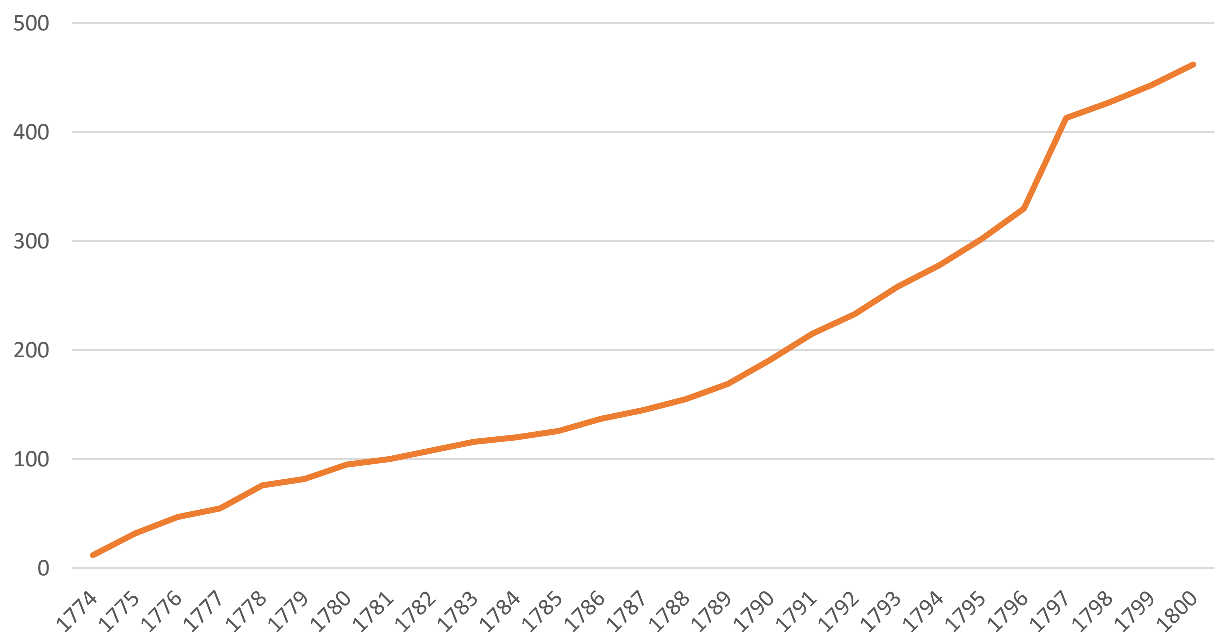
Chapter 5: A Sectoral Analysis of Diffusion: Mining and Iron (Blast Furnaces)

The annual operating cost of steam relative to other power sources was a critical factor in the decision-making process of potential adopters during the last quarter of the 18th century. But adoption decisions also hinged on factors which were sector-specific such as the purchase price of a steam engine, sometimes in conjunction with a complementary technology, in the context of the asset structure of firms; location determined demand growth and thus the ability of a firm to afford such purchase; and sometimes factors specific to business cycle activity. This chapter will delve into such issues in the context of two pioneering sectors of the economy, mining and iron. The former continued, through 1800, to be the leading sector in terms of steam power diffusion while iron shed to the textile industry the second place it held up to the 1770s.

Collieries

There was no other sector of the economy in which steam power came to be as dominant as in collieries. Both in the pre-Watt era and by 1800 the pumping operations of mines were virtually monopolized by steam while it came to account for one-third of power in winding in the course of less than two decades, from the early 1780s to 1800 (see Figure 5.1 and chapter 1).

***Figure 5.1*: Cumulative number of steam engines installed in collieries, 1774-1800**



The purchase prices of steam engines declined in the last quarter of the century compared to previous decades but the ancillary costs of erection and other elements involved in the cost of opening new pits increased substantially, especially during the war years in the 1790s. A figure of £7,000 when it comes to the investment cost of opening new pits, including the purchase of steam engines, seems fairly reasonable; in fact, it may be an underestimate.[1] It is hard to generalize on the extent to which this figure proved to be an obstacle for colliery owners. One may find in the literature some data on profitability which indicate very wide margins of variation. In a report made to the Parliament by Francis Thompson, he stated that the "appropriate" rate of return was considered to be 15%. However, the average profit rate from a sample of 8 collieries, referring to either single years or a number of them, gives a mean of 31.5%. On the other hand, Cunninghhame and Warner made a profit of 3.3%, specifically, £4,918 on an expenditure of £147,084 over the period 1770-1798.[2] Despite the fact that collieries were some of the most heavily capitalized businesses at that time, in some cases their owners were unable to afford the purchase of an engine.[3] In Blakey's words written in 1793:

> Engines for extracting water from mines, are so expensive, that many proprietors of mines cannot purchase them … If the price of them were as moderate as the nature of their principles of power point out, an infinite number of manufacturers would have them sooner.[4]

Those who could afford to engage in the exploitation of new seams had to ponder on the marginal cost and the level of output at which it was met and exceeded by marginal revenues. Pollard distinguished three categories of collieries, the largest ones producing above 15,000-25,000 tons per year while those

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[1] Flinn has cited figures on the weight of steam engine cost in the context of total investment projects when opening new pits, hence by knowing the former we can extrapolate the latter. However, his data come from years preceding and following the last quarter century, hence a mean figure was adopted. Also, it is unclear whether his calculations take into account only the purchase price of engines or the latter plus the ancillary costs of erection. See Flinn, *The history of the British coal industry*, p. 193. Hence the figure of £7,000 entails a fair amount of guesswork regarding the variables involved and it should be viewed only as a ballpark figure since variations in the physical conditions of collieries could produce a fair amount of deviation. The author feels that the figure may be an underestimate given cases such as the *ex ante* estimate for a new pit at Lumley which specified the cost of the initial investment at £10,836 in 1775 and the estimated output at 53,000 tons. Eventually the *ex post* cost got up to £17,000. See ibid., p. 192.

[2]Deviations also abound when absolute figures on annual average net profits are cited. Some examples:
Bridgewater collieries (Lancashire = £2,350 (1774-1800)
Fordel colliery (Scotland) = £1,364 (1774-90, 1800)
Sheffield colliery (Yorkshire) = £849 (1781-7)
Lothian collieries (Scotland) = £529 (1796-1800)
Ibid., pp. 320-6; Duckham, *A history of the Scottish coal industry*, p. 197.

[3] Lord provided a list of companies which inquired to B & W but did not proceed with the purchase of an engine. One-fifth of them were colliery owners. See his *Capital and steam-power*, pp. 236-7.

[4] *A short historical account of the invention, theory and practice of fire machinery*, pp. vi, viii.

of medium size falling just below this range. He calculated the average operating cost of producing 1,000 tons of coal in these two categories as follows (figures in £):[5]

	Large	Medium
1780	29.1	29.7
1790	28.1	30.4
1800	45.4	39.3

The calculation of marginal revenues hinged to a large extent on the behavior of coal prices. Prospects for collieries prior to the 1770s did not seem bright in the northeastern coalfield. The utilization of Newcomen engines led to an intensified exploitation of seams in the Wallsend and Wear districts, a development that was against the interests of families which were involved in the business since earlier times, such as the Ravensworths, Strathmore, and Wortley. These individuals signed long leases hoping to acquire a monopolistic position. As a result of overproduction pithead prices were depressed, standing, on average, at 4.6s/ton in the period 1740-71. In light of this situation the representatives of coalmine owners from Sunderland and Newcastle met to work out some sort of agreement. In 1771 a permanent union rose which was to last, with some interruptions, until 1844.[6] The association had two goals. First, to create a plan aimed at controlling production within the effective area of the association, thereby regulating prices. Second, establishing the control of a market in order to prevent penetration from outside competition. Such market was London and its neighborhood. As late as 1800 the northeastern coalfield dominated the capital's market based on the advantage offered by its lower transportation cost, with other producers sending coal only intermittently in times demand reached extraordinary levels. Collieries in Yorkshire, Warwick or Derby which had to deal with the cost of inland transportation could not compete in any effective way even following the ushering of the canal era. Welsh coal was also unable to penetrate the London market since freight costs were higher. The provisions of the agreement were to set maximum production levels for each colliery and prohibit each from selling below a price. The objectives of the association were met. Nominal pithead prices increased by 34%, to 6.2s or £0.31/ton by 1790; and by another 8%, to 6.7s or £0.33/ton, by 1800.[7]

