards (i.e., for carding wools) in preparing woollen warp yarns (the yarns stretched between the warp and cloth roller-beams). Although together they increased productivity at least three-fold, the yarns were weak, uneven, with insufficient twist, and 'too many knots' (*Livre des mestiers*, at Bruges, c. 1349), compared to the very fine but very strong yarns spun on the traditional hand-held drop-spindle. Such concerns about strength and quality may have been alleviated, however, by the fifteenth-century introduction of the Saxony Wheel, which permitted continuous drafting, spinning, and winding on of the yarns, with superior strength and better, more homogenous quality. On the other hand, all medieval draperies fully welcomed and quickly adopted the most important innovation in medieval textiles: the horizontal, foot-operated, treadle loom, which evolved, from the eleventh to thirteenth centuries, into the full-fledged broadloom. For clearly it not only vastly increased the productivity but even more so the quality of woven cloth (compared to the earlier, vertical or warp-weighted looms).[112]

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110 Great Britain, *Statutes of the Realm*, cit., IV/1, p. 156: statute 5-6 Edwardi VI, c. 22, 'An Acte for the Puttinge Downe of Gygg Mills' (1551-52). The penalty of forfeiture and five pounds sterling (the equivalent of 160 days wages for an Oxford master mason at 7.5d per day) was a severe one.

111 Mention should also be made of the invention of the water-powered shearing-machine, first documented (at least in England), in a patent of 1794; and by the 1840s, both gigmills and shearing mills (with more refined machinery) were widely accepted in the woollen cloth industry. P. RAMSAY, *The Wiltshire Woollen Industry,* cit., pp. 13, 24; J. DE LACEY MANN, *The Cloth Industry in the West of England from 1640-1880*, Oxford 1971, pp. 133-138, 141-146, 151, 160-161, 189, 245-246, 298-307.

112 *Le livre des mestiers: dialogues français-flamands composés au XIVe siècle par un maître d'école de la ville de Bruges,* ed. H. MICHELANT, Paris 1875; W. ENDREI, *L'evolution des techniques du filage et du tissage: du moyen âge à la revolution industrielle,* trans. by Joseph Takacs and Jean Pilisi, Paris-The Hague 1968 (École Pratique des Hautes Études-Sorbonne, Vie section: Industrie et artisant no. 4); IDEM, *Changements dans la productivité de l'industrie lainière au moyen âge*, in "Annales: E.S.C.", 26, 1971, pp. 1291-1299; M. HOFFMANN, *The Warp-Weighted Loom: Studies in the History and Technology of an Ancient Implement*, Oslo 1964; P. CHORLEY, *The Evolution of the Woollen, 1300 - 1700*, in *The New Draperies in the Low Countries and England, 1300-1800*, ed. N.B. HARTE, Oxford 1997 (Pasold

IX. THROWING MILLS IN THE SILK INDUSTRY

Nor did water-powered machinery prove to be an obstacle to ensuring quality in the most-luxury oriented of all the textile industries: namely, the silk industry, whose very origins in thirteenth-century Italy were evidently based upon the adoption and diffusion of the silk-throwing machine, to produce silken yarns. Although Reynolds asserts that there is no documentary proof of water-powered throwing mills before Vittorio Zonca's illustration of one (in Italy), in 1607, other evidence indicates that, in1272, a Lucchese textile artisan and a refugee in Bologna, named Borghesano, constructed a silk-throwing machine there, evidently one that was water-powered.[113] The fully-developed machine had two concentric wooden structures, an inner one that revolved on the axle of the water-wheel and the outer fixed, stationery framework, which supported two rows of twelve horizontal reels (swifts), each of which was fed by ten revolving spindles below (for a total of 240 spindles). Attached to the revolving inner framework were spokes (blades) that made intermittent contact with grooved drum-gears on the outer framework, which, in turn rotated the spindles and then the reels at different speeds. The silk filaments were wound onto the rotating bobbin within the spindle, and then were fed from the bobbin through eyelets of an S-shaped wire 'flyer' on to the swift-reels above. This machine thus effected a continuous process of upward drafting of the filaments, twisting, and winding-on to the reels, producing a strong and thoroughly homogenous good quality yarn (as the Saxony Wheel later did for woollens). Subsequently, in the later fourteenth and fifteenth centuries, silk-throwing mills in Florence and Venice doubled the rows of reels, with 480 spindles. Such machines permitted from

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Studies in Textile History no. 10), pp. 7-34; J. MUNRO, *Textiles*, in *Medieval Latin: An Introduction and Bibliographical Guide*, eds. F.A. MANTELLO, G. RIGG, Washington D.C. 1996, pp. 474-484; J. MUNRO, *Textile Technology*, cit., pp. 694-705; IDEM, *The New Draperies*, cit., pp. 51-53; and more fully in IDEM, *Medieval Woollens*, cit., pp. 191-204; A.P. USHER, *Mechanical Inventions*, cit., pp. 267-269. Not to be trusted however is A. WOODGER, *Eclipse of the Burel Weaver*, cit., pp. 50-76 (see n. 70 above).

