

Prof. John H. Munro
Department of Economics
University of Toronto

munro5@chass.utoronto.ca
john.munro@utoronto.ca
<http://www.economics.utoronto.ca/munro5/>

3 November 2010

ECONOMICS 303Y1

The Economic History of Modern Europe to 1914

Prof. John Munro

Lecture Topic No. 8:

**II. GREAT BRITAIN AS THE HOMELAND OF THE INDUSTRIAL
REVOLUTION, 1750-1815**

I. The Revolution in Mechanical Power: the Steam Engine

I. The Revolution in Mechanical Power: the Steam Engine
The Economic History of a Capital-Goods Manufacturing Industry

1. Introduction: on the Industrial Importance of Coal: its relations to Steam and Iron

i) **The very heart and essence of the British Industrial Revolution**, from about the mid 18th century, and of modern industrialization everywhere in the 19th century was:

- (1) coal itself, as an industrial fuel, with a wide variety of applications
- (2) coal-fired steam power, so vitally necessary for the industrial revolutions in both in metallurgy (iron and then steel) and textiles (cottons, and then woollens, etc.)
- (3) then purified coal, in the form of coke, as an even better and necessary fuel for iron and steel
- (4) an industrial revolution in iron manufacturing: using both coke fuels and steam power.

ii) **This importance is exemplified by this observation from an economic geographer:**

- (1) ‘An industrial map of Europe in the 19th century was essentially a map of its coal fields.’
- (2) We will see the truth of this statement, not only in examining the Industrial Revolution in Great Britain, from the 1760s, but also continental industrialization from 1815 to 1914: from the Napoleonic Wars to World War I.
- (3) A major factor for this is transportation and marketing costs: given the overwhelming need for coal, it was usually cheaper to locate industries as close as possible to coal-fields
- (4) for reasons we will also see, coal and coal-fired steam power become essential ingredients in urbanization: urban industrialization.

iii) **the environmental costs of coal-based industrialization: global warming**

- (1) coal is an exceptionally dirty fuel, as opposed to what it displaced: wood-based charcoal
- (2) but its use in iron-manufacturing, and other forms of manufacturing, to be investigated in the next lecture, meant the creation and dispersion in the atmosphere of immense amounts of carbon dioxide
- (3) and that of course has provided an important component of global warming, whose disastrous consequences for the future should not be underestimated.

iv) **England’s primacy in the use of coal for industrial purposes:**

- (1) As I have sought to demonstrate in ECO 301Y, England was the first country in the world to embark on a new coal-based technology for industrialization: as early as the 16th century
- (2) That gave England a two-centuries’ head start over all other countries
- (3) And supplies another reason why England became the homeland of the Industrial Revolution.

b) **Consider that the European and indeed world economy before modern industrialization was one based on both wood and water:** on which I shall elaborate in a moment

- (1) wood for fuel, wood for construction, wood for shipbuilding
- (2) and water: water -power from water-mills
- (3) wind power: in two respects

- wind power from wind-mills: but in England only about 10% of power derived from water
- wind-power: to operate sailing ships: far more important

c) **In the words of views of the famous British economic historian,**

i) **Anthony Wrigley (Cambridge):** on the transition from an advanced early modern European economy to the more fully advanced industrial economy represented the shift from ‘an advanced organic economy’ [wood and water] to ‘mineral-based’ economy:

ii) **in the form of coal fuels:** and the more advanced form of coal fuels in the form of coke (purified coal – pure carbon), and of course coal-fired steam power.¹

d) **For most of us economic historians, the modern British Industrial Revolution, has three key components on which these following lectures are based:**

i) **those key components, whose importance will be seen later were all-coal based:**

- (1) steam power,
- (2) iron manufacturing, and
- (3) cotton-textile manufacturing

ii) **I am going to emphasize the primary importance (though not all will agree with me) of steam power:** because we shall see how important steam power, James Watt’s steam engine, was in the industrial revolutions in both iron and cotton manufacturing

iii) **subsequently, of course, it was vital to the second and third transportation revolutions:** in the form of steam-powered locomotives for railroads, and then steam-powered shipping

iv) **That latter transportation revolution culminated in yet a new form of coal-fired steam power:** the steam turbine

- (1) the steam turbines: for a quantum leap in power for ocean going vessels, from the 1850s,
- (2) but also equally important for the generation of electricity

v) **For historical perspective,** you must realize that European from the end of the Roman era to the advent of steam power in the 18th century had relied on three forms of non-human power (and in so doing was well in advance of most of the rest of the world:

- (1) animal power: both oxen and horses
 - especially, of course, as draught power in agriculture
 - but many mills (e.g., for grinding) were also powered by horses:
 - hence the term ‘horse-power’ as an energy measure

¹ See E. Anthony Wrigley, *Continuity, Chance and Change: The Character of the Industrial Revolution in England* (Cambridge University Press, 1988). For his latest study, see: E. Anthony Wrigley, ‘The Transition to an Advanced Organic Economy: Half a Millennium of English Agriculture’, *The Economic History Review*, 2nd ser., 59:3 (August 2006), 425-480.