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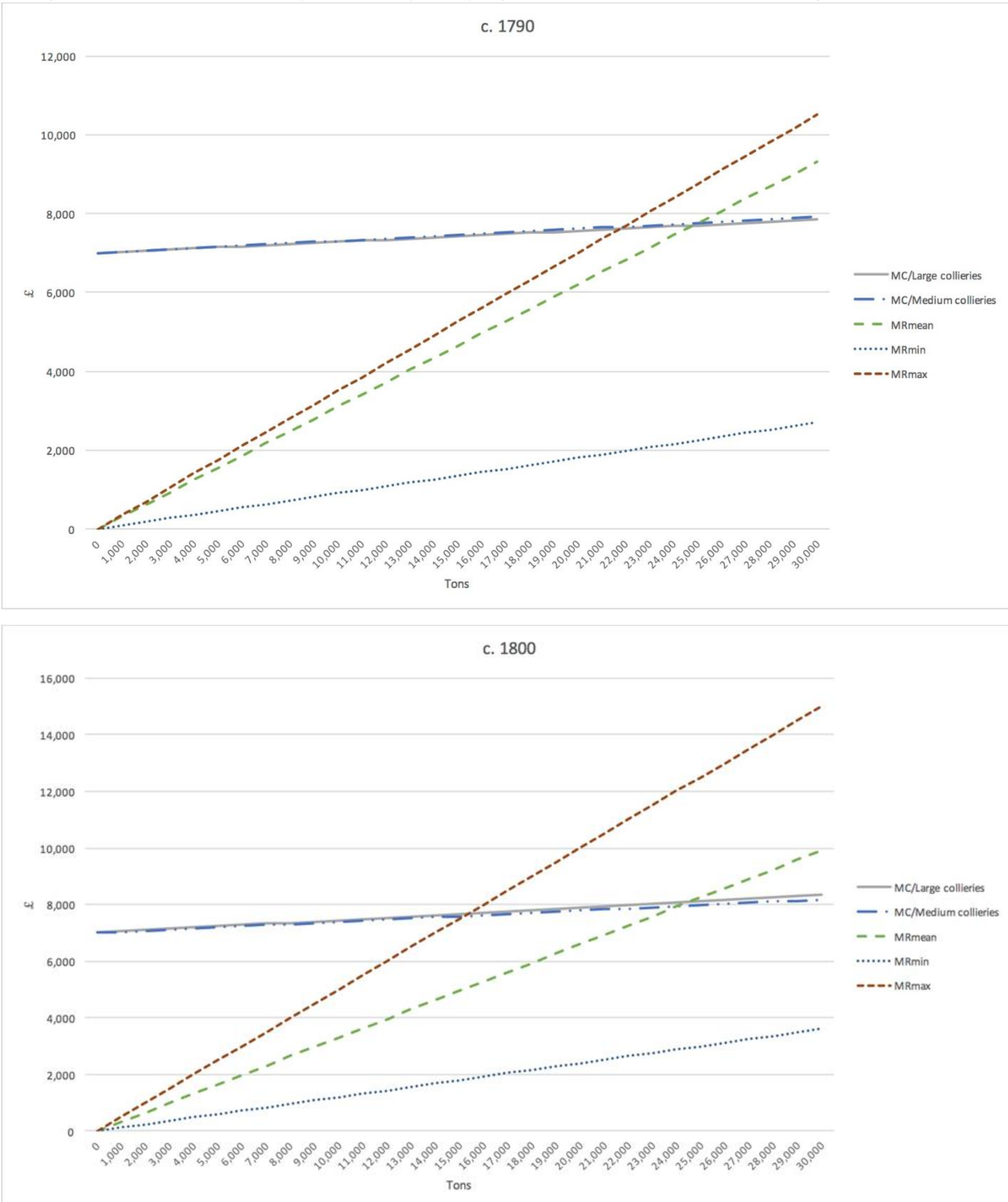
[5] The sharp rise that takes place in the 1790s is due to the inflation of the Napoleonic Wars; see his "Coal mining," pp. 37-49.

[6] It should be noted that attempts to regulate production and the market started appearing sporadically beginning in the early 17th century. Levy, *Monopoly and competition*, pp. 108-11; Fordyce, *A history of coal*, p. 105.

[7] The minimum pithead price for 1790 was £0.09/ton and the maximum £0.35/ton. The respective figures for 1800 were £0.12 and £0.5 respectively. Between 1740-71 and 1790 London retail prices remained stable at c. 27s/ton but then they increased by 41% in the 1790s, reaching 38s/ton in 1800. Sales also increased noticeably. Observations on

***Figure 5.2*: Threshold output levels justifying the installation of steam engines in collieries**



pithead prices were found in the following sources: Aiken, *A description of the country*, pp. 237, 239; Farey, *A Treatise on the steam engine, vol. II*, p. 159; Ashton and Sykes, *The coal industry*, pp. 252-3; Dunn, *An historical, geological, and descriptive view of the coal trade*, pp. 26-7, 80; Meade, *The coal and iron industries*, p. 158; Turnbull, "Canals, coal and regional growth," p. 548.

Figure 5.2 depicts the behavior of marginal costs and revenues in 1790 and 1800 for both medium and large collieries. The intersection points in both years, when taking into account mean pithead prices, stood at outputs of c. 24-25,000 tons for both large and medium collieries, up from c. 23,000 tons during the period 1740-71.[8] It follows that defraying the investment cost involved in opening a new pit in conjunction with the purchase of a new engine was well within the means of medium- to somewhat large size collieries, based on Pollard's classification. For collieries producing the highest grades of coal and thus selling at maximum pithead prices, the threshold outputs oscillated c. 3,000 tons above and below pre-Watt figures without signifying radical changes. But what was different towards the end of the century compared to pre-Watt decades was the very substantial increase in the threshold output (over 110,000 tons in 1790 and in the vicinity of 90,000 tons in 1800) when pithead prices were at a minimum. In other words, for collieries which extracted very low-quality coal it would have been a very tall order to engage in the opening of new pits accompanied with the purchase of a new steam engine. But this would have been the exception rather than the rule. In the vast majority of cases collieries which sold coal of a standard quality would have the financial means to engage in such an investment project since the increase of coal prices counterbalanced to a large extent the substantial increase of the initial investment figure.

Table 5.1: Fixed capital and output in several collieries

Date	*Colliery/Region*	*Fixed capital (£)*	*Output in tons*	*Fixed capital per ton (£)*
1770s	Griff, E. Midlands	1,992	18,000	0.11
1777-83	Lumley, northeast	17,000	87,821	0.18
1788	25 Tyne collieries, northeast	246,000 (9,849/colliery)	2,071,134 (82,845/colliery)	0.12
1789	Attercliffe, West Riding	10,535	24,300	0.43

Source: Flinn, *The history of the British coal industry*, p. 201.

It is important to stress that a potential adopter did not have to produce the output specified by the thresholds at the time of contemplating purchasing a new engine and opening a new seam. Table 5.1 provides data on the amount of fixed capital and output size for several collieries. Northeastern collieries, like Lumley, which tended to overshadow their counterparts in other parts of the country in terms of capital endowments and size, were well above the output thresholds justifying large capital investments

[8] Kitsikopoulos, *Innovation and technological diffusion*, pp. 158-9.

and the purchase of a steam engine. Lumley, for instance, did buy a Newcomen pumping engine in 1780. Attercliffe reached a level of output in the late 1780s which was right at the specified thresholds. It also adopted three pumping engines around that time. But even Griff, whose output in the 1790s fell short of the thresholds, did adopt two Newcomen pumping engines (1773 and 1776) since the anticipated expansion of output would presumably have allowed it to surpass the thresholds.

