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ECONOMICS 303Y1

The Economic History of Modern Europe to1914

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Lecture Topic No. 9 (week 9):

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

J. The Revolution in Metallurgy: Iron Production with Coke & Steam

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The Economic History of a Capital Goods Manufacturing Industry

1. **Introduction: the importance of iron in modern industrialization**

a) **The twin spearheads of modern industrialization everywhere in the world, beginning with the British Industrial Revolution are both coal-based:**

(1) Metallurgy: first iron, and then steel (the ideal form of iron)

(2) Textiles: usually beginning with cotton textiles, everywhere, but then including worsteds, woollen, linens

b) **Iron in its various forms provided (and still does) the essential 'building blocks':** or construction materials for modern industrialization: machines, transportation facilities, factories, buildings, bridges, etc.

c) **The various forms of iron: ancient and modern, in terms of carbon contents:**

i) **wrought or malleable iron:**

(1) fully purified iron, with only 0.1% or less carbon

(2) the predominant form of iron before the 16th century

(3) problem: very soft, bendable, with low resistance to stress

ii) **cast iron:**

(1) contains about 3% to 5% carbon

(2) the product of the major innovation in early-modern iron manufacturing: with the introduction of the Blast Furnace, in smelting iron ores: next topic

(3) extremely hard metal

(4) problem: very brittle, shattering into shards in encountering stress

iii) **steel: the ideal form of iron**

(1) contains about 1% carbon or less

(2) made from purified wrought iron, with the optimum amount of carbon added to it, with an even or homogenous mix

(3) has best resistance to stress: neither shattering nor bending

(4) problem: extremely costly to make, and thus a luxury metal before the 19th century

(5) Industrial Revolution era: the Huntsman Crucible process provided a lower cost improvement

(6) Revolution on steel making did not come until 1856: with the Bessemer Converter, to be discussed next term

d) **The Industrial Revolution in iron manufacturing (wrought iron):** as an aspect of the application of coal: with purified coal as the fuel, and coal-fired steam power (steam engines_

i) **In this lecture, we continue our 'Wrigley' theme on the origins of modern industrialization:** namely, the shift from an 'advanced organic economy' [one based on wood and water] to 'a mineral-based economy' [one based on coal, coal-fired steam power, and coke-produced iron]. [1]

ii) **The 'The Tyranny of Wood and Water':**

(1) is a another closely related theme is one advanced by T.S. Ashton [the first major, modern historian of the Industrial Revolution] and then by the American economic historian John Nef:

(2) how England responded to the challenge of the 'tyranny of wood and water' by shifting to the use of coal throughout the entire process of iron-manufacturing: using distilled or purified coal in the form of coke as the fuel for both smelting and refining and using coal-fired steam power (last lecture).[2]

2. <u>The Iron Industry in the Early 18th Century: Organization and Technology under a 'Tyranny of Wood and Water'</u>

a) **The Basic Technology of Iron-Making**:

i) **the chemical process of iron making is important to understand**:

(1) iron ore contains not iron itself but the compound *iron oxide* [Fe_20_3]: so that iron in its natural form thus appears as 'rusted' metal.

(2) thus the iron has to liberated or separated from the iron oxide.

ii) **iron-extraction or 'iron-winning':**

(1) this meant subjecting the iron ore (once cleansed of all impurities) to intense heat directly in a wood-charcoal fire.

(2) Wood-charcoal was required because

- it was the fuel that burned with very high heat,
- but with the fewest contaminants;
- and it was vital that the carbon-fuel not contaminate the iron being produced.

(3) The main object was to have:

- the carbon from the charcoal fire combine with the oxygen in the iron oxide to produce carbon dioxide gas [CO_2], leaving pure iron: [3]
- $C + Fe_2O_3 \rightarrow Fe + CO_2$
- in fact, more formally and accurately, as the chemical equation: $3C + 2Fe_20_3 \rightarrow 4Fe + 3CO_2$

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[1] See E. Anthony Wrigley, *Continuity, Chance and Change: The Character of the Industrial Revolution in England* (Cambridge University Press, 1988).

[2] Thomas Southcote Ashton, *Iron and Steel in the Industrial Revolution* (Manchester, 1924; reprinted 1951).

[3] The Iron Age, displacing or superseding the Bronze Age, is generally regarded as marked by the ascendancy of the Hittites in Asia Minor (c. 1450 - 1200 BCE), whose military superiority was based on the use of iron swords and spears, much superior to the softer bronze weapons (copper and tin) of that era.

(4) But initially some carbon adhered to the iron: and that carbon had to be oxidized and burned off, by repeated heating and pounding, to produce pure iron, with less than 1% carbon. [Decarburization]

(5) Just the same, the carbon in carbonized pig or cast iron permitted the iron to melt (become liquid at) a much lower temperature: about 1000º Celsius.

iii) **Forging**: **or the direct process** was the name given to this age-old, indeed very ancient process of producing iron in this fashion:

(1) by constant heating and pounding, in a red-hot, plastic, but not molten state, at about 700° C.;

(2) a **bloomery forge**: using a charcoal fire and powerful hammers

iv) **Water-Power:** by the later Middle Ages, water-power had been applied to this process, both

(1) to work leather bellows for fanning the heat, and

(2) to operate the forge hammers in pounding the iron (to force out impurities).[4]

v) **Wrought or malleable iron** were the terms applied to such iron:

(1) because it was a soft, bendable, i.e., malleable, workable form of iron

(2) This was indeed the chief form of iron known to medieval and early-modern Europe.

vi) **The Blast-Furnace (Smelter): as an early-modern technological revolution:**

(1) During the later 14th century [see below], this age-old method of iron making underwent a fundamental, indeed revolutionary change with the introduction of the blast-furnace.

(2) It converted this industry into a large-scale, capital intensive, and capitalistic industry;

(3) Capitalistic in the sense that:

- the ownership of concentrated capital was quite separate from the artisans who manufactured the iron (who thus owned nothing but their own labour).
- the artisans had only one thing to sell: their labour power:
- i.e., they worked for wages alone.

b) **The Blast Furnace: and the Indirect Process with Smelting**: **an early industrial revolution**

i) **The specific origins are unknown:**

(1) possibly German in origin: the blast furnace may have first developed in Rhineland;

(2) but the first evidence for it is in the eastern Low Countries: in the iron-making district of Liège, in 1384.

ii) **The blast furnace was introduced into England by the 1490s:**

(1) an early blast furnace in the iron-working Weald area of SE England has been dated to 1496;

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[4] For this, and the following, see John 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 altrie Convegni, Istituto Internazionale di Storia Economica, 'Francesco Datini da Prato', vol. 34 (Florence, Le Monnier: 2003), pp. 223-69. Also available on my Home Page (Working Papers), with a PDF file that can be downloaded, at the following URL: http://www.economics.utoronto.ca/ecipa/archive/UT-ECIPA-MUNRO-02-01.html

(2) and its use spread rapidly from the early 16th century to revolutionize the industry and iron production, both on the continent and in England.

(3) Initially its greatest impact was probably on England

(4) but subsequently other continental producers would leap ahead of England: Sweden & Russia

iii) **The blast furnace (smelter) was a large brick-kiln furnace,** some 25 ft. [8.5 metres] high:

(1) again necessarily using wood-charcoal -- not coal, but wood-charcoal as a pure fuel -- with much larger water-powered bellows to fan charcoal fire to high heat of about 1000° C.

(2) This was also one of the most important late-medieval applications of water-power: in order to power the leather bellows used to produce the blasts of air driven into the furnace. [5]

(3) An immense charcoal fire was built up inside the brick kiln;

(4) and the immense heat produced then achieved rapid oxidation to convert the iron oxide into pure iron and carbon dioxide.

(5) While the carbon in the fuel achieved the liberation of iron from iron oxide (by the formula just noted)

- the carbon residues, with this rapid oxidation, also formed an alloy or amalgam with the iron;
- and that iron-carbon alloy would become molten at around 1000° C. (as noted earlier)
- while pure unalloyed iron will melt only around 1535° C.

(6) the carbon in this smelted iron, generally around 3% - 5%, made it very hard and brittle;

(7) consequently, the only way it could be further fashioned or worked was by being poured molten into casts or molds (to be discussed later).

iv) **Smelted iron**, **as extracted from its ore in this fashion,** was given two names, depending upon subsequent use of the metal:

(1) **Pig iron:** when the smelted iron serves only as an industrial input to be further forged and refined into pure iron, i.e., into malleable or wrought iron; and that accounted for perhaps 80% - 90% of the output of blast furnaces (smelters).

(2) **Cast iron:** when used directly from the furnace (smelter).

c) **Cast Iron**: **as new and alternative use of iron**

i) **cast iron:**

(1) was the name given to the molten iron poured from the blast furnace into pre-shaped casts or molds,

(2) according to the desired shape for the end product.

ii) **Because of the carbon content: with 3% - 5% carbon, as noted earlier**

(1) this form of iron, was extremely hard, indeed as hard as steel,

(2) but also very brittle, cracking or breaking under stress.