(2) water-power: from water-powered mills of wide variety from at least the 3rd or early 4th centuries.²

- undershot water-mills: were driven directly by the stream or river
- overshot mills: were driven by water (coming from sluices) poured from above into buckets attached to the wheel rim, thus forcing the wheel to rotate
- both permitted either rotary or reciprocal power.

(3) wind-power: from wind mills, from about the 12th century

- by far the least important of the three.
- never accounting for any more than 10% of the power generated by water mills.

2. Ancient and Early Modern Experiments with Steam Power

a) **The principle of the expansive power of steam had in fact been known to the ancient Greeks:**

i) **Hero of Alexandria**, in 1st century BCE [i.e., Before the Common Era] had accurately described a mechanism using steam – the expansive force of steam – to open and close temple doors.

ii) **But this was merely a curiosity:**

(1) It was never acted upon or applied

(2) after all, who needed a device to open temple doors when there were plenty of slaves to do that?

(3) though, of course, slaves were not ‘free labour: did have to be housed, fed, and clothed

iii) **Water-mills were another mechanical device known in this era but not applied:**³

(1) again water-mills were not needed, simply because of that abundance of slave labour in the ancient World.

(2) Water-mills do not, in fact, come into general use until after the 4th century, when labour had become so scarce:

- after the slave supply virtually disappeared (with the Pax Romana, or Roman peace, and the end of major conquests).
- and after the population had fallen sharply, from various epidemics, certainly by the 6th or early 7th century.

v) **There were no really serious attempts to exploit the expansive power of steam:** not until the 17th century (which, though perhaps only coincidentally, was an era of labour scarcity).

b) **17th Century Experiments with Steam:**

² See John H. Munro, ‘Industrial Energy from Water-Mills in the European Economy, 5th to 18th Centuries: the Limitations of Power’, in Simonetta Cavaciocchi, ed., *Economia ed energia, secoli XIII - XVIII*, Atti delle ‘Settimane di Studi’ e altre Convegni, Istituto Internazionale di Storia Economica, ‘Francesco Datini da Prato’, vol. 34 (Florence, Le Monnier: 2003), pp. 223-69. Available online: <http://www.economics.utoronto.ca/munro5/MunroDatini34Energy.pdf>

³ See the previous note.

i) **first, in Italy:**

(1) della Porta of Naples (1606), and then

(2) Torricelli (1643), a student of Galileo:

(3) though unsuccessful, their published accounts influenced the first quasi-successful engine, in England.

ii) **Germany** produced the next attempts, with von Guericke, 1650.

iii) **In Holland:** the scientist Christian Huygens and his French assistant Denis Papin worked on a prototype steam engine from 1679 to the 1690s.

iv) **England: The Royal Society** (founded 1660).⁴

(1) In 1697, the Royal Society of London published an account of the Huygens-Papin steam cylinder using a piston:

(2) In fact, it was a prototype for subsequent piston-drive steam engines.

3. **Early English Steam Engines: Savery and Newcomen**

a) **Coal-mining:** provided the necessary incentives for the development of a practical steam-powered pump by the beginning of the 18th century:

i) **The economic problem:**

(1) during the later 17th century, the problem of fuel prices became more pressing:

- the real cost of wood fuels, especially charcoal as by far the chief industrial fuel, soared in England (as will be shown later, in the next topic on metallurgy)
- and far more so than on the continent -- to be explained in the next topic on the iron industry.

(2) The rising cost of charcoal encouraged substitution, in the form of coal, though it was a much less efficient and indeed (as we shall see) a problematic fuel;

(3) Nevertheless, by 1700, coal mining had rapidly expanded in England -- again far more so than on the continent:

- when England produced and consumed five times as much coal as the rest of the world combined.⁵

⁴ See lecture no. 3.