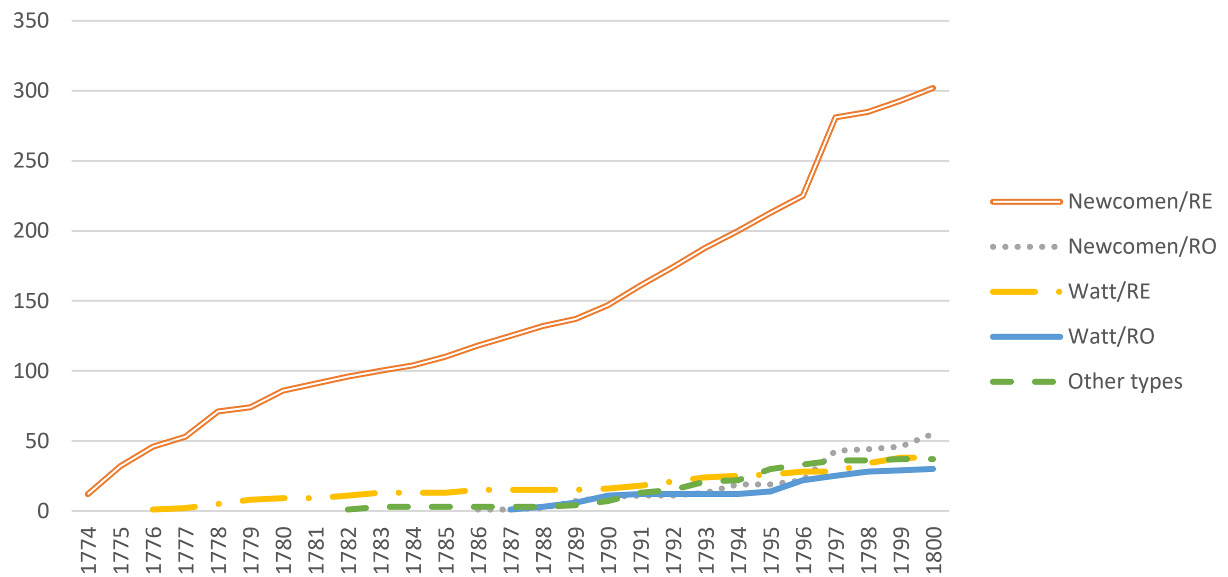
But despite the fact that the threshold level of output remained virtually unchanged from previous decades, the diffusion of steam engines in collieries greatly accelerated. Nearly 400 pumping engines were installed in the period 1706-73. In contrast, within just 27 years (1774-1800) 328 pumping engines and another 137 winding engines were adopted. To these figures, we have to add the 72 engines which appear in the revised Kanefsky database as "water-returning" and those whose function is unknown. Stated in other words, the rate of steam power diffusion in collieries quadrupled during the last quarter of the century compared to previous decades.

What made the crucial difference? The key to the explanation lies on the demand side, specifically, the transportation improvements which took place throughout the country.[9] The expansion of turnpikes was certainly helpful. Pits in north Derbyshire were small in terms of their output but when turnpiking got under way output started increasing, though modestly, and the exploitation of pits aligned in relation of their proximity to turnpikes. But improvements in water transport were of much greater consequence. Output and sales expanded more rapidly both in Derbyshire and Nottinghamshire with the opening of the Chesterfield canal (1777) and those tapping the Erewash valley (1779). The northern and southern fringes of the Yorkshire coalfield served by the Calder and Trent allowed nearby collieries to expand their sales. But the rich seams at Barsnley in the central section were landlocked until the improvement of the Don and the opening of Barnsley canal, beginning in 1799 with its northern segment, as well as other local canals which allowed the exploitation of deep and rich seams near these waterways. An even more dramatic development took place in south Wales. Small scale mining first took place in the western section serviced by roads, tramways and few small canals. But in the 1790s the Glamorganshire and Monmouthshire canals opened up the rich seams near Cardiff and Newport moving the focus from west to east and rendering these two towns major ports in the export trade. An equally impressive example refers to southwest Lancashire. The improvements brought by the Sankey and Douglas navigations and the Leeds-Liverpool canal led to boosting output from 225,000 tons c. 1773 to 680,000 tons c. 1799. In other words, the ushering of the canal era allowed previously landlocked collieries of modest size to justify

[9] Turnbull, "Canals, coal and regional growth," pp. 548-9; Pollard, "A new estimate of British coal production," pp. 226-7.

large investments, which included the installation of new steam engines, and in the process increasing their size to the point of surpassing the threshold points specified in figure 5.2; hence the quadrupling of the steam power diffusion in this sector.

***Figure 5.3*: Number of reciprocating and rotary engines of various types installed in collieries, 1774-1800**



When it comes to the choice of the particular model, the cost analysis in chapter 3 has shown that collieries were the only location where the Newcomen model was somewhat cheaper compared to Watt engines based on its lower purchase price, an advantage which was not negated by its inefficiency given the very low prices of coal at the pithead, particularly of sleck. The installation of the relatively few Watt engines (see Figure 5.3) was justified based on their superior capacity in reaching deep seams, an example being the mines of Tyneside which sank to depths of 600 feet and dealt with large quantities of water. In such cases it was cheaper, overall, to install a single Watt engine than two Newcomen ones doing the same job.[10]

Cornish metal mines

[10] To give an example, though not from collieries, when a Watt engine came to replace a Newcomen one in Godolphin mine, Cornwall, the depth of raising water increased from 62 to 89 fathoms. See von Tunzelmann, "Technical progress," in Floud, and McCloskey, eds., The economic history of Britain, p. 157; Wilson, *A comparative statement*, p. 4; Mott, "The Newcomen engine in the eighteenth century", p. 84.

The amount of steam power introduced in metal mines during the last quarter of the 18th century was very impressive in light of the fact that it accounted for 90% of pumping operations, with water power taking up the remainder as well as the vast majority of the energy output generated in the winding process. The near monopoly of steam power in pumping operations is a remarkable feat given the volatility of economic conditions which prevailed during this period, to be illustrated by taking a closer look at the Cornish market of copper.

Cornish production of metals witnessed a resurgence beginning in the 1740s acting as one of the key factors boosting the diffusion of steam power but the region faced stiff competition in the copper market since the discovery of the Anglesea ores in 1768. The growth rate of production in the latter surpassed the one in Cornwall. In 1778 Anglesea produced 1,200 tons of copper while Cornwall's output stood at 3,000 tons. By 1785 the respective figures were 3,000 and 4,400 tons.[11] The competition raised by Anglesea came at the worst possible moment. Newcomen engines were used since the very first appearance of this technology but by the 1770s they were proving inadequate due to the exhaustion of many seams and the need to get to greater depths. On the other hand, the Anglesea seams were shallow and thus no shafts had to be sunk and no machinery was necessary for draining water, hence production cost was considerably lower. In the context of these configurations, the Watt engine appeared as a *deux ex machina* when it came to the market in the 1770s since its lower fuel consumption was critically important.[12] B & W installed their first engine in 1777 and in the next two years they added another 5 engines, compared to 15 Newcomen engines adopted in the period 1774-9.[13]

The introduction of Watt engines led to an increase of production through greater intensification since the presence of expensive fixed capital, which carried the payment of premiums, discouraged idleness of the engines (see Figure 5.4).[14] As an illustration, annual output jumped from 28,122 tons of copper *ore* in 1782 to 35,799 tons in 1783. According to Rowe, quoting an estimate by Wilson, the application of the Watt engine in Cornwall saved mine adventurers £40,000/year or roughly £1 per ton raised. If we deduct

[11] Watson, *A compendium of British mining*, p. 4; Allen, "An eighteenth-century combination," p. 76-7. Tin production was also going through a growth phase testified by some export figures cited by Davis; see his "English foreign trade," p. 302.

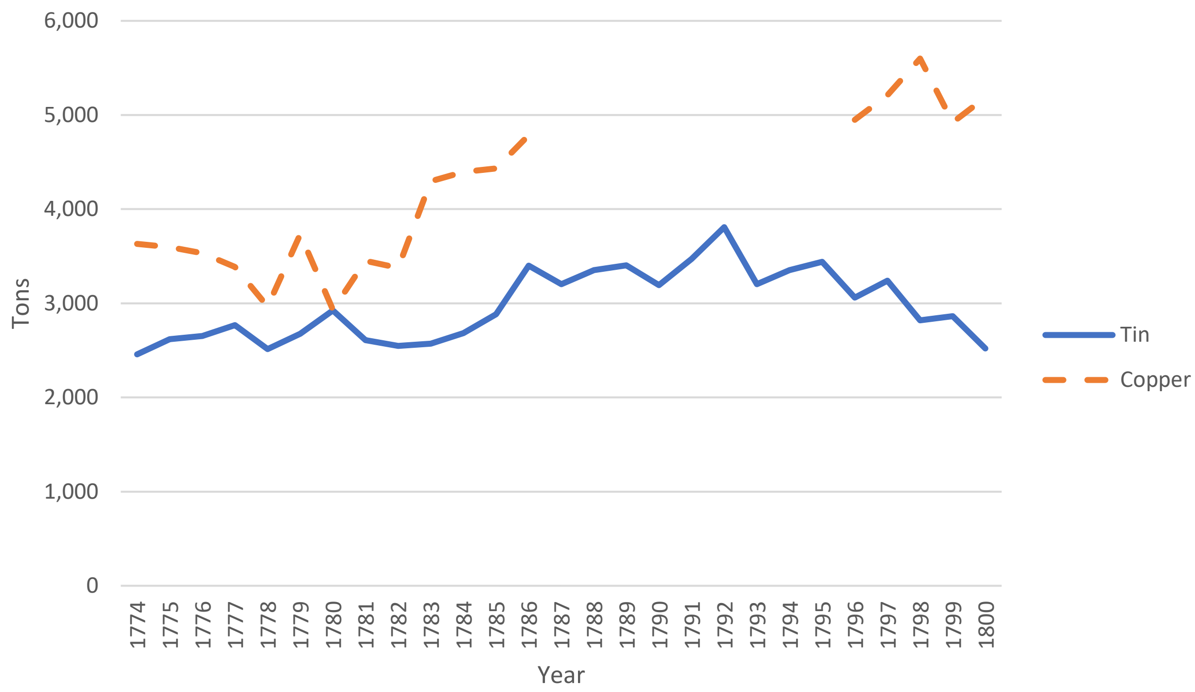
[12] When Poldice mine proceeded with an agreement to erect a Watt engine in 1778, the company was facing a loss of £150/month because of its inability to drain the mine effectively. See Roll, *An early experiment in industrial organization*, p. 75; also, Barton, *The Cornish beam engine*, p. 22.