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[5] See the previous note.

iii) **cast iron, however, was cheap and useful for non-stressful purposes,** in the following consumer and capital goods: especially cast-iron pots and pans, pipes, and also some tool parts.

iv) **cast iron artillery**: was its chief initial use

(1) Casting in bronze -- as an amalgam of copper and tin (8:1 ratio) --

- was a far older metallurgical technique,
- first devised, probably during the early 14th century, in casting bronze church-bells
- and then applied to cannon (artillery).

(2) cast-iron artillery was produced as a cheaper alternative to this cast-bronze artillery.

(3) the English iron industry evidently did develop a technical superiority over the continent in producing cast-iron cannon, though not for over a century;

(4) Nevertheless, European military forces continued to prefer bronze cannon, even though they were more expensive,

- because they were safer than cast-iron cannons
  - that is, as just noted, because cast-iron is extremely brittle, as well as being hard
  - cast iron was then also a metal usually containing cracks and fissures, which would become larger/deeper, if water in them froze
  - if gunpowder charge was too powerful, in exploding, the cast-iron cannon would break into pieces, hurling razor-sharp shards that often killed many gunners and military engineers: a dreadful waste of human capital
  - while bronze cannon, when more rarely exploding, would merely peel apart, like a banana, without killing anybody
- and that preference for bronze artillery continued until the later 17th or early 18th century.

v) **The Blast Furnaces and Industrial Scale:** a quantum leap forward

(1) thus, while the forges of the old direct process, wasting about a third of the metal, had annual outputs of just 20-30 tonnes, the blast furnaces could produce ten times that amount.[6]

(2) Even the early blast furnaces (ca. 1530) typically produced 200 tonnes of iron a year.

(3) By the 1680s, they had grown in scale to 300 tonnes per year, on average;

(4) and then, by the 1740s, to 375 tonnes:

(5) with some monster furnaces then producing up to 700 or 800 tonnes of pig iron a year.

d) **Iron-Refining and the Refinery Forges**: to produce malleable or wrought iron

i) **Because most of the iron produced by blast furnaces:**

(1) was classed as pig iron destined for further refining into purified wrought iron,

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[6] A ton (2,000 lb.) weighs 907.1847 kg; a tonne, or metric ton, weighs 1,000.00 kg.

(2) the blast furnace thus meant an indirect process,

(3) one that necessitated a second and final stage, in refining.

ii) **These refining forges were also known as fineries, or chaferies, which worked as follows:**

(1) This forge or chafery was a much smaller scale furnace than the blast furnace,

- again with water-powered bellows and forge-hammers
- and necessarily using wood-charcoal as a fuel, in large quantities.

(2) Through constant, repeated pounding and heating, the carbon and other impurities in the pig iron (sulphur, silicon) were brought to the surface and oxidized (burned off).

(3) One ton of pig iron so refined would produce about 3/4 ton wrought iron (also called bar iron).

iii) **Industrial Scale:**

(1) the early-modern water-powered refinery forges, though much smaller in scale than the blast furnaces (smelters) were still considerably larger in scale than the older forges,

(2) with annual outputs ranging from 120 tonnes to 200 tonnes by 1700.

e) **New Industrial Organization:**

i) **This really marks the true beginnings of a capitalistically organized iron industry, as early as the 15th century:**

ii) **The Blast Furnaces, Industrial Scale, and Industrial Capitalism:**

(1) In historic perspective, one of the most ‘revolutionary’ features of the Blast Furnace was that its introduction necessarily meant a radical transformation from artisan handicraft production (for Marxists: ‘petty capitalism’) to genuine industrial capitalism

(2) a definition of ‘industrial capitalism’:

- a system of production in which the ownership and use of capital is separate and divorced from labour, from those who actually produce the goods and services
- industrial labour becomes, in Marxist terminology, an ‘industrial proletariat’: one that does not possess or control capital, the means of production – including tools and raw materials – but only its own labour power, the only commodity that it can sell

(3) In the case of the early-modern Blast Furnace

- the large size, large-scale production, and technological complexity, involving mechanical water power for the furnace bellows (to produce the ‘blast’)
- meant that the capital requirements were far too large, too costly, for any artisan to acquire and invest

iii) **in contrast, the previous technology, for the Bloomery Forge or Catalan heath, was not very capital costly:**

(1) so that the actual artisan, the iron-maker, was able to own and operate his own forges, tools, iron-ore, fuels, etc. and hire labour to help him

(2) with the Blast Furnace (and then the Reverberatory Furnace: see below) its construction or acquisition and operation depended on an industrial capitalist who invested the funds and organized the enterprise

(3) and who thus hired the labour who produced the iron

iv) **the transformation of metamorphosis from artisan to capitalist production thus first took place in the 15th century:**

(1) with a more centralized production, with vastly larger scale fixed capital investments in blast furnaces and finery forges, both using water-powered machinery;

(2) This capital stock, in plant and machinery, was directly owned by the industrial entrepreneur,

(3) to repeat the earlier point: entrepreneurs who employed wage-labourers throughout:

(4) i.e., workers who had nothing to sell but their labour power (to use the Marxist terminology)

(5) and they were congregated about each of the furnaces and forges.

(6) The later Industrial Revolution brought about no real changes in industrial organization, but only changes in industrial scale, though those were very important.

v) **Some industrial capitalists owned mines,** furnaces, and forges.

vi) **The advantages of the new methods,** in both organization and technology, led to a rapid growth in the English iron industry;

vii) **but from the mid 17th century,** the iron industry grew very slowly -- too slowly for the English economy -- for economic reasons now to be considered.

f) **Technological Problems: 'The Tyranny of Wood and Water'**

i) **Ashton's 'tyranny of wood and water' thesis**:

(1) The term was coined by Thomas Ashton, in his famous monograph: *Iron and Steel in the Industrial Revolution* (London, 1924);

(2) and the concept was further developed by the American historian John Nef, who produced even more evidence about high fuel prices in England, from the 16th to early 18th centuries, as evidence of the costly consequences of a growing 'tyranny of wood.[7]

(3) They both argued that costly fuels brought about industrial stagnation and indeed net decline, by the mid -17th century.

(4) Their views, however, were later challenged by a variety of historians, many of whom argued that the fuel problem was a mirage, for a variety of reasons:

- because smelters used young green trees,

[7] John Nef, *The Rise of the British Coal Industry*, 2 vols. (London, 1923); 'The Progress of Technology and the Growth of Large-Scale Industry in Great Britain, 1540-1640', *Economic History Review*, 1st ser. 5:1 (1934). More recently, see: John Hatcher, *The History of the British Coal Industry*, Vol. I: *Before 1700: Towards the Age of Coal* (Oxford, Clarendon Press: 1993).

- in forests that iron-makers could readily grow themselves.
- that any rise in fuel costs was overcome by increasing economies of scale in furnace production.[8]

(5) Consider, for examples, these following blunt statements from the esteemed economic historian Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (Oxford and New York, 1990).

- p. 93: 'New research on the iron industry has refuted the widespread myth that coke smelting was triggered by a scarcity of wood.....' (citing Michael Flinn).
- p. 160: 'Traditional accounts, such as Ashton's (1924), or Clow and Clows' (1956), related the adoption of coke smelting to the rise of the price of charcoal caused by deforestation. Flinn (1959; 1978) has shown, however, that evidence on these prices does not confirm this view'.
- p. 192: 'The timber famine, on which [Richard D.] Wilkinson bases his argument, never existed, as we have seen.'

(6) To be sure, the concept of an overall national 'timber famine' is grossly exaggerated:

- the problem was largely regional, with abundance of wood in some areas
- but a scarcity of wood and wood-charcoal in other region

(7) **My views on the 'fuel crisis' differs from both the Ashton-Nef school and from its critics**

- Nef, in my view, improperly focused on what we call Tawney's century, from ca. 1540 to ca. 1640, as the crucial period of rising fuel price, the era of a 'fuel crisis'