113 T.S. REYNOLDS, *History of the Vertical Water Wheel*, cit., pp. 79-80 (with figure 2-20), 116, 136-37. For the following see A.P. USHER, *Mechanical Inventions*, cit., pp. 275-276 (and figures 96-97, showing Vittorio Zonca's 'Piedmont' silk mill; see n. 51); W. ENDREI, *Evolution des techniques du filage*, cit.; W. ENGLISH, *A Study of the Driving Mechanism in the Early Circular Throwing Machines*, in "Textile History", 2, 1971, pp. 65-75, 107-12 (plates); R. PATTERSON, [put in italics]*Spinning and Weaving*, in *A History of Technology*, cit., II, pp. 191-200; J. MUNRO, *Silk*, in *Dictionary of the Middle Ages*, cit., XI, pp. 293-296. Usher cites E. PARISET, *Les industries de la soie*, Paris 1862-65, p. 115 [unavailable to me], contending that Borghesano's Bologna machine was basically like that depicted by Zonca; but Usher doubts (p. 276) 'that mills were built in the earlier period on the scale indicated by Zonca' (see n. 56 above).

two to four operatives to displace several hundred hand-throwsters in producing silk yarn in no way inferior in quality. As is much better known, an English entrepreneur named Thomas Lombe established England's first water-powered factory, in the Derwent near Darby, in 1717, in the form of an immense silk-throwing mill, five stories high, and 150 metres long.[114] But the road to the modern industrial revolution did not, of course, follow the route of silk-manufacturing, which could not (even with intermixed fibres) be based upon mass consumption.

X: Water-powered machines in the 'Industrial Revolution' in cotton manufacturing

For those who still believe in the concepts of the Industrial Revolution, that road to modern industrialization did indeed begin with textiles but, as is so well known, with relatively cheap cotton fabrics, indeed with the cotton yarn itself. Less well known is the fact that before the machines of this Industrial Revolution, Europeans, equipped only with spinning wheels, and no longer willing to expend the human energy required for spinning with traditional drop-spindles, could not in fact produce an all cotton fabric with the durability and quality of Indian calicoes and especially muslins. What Europeans, borrowing techniques from Islamic Egypt and Spain, had been producing as a cotton-based textile, from the twelfth century CE, were instead *fustians*, whose warp yarns were necessarily made from the far stronger linen (flax) yarns, sufficiently strong to withstand the stress of being stretched between the loom's two roller beams (warp and cloth) and pulled apart by heddles to allow the passage of the shuttle containing the cotton weft yarns.[115]

The problems in producing suitable cotton warp yarns were akin to those just discussed for spinning medieval woollen warp yarns (at least before the arrival of the Saxony Flyer), but far more severe. There was, however, probably little incentive to solve them so long as increasing restrictions on the importation of Indian calicoes and muslins allowed the native fustians industry in Lancashire to gain a more or less captive domestic market, while the East India and Royal African Companies continued to enjoy an ample re-export

[114]. T.S. Reynolds, *History of the Vertical Water Wheel*, cit., pp. 136-167; A. Wadsworth, J. De Lacy Mann, *The Cotton Trade and Industrial Lancashire, 1600-1780*, Manchester 1931; reprinted 1965, pp. 106-108; J. Mokyr, *Lever of Riches*, cit., p. 68, contending that the water-wheel drove 25,000 smaller wheels and reels.

[115] See M. Mazzaoui, *The Cotton Industry of Northern Italy in the Late Middle Ages, 1150-1450*, in "Journal of Economic History", 32, 1972, pp. 262-86; idem, *The Italian Cotton Industry in the Later Middle Ages, 1100-1600*, Madison 1981.

trade in these Asian textiles. But disruptions to the supplies of these textile and of fine Indian cotton yarns, from the disintegration of the once so powerful Mughal Empire (with the death of Aurangzeb, in 1707), especially in the anarchic 1720s, created both a predicament and the necessary opportunity and incentives to innovate:[116] to allow the English fustians industry to transform itself and expand by capturing some foreign markets in cotton textiles.