[13] However, the higher capital cost of the Watt presented a problem for several adventurers. John Edwards, owner of the Hayle copper company in Cornwall contemplated of buying a Watt engine to lift a hammer. The engine was never installed because, Harris speculates, of Edward's concerns regarding the purchasing price and the cost of fuel; see Harris, "John Edwards," pp. 15-6.

[14] Rowe, *Cornwall*, pp. 80-2. For a map of Cornwall with the location of Watt engines installed during 1777-1800, see Dickinson and Jenkins, *James Watt*, following p. 338.

from this amount Soho's one-third premium and the cost of installing and operating the engines, then the savings would have allowed them to reduce ore prices by c. 10s without compromising profits. But the

***Figure 5.4*: Annual production of Cornish copper and tin, 1774-1800**



price reduction was steeper. During the period 1766-1775 the average price of ores was £6 14s 6d. In contrast, by 1776-85, and while the use of Watt engines became widespread, the average price went down to £6 1s 3d. Rowe estimates that the introduction of the Watt engine allowed the adventurers to make a profit of 3s 3d per ton or 2.75%. The reason the reduction of ore prices exceeded the cost savings is because some additional factors came into play. The mine owners were selling their ores to 11 smelters who were competing with each other, in the process lowering the price of copper, and thus they were pushing for lower ore prices. The presence of Anglesey copper was used as a further tool to suppress them and the static level of demand was also working at the expense of the adventurers. Given the thin profit margins and limited cash flows, which had to be used to cover the operating cost for the next month, the adventurers had no much leverage facing pressures on the part of smelters. The adventurers tried to relieve this pressure by raising grievances on the level of the premiums addressed to B & W and emboldened by claims made by the younger Jonathan Hornblower and his brothers that they could come up with engines which were more efficient without infringing on the B & W patent. Boulton reacted to these grievances by acquiring a shareholder's stake in several mines thus rendering him more appreciative of the problems faced by the adventurers and gave him the ability to influence, but not control, the decision-making process of these companies; at the very least, he could help address multiple sources of inefficiency in their management. Taking no action would have involved losing revenues both from the engine sales and premium payments. He ended up losing money from these partnerships but more than made it up through the engine business. Boulton went a step further by initiating a coinage business which attempted to help the local adventurers by buying copper from them; but he was also driven by the profit opportunity presented by the low copper prices.

While Cornish metal mines were operating under strains, their counterparts in Anglesea were thriving. The Parys mine, in particular, was fortunate to have at its helm Thomas Williams, an individual who rivalled Boulton in business acumen. Williams made use of travelling agents both domestically and abroad and was successful in finding new uses for copper such as the making of forged and rolled nails. It became increasingly obvious to Boulton that Cornwall had to enter into some sort of agreement with their Welsh counterparts. Following conversations towards that end, the Cornish "Metal Company" came into being in September 1785, comprising a form of a cartel.[15] The provisions of the agreement were that the Company would raise the capital to be used towards buying all the ore raised in Cornwall in the next 7 years, at that point imposing no restrictions on output, and that sales to the Company were to be fixed in a ratio of 3:2 between Cornwall and Anglesea. In addition, the Company entered into agreements with certain smelting houses which were to purchase ore from Cornish mines as well as those at Anglesea at predetermined prices. Such prices were aimed to be high enough to ensure an 8% profit rate. The price of copper was fixed at £86/ton in 1786, £12 higher than the one prevailing a year earlier. But this generous spirit on the part of the Company's directors encouraged acceleration in the production of ore to levels that were not justified by market demand. Stocks started accumulating. At the same time, the higher prices stimulated production on the part of mining companies which were not included in the price association; they could afford to sell at prices which were lower than those specified by the Metal Company thereby worsening the excessive stock problem the latter suffered from. The higher prices also stimulated foreign producers (e.g., from Hungary, Sweden and Holland) who started sending large imports to England.

Not long after the initiation of the agreement, in 1787, the economic deterioration of Cornish mines reached a crescendo. The number of requests to B & W for reduction of the premiums kept coming.

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[15] The narrative on developments following the initiation of the cartel is largely based on Allen, "An eighteenth-century combination," p. 77-81; see also Rowe, *Cornwall*, p. 82.

Boulton, who had assumed a leading position in the cartel, had every interest to help the Cornish adventurers but not at the expense of the Soho firm. The idea that was floated was to impose quotas on production but that would have involved closing mines, something that was considered practically not feasible due to the fears of extensive riots which were already under way. Unemployment, which would throw a large number of miners to the care of parishes thus bringing the burden back to the Lords and mine adventurers, made this decision hard to come by. Another important factor was the large sums of fixed capital that were sunk. There was no easy way out of this predicament. The agreement was renegotiated in 1787 with Williams taking absolute control. It was agreed that for 1788 Cornwall would produce double the output than Anglesey but that in subsequent years the output would be kept at 3,000 tons for each region. Moreover, the price of copper was reduced to £80. In the absence of alternative options, many Cornish mines, the most unprofitable ones, were abandoned in 1788 by being compensated by the Metal Company with 40s for every ton produced in an effort to force their exit from the business. It was not until October of 1789 that a sufficient number of mines closed, some of them quite large, and the restriction of output was drastic enough to start making a dent on inventories that were piling up until then. But most of the mines at that point were still losing money and so was B & W who had trouble collecting their payments. By 1790 the decline of inventories continued but it was still 5,500 tons on both sides.

An unexpected development took place at that point leading to the final resolution of the problem. The Welsh side witnessed a drastic reduction of its stock due to the fact that its copper reserves were getting exhausted. Prices paid for the ores increased considerably. But production in Cornwall remained fairly static in the years 1790-1 because it would take some time to get mines which ceased operating to start production again. The delay was also due to extensive flooding which took place in 1791.Things improved drastically by 1792. The Cornish stock was sold and debts were wiped out. The final resolution came about because of the ruin of several Cornish mines and the reduced production of their counterparts in Anglesea. The price of copper went from £80 in 1790, to £90 in 1791, and £100 by 1792. Anglesea was pretty much removed as a competitor unable to supply large quantities and thus the agreement regarding the respective quotas (i.e., equal quantities for both regions) became irrelevant. The presence of the Metal Company came to an end by 1792.

The next year (1793) ushered a phase of prosperity due to the expansion of manufactures and the demand coming from the government due to the French war. Cornwall stood to reap most of the gains since Anglesea was rendered irrelevant, by and large, by that time. Prices rose, both for ores and at the retail level. While average profits in Cornwall were still quite slim, certain mines were doing exceptionally well.