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[8] For the literature on this debate, see in particular: George Hammersley, 'The Crown Woods and their Exploitation in the Sixteenth and Seventeenth Centuries', *Bulletin of the Institute of Historical Research, University of London*, 30 (1957), 154-59; George Hammersley, 'The Charcoal Iron Industry and its Fuel, 1540-1750', *Economic History Review*, 2nd ser. 26 (1973), 593-613; George Hammersley, 'The State and the English Iron Industry in the Sixteenth and Seventeenth Centuries', in Donald Coleman and A. H. John, eds., *Trade, Government, and Economy in Pre-Industrial England: Essays Presented to F. J. Fisher* (London, 1976), pp. 166 - 86; Michael Flinn, 'The Growth of the English Iron Industry, 1660-1760', *Economic History Review*, 2nd ser. 11 (1958), 144-53; Michael Flinn, 'Timber and the Advance of Technology: A Reconsideration', *Annals of Science*, 15 (1959), 109-20; Michael Flinn, 'Technical Change as an Escape from Resource Scarcity: England in the Seventeenth and Eighteenth Centuries', in Antoni Maczak and William N. Parker, eds., *Natural Resources in European History* (Washington, D.C., Resources for the Future, 1978), pp. 139-59; Philip Riden, 'The Output of the British Iron Industry Before 1870', *Economic History Review*, 2nd ser. 30 (1977), 442-59; Charles 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.]; Donald C. Coleman, *Industry in Tudor and Stuart England* (London, 1975), pp. 35-49; Sybil Jack, *Trade and Industry in Tudor and Stuart England* (London, 1977), especially chapter 2, pp. 66-121; Oliver Rackham, *Trees and Woodland in the British Landscape* (London, 1976); Oliver Rackham, *Ancient Woodlands: Its History, Vegetation and Uses in England* (London, 1980). For an overview, see John Hatcher, *The History of the British Coal Industry*, vol. I: *Before 1700: Towards the Age of Coal* (Oxford: Clarendon Press 1993), pp. 31-55, in effect, while acknowledging the many faults in Nef's research and analyses, lending support to the Ashton-Nef thesis, as does Brinley Thomas, 'Was There an Energy Crisis in Great Britain in the 17th Century?' *Explorations in Economic History*, 23 (April 1986), 124 - 52;

- In doing so, he was (in my view) unduly mesmerized by the focus that two major economic historians had given to this century, 1540-1640: Tawney and Hamilton
- Richard Tawney (1880-1962), who taught at the London School of Economics from 1917 to 1949, was unquestionably one of the very most important economic historians that England has ever produced:
- and this century, 1540 - 1640 – between Henry VIII's Protestant Reformation (in 1536), confiscation of church lands, the 'rise of the gentry', and the outbreak of the English Civil War in 1650 – produced, in Tawney's view, the essential elements in the transition from medieval feudalism to modern capitalism (thus a quasi-Marxist point of view).
- Earl Hamilton (1899-1989), a one-time colleague of Nef's, at the University of Chicago, also made this century famous in his concept of the inflationary 'Price Revolution'.[9]
- Obviously, with such inflation we will find that the nominal (silver-based money-of-account) prices did rise: but did 'real prices' rise?
- More to the point: did the prices for wood-charcoal and coal diverge, and diverge enough, to offer any incentive to shift from wood to coal?
- The accompanying graph clearly shows that there was no rise in 'real' fuel prices in Tawney's century: that the nominal prices of both wood-charcoal and coal prices rose together in tandem[10]
- From the 1640s, however, there did begin to be and become a growing, and ever wider disparity between charcoal and coal prices.
- Thus, for example, at both Cambridge and Westminister, by the 1630s, the cost of a ton of coal was less than half the cost of a ton of charcoal, when both had the same heating power.

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[9] See my "Classic" Review of Earl Hamilton, *American Treasure and the Price Revolution in Spain, 1501-1650* (Cambridge, MA: Harvard University Press, 1934. xii + 428 pp.). Subtitled: *Hamilton and the Price Revolution: A Revindication of His Tarnished Reputation and of a Modified Quantity Theory of Money*. Reviewed for EH.NET BOOK REVIEW, <eh.net-review@eh.net> on 15 January 2007. This review is archived at EH.NET, at this web site: http://eh.net/bookreviews/library/munro. See also this recent publication on Hamilton's concept of 'profit inflation': John Munro, 'Money, Prices, Wages, and "Profit Inflation" in Spain, the Southern Netherlands, and England during the Price Revolution era: ca. 1520 - ca. 1650', *História e Economia: Revista Interdisciplinar*, 4:1 (2008), 13-71. An accessible PDF file of the offprint can be found in my online publications, provided by the Department of Economics: http://www.economics.utoronto.ca/index.php/index/research/publications?personId=51

[10] This graph has been published in my essay: John Munro, 'Tawney's Century: (1540 - 1640): the Roots of Modern Capitalist Entrepreneurship', in Will Baumol, David Landes, and Joel Mokyr, eds., *The Invention of Enterprise: Entrepreneurship from Ancient Mesopotamia to Modern Times*, Kauffman Foundation Series on Innovation and Entrepreneurship (Princeton: Princeton University Press, 2010), pp. 107-55. See pp. 121-26 for section on the Nef thesis (below) and the growth of the early-modern English iron industry to the eve of the Industrial Revolution; and the graph on p. 123. For the online version: http://www.economics.utoronto.ca/munro5/TawneysCenturyPUP2010.pdf

- My tables and graphs, however, do not display coke prices (which are not available).
- **In sum**: my graph, using prices drawn from original sources (produced as an appendix to this lecture) demonstrate that both Nef and his critics were wrong: and that the proper crisis period is not 1540 - 1640, but rather 1640 - 1740.

(7) Furthermore, the critics never, in my view, dealt fairly with Ashton's key arguments on the tyranny of both wood and water together:

- namely, that total dependence on both wood and water imposed strict, finite limits on both the location and scale of the iron industry.
- After all, in any one given location, there is only so much wood and so much free water available.

(8) In my own view, therefore, the concept of 'the tyranny of wood and water' has much merit.

(9) On the other hand, the most recent statistical evidence indicates that

- the Ashton-Nef view was unduly pessimistic, for there was no net decline;
- indeed there was some continued growth, albeit very slow growth from the mid-17th century and into the 18th century.

ii) **The Tyranny of Wood and the fuel problem**:

(1) these processes, both smelting and refining, remained strictly tied to and dependent upon wood charcoal,

- whose costs were rising steeply from especially the mid-17th century:
- from a growing shortage, relative shortage, of forests and wood-supplies, but again only from the 1640s
- that again can be clearly seen on the overhead graph (and Table 1 in the Appendix)

(2) In essence, England became deforested at a much early period than did most of the continent;

(3) and forest clearings from the combination of agricultural expansion and urban growth meant that available wood supplies were further and further away from markets.

(4) The major factor in rising fuel prices was in fact in transporting the wood to sites where it could be burned and converted into charcoal.

(5) Those conditions might be blamed on population growth, from the mid-sixteenth century

- but note from the graph that charcoal prices rise faster than the overall price index, and rise faster than coal prices only from the mid-seventeenth century
- and, as indicated in earlier lectures, English population had ceased growing and began to fall, if only slightly, from the mid-17th century
- nevertheless increasing urbanization and now a much increased demand for wood (timber) for shipbuilding undoubtedly exacerbated the wood supply problem

(6) That growing scarcity of timber, in relation to aggregate demand, in turn meant that blast furnaces and refineries had to be located as close as possible to those sites, since charcoal cannot be transported.

iii) **The Evidence for Rising Charcoal Prices: See the tables on the screen (appended to text)**

(1) Again consider the detailed evidence on prices for timber, wood-charcoal, and coal in both Table 1, also containing the Phelps-Brown Hopkins Consumer Price Index, with its components (Appendix)

(2) And more clearly – indeed dramatically – on the coloured graph on the overhead: again I stress that the crucial divergence in prices occurs only from the mid-17th century (**not** from the mid-16th century, as Nef had wrongly asserted).

(3) and those prices were also rising much faster than coal prices, which indeed experienced some decline (in both nominal and real terms) during the later 17th and early 18th centuries.

(4) Evidence at on-site blast furnaces show that in some places charcoal costs rose up to 11 fold from the 1540s to the 1690s (3s to 33s load).

(5) Brinley Thomas's table: a 3-fold increase at Westminster from 1580s to 1730s (Table 3)

The English Iron Industry, 1580 - 1740

Charcoal Prices, Pig Iron Outputs, and Bar Iron Imports in selected decades,

PERIOD	CHAR-COAL PRICES £ per load	PIG IRON OUTPUT in thousands of tons	BAR IRON IMPORTS in thousands of tons	PRICE INDEX 1451-75 = 100
1580-89	1.0	15.2	1.7	357
1630-39	1.4	20.0	3.7	616
1680-89	2.6	21.0	23.0	577

PERIOD	CHAR-COAL PRICES £ per load	PIG IRON OUTPUT in thousands of tons	BAR IRON IMPORTS in thousands of tons	PRICE INDEX 1451-75 = 100
1730-39	3.0	27.5	34.6	553

Observe that:

- the charcoal prices at Westminster tripled between 1580-9 and 1730-9 (from £1 to £3 a load),
- while the general consumer price index rose only 55%;

(4) The other table on screen (for 1720) shows that charcoal fuels accounted for about 70% of the total production costs.