⁵ According to the most recent research, undertaken by John Hatcher, British coal output (England, Scotland, Wales) had expanded almost 12-fold from about 227,000 tons in 1560 to about 2,640,000 tons in 1700, when it was supplying about half of England's fuel needs. John Hatcher, *The History of the British Coal Industry*, vol. I: *Before 1700: Towards the Age of Coal* (Oxford: Clarendon Press 1993), Table 4.1, p. 68. As Anthony Wrigley has observed that British coal output was then at least five times greater than the combined output in the rest of the world; by 1800, British coal output had expanded at least five-fold, to about 15 millions tons a year, which was at least five times greater than the aggregate coal output in continental Europe. E. Anthony Wrigley, *Continuity, Chance and Change: The Character of the Industrial Revolution in England* (Cambridge University Press, 1988), p. 54. See also E. Anthony Wrigley, 'The Divergence of England: the Growth of the English Economy in the Seventeenth and Eighteenth Centuries', *Transactions*

- in the later 17th century, coal was providing over half of England's fuel needs
- and was being used by most manufacturing industries, and certainly by most of the so-called 'new industries'
- but not yet for iron manufacturing, for reasons to be explained in the next topic (on iron)
- Just the same, coal was now a major factor (by 1700) in determining industrial location

(4) that expansion involved much larger scale coal-mining with deeper shafts, which created severe technological problems.

(5) especially flooding: as European miners had long known, any mining shafts sunk into the ground are soon faced with the problem of water flooding, from underground water networks.

ii) Drainage pumps in European mining:

(1) in the 15th century, the South Germans had developed horse- and water-powered drainage pumps to try to resolve that problem of flooded mine shafts, for silver and copper mining.⁶

(2) but mine shafts were now reaching depths of over 100 metres,

- they were far too deep to be drained by any existing horse-drawn or water-powered pumps,
- the basic design of these pumps had not changed from those of the 15th century.

(3) Hence the need for an entirely new kind of pump -- this time involving a prototype of steam power.

b) The Savery Steam Pump:

i) Thomas Savery was an English military engineer: ⁷

of the Royal Society, 6th ser., 10 (2000), 117-41; Hatcher, *British Coal Industry*, pp. 555-56 (also citing a figure of 15 millions tons for 1800), stating that 'the major turning point for the British coal industry occurred in the second half of the eighteenth century'; Sidney Pollard, 'A New Estimate of British Coal Production, 1750-1850', *Economic History Review*, 2nd ser. 33 (1980), 212-35.

⁶ Discussed in my essay, as listed in n. 1 above; and also in John Munro, 'The Monetary Origins of the "Price Revolution": South German Silver Mining, Merchant-Banking, and Venetian Commerce, 1470-1540', in Dennis Flynn, Arturo Giráldez, and Richard von Glahn, eds., *Global Connections and Monetary History, 1470 - 1800* (Aldershot and Brookfield, Vt: Ashgate Publishing, 2003), pp. 1-34.

⁷ From Answers.com: Thomas Savery (c.1650-1715) was an English inventor, born at Shilstone, a manor house near Modbury, Devon, England. Initially interested in naval applications of engineering (he designed an early paddle-wheel), Savery then became interested in pumping machines. On July 2 1698 he patented an early steam engine, and in 1702 he published details of the machine in the book *Miner's Friend* [1], which claimed that it could pump water out of mines. Savery's pump had no piston, but used a combination of atmospheric pressure and steam pressure to raise water. The atmospheric action was limited to lifting a column of water about thirty feet high. This could be increased to about fifty feet by using steam pressure, but the extra stress placed on the boiler by this pressure made it unreliable. The machine was therefore not capable of raising water from the depth of a mine, and the almost only known working versions were used for water-supply pumping in London [2]. However an attempt was made (unsuccessfully) to use one to clear water from a mine at Broadwaters in Wednesbury, then in Staffordshire.[3] Savery worked for the Sick and Hurt Commissioners. His duties took him to Dartmouth, which is probably how he came into contact with Thomas Newcomen. The Commissioners contracted the supply of medicines to the Navy Stock

(1) In 1698, the year after the Royal Society's publication of the Huygens-Papin paper, Savery took out a patent for what he called a 'steam pump raising water by the impellant force of fire' (i.e., coal-fired steam power).