Wheal Unity was the most profitable mine in the county achieving profits of over £85,000 on sales of £156,200 during the period 1792-8. During this period Tincroft and Wheal Unity sold less than 14% of the value of output but cleared over 40% of all the profits made during these years.[16]

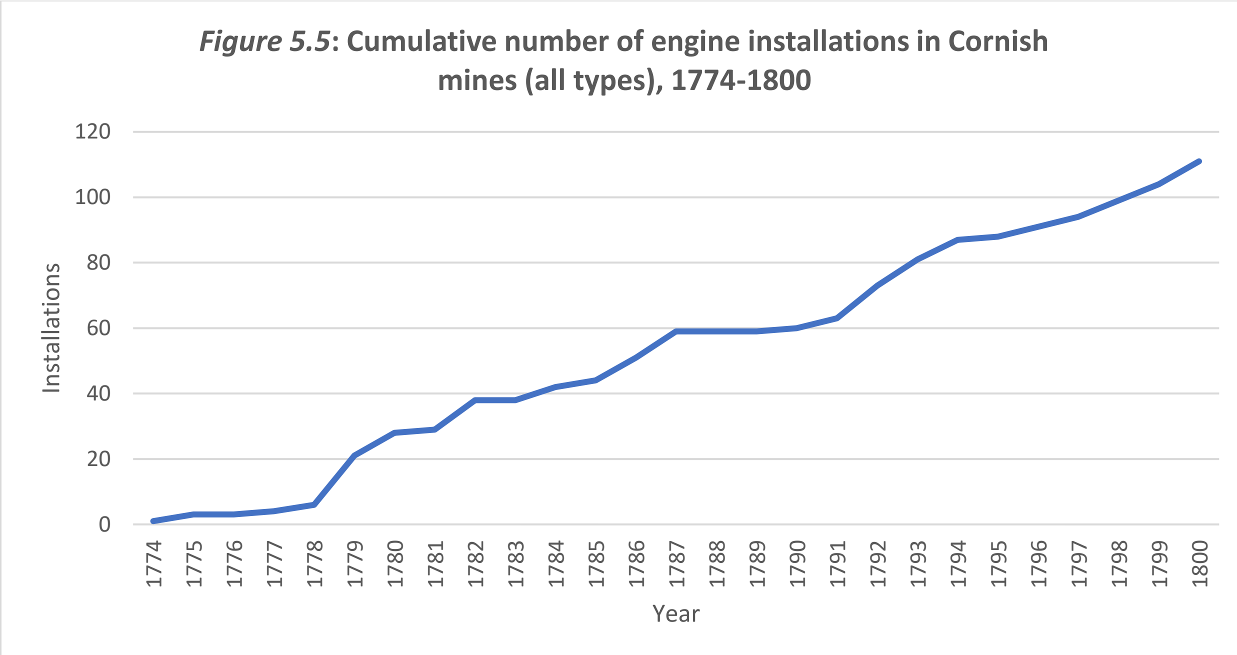
These developments offered great opportunities for expansion not only for the adventurers but also for engine makers. But a combination of factors rendered B & W a non-player during this phase of prosperity. First, the acrimony that developed between the firm and the adventurers during the 1780s proved too much to overcome and it was compounded by the centrifugal tendencies brought by the presence of Bull and Hornblower. There were no engine installations in Cornwall in 1788 and 1789, while stocks were still at high levels. By 1794 total B & W engine installations were barely half the engines in Cornwall, in contrast to a decade earlier when they monopolized the market, not to mention that they were responsible for some old and very problematic engines. It was a particularly hard blow to have the very profitable Tincroft and Wheal Unity turning to the side of the Hornblowers in contrast to several others which stuck with Soho but faced serious financial difficulties. During the years 1790-1800 B & W installed a dozen engines. In contrast, Bull, Trevithick, and the Hornblowers had installed 37. Boulton had an extra reason for turning away from this market. He had played an instrumental role by investing in several mines, establishing the Metal Company, and absorbing part of the accumulated stocks through his coinage business. The 1780s must have been a frustrating time for him given the aggravation generated by the constant demands for premium reductions. But at least the price of copper was kept at low levels which favored his coinage business; a large purchase of copper was, in fact, made in 1788 in order to relieve the problem of stock accumulation. The price increase of the 1790s, on the other hand, harmed his interests in the context of the latter company and gave the final blow to the B & W involvement in Cornwall. Other markets offered at that point better and less stressful prospects for the engine-making business.[17]

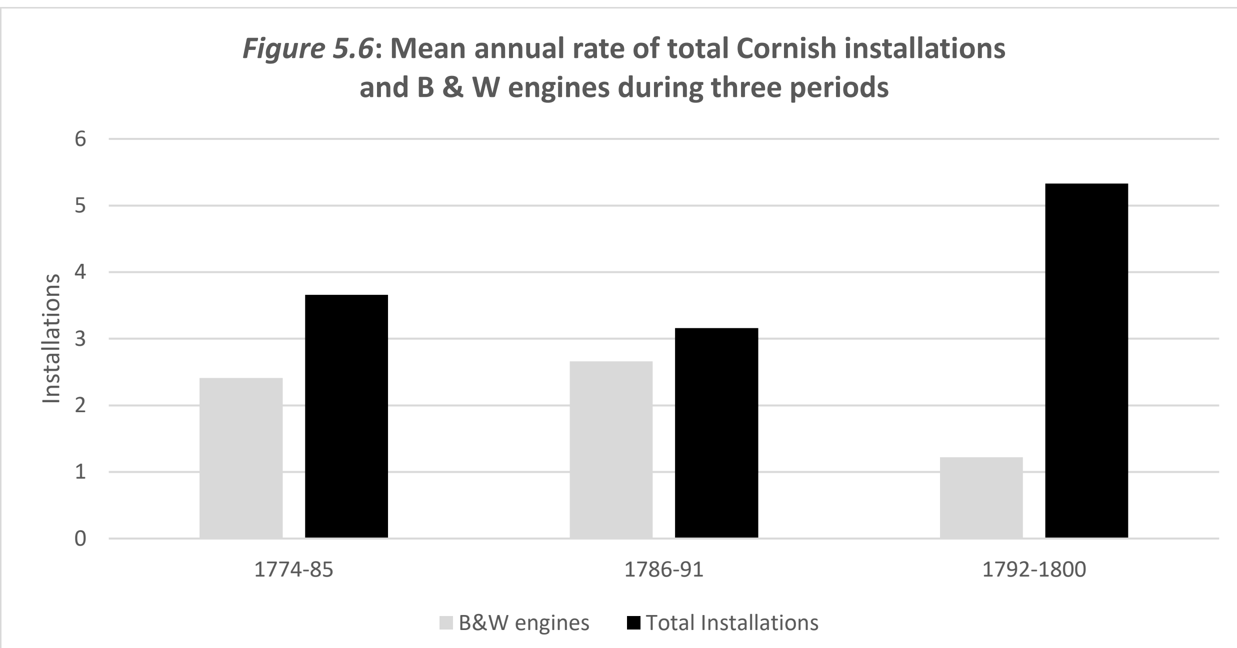
The ebbs and flows of steam power diffusion during this period are captured in Figure 5.5 in terms of the three distinct periods which defined the business cycle at the time: 1) 1774-85 when the introduction of Watt engines and the increase in Anglesea output was in the process of creating a glut. 2) 1786-92 when the initiation of the Metal Company worsened the problem by defining artificially low prices followed by the resolution that was provided through the market exit of several mines thereby reducing the

[16] Rowe, *Cornwall*, pp. 100-1. Watson claimed that the total value of copper sold in Cornwall in 1798 was £405,489 while total cost of production stood at £408,240, a claim that could not be confirmed through other sources. See his *A compendium of British mining*, pp. 3-4.

[17] Allen, "An eighteenth-century combination," pp. 74-5, 82-5; Roll, *An early experiment in industrial organization*, pp. 90-4; Rowe, *Cornwall*, p. 112.

accumulation of stock; this outcome providing a glorious affirmation of the invisible hand at the expense of non-market interference and manipulation. 3) And the period 1793-1800 when Cornish production





followed an upward trajectory due to the resurgence of demand at a time its main competitor was rendered largely irrelevant.

The diffusion of steam power hinged on the profitability of the local mines. We cannot engage in a statistical analysis regarding these two variables since there is no comprehensive data on profitability. Copper and ore prices cannot function as a substitute since the introduction of engines both by B & W as well as their competitors offered the potential of reducing average total cost but the extent this potential was realized hinged on whether constraints on the demand side allowed mines to reach minimum efficient scale. But the broad effects of the business cycle on steam power diffusion is beyond doubt. Total engine installations declined from a mean of 3.66 per year during the first period to 3.16 when the crisis reached a nadir point, while the rate jumped to an impressive 5.33 per year when the phase of recovery was ushered in. The installation of various engine models was also dictated by market imperatives (see Figure 5.6). During the first phase B & W engines achieved a mean annual rate of 2.41 while vying for supremacy against atmospheric engines, a contest they were bound to win in the Cornish environment of high coal prices. The respective rate did not budge when the crisis hit its lowest point (1786-91) but that is an artificial outcome affected by the high number of installations in 1786-7 (15 in total); for all practical purposes, B & W was rendered a non-player beyond that point. By the third phase the installation rate of the company dipped down to an annual rate of 1.22, reflecting a detached opportunistic interest in the county, at a time Hornblower, Bull, and Trevithick came to dominate the local market.