Charcoal-Smelted Pig Iron: Production Costs ca. 1720-21

To Produce 360 Tonnes of Pig Iron per year

Production Input	Total Costs per year	Percentage of Total Cost
(1) Charcoal	£1,459	71.0%
(2) Iron Ore	313	15.2%
(3) Furnace Labour	61	3.0%
(4) Clerical salaries	40	1.9%
(5) Rent	40	1.9%

Production Input	Total Costs per year	Percentage of Total Cost
(6) Repairs and Maintenance	63	3.1%
(7) Other Costs	78	3.8%
TOTAL COSTS	**£2,054**	**100.0%**

Cost per ton of pig iron = £5.70

iv) **Physical Limitations of Charcoal as a Fuel**: also imposed a physical limit on the size of the smelter, an upper limit of about 25 ft. before charcoal collapse, crumble into dust.

v) **Why this dependence on charcoal? Why was coal not used?**

(1) Because iron-smelting required *direct* contact of the fuel with the ore, so that the carbon would combine with the oxygen in ferric oxide: thus, it was not just question of heat.

(2) But if coal were used instead, all the sulphur, phosphoreus, and other impurities in coal would contaminate, and so ruin the iron.

vi) **The initial solution to the coal-contamination problem: Reverberatory Furnaces**:

(1) **the development of a *reverberatory* furnace:**

- a very large-scale and complex brick kiln furnace that transmitted heat by convection and reflection ("reverberation")
- reflecting heat from the roof of the furnace on to the product being manufactured,
- while isolating the coal fuel itself and the fumes by eliminating the chimneys
- and using underground pipes to expel fumes and to draw in fresh air.[11]

(2) That heat reflection required, as noted, very large scale and capital costly brick-kiln furnaces,

(3) This new furnace also required hydraulic machinery, with large water-powered leather bellows, in order to fan the burning coal fuels with air (oxygen) to achieve the required high levels of combustion.

[11] The reverberatory furnace, is first described in Vanoccio Birunguccio's *De la pirotechnica*, about 1540, though we do not know who were the original inventors, or rather the entrepreneurs who first succeeded in achieving this vital technological advance. See Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* Oxford and New York: Oxford University Press, 1990), p. 62.

(4) Initially, the most important use was in England's new glass industry, ca. 1610

(5) **but for the English iron industry:** both smelting and refining also required far more intense heat than could be provided by reflection in these reverberatory furnaces.

vi) **The Tyranny of Water:**

(1) These processes were also dependent upon water-power:

- to drive the bellows for fanning the flames: for the blast furnace (smelting) and fining forges
- to power the forge-hammers in refining the iron.

(2) That dependence on water-power meant that a typical blast furnace in particular was in operation only about 30 - 40 weeks a year,

- with insufficient water in dry summer months,
- and sometimes with mid-winter freezing

vii) **Rarely was there enough wood and water together**:

(1) i.e., to permit the dual operations of both furnaces and forges in one side-by-side location.

(2) So this industry suffered from high transport and transactions, with the physical separation of the two processes (with further costs in transporting the refined iron to slitting and cutting mills in towns).

viii) **Industrial Organization:**

(1) The scarce supplies of wood and water together necessarily tied this iron industry to scattered rural sites across England.

(2) The changes of the Industrial Revolution would make this industry much less scattered,

(3) i.e., more concentrated, and much larger in scale.

g) **English Dependence on Iron Imports from the 1660s:**

i) **The question of iron imports (from the Baltic) may resolve the debate**:

(1) for a growing English dependence on Swedish and Russian iron imports shows that the English iron industry, under a wood and water regime, was incapable of meeting growing domestic demand:

(2) Imports of Swedish bar iron rose from about 1200 tonnes in the 1580s to perhaps 18,000 tonnes by the 1690s to over 25,000 tonnes by the 1730s.

(3) As the table on the screen shows for the early 18th century, Swedish iron imports accounted for over half of total English consumption:

English Iron Production and Imports: Average Annual Estimates per

Decade of Imports and Production of Bar Iron, 1720-9 to 1740-9

Decade	**Bar Iron IMPORTS in tonnes**	**Bar Iron Domestic PRODUCTION in tonnes**	**Imports as Percentage of Total Consumption**
1720-9	19,650	19,700	50%
1730-9	25,650	19,350	57%
1740-9	22,500	18,650	55%

Note: 1 ton of bar (wrought) iron requires about 1.35 tonnes of pig iron; and about 5% of pig iron production was reserved for castings. Therefore bar production in England has been estimated as: 0.95/1.35 = 0.7037 tonnes of pig iron per ton of bar iron.

(4) According to Brinley Thomas's more recent and revised figures, imports were accounting for half of domestic consumption by the 1680s.

The English Iron Industry, 1580 - 1740

Charcoal Prices, Pig Iron Outputs, and Bar Iron Imports in selected decades

PERIOD	**CHAR-COAL PRICES £ per load**	**PIG IRON OUTPUT in thousands of tons**	**BAR IRON IMPORTS in thousands of tons**	**PRICE INDEX 1451-75 = 100**
1580-89	1.0	15.2	1.7	357
1630-39	1.4	20.0	3.7	616

PERIOD	CHAR-COAL PRICES £ per load	PIG IRON OUTPUT in thousands of tons	BAR IRON IMPORTS in thousands of tons	PRICE INDEX 1451-75 = 100
1680-89	2.6	21.0	23.0	577
1730-39	3.0	27.5	34.6	553

ii) **The volume of Swedish bar iron imports is all the more remarkable,** when we find that:

(1) they were burdened with both export duties in Sweden

(2) and also import duties in England, equalling 36% of the English price, which was £15.20 per ton in 1750s.

Duties Paid on a Ton of Swedish Bar Iron (Fully Refined Wrought Iron)

Swedish exports duties:	£3.45 per ton
English import duties:	£2.05 per ton
TOTAL DUTIES	£5.50 per ton

iii) **What then were the Swedish and Russian advantages?**

(1) higher quality, with higher grade ores

(2) lower costs: with almost unlimited supplies of wood fuel and water power,

(3) along with relatively cheap labour: but labour costs a very minor factor

iv) **Why was English dependence on cheaper Swedish & Russian iron a problem?**

(1) Because of the growing danger that those Baltic iron imports, so vital for military as well as industrial purposes, would be cut off in time of war;

(2) certainly it was easy enough to blockade entrance to the Baltic.

h) **Conclusion:** Thus the subsequent task of the Industrial Revolution was to convert England from being a sluggish backwater in iron production (far behind not only Sweden but also Russia and Germany and even France) to become the world's overwhelmingly dominant iron producer.

3. <u>General Character of the Industrial Revolution in Iron-Making</u>

a) **Coal-based revolution to break the two internal and one external dependencies:**

i) **the internal dependencies: the 'tyranny of wood and water'**:

(1) the revolution thus meant the use of coal throughout to break those two dependencies

(2) For that dependence on wood and water had been making the iron industry a relatively small-scale, scattered rural industry with uncompetitive high costs, and sluggish growth.

ii) **the external dependency had been the result: the reliance on imported bar iron:** especially Swedish iron, that was accounting for well over half of English consumption.

b) **Nature and Consequences of the Technological Changes**:

i) **all were based on coal and were designed to economize on raw materials,** rather than on labour.

ii) **the innovations were essentially chemical rather than mechanical,** except for coal-fired steam-power.

iii) **That coal-based technology, the use of coal throughout,** promoted the complete integration of the key processes, smelting and refining.

iv) **Industrial integration was both vertical and horizontal**:

(1) **Vertical Integration**:

- with coal and iron mines, smelters, refineries, and finishing mills (cutting, slitting) under one ownership;
- and physical amalgamation of smelting and refining in many cases.

(2) **Horizontal Integration**: with fewer but much larger scale industrial units replacing many small units (as bigger firms bought out smaller).

v) **Result**: **was urban industrial concentration of very large scale firms clustered about the major British coal fields:**

(1) first in South Wales, Shropshire, and Staffordshire in West Midlands;

(2) then in Lancashire and Cumberland in the north-west, and Northumberland-Durham in the north-east;

(3) and, finally, Scotland, which became especially important after 1830.

d) **But no other fundamental organizational changes,** other than those of scale, integration, and concentration, resulted from these technological changes.

4. <u>The First Stage of the Iron Revolution: The Revolution in Smelting</u>

a) **Coke Smelting and Abraham Darby**: **Solving the fuel problem**

i) **Attempts to solve the fuel problem in iron manufacturing:**

(1) attempts to find some way of using much cheaper coal in place of costly charcoal had been sought in the later 17th century, thus indicating that there was a real problem;

(2) but those 17th century attempts had virtually all failed, certainly for the iron industry (and for that reason, I need not bother discussing them here).

ii) **Purification of the Coal by distilling it into Coke**: was the technique that finally worked; but not right away.

iii) **The Discovery of Coke-Smelting**: Abraham Darby of Coalbrookdale (a Quaker), in Shropshire, was the first to succeed, around 1709-10.