(2) It was based, however, not on the Huygens-Papin paper,

(3) but rather on the work of the Italian scientist, della Porta of Naples [see above].

ii) **basic principles of the Savery steam-pump:** atmospheric pressure against a vacuum

(1) steam from a boiler was admitted into a closed cylinder,

- which was then cooled with ice water, thus condensing the steam,
- and thereby producing a vacuum inside the cylinder.

(2) An air-tight valve was opened: so that the vacuum drew water up into the cylinder through a suction pipe.

(3) Note that this device did not use a piston.

iii) **But attempts to apply the Savery pump** were commercially failures.

c) **Thomas Newcomen (1663 - 1729) and his Steam Pump for Coal Mining:** an 'Atmospheric Engine with Steam' (rather than a genuine steam engine).⁸

Company, which was connected with the Society of Apothecaries, John Meres being clerk to both. In 1701, he obtained an Act of Parliament extending the life of his patent for a further 21 years, to 1733. Rights under this passed to the unincorporated Proprietors of the Invention for Raising Water by Fire. The John Meres was their secretary and treasurer. By 1712, arrangements were made with Thomas Newcomen to develop Newcomen's more advanced design of steam engine, which was marketed under Savery's patent. Newcomen's engine worked purely by atmospheric pressure, thereby avoiding the dangers of high-pressure steam, and used the piston concept invented in 1690 by the Frenchman Denis Papin to produce the first steam engine capable of raising water from deep mines.[4] Several later pumping systems may be based on Savery's pump. For example, the twin-chamber pulsometer steam pump was a successful development of it[5]

⁸ From Answers.com: The English inventor and engineer Thomas Newcomen (1663-1729) developed the first practical steam engine, an important feature of the industrial revolution. Thomas Newcomen was born on Feb. 24, 1663, at Dartmouth, Devonshire. It seems probable that as a youth he was apprenticed to learn the blacksmith trade and later became an itinerant ironmonger, a craftsman who made tools, nails, and other hardware, which he sold throughout the mining areas about Dartmouth. Many mines at that time had been dug so deep that they were constantly flooded, and to continue them in operation the operators had to find a better means to pump out the water. It was this omnipresent problem which led Newcomen to attempt to devise a machine which could drive a water pump. As to how Newcomen might have achieved this, 18th-and 19th-century writers usually pointed to earlier attempts to use steam as a motive force. However, no evidence has been found of any borrowing on the part of Newcomen. On the other hand, he never took out a patent of monopoly on his engine, as Thomas Savery did in 1698, because Savery's patent covered all means utilized to raise water by fire. This is probably why Newcomen found it necessary to purchase, from the proprietors of the Savery patent, the right to build a steam engine - a transaction which probably occurred about 1705. Thus it is doubtful whether Newcomen benefited financially from his invention, since it had to be exploited under another's patent. The first Newcomen engine which can be documented dates from 1712. It has been estimated that it required at least 10 to 15 years of development. Both the Newcomen and Savery engines were based upon the use of condensed steam; however, they also differed in important fundamentals. The basic principle of Newcomen's engine was simple. Steam was injected into a cylinder, forcing a piston to move out. Cold water was then sprayed into the piston, the steam

i) **Newcomen had been working on lines similar to those of Savery,**

- even before Savery had obtained his patent, and
- when he developed his pump, he had to pay royalties to Savery,
- though his machine was, in fact, quite different.

ii) **The main objective:** was to devise a pump to remove water from coal-mining shafts.

iii) **In 1712, after about fifteen years of experimentation,** he successfully applied his steam-powered pump to a coal mine (colliery) in Staffordshire.

iv) **Though steam driven, his pump was not a true steam engine, but again really an atmospheric engine, with air pressure acting against a vacuum:**

(1) steam was created in a coal-fired boiler and then injected into a copper cylinder, containing a piston head, which was attached to a pivoted beam (see diagram on screen).

(2) That piston head was *lighter* than the counterweight attached to the other end of the pivoted beam;

(3) And, therefore, the lighter piston head initially rested at the *very top* of the copper cylinder;

(4) and that *heavier* counterweight in turn was attached to the end of the pump rod in the mining shaft.

(5) After steam had been injected into the cylinder, valves were closed,

- the cylinder was doused in ice-water (as in Savery's model), to condense the steam
- and thus to produce a vacuum inside the cylinder.

(6) When that vacuum was so created, below the piston head inside the cylinder,

- then atmospheric pressures (14.7 lb. per square inch, at sea-level = 1.0312 kg per cm², or 1013.25 millibars per cm²) pushed against the piston head,

- driving it down to bottom of the cylinder.