The iron industry

The iron industry was in a precarious position at the dawn of the 18th century facing stiff competition from its Swedish and Russian counterparts due to several disadvantages which raised its cost, particularly when it comes to smelting: one source of it being that water shortages meant that furnaces could not be operated at full-capacity thus raising overhead cost; charcoal was expensive because a unit of land could generate more income from uses other than coppicing; finally, labor cost was higher in England than among its competitors.[18] Iron smelting in Scotland was more backward. Several furnaces were established through the initiative of firms based in Lancashire because the latter faced a local scarcity of timber and thus higher prices. Charcoal was cheaper in Scotland but the ore had to be transported from England hence counterbalancing the cost savings. Production in Scotland had additional disadvantages such as the lack of skilled labor.[19] Russian and Swedish iron was penetrating the English market at an alarming pace.

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[18] The inadequacy of water power was so problematic that the Swedish engineer Martin Triewald invented a new type of water-powered bellows in the early part of the century requiring less water to produce a given amount of power. His innovation was not adopted in the English iron industry but it reflects how keen was the problem. See Flinn, "The growth of the English iron industry", p. 151; Landes, *The unbound Prometheus*, p. 94.

[19] Campbell, *Scotland since 1707*, pp. 64-5.

The amount of iron produced in Britain increased, at most, by 75% in the period 1660-1760. By comparison, Swedish and Russian imports of iron more than doubled between the 1710s and 1750s. The situation could have been worse if it was not for the presence of import duties. However, the introduction of coke in the smelting process by Darby initiated a domino of innovations which rendered England the leading producer by the end of the century. The use of coke at the place of charcoal led also to a dramatic shift in the location of blast furnaces, away from Sussex, Kent and Surrey where they used to rely on local timber supplies, moving towards the Midlands with its abundant coal deposits while, at the same time, it led to a revival of the iron industry in south Wales.[20] The use of coke in blast furnaces and the utilization of steam engines proceeded hand in hand from the very beginning because the use of coke needed a stronger blast.[21] This section will trace certain key developments during the 18th century referring to the growth in the number of furnaces and the radical realignment from charcoal- to coke-based production of pig iron, the dramatic increase in output which led to the reduction of unit costs and the expansion of profits which was ultimately the most important factor driving the diffusion of steam power in this sector of the economy.

There is a fair amount of estimates regarding the number of blast furnaces during the second half of the 18th century. The author consulted well over a dozen of them, in the end deciding to adopt those by Hyde, and Davies and Pollard (see Figure 5.7) having the merit of being both reliable and providing the most continuing series of figures. The methodology of these authors is different: Hyde provides the most analytical figures counting charcoal and coke furnaces in blast while Davies and Pollard provide mainly cumulative figures for furnaces in stock. The two series provide virtually the only estimates for the period 1750-88.[22] The detailed breakdown of figures continues through 1791 but from that point on the data become less plentiful. We have cumulative figures for furnaces both in stock and in blast but not broken

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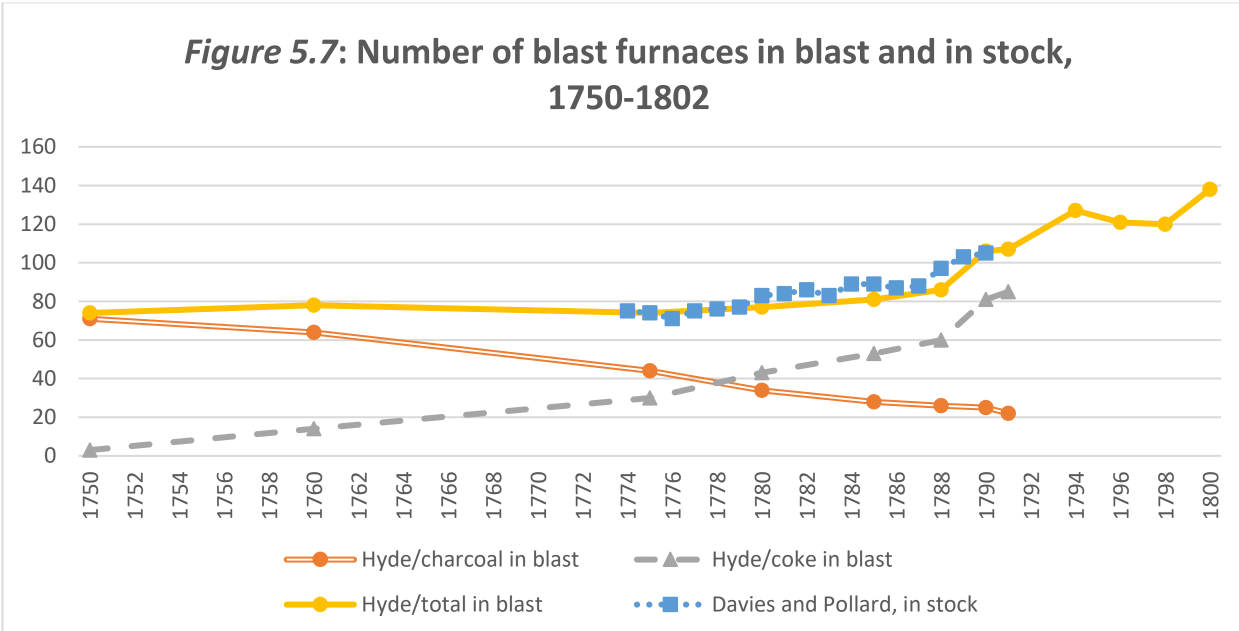
[20] Schumbert, *History of the British iron and steel industry*, p. 333. Attempts to use coke for fuel date back to the 16th century. These efforts involved several industries, from soap boiling to brewing as well as iron smelting, and were driven by the fact that the labor cost of preparing coke was lower than the one involved in charcoal making. Darby stood at the tail end of a list of other nameless individuals who tried to use coke in smelting. He was lucky but also benefited from his familiarity with malting, another process using coke by that time.

[21] Another factor that favored the adoption of steam power in blast furnaces is the fact that iron-works were usually located close to coal fields where water power was often not available. See Lord, *Capital and steam-power*, p. 177.

[22] But there is a plethora of figures regarding 1788 many of which revolve around a list compiled by Mushet. There is agreement among various authors (Hyde, Fairbairn, Farey, Fordyce, Scrivenor, and Riden) that the number of charcoal furnaces was 26, albeit with a minor deviation (amounting to one on either side of Hyde's figure) when it comes to coke furnaces. The only exception being Ure who consistently underestimates the figures. See Ure, *A dictionary of arts*, p. 1067. See also, Fordyce, *A history of coal, coke, coal fields …*, p. 111; Farey, *A treatise on the steam engine*, p. 275; Fairbairn, *Iron*, pp. 283-5; Scrivenor, *History of the iron trade*, pp. 87-8; Riden, "The output of the British iron industry," pp. 446, 448-9. The other consulted sources were: Ashton, *Iron and steel*, pp. 98-9; Schumbert, *History of the British iron and steel industry*, pp. 175, 333, 335; Porter, *The progress of the nation*, p. 271;



Note: The 1798 figure on the total number of furnaces in blast belongs to Riden who adopts identical figures with Hyde. The 1800 figure on the total number of furnaces in blast is an estimate.

Sources: Hyde, "The adoption of coke smelting," p. 408; Ibid., *Technological change*, p. 218; Davies and Pollard, "The iron industry," pp. 75-80, 90; Riden, "The output of the British iron industry."

down to the fuel they used.[23] The final deficiency of the data lies in that we lack data for 1800, instead having a figure for the total number of furnaces in blast for 1798 (Riden) followed by one from 1802 referring to the total number in stock (Davies and Pollard). In this case an estimate for the total number in blast was obtained for 1800 by adjusting Davies and Pollard's 1802 figure and following linear extrapolation, thus obtaining a figure of 138.[24]

The trend that emerges out of the statistics is one of the eventual domination of coke-blast furnaces over their charcoal counterparts. The increase in the former was initially modest, with about one coke furnace

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Bell, *Principles of the manufacture of iron and steel*, pp. 14-5; Birch, *The economic history of the British iron and steel industry*, 46; Meade, *The coal and iron industries*, p. 831; Rees, *Industry before the industrial revolution*, p. 355.

[23] The only exception being Fang's figures but they seem to be an overestimate. See Fang, *The triumph of the factory system,* p. 143. In addition, 1796 is another year for which there are multiple figures when it comes to the total number of furnaces in blast.