(1) **He finally developed a coke fuel pure enough**: pure enough in containing only carbon, so that the fuel would not contaminate the iron during the smelting process.[12]

(2) **His coke-smelting process was otherwise essentially same as wood-charcoal**:

- a blast furnace at tremendously high heat caused the carbon in coke to unite with the oxygen in ferric oxide to release the iron,
- but the resulting cast-iron was mixed with 3% to 5% carbon from the fuel.

iv) **Darby's coke-smelters, however, did not create any revolution in iron making**: as the statistics on iron output clearly indicate: in fact, pig-iron output, while rising slightly in the 1720s, thereafter fell (about 5%) in the 1730s and 1740s.

v) **Furthermore, during that period,**

(1) the only coke smelter in operation was Darby's, i.e., not a single new coke smelter was built,

(2) while 22 new charcoal smelters were built (replacing 25 that were shut down) from the 1720s through the l740s.

b) **The Initial Failure of Darby's Coke-Smelting:**

i) **Why was Darby's process not copied by others:** why did coke smelting fail to spread before the 1750s or really the 1760s?

ii) **Ashton offered several explanations,** all of which have been challenged by Charles Hyde (*Technological Change and the British Iron Industry*, 1977; see note 8 above):

iii) **Changes in relative costs** – continually falling costs of coke with continually rising costs of charcoal – provide the real explanation, as elaborated below

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[12] According to the estimable *Columbia Encyclopedia*, 'Coke is a solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal. The volatile constituents of the coal (including water, coal-gas and coal-tar) are driven off by baking [the coal] in an *airless* oven at temperatures as high as 1,000 degrees Celsius, so that the fixed carbon and residual ash are fused together. Since the smoke-producing constituents are driven off during the coking of the coal, coke forms a desirable fuel for stoves and furnaces in which conditions are not suitable for the complete burning of bituminous coal itself. Coke may be burned with little or no smoke under combustion conditions which would result in a large amount of smoke if bituminous coal were the fuel'. The process is, in fact, similar to that of converting wood into charcoal.

iv) **But it is worth while to consider Ashton's hypotheses:** with Hyde's rebuttals:

c) **The Ashton-Hyde debate on why Darby's process was not imitated before the 1750s:**

i) **That Darby kept his process a secret**:

(1) But there is no evidence for this assertion.

(2) On the contrary, Darby wrote openly about his process;

(3) any one of his several partners and many employees could have given the exact process to others.

ii) **Darby's use of high quality coals?**

(1) That Darby's success was based on the accident of unusually excellent qualities of coking coal at Coalbrookdale (with very low sulphur).

(2) True: but other low-sulphur coal field were readily available (Staffordshire);

(3) and when coke smelting spread from 1750s, many smelters successfully used coals with much higher sulphur contents.

iii) **That Darby's original coke-smelting process was crude**: producing only low quality pigs.

(1) But there is no evidence for this,

(2) nor for any significant subsequent changes or refinements in his smelting techniques, before it was finally adopted by other iron makers.

d) **The Problem with Darby's Coke-Smelting**: **Silicon**

i) **coke-smelting differed from charcoal-smelting because this technique left too much silicon (or silicon oxides) in the pig iron**: [13]

(1) because the coke blast produced such a rapid smelting of the iron ore,

(2) the ore was reduced to pig iron before the silicon in the iron ore could be burnt off (according to Hyde).

ii) **That silicon, consequently, had to be burnt off in the subsequent refining process, adding to its cost**: i.e., making the cost of refining coke pigs much higher than refining charcoal pig iron.

iii) **Consequently, the price difference between coke pigs and charcoal pigs:**

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[13] Answers.com: ' Second only to oxygen, silicon is the most abundant element in Earth's crust. It is found in rocks, sand, clays and soils, combined with either oxygen as silicon dioxide, or with oxygen and other elements as silicates. Silicon's compounds are also found in water, in the atmosphere, in many plants, and even in certain animals. Silicon is the fourteenth element of the periodic table and is a Group IVA element, along with carbon germanium, tin and lead. Pure silicon is a dark gray solid with the same crystalline structure as diamond. Its chemical and physical properties are similar to this material. Silicon has a melting point of 2570° F (1410° C), a boiling point of 4271° F (2355° C), and a density of 2.33 g/cm3. When silicon is heated it reacts with the halogens (fluorine, chlorine, bromine, and iodine) to form halides. It reacts with certain metals to form silicides and when heated in an electric furnace with carbon, a wear resistant ceramic called silicon carbide is produced. Hydrofluoric acid is the only acid that affects silicon. At higher temperatures, silicon is attacked by water vapor or by oxygen to form a surface layer of silicon dioxide.'

(1) had to be large enough, in favour of coke pigs, to justify this extra refining cost in removing the silicon.

(2) Initially the cost difference was not great enough to justify coke smelting

(3) but more on that in a moment.

iv) **The presence of silicon in smelted cast iron provided, however, one unintended benefit:**

(1) It actually improved its quality for castings, providing much more even and smoother cast iron, with far fewer holes, cracks, bubbles.

(2) Darby himself turned this silicon problem into an advantage:

- by advertising the high quality of his castings,
- and thus by creating an increased demand for cast iron as a direct consumer product.

(3) Undoubtedly also that improvement facilitated the absolute and relative growth in demand for cast-iron artillery,

(4) which became a lot safer, with this elimination of cracks and bubbles.

(5) Nevertheless, in early 18th century, about 80% - 90% of the demand for iron was still for refined, wrought iron.

e) **Charles Hyde's Explanation for the Shift to Coke Smelting in 1750s**: [14]

i) **Essentially a matter of changes in smelting costs**: in terms of both relative costs and the economics of sunk costs:

(1) Why sunk costs: i.e., the cost of capital previously invested in charcoal smelters (furnaces)?

- Because, even when the fuel costs for coke-smelting had fallen below those for charcoal-smelting, fallen low enough to account for the extra refining costs in removing silicon as well, no iron master would close down his charcoal smelter and build a coke smelter,
- *unless* the total costs of coke-smelting (i.e., including capital costs of coke smelters) were lower than the marginal (indeed the variable) costs of charcoal smelting.

(2) Note, however, that these economics of sunk costs (total vs. variable) do not apply in this manner to new entrants into the industry,

- for they do not have to make the switch from charcoal to coke-smelters, but
- will instead choose to invest in coke smelters, when the operating costs are lower (including capital cost financing and depreciation on the smelter).

(3) Note also: coke smelters became much larger scale than charcoal smelters, and so had a much higher productivity -- marginal productivity of capital.

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[14] See n. 4 above.

iii) **The fall in coke-smelting costs to the 1750s**:

(1) When Darby began his process, his costs for smelting a ton of pig iron were about £7 a ton, while some charcoal smelters were producing pig-iron at around £5 - £6 per ton.

(2) By the 1730s, Darby's coke-smelting production costs had fallen below that level of £5 a ton;

(3) but that fall in coke-smelting costs was still not large enough, even for new producers, when those extra refining costs for removing the silicon are taken into account.

(4) From the 1750s, argues Hyde, coke fuel costs had fallen sufficiently low (low enough to justify those extra refining costs), while charcoal costs were continuing to rise, to give coke smelting a decisive advantage.

(5) Thus from the 1750s, the cost differences between the two processes became large enough, i.e., with total costs in coke smelting falling well below variable costs in charcoal smelting, to justify replacing charcoal smelters with coke smelters.

iv) **From 1750 to 1770,** notes Hyde, some 27 coke smelters were built while 25 charcoal smelters were shut down.

v) **The evolution of that cost differential in smelting, however, is not adequately explained by Hyde**:

(1) Evidently charcoal prices continued to rise, especially because of renewed population growth;

(2) while coal prices fell because of the continuing expansion in coal mining,

(3) especially the large growth in mining made possible by the Newcomen engines for water drainage.

(4) Remember that Darby's coke smelting techniques were devised *before* Newcomen had developed his so-called steam engine, and well before its application in coal-mining.

f) **The decisive victory of coke-smelting**: **air-pumps and steam.**

i) **first came from the application of piston air-pumps and then from the application steam power to coke-fired blast furnaces:**

(1) For coke smelting to succeed effectively, at lower cost,

- a much higher air pressure blast was required in the smelter,
- higher pressure than for wood-charcoal;

(2) and those changes came only from the 1750s.

ii) **John Smeaton (ca. 1760)**: an English engineer working in the Carron ironworks near Edinburgh made the first improvements:[15]

(1) by replacing the old-fashioned air bellows with piston air-pumps, achieving a higher pressure blast;

(2) but these piston air pumps were also powered by watermills.

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[15] See the previous lecture, on Steam Power (no. 8)

iii) **James Watt (1776)**: initial application of his steam-engine (along with coal mine pumps) was in fact to power the piston air-pumps in Joseph Wilkinson's coke blast furnace in his iron works in Shropshire.[16]

(1) That steam-powered blast provided such an intensity and efficiency that it cut the cost of coke fuels in the smelter by a third.

(2) Thus many historians have argued that this application of steam power provided the crucial breakthrough to ensure the victory of coke smelting .