(7) As soon as air and steam were again admitted into the cylinder, eliminating the vacuum, the piston head rose naturally, because of the heavier counterweight attached to other end of the beam: i.e., the simple force of gravity.

(8) Hence the reciprocal, up and down motion created, providing pumping action.

(9) This atmospheric engine could pump about 10 gallons [45.5 litres] of water at every stroke, with a force of 5.5 horsepower: a relatively powerful engine, in its day.

v) **Newcomen's engine did provide a crucial breakthrough that permitted a considerable expansion in**

condensed, and a partial vacuum was formed. Atmospheric pressure then returned the piston to its original position, so that the process could be repeated. The piston's reciprocating motion was finally transferred to a water pump by a beam which rocked about its center. That this to-and-fro motion might somehow be transformed into the more useful rotary motion was a problem which had not as yet been recognized. Newcomen's steam engine spread throughout the mining area of England and rescued many mines from bankruptcy. It was not until John Smeaton's and, more important, James Watt's versions of the steam engine were developed, almost three-quarters of a century later, that Newcomen's machine was superseded. Newcomen died in London on Aug. 5, 1729.

coal-mining:

- it was used for more than a century
- indeed the last one was dismantled as late as 1930.

vi) **In truth, however, it was a very inefficient engine:**

(1) because the alternate heating and cooling of the steam-cylinder meant extra fuel to reheat the cylinder: which was therefore very wasteful of the coal fuel;

(2) and because the motion of its engine was too rough to be applied to anything but a pump in mining shafts.

vii) **For such purposes in coal-mining, and only in coal mining, was it commercially feasible, because the fuel there was so-cheap:** i.e., pit-head coal, with no transport or other costs, so that fuel consumption was not a major problem.

viii) **For any other purpose, however, coal costs were prohibitive:**

(1) and so a more efficient engine was required.

(2) The most surprising thing is that it took so long to produce an improved and true steam engine.

4. **James Watt's Steam Engine: 1763 to 1782**⁹

⁹ From Answers.com. James Watt was born on Jan. 19, 1736, in Greenock, Scotland, the son of a shipwright and merchant of ship's stores. He received an elementary education in school, but of much more interest to him was his father's store, where the boy had his own tools and forge and where he skillfully made models of the ship's gear surrounding him. In 1755 he was apprenticed to a London mathematical instrument maker; at that time the trade primarily produced navigational and surveying instruments. A year later he returned to Scotland. By late 1757 Watt was established in Glasgow as "mathematical instrument maker to the university." About this time Watt met Joseph Black, who had already laid the foundations of modern chemistry and of the study of heat. Their friendship was of some importance in the early development of the steam engine.

Invention of the Steam Engine

In the meantime, Watt had become engaged in his first studies on the steam engine. During the winter of 1763/ 1764 he was asked to repair the university's model of the Newcomen steam engine. After a few experiments, Watt recognized that the fault with the model rested not so much in the details of its construction or in its malfunctioning as in its design. He found that a volume of steam three or four times the volume of the piston cylinder was required to make the piston move to the end of the cylinder. The solution Watt provided was to keep the piston at the temperature of the steam (by means of a jacket heated by steam) and to condense the steam in a separate vessel rather than in the piston. Such a separate condenser avoided the large heat losses that resulted from repeatedly heating and cooling the body of the piston, and so engine efficiency was improved. There is a considerable gap between having a good idea for a commercial invention and in reducing it to practice. It took a decade for Watt to solve all the mechanical problems. Black lent him money and introduced him to John Roebuck of the Carron ironworks in Stirlingshire, Scotland. In 1765 Roebuck and Watt entered into a partnership. However, Watt still had to earn his own living, and his employment as surveyor of canal construction left little time for developing his invention. However, Watt did manage to prepare a patent application on his invention, and the patent was granted on Jan. 5, 1769. By 1773 Roebuck's financial difficulties brought not only Watt's work on the engine to a standstill but also Roebuck's own business. Matthew Boulton, an industrialist of Birmingham, England, then became Watt's partner, and Watt moved to Birmingham. He was now able to work full time on his invention. In 1775

a) **James Watt was a Scottish scientist:**

i) **an assistant for the famed physicist Dr. Joseph Black**, serving as a laboratory technician at the University of Glasgow.

ii) **In 1763, he was given a Newcomen engine to repair,**

(1) He was immediately struck by its inefficiency, for the reasons just noted:

(2) i.e., the alternate heating and cooling of the piston cylinder.

b) **Watt's Solution:** the separate Condenser

i) **This was a separate cylinder attached to the piston cylinder:**

(1) it was kept permanently cold, permanently immersed in ice water,

(2) while the piston cylinder was kept permanently hot with a 'steam jacket' [see diagram].

ii) **First, steam was injected into the piston cylinder:**

(1) then the valve on the cold condenser was opened to permit the steam to enter;

(2) the steam was immediately condensed by the coldness, creating the necessary vacuum in both the condenser and the piston cylinder

(3) again, as in the Newcomen engine, below the piston.

iii) **Watt's original engine was also an atmospheric engine like Newcomen's:**

(1) i.e., again, the original piston head was *lighter* than the counterweight, so that it rested at the *top* of the cylinder.

(2) When the vacuum had been created *below* the piston head, then air pressure pushed the piston head down.

(3) Gravity then brought the piston head back up to its resting position, at the top of the cylinder.

iv) **subsequent refinements produced a true steam engine:**

(1) an injection of steam to push down the piston head, in conjunction with air pressure.

(2) the piston head was now made *heavier* than the counterweight,

Boulton accepted two orders to erect Watt's steam engine; the two engines were set up in 1776 and their success led to many other orders.

Improvements in the Steam Engine

Between 1781 and 1788 Watt modified and further improved his engine. These changes combined to make as great an advance over his original engine as the latter was over the Newcomen engine. The most important modifications were a more efficient utilization of the steam, the use of a double-acting piston, the replacement of the flexible chain connection to the beam by the rigid threebar linkage, the provision of another mechanical device to change the reciprocating motion of the beam end to a rotary motion, and the provision of a centrifugal governor to regulate the speed. Having devised a new rotary machine, the partners had next to determine the cost of constructing it. These rotary steam engines replaced animal power, and it was only natural that the new engine should be measured in terms of the number of horses it replaced. By using measurements that millwrights, who set up horse gins (animal-driven wheels), had determined, Watt found the value of one "horse power" to be equal to 33, 000 pounds lifted one foot high per minute, a value which is still that of the standard American and English horsepower. The charge of erecting the new type of steam engine was accordingly based upon its horsepower.

(3) and the vacuum was created *above* the piston head.

c) The economic applications of Watt's steam engine:

i) Financial and technical support for Watt:

(1) From the beginning, Watt's own professor Dr. Joseph Black aided him with finance and advice,

(2) and then introduced him to Dr. John Roebuck, an English scientist, chemist, and inventor; and also an industrial engineer working for coal mines in England (Birmingham) and Scotland, who formed a financial partnership with Watt.

(3) In 1773, when Roebuck went bankrupt, his interest was taken over by one of his creditors, the Birmingham firm of iron manufacturers, owned by the famous Matthew Boulton.

ii) Boulton and Wilkinson partnership:

(1) They were then joined by another industrialist-engineer, John Wilkinson, who had just devised a new technique for boring cast iron cylinders with far greater accuracy: especially for artillery

(2) thus providing an almost airtight fit for the piston moving in the cylinder.

iv) By the revolutionary year of 1776 (the year also of Adam Smith's *Wealth of Nations*), Watt's steam engine had been sufficiently perfected and was applied as follows:

(1) in a coal mine in Staffordshire, to power water-pumps for drainage.

(2) in Wilkinson's blast smelter in Shropshire, to drive piston airpumps (that had replaced the old fashioned leather bellows, to fan flames).

d) Further Refinements in the Watt Steam Engine: in 1781-82

i) a true double acting steam engine: with blasts of steam driving the piston head (now heavier than the counterweight) both up and down the cylinder.

ii) a rotary steam engine: to provide circular power instead of the original reciprocal or up-and-down motion of original steam engine.

(1) Reciprocal motion was converted into rotary motion by using a crank, flywheel, and planetary gears (sun and planet type), providing 50 horsepower (vs. Newcomen's 5.5 hp), with 17 strokes a minute.

(2) From then on, the chief demand for steam engines was in this rotary form.

iii) 1795: in Birmingham, Watt established the Soho Foundry to build his steam engines for sale throughout Great Britain.