The central problem to be resolved, therefore, was a low cost means of producing cotton yarns strong enough to serve as warps and yet fine enough to rival the better Indian textiles. The tripartite solution was, of course, supplied by those three classic innovations that commenced the Industrial Revolution in cotton textiles: the Spinning Jenny, the Water-Frame, and the Mule. As stressed earlier, in the beginning of this study, that revolution did commence with watermills; and hence the very term 'cotton mills', lasting well into the steam era. Only the last two were water-powered machines, for the first, Hargreaves' Spinning Jenny (c.1764-70), used the same principle of the foot-powered spinning wheel and belt-transmission of power, to rotate not one, but eight and then ultimately 100 spindles, with a movable carriage containing the cotton rovings, to attenuate and thus increase the fineness of the yarns as they moved away from the rotating spindles. The yarns, however, lacked the strength to serve as warps on the loom; and the task of producing strong such warp yarns was achieved by Arkwright's Water-Frame (1768-69), with water-powered rollers or throstles to feed out the yarn. He also succeeded in establishing England's first cotton mill or factory, at Nottingham (though one originally using horses). Nevertheless, although the strong warp yarns produced by the water-frame did achieve one quality-oriented objective -- in spinning an homogenous yarn that would hold fast Turkey Red dyes – they were still too coarse to produce woven fabrics that would match the quality of Indian textiles.

Hence the significance of the third stage of the early Spinning Revolution. For Crompton's aptly named Mule (c. 1774-79) combined the optimum elements of the Spinning Jenny, in using the moving carriage, to attenuate and increase the fineness of the yarns, and the throstles of the Water-Frame to provide the strength of the best made contemporary Indian cotton yarns. In cottons, the fineness of the yarn is indicated by the s-count; and with further improvements, by 1790, Crompton's water-powered mules (with at least 80 and up to 300 spindles) could produce yarns with 80s and then 100s count, rivalling the fineness of the best Indian yarns, compared to just a 20s

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[116] See R. LOPEZ, TH. BARNES, J. BLUM, R. CAMERON, *Civilizations Western and World*, I, *From Prehistory to the End of the Old Regime*, Boston 1975, pp. 446-449.

count for traditional wheel-spun wefts and early jennies. Of course labour-cost considerations were important in this matrix of inventions. Thus a comparison with contemporary Indian spinning techniques should be noted: in order to spin 100 lb. of cotton yarn with 80s count, Indian hand spinners required over 50,000 hours; but Crompton's improved water-powered mule had, by 1800, reduced that to just 300 hours. Robert's self-acting steam powered mule of 1825 could spin the same quantity (and quality) in just 125 hours – but hardly as revolutionary a change as that effected by the water-powered mule.[117]

If the mechanical innovations, and especially water-powered machines, of medieval and early modern Europe often – though not always – sacrificed some quality to achieve productivity gains, such was not the case with the application of water-power in the textile industries of the modern Industrial Revolution, whose initial goals were more often oriented to quality improvements than to labour-saving productivity gains, even if the latter were a highly valued bye-product of those innovations. For the Industrial Revolution in metallurgy, water-powered machinery was also crucial, as noted earlier, in permitting the initial breakthrough in coke-smelting; though it should be noted that the subsequent 'revolution' in producing wrought iron with coke fuels and steam power did not initially produce as highly a refined quality product as did the traditional charcoal-based process.[118]

Of course severe impediments still remained in the application of water-power in terms of industrial location and opportunity costs, variable supplies of power, and relative capital investments. Thus the subsequent history of modern industrialization in the nineteenth and early twentieth centuries came to be much more based on steam power (and other power sources derived from coal – including electricity). Yet, as Nicholas von Tunzelman has demonstrated, early steam engines were often less efficient or cost-effective than water mills; and the industrial changes based on steam-power were slow to be diffused in replacing water power, and with an impact that was far from revolutionary.[119] The role of water power, despite the limitations, should never be

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[117] S. Chapman, *The Cotton Industry in the Industrial Revolution*, London 1972, p. 20; Ch. Mukerji, *From Graven Images: Patterns of Modern Materialism*, New York 1983, pp. 166-142 (especially important for dyeing cotton); A. Wadsworth, J. De Lacy Mann, *The Cotton Trade*, cit., pp. 472-502; J. Mokyr, *Technological Change*, *1700-1830*, in *The Economic History of Britain Since 1700*, eds. R. Floud, D. McCloskey, I, *1770-1860*, Cambridge 1994 (2nd revised edn.), pp. 12-43. Crompton's original mule required about 2,000 hours to produce 100 lb. of cotton yarn.

[118] See n. 53 above.

[119] G.N. von Tunzelmann, *Steam Power and British Industrialization to 1860*, Oxford-New York 1978.

discounted in recounting the history of western Europe's economic and industrial development, to surpass the rest of the world, certainly by the eighteenth century, if not well before.[120]

[120] For the current debate about how, when, where, and why the West finally superseded the rest of the world in economic power, see: D.S. LANDES, *The Wealth and Poverty of Nations: Why Some Are So Rich and Some So Poor*, New York-London 1998; K. POMERANZ, *The Great Divergence : Europe, China, and the Making of the Modern World Economy,* Princeton 2000.

INDICE