(3) though Hyde still argues that the widening differential in prices between charcoal and coke fuels was the crucial factor.

g) **Neilsen's Hot Blast of 1829**: the Final Technological Breakthrough:

i) **Neilsen was a Scottish metallurgical engineer**: who found that if the air blast going into the smelter was preheated, then the smelter could achieve very major fuel economies and greatly expand output.

ii) **Preheating the air:** brought about a much more complete combustion and greatly accelerated the oxidation process.

iii) **permitted use of raw coal in smelting in place of more costly coke**: since the much higher temperatures quickly removed the sulphur and other impurities in the coal (along with the furnace slags).

h) **Consequences**: the Increase in Scale of Blast Furnaces (Coke Smelters)

i) **In the 1750s,** the average output of blast furnaces was still only about 350 tonnes a year, not much more than the mean of 300 tonnes for 1700.

ii) **But by 1815,** at the end of the Napoleonic wars, blast furnaces (coke smelters) were averaging 1,500 tonnes a year in outputs, almost a five-fold increase over that of the early 18th century.

iii) **and many could boast double that,** around 3,000 tonnes a year -- i.e., 10 times output of blast furnaces in 1700s.

iv) **Factors in this great increase in blast-furnace scale and outputs**:

(1) no limitations imposed by the nature of the fuels: charcoal fires, as noted, had a limit of 25 feet (before imploding, collapsing).

(2) much higher intensity, more efficient blast with steam-engine

(3) no necessity, therefore, to shut down for some 15-20 weeks a year, as was true of water-powered blast furnaces, because of water shortages.

(4) Thus another great advantage of steam power: in allowing blast furnaces to work year around:

- it would have been uneconomic to construct very large-scale capital installations

[16] See the previous lecture, on Steam Power (no. 8).

- if they were to lie idle for 20 weeks a year.

(i) **Economic Consequences of the Revolution in Coke Smelting**:

i) **for cast iron**: much greater direct utilization of cast-iron itself:

(1) in artillery (cannons), as noted;

(2) in pots and pans, pipes, machine-frames, tool parts, cast-iron bridges:

ii) **economic and technical factors:**

(1) First, because Darby's coke-smelting process, by leaving silicon in the iron, actually improved the quality of cast-iron, as noted: smoother, more even, with far fewer cracks and bubbles, etc.

(2) Second, because coke-smelting greatly reduced the price, making this a very cheap form of quality iron.

(3) Consumer demand was limited to those products and uses where the carbon content was not a problem: where hardness desirable, and shattering from brittleness was a low risk.

iii) **For wrought iron**:

(1) the chief demand for iron (80% - 90% in 18th century) was still in the form of wrought or malleable iron, i.e., iron with all carbon removed (well under 1%);

(2) obviously these innovations in smelting were quite unrelated to the second stage, of iron refining.

iv) **Hence the coke-smelting revolution, at least from the 1760s, created a severe and growing bottleneck in the production process**:

(1) as the supply of coke-smelted pig iron rapidly expanded well beyond the capacity of England's refinery forges (with average outputs of only 150 - 200 tonnes a year),

(2) thus still leaving England highly dependent upon imported Swedish or Russian bar iron.

4. **<u>The Revolution in Iron Refining: ‘Puddling and Rolling’</u>**

a) **The standard procedures in refining had been**:

i) **to heat and reheat the pig iron in a wood-charcoal furnace:**

(1) to burn off the carbon, silicon, sulphur, and other impurities;

(2) and then to place the partly-purified pig in a chafery fire at welding heat to remove the remaining impurities by combined pounding of the metal (with water-powered forge hammers) and heat.

ii) **From 1740s,** more and more chaferies had become coal or coke heated.

iii) **By the 1760s,** increasing pig iron outputs were creating formidable pressures on refining capacities, necessitating some innovation.

b) **The Wood Brothers**: First Advance in ‘Potting and Stamping’ Process

i) **Process devised about 1760-61 to achieve larger-scale refining at lower cost**: an intermediate process that greatly increased output.

ii) **The pig iron was first placed in a coal (later coke) burning furnace called a 'refinery**', and brought to a virtual molten stage to burn off the silicon.

iii) **The pigs were then removed from the refinery,** cooled down, and broken up into small pieces by a water-powered stamping machine.

iv) **These broken up pieces were then placed into clay pots or air-tight crucibles**:

(1) they were then heated in a coke-fired reverberatory furnace, so that the iron was totally isolated from the fuel.

(2) Their design has so improved that they could produce enough reflected heat for refining iron, under these circumstances, if not, of course, for smelting iron ore.

(3) The clay pots were lined with lime, to combine with and so remove the sulphur.

v) **The intense heat built up in crucibles:** oxidized and burned off the carbon and the sulphur.

vi) **The semi-molten iron was then removed from the pots,** and was reheated in a coal-fired chafery forge, for final pounding and refining.

vii) **Hyde:** claims that this process:

(1) was an important advance that reduced the refining costs by £2 - £3 a ton (from £15 to £12 per ton),

(2) greatly increased iron output, accounting for about half of British iron production by 1780.

c) **Cort and Onions**: 'Puddling and Rolling' Process: provided the real solution

i) **The British Navy provided the source of inspiration for invention**

(1) It was concerned about British dependence on imported Swedish and Russian bar iron, especially for military purposes, when this Baltic supply could be so easily cut off in time of war;

(2) Thus it commissioned various engineers to devise some means of mass producing cheap but high quality wrought or bar iron to end that dependence on foreign supplies.

ii) **Henry Cort and Peter Onions were the two engineers** who responded:

(1) they were working independently, and both came up with similar solution in 1783;

(2) but Henry Cort was the one who actually made it work (although subsequently, in 1789, he went bankrupt).

iii) **A Coke-fired Reverberatory Furnace**: was the key:

(1) they devised a new coke-fired furnace, as a *reverberatory* furnace, of a much improved design, to reflect the heat onto the pig iron until it became semi-molten, or 'viscous',

(2) while also isolating the pig iron from the coke fire and its exhaust fumes.

(3) Note, however, that the heat required for refining was less than that demanded for smelting.

(4) Remember that,

- while smelting required the direct contact of the carbon in the fuel with the iron ore (Fe_2O_3) in order to liberate the iron,
- refining instead meant essentially *decarburization* – the removal of the carbon (along with silicon and all the other remaining impurities.

(5) While reverberatory furnaces were designed to isolate the smoke or fumes from the metal, refining to produce fully purified iron was all the better assured in using coke fuel (i.e., as purified carbon from coal).

iv) **Puddling was the essential process, working as follows**:

(1) The pig iron was placed in this coke-fired reverberatory furnace;

(2) and the heat from the coke fire was reflected from the furnace roof on to the pig iron.

(3) The pig iron was heated to almost to a molten state,

(4) and then iron rods were inserted to stir the pig iron, bringing the silicon, sulphur, carbon, and other impurities to the surface to be oxidized, burned off.

(5) Called 'puddling' because the purified iron formed a puddle or pool at the bottom of the furnace.

(6) This refining was obviously done on a far vaster scale than the Woods potting process.

v) **Rolling:** was the second stage.

(1) The iron was transferred to another furnace,

- reheated to welding heat, and squeezed through water-powered rollers,
- with preshaped grooves to produce bars and rods of various shapes and dimensions.

(2) These water-powered rollers also skimmed off or squeezed out any remaining impurities and slag (from puddling).

v) **Application of steam-power was again the final step**: in 1788, Wilkinson adapted Watt's steam engine to the rollers of his rolling mills in Shropshire.

d) **Richard Crawshay of Cyfarthfa Ironworks in South Wales**:

i) **improved the puddling process in various ways in the 1790s,** especially in using a cast iron plate instead of clay for the reflective ceiling of the furnace;

ii) **and his firm promoted the use of the new process,** in the 1790s, when it began to spread.

e) **Scale of Operations**: even greater leap forward than for blast furnaces.

i) **In early 18th century,** as noted, refining forges had outputs from 120 to 200 tonnes per, with an annual average of 150 tonnes.

ii) **By 1815,** British iron refineries had an average annual output of 5,000 tonnes; and Crawshay's Cyfarthfa Iron Works in South Wales produced 13,000 tonnes of wrought iron a year.

5. **Results of the Revolution in Iron Making**

a) **Ended forever the 'Tyranny of Wood and Water' by using coal throughout the entire sequence**: for smelting, refining, and applied steam power.

b) **Importance of coal**:

i) **coke:**

(1) by the 1760s, with advances in coal-mining technology, especially with the use of the Newcomen steam pump,

(2) coke fuels had become much cheaper than charcoal,

(3) even taking account of the silicon problem in coke-produced pig iron.

ii) **steam**:

(1) from 1776, James Watt's coal-fired steam engine provided the revolutionary breakthrough in smelting,

(2) and it would soon do the same (from 1783) in iron-refining as well

iii) **thus coal made possible the total integration of the iron industry** in single, very large-scale units, with very considerable savings on internal transportation and transactions costs as well as economies from increasing returns to scale.

iv) **By combining smelting and refining**:

(1) iron makers achieved considerable savings on fuel costs by refining the pig iron when it was still hot, i.e., saving fuel on reheating the pig for the Puddling and Rolling process.