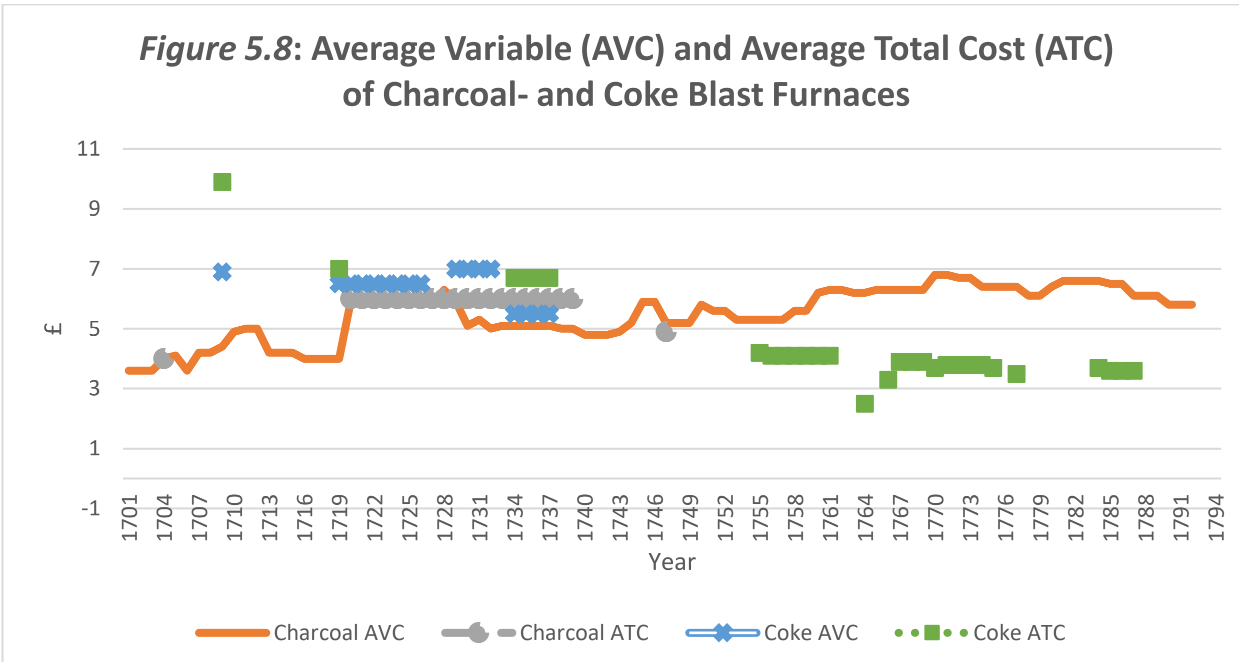
[24] Davies and Pollard's figure of 168 furnaces in stock for 1802 was adjusted downwards by 6.7%, being the mean of figures provided by Hyde regarding the number of furnaces in and out of blast in 4 different years; see Hyde, *Technological change*, p. 113. Then linear extrapolation was applied between the extracted figure (157) and Hyde's 1798 figure.

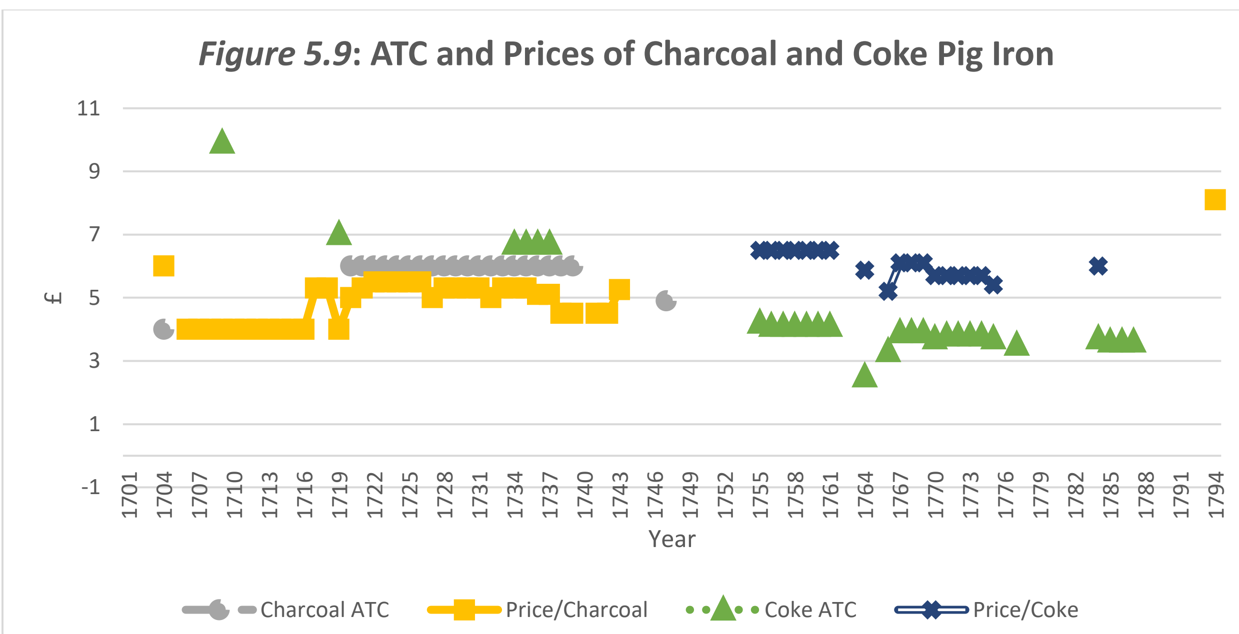
added per year during the period 1750-75 and about the same number of charcoal furnaces being withdrawn. The annual addition of coke furnaces reached a rate of 2-3 during the years 1775-88 though the number of charcoal ones kept declining at the same steady rate. But it was towards the end of the decade (1788) when the addition of coke furnaces started becoming really impressive while the withdrawal of charcoal ones started picking pace before the data become silent by failing to discriminate on the furnace type from 1792 on. But the paucity of the records is not as detrimental as it appears. The total number of furnaces in blast increases by 20 during the period 1791-94. Making the reasonable assumption that all of them were fueled by coke, the rate of adoption of the new technology kept at an impressive rate. But from this point on an apparently inexplicable decline takes places regarding the total number of furnaces (1794-98), from 127 down to 120. Extrapolating backwards from the 1802 data, this decline was reversed by the turn of the century.

Ashton was one of the first authors to discuss analytically the slow diffusion of coke furnaces offering several explanations, among them Darby's ultra-secretive attitude towards his innovation and the special quality coal he utilized which was not available elsewhere. However, such explanations were eventually discounted by Hyde who focused instead on the evolution of cost and profit configurations of the two types of furnaces.[25] The diffusion of coke blast furnaces and the concomitant adoption of steam power hinged on the fulfillment of two conditions: the average total cost (ATC) of coke furnaces had to be lower and the price substantially lower than the one of their charcoal counterparts. There was a quality difference between coke and charcoal pig iron. The former had higher silicon content which rendered both more difficult, and hence more expensive, to convert pig to bar iron in the forge; the amounts of pig iron and charcoal needed to produce bar iron were higher and hence the production cost was as much as 30% higher when the input was coke pig iron. Given these higher amounts of inputs, the pig iron made by

[25] Hyde rejected several of the reasons cited by Ashton as to why the use of coke was not more widespread before the middle of the century. On the supposed lack of knowledge of this technique, he pointed out that the news would have spread through Darby's contacts with fellow Quakers and business partners as well workers who were under his employ but sought jobs elsewhere. On this issue, Hyde may be overstating his case. It is true that Darby did not take a patent nor did he keep it a secret; but he was not very keen in spreading the news widely either. There were at least two instances of furnaces using coke, at Redbrook near the Forest of Dean (in 1716-7) and at Bersham where it was used for the first time in 1721. In both cases, however, this method was discontinued fairly quickly. Another reason forwarded by Ashton is the type of coal Darby worked with which was low in sulphur content (0.50%), hence making it less "cold-short" (brittle when cold). It is true that coal deposits elsewhere (Forest of Dean, South Wales, Scotland) contained higher quantities of sulphur; on the other hand, coal deposits in Shropshire, near Coalbrookdale, and in South Staffordshire had sulphur contents similar to the one worked by Darby but without using coke in blast furnaces. Most importantly, pretty much every British iron ore contained phosphorus which also led to the production of cold-short pig iron regardless of the fuel used. See Hyde, "The adoption of coke smelting"; idem, *Technological change*, pp. 24-41, 53-75; Schumbert, *History of the British iron and steel industry*, pp. 331-2.

coke would have to have a price that was c. £1-2 lower compared to pig iron made by charcoal in order to justify its use.