5. The Economic Significance of the Steam Engine

a) the single most important technological innovation of the entire Industrial Revolution:

i) It provided a revolution in mechanical power: eventually (if not immediately) to replace the water-wheel and hydraulic machinery, wind-mills, horse-powered mills.

ii) In particular, the steam-engine powered the principal machines and technological innovations in both the

iron and cotton industries; powered transportation revolution in railroads and steam shipping in the nineteenth century.

b) It economized on all three physical factors of production:

i) **economized on labour:** that should be self evident, since steam engines provided an efficiency through powered machinery (rotary engines) that no human labour could possibly match, obviously.

ii) **economized on resources:** in that far greater power was derived than any from water-mills and from the prior Newcomen engine, with relatively far fewer resources utilized.

(1) In particular, it liberated those sites on rivers and streams for other, more productive uses;

(2) in comparison with Newcomen engines, the Watt steam-engines saved greatly on coal fuels.

- It used less than a third of the coal required for a Newcomen engine:

- only 9 lb. of coal per HP per hour, compared to 32 lb. of coal per HP/hour in Newcomen engine.

(3) The fully perfected Watt steam engine produced over 50 HP, compared to just 5.5 HP for the Newcomen engine.

iii) **economized on capital:**

(1) in that Watt's steam engines were so much cheaper to build than the big bulky water-mills and hydraulic machinery;

(2) This was especially true if the water-wheels used overshot wheels: ¹⁰

- The original technology for water-mills employed undershot wheels: i.e., with wooden paddles that were placed directly into the stream, and rotated directly by the flow of the river or stream against those paddles

- These undershot wheels were *relatively* small and cheap to build, and to maintain

- Overshot-wheels, which come into prominence from the 15th and 16th centuries used wooden buckets attached to the rim of the wheel, into which water pours, flowing down from an overhead trough or pipe

- Thus these water-wheels involved far greater capital expenditures, particularly in the creation of artificial canals, sluice-gates, and water-trough to direct the water above the level of the wheels (i.e., from upstream)

- But, though much more capital costly, they were also much more efficient and powerful than were the older, traditional undershot wheels.

- And thus, far more expensive in capital costs and maintenance than were Watt's steam engines.

- Nevertheless, it is also important to note that the advent of the steam engine provided a strong

¹⁰ See n. 1 above.

challenge to improve the efficiencies of water mills: especially John Smeaton's breast water mill.¹¹

(3) far greater power per unit of investment than with water-mills, wind-mills, or Newcomen engines.

c) Provided a far more elastic, mobile source of industrial power:

i) permitted much greater flexibility in industrial location than did water-mills:

(1) water-power had tied industries to fixed river sites, usually in rural areas far from town markets.

(2) water-power was also only seasonal: with summer droughts and winter freezes.

(3) In the iron industry, as we shall see in the next topic, water-power usually meant the geographic separation of smelting from refining; and refining from cutting, slitting mills.

(4) furthermore, water-power had also meant long periods of shutdowns (on average 15 weeks a year), when water flows were insufficient from either winter freezing or summer drought.

(5) Industries were now far freer to locate where other economic considerations, such as labour supplies, financing, and markets dictated.

ii) But this greater industrial mobility, or flexibility of location should not be exaggerated:

(1) because coal, that necessary fuel for steam power, long remained costly to transport, even with canals and then, from the 1830s, railroads.

(2) Consequently there remained a strong incentive to locate industries as close as possible to coal-fields, which in Britain were well distributed.

iii) Note also that early steam engines were often less efficient than the best watermills, especially after the introduction of Smeaton's breast water wheel: and thus steam engines were, initially, slow to spread.¹²

d) The Nature of Urban Industrialization:

¹¹ See n. 5 below.

¹² See above n. 1, and 4; and G.N. von Tunzelman, *Steam Power and British Industrialization to 1860* (Oxford and New York, 1978). See also Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (Oxford-New York, 1990), pp. 90-91: 'The most important advance was the breast wheel, which was introduced by John Smeaton in the 1750s, and soon spread all over Britain. Breast wheels received water at an intermediate point between the summit and bottom of the wheel, and thus in a sense are a compromise between overshot and undershot wheels. The breast wheel was as efficient as the overshot wheel, but had the advantage that the wheel turned in the same direction as the flow of the water in the tail race, which allowed it to work under flooding conditions. Smeaton's work was improved by the introduction of the sliding hatch, introduced by John Rennie in the 1780s, which allowed breast wheels to adapt to varying water levels. Smeaton, John (from Answers.com): (born June 8, 1724, Austhorpe, Yorkshire, Eng.-died Oct. 28, 1792, Austhorpe) British civil engineer. In 1756-59 he rebuilt the Eddystone Lighthouse (off Plymouth), during which he rediscovered hydraulic cement (lost since the fall of Rome) as the best mortar for underwater construction. He constructed the great Forth and Clyde Canal in Scotland; built bridges at Perth, Banff, and Coldstream; and completed the harbour at Ramsgate, Kent. He was a leader in the transition from wind-and-water to steam power; with his improvements, Thomas Newcomen's atmospheric steam engine achieved its maximum performance. He designed atmospheric pumping engines for collieries, mines, and docks. In 1771 he founded the British Society of Civil Engineers (now the Smeatonian Society). He is regarded as the founder of the civil engineering profession in Britain.