(2) Obviously with geographically separate units refiners had to begin with cold pig iron.

v) **Both vertical and horizontal integration were promoted**:

(1) with a few very large firms replacing dozens of smaller ones, often by buying out smaller competitors, or by forcing them out of production.

(2) by 1815 (end of Napoleonic Wars), just 15 iron firms accounted for over half of output.

(3) That structure resembled more or provided greater possibilities for **oligopolistic** competition; and it was certainly not the structure of pure competition (as we shall in the cotton industry).

vi) **Oligopolistic Competition: its forms and nature**

(1) fierce, often cut-throat competition by a few very large-scale producers,

- all producing homogeneous or very similar products:
- possibly a wide range of products -- pig iron, bar iron, sheet iron, rods, wire, etc,
- each product being indistinguishable in form and quality from those of their competitors;

(2) or production by a few dominant large-scale producers, acting as price-leaders, who overwhelm and subordinate smaller competitors, who are forced to follow their lead;

(3) entrance into the industry restricted by the very high start-up costs of large-scale production;

(4) continuous horizontal integration as larger firms buy up and amalgamate smaller competitors, often forcing them out of production by price-cutting ('cut-throat pricing').

vii) **Geographical industrial concentration:**

(1) Using coal throughout also provided a strong incentive to concentrate and cluster the entire iron industry about coal-fields -- to transport the iron to the coal, not coal to the iron -- especially when it took about 10 tonnes of coal to smelt one ton of iron.

(2) Thus regional concentration about Britain's major coal fields:

(3) By 1815, we find a very marked shift of the iron industry to the coal fields of South Wales and of Staffordshire and Shropshire in the West Midlands, both regions accounting for about 75% of national iron output.

(4) From the 1830s, new areas developed, with the discovery of new and richer coal fields:

- principally in the North-West (Lancashire-Cumberland),
- the North-East (Durham-Northumberland) and Scotland.
- By the 1870s, these newer regions were accounting for over half of total output.

d) **Economic Contribution to Industrialization**:

i) **cheap iron and cheap coal together** were the essential ingredients of 19th century industrialization across the world.

ii) **The revolution in iron-making gave Europe its first cheap but high quality metal**:

(1) cheap metal as the most important building blocks of modern industrialization

(2) Thus iron was primarily a capital good rather than as a consumer good,

(3) even though some wrought iron and even more cast iron products were produced as consumer goods.

ii) **this revolution permitted the development of a new engineering industry based on powered machinery, principally steam power**:

(1) for obviously only iron machines (rather than copper, brass, or bronze) had the durability to withstand the stress produced by steam power;

(2) and only iron products could be crafted to the exact precision required in steam engineering.

iv) **Because Britain was the innovator** with mastery over this new technology, her primacy in iron, coal, and steam engineering is the major factory explaining Britain's industrial leadership for almost a century, from the 1780s to the 1880s.

e) **Importance of Iron for British exports**:

i) **as the table on the screen indicates, iron certainly could not compare with cotton in exports,** at least for the first phase of the Industrial Revolution, when cottons accounted for 60% of British exports.

ii) **On the import side, however,** note that the revolution in iron-making did eliminate virtually all iron imports from Sweden, Russia, and elsewhere.

iii) **Then, with the coming of the Railway Age,** iron became a much more important export, as Britain exported vast quantities of railway iron abroad, especially in helping to build railways across the world.

f) **Conclusions:**

i) **So, in sum, these are the major developments that rapidly converted Great Britain from being a sluggish backwater in European iron production,** way behind Sweden and Russia especially, to become the world's overwhelmingly dominant iron producer by the early 19th century.

ii) **but consider again 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, as we have seen in this 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.

Table 1. **Price Relatives for Fuels (Wood, Charcoal and Coal)**

and Components of the Phelps Brown and Hopkins 'Basket of Consumables' (Revised Version)

1451-60 to 1781-90, in decennial means

Base (1) 1451 - 1475 = 100 **Base (2) 1581-90 = 100**

Decade	Charcoal Index 1451-75 = 100	Charcoal Index 1581-90 = 100	Coal Index 1451-75 = 100	Coal Index 1581-90 = 100	Timber Index 1451-75 = 100	Timber Index 1581-90 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1451-75 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1581-90 = 100
							112.801 d. sterling	
1451-60	101.901	42.582			109.451	32.174	99.855	29.353
1461-70	88.482	36.975			94.712	27.841	102.109	30.016
1471-80	99.226	41.464			94.155	27.678	94.370	27.741
1481-90	87.791	36.686			108.235	31.817	111.326	32.725
1491-1500	81.152	33.912			92.332	27.142	100.542	29.555
1501-10	88.261	36.882			86.254	25.355	105.719	31.077
1511-20	93.910	39.243			99.291	29.187	114.921	33.782
1521-30	95.125	39.751			102.816	30.224	153.430	45.102

Decade	Charcoal Index 1451-75 = 100	Charcoal Index 1581-90 = 100	Coal Index 1451-75 = 100	Coal Index 1581-90 = 100	Timber Index 1451-75 = 100	Timber Index 1581-90 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1451-75 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1581-90 = 100
							112.801 d. sterling	
1531-40	90.205	37.695			97.954	28.794	158.278	46.527
1541-50	106.839	44.646			120.644	35.464	204.838	60.214
1551-60	171.315	71.589			181.625	53.390	296.195	87.069
1561-70	187.847	78.498			179.498	52.765	286.075	84.094
1571-80	208.752	87.233			216.066	63.514	313.903	92.275
1581-90	239.303	100.000	274.605	100.000	248.987	100.000	340.184	100.000
1591-1600	254.108	106.186	260.707	94.939	295.583	118.714	430.784	126.632
1601-10	280.911	117.387	288.045	104.894	349.473	140.358	436.652	128.357
1611-20	329.714	137.781	288.171	104.940	408.732	164.158	477.818	140.459
1621-30	325.204	135.896	316.146	115.128	455.835	183.076	488.775	143.680
1631-40	332.175	138.809	354.618	129.138	494.834	198.739	558.621	164.211

Decade	Charcoal Index 1451-75 = 100	Charcoal Index 1581-90 = 100	Coal Index 1451-75 = 100	Coal Index 1581-90 = 100	Timber Index 1451-75 = 100	Timber Index 1581-90 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1451-75 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1581-90 = 100
							112.801 d. sterling	
1641-50	433.398	181.108	530.691	193.256	528.363	212.205	585.240	172.036
1651-60	539.616	225.495	473.712	172.507			571.151	167.895
1661-70	607.687	253.940	454.453	165.493			567.490	166.819
1671-80	593.218	247.894	502.520	182.997			555.113	163.180
1681-90	572.798	239.360	400.096	145.699			501.543	147.433
1691-1700	572.030	239.040	488.295	177.817			574.244	168.804
1701-10	685.289	286.368	535.404	194.973			603.321	177.351
1711-20	727.951	304.196	503.508	183.357			646.880	190.156
1721-30	727.951	304.196	486.866	177.297			604.489	177.695
1731-40	729.749	304.947	516.680	188.154			557.411	163.856
1741-50	757.913	316.716	545.668	198.710			593.490	174.461

Decade	Charcoal Index 1451-75 = 100	Charcoal Index 1581-90 = 100	Coal Index 1451-75 = 100	Coal Index 1581-90 = 100	Timber Index 1451-75 = 100	Timber Index 1581-90 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1451-75 = 100	Phelps Brown & Hopkins Basket of Consumables Index 1581-90 = 100
							112.801 d. sterling	
1751-60	757.913	316.716	593.049	215.964			633.596	186.251
1761-70	794.754	332.111	604.946	220.297			710.712	208.92
1771-80	794.754	332.111	656.900	239.217			806.887	237.191
1781-90	794.754	332.111	669.944	243.967			838.616	246.518

coal Cambridge coal: spliced to combined charcoal index over 1586-1635multiplier = 20.15607

coal Westminster coal: spliced to combined charcoal index over 1586-1635multiplier = 17.3983

Sources:

The Phelps Brown Papers Collection, Archives of the British Library of Political and Economic Science (LSE Archives);
Peter Bowden, 'Agricultural Prices, Farm Profits, and Rents', in Joan Thirsk, ed., *The Agrarian History of England and Wales*, Vol. IV: *1500 - 1640* (Cambridge: Cambridge University Press, 1967), Table VI, pp. 846-850. I have converted his original base, 1450-99= 100 (7.99s for 100 faggots) to the PBH base of 1451-75.

This table has now been published in: John Munro, 'Money, Prices, Wages, and "Profit Inflation" in Spain, the Southern Netherlands, and England during the Price Revolution era: ca. 1520 - ca. 1650', *História e Economia: Revista Interdisciplinar*, 4:1 (2008), 13-71.

Table 2:

The English Iron Industry, 1580 - 1740

Charcoal Prices, Pig Iron Outputs, and Bar Iron Imports in selected decades

PERIOD	CHAR-COAL PRICES £ per load	PIG IRON OUTPUT in thousands of tons	BAR IRON IMPORTS in thousands of tons	PRICE INDEX 1451-75 = 100
1580-89	1.0	15.2	1.7	357
1630-39	1.4	20.0	3.7	616
1680-89	2.6	21.0	23.0	577
1730-39	3.0	27.5	34.6	553

Source: Brinley Thomas, 'Was There an Energy Crisis in Great Britain in the 17th Century?' *Explorations in Economic History*, 23 (April 1986), 124 - 52.

Table 4:

OCCUPIED BLAST FURNACE SITES, BY DECADES

Decade	**Total Furnace Sites**	**Index 1600-09 = 100**	**Weald Furnace Sites**	**Index 1600-09 = 100**
1530-9	6	6.7	6	11.5
1540-9	22	24.7	22	42.3
1550-9	26	29.2	26	50.0
1560-9	44	49.4	36	69.2
1570-9	67	75.3	52	**100.0**
1580-9	76	85.4	54	103.8
1590-9	82	92.0	50	96.2
1600-9	89	**100.0**	52	100.0
1610-9	79	88.8	47	90.4
1620-9	82	92.1	46	88.5
1630-9	79	88.8	41	78.8
1640-9	82	92.1	43	82.7
1650-9	86	96.6	42	80.8
1660-9	81	91.0	37	71.2
1670-9	71	79.8	24	46.2
1680-9	68	76.4	22	42.3
1690-9	78	87.6	23	44.2
1700-9	76	85.4	23	44.2
1710-9	82	92.1	21	40.4
1720-9	60	67.4	13	25.0
1730-9	55	61.8	12	23.1
1740-9	49	55.1	12	23.1

***** Data on total furnace site do not necessarily mean that all of these furnaces were in operation, or full time operation, over the entire decade indicated.

Source: George Hammersley, ‘The Charcoal Iron Industry and Its Fuel, 1540 - 1750', *Economic History Review*, 2nd ser., 26 (1973), 595. Index numbers added.

Table 5:

English Pig Iron Production, 1530-1750

Occupied Blast Furnaces Average Output per Furnace, and Estimated Annual Average Output in Tonnes, per Decade, 1530-9 to 1740-9

Decade	**No. of Blast Furnaces Occupied**	**Average Output per Furnace in tonnes**	**Average Annual IRON OUTPUT in tonnes**
1530-9	6	200	1,200
1540-9	22	200	4,400
1550-9	26	200	5,200
1560-9	44	200	8,800
1570-9	67	200	13,400
1580-9	76	200	15,200
1590-9	82	200	16,400
1600-9	89	200	17,800
1610-9	79	215	17,000
1620-9	82	230	19,000
1630-9	79	250	20,000
1640-9	82	260	21,000
1650-9	86	270	23,000
1660-9	81	270	22,000
1670-9	71	270	19,000
1680-9	68	300	21,000
1690-9	78	300	23,000
1700-9	76	315	24,000
1710-9	74	340	25,000
1720-9	80	350	28,000
1730-9	75	365	27,500
1740-9	71	375	26,500

Sources: G. Hammersley, 'The Charcoal Iron Industry and its Fuel, 1540-1750', *Economic History Review*, 2nd ser. 26 (1973), 595. Charles Hyde, *Technological Change and the British Iron Industry, 1700-1870* (Princeton, 1977); Philip Riden, 'The Output of the British Iron Industry before 1870', *Economic History Review*, 2nd ser. 30 (1977), 443, 448.

Table 6

Charcoal-Smelted Pig Iron: Production Costs ca. 1720-21
To Produce 360 Tonnes of Pig Iron per year

Production Input	**Total Costs per year**	**Percentage of Total Cost**
(1) Charcoal	£1,459	71.0%
(2) Iron Ore	313	15.2%
(3) Furnace Labour	61	3.0%
(4) Clerical salaries	40	1.9%
(5) Rent	40	1.9%
(6) Repairs and Maintenance	63	3.1%
(7) Other Costs	78	3.8%
TOTAL COSTS	**£2,054**	**100.0%**

Cost per ton of pig iron = £5.70

Table 7:

English Iron Production and Imports: Average Annual Estimates per

Decade of Imports and Production of Bar Iron, 1720-9 to 1740-9

Decade	**Bar Iron IMPORTS in tonnes**	**Bar Iron Domestic PRODUCTION in tonnes**	**Imports as Percentage of Total Consumption**
1720-9	19,650	19,700	50%
1730-9	25,650	19,350	57%
1740-9	22,500	18,650	55%

Note: 1 ton of bar (wrought) iron requires about 1.35 tonnes of pig iron; and about 5% of pig iron production was reserved for castings. Therefore bar production in England has been estimated as:

0.95/1.35 = 0.7037 tonnes of pig iron per ton of bar iron.

Duties Paid on a Ton of Swedish Bar Iron (Fully Refined Wrought Iron)

a) Swedish exports duties: £3.45 per ton

b) English import duties: £2.05 per ton

TOTAL DUTIES £5.50 per ton

Source: Charles Hyde, *Technological Change and the British Iron Industry, 1700-1870* (Princeton, 1977).

N.B. Brinley Thomas (1986), in Table 3, provides even larger estimates of bar iron imports for the decade 1730-9: in absolute amounts, and as a proportion of total consumption.

Table 8

Geographical Distribution of Early

Eighteenth-Century Ironworks

Region	**Number**	**Tonnes of Output**	**Share of National Output (%)**	**Tonnes Output Per Furnace**
		A. Furnaces (1720)		
1. The Weald	15	2,000	11.5	133
2. Forest of Dean	9	4,250	24.4	472
3. South Wales	6	1,500	8.6	250
4. N. Wales-Cheshire	5	2,250	12.9	450
5. Shropshire	7	2,550	14.6	364
6. Staff.-Worcester.	6	2,400	13.8	400
7. S. Yorkshire-Derby	11	2,400	13.8	218
8. Lancashire-Cumberland	-	-	-	-
9. Scotland	-	-	-	-
Total/Average	59	17,350		297
		B. Forges (1717)		
1. The Weald	15	920	6.9	61
2. Forest of Dean	20	1,840	13.8	92
3. South Wales	13	1,750	13.1	134
4. N. Wales-Cheshire	8	880	6.6	110
5. Shropshire	14	2,010	15.0	143
6. Staff.-Worcester.	28	3,920	29.4	140
7. S. Yorkshire-Derby.	16	1,690	12.6	105
8. Lancs.-Cumberland	2	320	2.4	160
9. Scotland	-	-	-	-
Average or Total	**116**	**13,330**		**115**

Source: Charles K. Hyde, *Technological Change and the British Iron Industry, 1700-1870* (Princeton, 1977).

Table 9

Estimates of the Output of British Pig Iron:
Decennial Averages, 1650-9 to 1850-9

Decade	**Output**	**Index in Tonnes 100**	**Decade** 1750-9 = 100	**Output**	**Index** in Tonnes 1750-9 = 100
1650-9	23000	78	**1760-9**	37000	125
1660-9	22000	75	**1770-9**	44,000	149
1670-9	19000	64	**1780-9**	71,000	241
1680-9	21000	71	**1790-9**	122,000	414
1690-9	23,000	78	**1800-9**	253,000	858
1700-9	24,000	81	**1810-9**	332,000	1125
1710-9	25,000	85	**1820-9**	525,000	1780
1720-9	28,000	95	**1830-9**	878,000	2976
1730-9	27500	93	**1840-9**	1,726,000	5850
1740-9	26500	90	**1850-9**	3,106,000	10529
1750-9	29,500	100			

Source: Calculated from Philip Riden, 'The Output of the British Iron Industry Before 1870', *Economic History Review*, 2nd ser. 30 (1977), 442-59.

Table 10

TEXTILE AND METAL EXPORTS DURING THE INDUSTRIAL REVOLUTION ERA

Exports of textile and metal products and of colonial re-exports as percentages of total exports from England and Wales (1750-9 to 1780-9) and Great Britain (1790-9 to 1820-9) in constant prices based on those of ca. 1700

Decade	Woollens & Worsteds	Cottons	Iron and Steel	Re-Exports	Total Exports in Millions of £ (pounds)
1750-9	48.85%	1.0%	4.8%	28.6%	12.25
1760-9	44.35%	2.3%	5.9%	30.9%	14.53
1770-9	43.0%	2.7%	7.3%	35.6%	14.42
1780-9	34.5%	7.4%	6.5%	29.5%	14.46
1790-9	29.9%	15.0%	6.9%	34.8%	27.12
1800-9	24.0%	40.2%	5.3%	28.9%	34.98
1810-9	16.0%	53.4%	4.5%	25.0%	46.72
1820-9	11.9%	61.9%	4.4%	17.5%	56.41

Source: B.R. Mitchell and Phyllis Deane, eds., *Abstract of British Historical Statistics* (Cambridge, 1962), pp. 279-83, 293-95.