i) **Thus, most industries using coal-fired steam engines did congregate in towns**, but in those towns that were clustered about coal-fields.

ii) **hence producing an industrial concentration around coal-fields:** to quote once more an prominent historical geographer: ‘an industrial map of Europe in the 19th century was essentially a map of her coal fields’.

e) **Steam Engines and the Factory System of Production:**

i) **Clearly steam-engines provided a powerful stimulus for the growth and development of the factory system of production,**

(1) itself a key feature of urban industrialization, industrial concentration:

(2) i.e., with steam engines providing a central source of power to drive many and various kinds of machines, integrated together under one roof.

ii) **BUT the steam engine was not, repeat NOT, the progenitor of the factory system of production:**

(1) because the original source of such centralized power in driving machines was instead traditional water-power, necessarily locating the early factories in rural locations.

(2) Indeed for that reason the early factories were called ‘mills,’ i.e., for water-mills.

iii) **Yet obviously the greater power, efficiency, and flexibility of steam engines:** especially location flexibility (indeed mobility within the factory itself) -- was a much greater encouragement to adopt a factory system of production.

iv) **And the steam engine was most obviously the key factor in permitting and promoting the shift of industrial location:**

(1) from rural to urban sites,

(2) in order to obtain more elastic labour supplies, credit, marketing, etc., as noted.

v) **Steam-engines, however, did not succeed in effecting this industrial location,** in superseding water-mills until 1820s or 1830s.

f) **Finally, the steam engine both permitted and demanded larger-scale:**

i) **obviously it permitted larger scale,** by being able to drive so many more and larger machines, in permitting integration of industrial processes within one very large scale industrial unit.

ii) **but also it required larger scale output,** in that it was not economic to apply steam engines unless many machines could be operated. But in this respect (unlike previous one) no more so than water-mills, which were even more capital costly than steam-engines.

iii) **For both, the application of centralized power to a larger-scale factory system of production was conditional upon actual or potential market expansion,** to absorb large outputs, to justify high fixed costs.

g) **Note:** Von Tunzelmann on Steam Power:

i) **In an important monograph,** *Steam Power and British Industrialization to 1860* (Oxford, 1978),

- (1) the British economic historian Nick von Tunzelmann has argued that the steam engine had a negligible impact on British economic growth during the traditional era of the Industrial Revolution, to the 1820s,
- (2) indeed, asserting that steam engines added no more than 0.8% to GNP per annum.
- ii) **Accepting that view:** literally demands accepting both the specifications of his econometric models and his data.
- iii) **but despite possible objections to his methods,** his study warns us to realize that the real impact of the steam engine was surprisingly delayed, and had to wait until well into the 19th century, for reasons we shall see more clearly in succeeding topics.

6. The Application of the Watt Steam Engine

a) in the coal industry:

i) **obviously,** to displace the Newcomen engine as a drainage pump for mine shafts.

ii) **But that displacement occurred only slowly:**

- (1) and chiefly in new mines, because the capital cost of displacing Newcomen engines with Watt engines was much higher than the variable and marginal cost of operating Newcomen engines,
- (2) especially with cheap pit head coal.

b) **In the Iron Industry:** its most important application: to be seen in the next lecture

- i) **in blast furnaces,** to power the piston airpumps.
- ii) **in new refining processes,** to power the rolling machines.
- iii) **to power the slitting and cutting mills,** for finished iron.

c) **In the Textile Industries, first in Cottons:** to be seen in the following lecture (after iron)

- i) **in spinning,** to displace water mills in spinning mules (though not until after the 1790s).
- ii) **in weaving:** not used to operate new power looms until the late 1820s.

d) **Other Industries:** in brewing, distilling, flour-milling, paper-making.

e) **Transportation:** its most important 19th century application: first in railways, with steam locomotives; then in steam-shipping.