Sources: Mott, "The Coalbrookdale Group Horsehay Works," p. 283; Raistrick, "The south Yorkshire iron industry", pp. 68-9; Marshall, *Furness*, pp. 22, 250; Rees, *Industry*, p. 216; Raistrick and Allen, "The South

Yorkshire ironmasters," p. 181; Allen, *The British industrial revolution*, pp. 218-20; Clow and Clow, *The chemical revolution*, pp. 340-1.

The data regarding cost and price figures, depicted in Figures 5.8 and 5.9, are incomplete but not to an extent precluding a general outline of how the relevant variables evolved.[26] The AVC of charcoal furnaces moved within the range of £3.6-6.3 per ton during the first half of the century following a trend that exhibited fluctuations but had clearly an upward trajectory while its ATC oscillated around £5-6, but closer to the latter figure more often than not, and its price in the range of £4-6.[27] In contrast, the AVC of coke furnaces started fairly high at c. £6.5-7 but declined down to £5.5 during the mid-1730s when the data discontinue. The AVC of coke furnaces at that point stood just a bit above the figure of their charcoal counterparts while their ATC scored a sizeable decline from nearly £10 down to nearly £7.[28] Despite the productivity improvements of coke furnaces, these two types of cost remained higher at c. 1750 compared to charcoal furnaces.[29] There is a scarcity of data on the prices of pig iron during the 1740s but it is virtually certain that coke pig iron sold at higher prices compared to its charcoal counterpart; and since both cost and price configurations failed to fulfill the two aforementioned conditions, the diffusion of coke blast furnaces failed to extend beyond Coalbrookdale.

But right at the middle of the century cost and price configurations started evolving in ways that eventually led to the demise of charcoal furnaces. The available data show that by the mid-1750s the ATC of coke furnaces was lower compared to the AVC of their charcoal counterparts by at least £1. By the 1760s, and through the 1790s, the respective gap widened to nearly £3. Price series are incomplete but they also

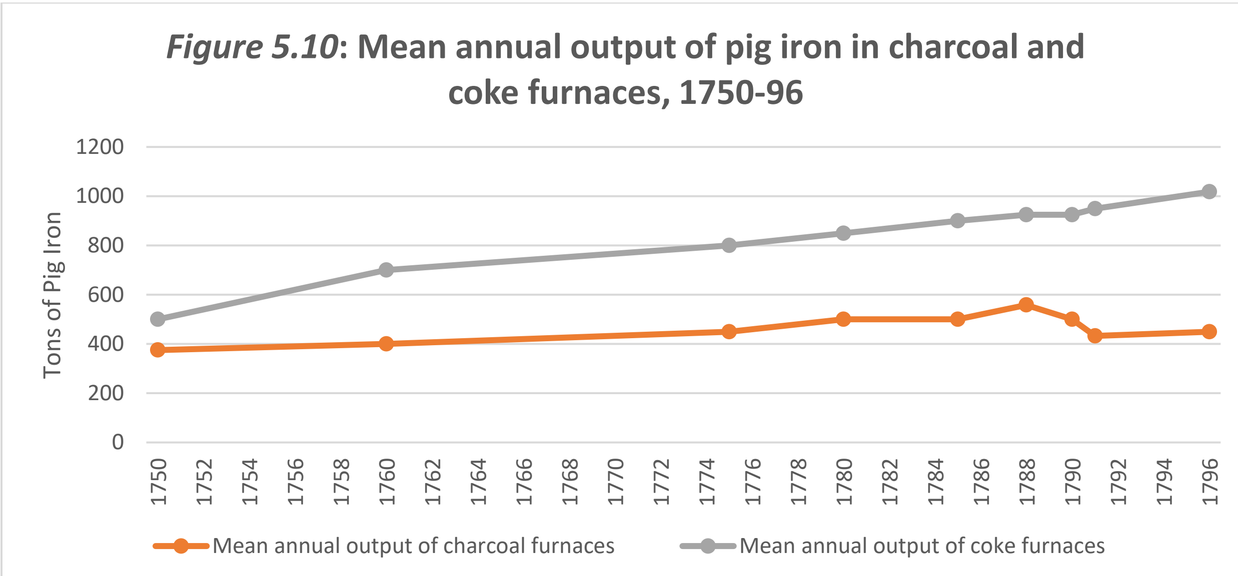
[26] The data recorded in these two figures are meant to outline only general, as opposed to precise, trends. The data used are means of figures which are cited by the sources either as individual figures or as means of several years.

[27] The quantity of charcoal needed to produce one ton of pig iron remained remarkably steady during the period 1690-1750 at c. 85 cwt though its cost had a tendency to move up. See Raistrick and Allen, "The South Yorkshire ironmasters," p. 176. For the price range see Allen, *The British industrial revolution*, pp. 225. The fact that the price of pig iron sometimes fell below its ATC did not translate to discontinuing its production since it was used as an input to the production of bar iron.

[28] In theory, certain producers in some regions may have been able to produce coke pig iron at prices lower than those of Coalbrookdale. However, the prices of coal and iron ore were higher in other parts of the country. The only reason Darby was able to stick to the new method is because he developed a superior casting method for making pots which allowed him to cut cost and charge fairly higher prices based on superior quality. This method was very well guarded by Coalbrookdale.

[29] Productivity improvements among coke furnaces were reflected on mean annual output figures standing, according to Hyde's estimates, at 500 tons in 1750 while the respective figure for charcoal furnaces was 375 tons. The mean output of 14 charcoal furnaces referring to various years during the first half of the century was 309 tons. See Hyde, "The adoption of coke smelting," p. 408; Fordyce, *A history of coal, coke, coal fields …*, p. 111; Chambers, *The Vale of Trent*, p. 8; Raistrick, "The south Yorkshire iron industry", p. 78; Raistrick and Allen, "The South Yorkshire ironmasters," p. 181; Kitsikopoulos, *Innovation and technological diffusion*, p. 164.

make it clear that by the last quarter of the century coke pig iron was over £2 cheaper. Coke pig iron was selling from £5.25 to £6.5 in 1794 whereas the price of the charcoal pig iron produced at Tintern was £8



Sources: The 1750-91 figures are estimates from Hyde, "The adoption of coke smelting," p. 408; the 1796 figures are cited in Fang, *The triumph of the factory system*, p. 143.

to £8.25, the price difference being necessary to account for the continuing perception that the quality of the former was inferior.[30]

The ultimate triumph of coke-smelting furnaces was due to the continuing productivity improvements reflected on the increase of mean annual output per furnace which came to double during the second half of the century (see Figure 5.10), rising from a figure of 500 to over 1,000 tons.[31] This substantial increase of output led to boosting the share of coke pig iron from 5% in 1750 to 90% of national output by the end of 1791.[32] The respective figures were particularly impressive among furnaces in south Wales

[30] Davies, *The economic history of South Wales*, p. 139. Based on evidence provided by Tooke, Bell provides figures for the range of prices of English pig iron during the 1780s and 1790s but he does not discriminate between coke- and charcoal pig iron; see his *Principles of the manufacture of iron and steel*, p. 16.

[31] According to a sample of 21 coke furnaces referring to various years, mean annual output stood at 1,069 tons while the respective figure for their charcoal counterparts was 525. See Allen, *The British industrial revolution*, pp. 218-20; Campbell, *Carron company*, p. 54; Tann, *The development of the factory*, p. 35; Fordyce, *A history of coal, coke, coal fields …*, p. 111; Davies, *The economic history of South Wales*, p. 139; Bell, *Principles of the manufacture of iron and steel*, p. 16; Hyde, *Technological change*, pp. 110-1; Farey, *A treatise on the steam engine*, p. 275; Fairbairn, *Iron*, pp. 283-4; Ashton, *Iron and steel*, p. 98; Scrivenor, *History of the iron trade*, pp. 87-8; Fang, *The triumph of the factory system*, p. 143; Riden, "The output of the British iron industry," p. 448; Hyde, "The adoption of coke smelting," p. 408.

[32] Hyde, "The adoption of coke smelting," p. 408.

whose mean annual output was 1,328 tons in 1796 accounting for 27% of national output, up from 18% in 1788.[33]

One feature of this process worth noting is that despite the dramatic increase of output per furnace, ATC declined through the 1750s but then stalled from the 1760s through the 1780s. The explanation lies in that the substantial increase of output went hand in hand with a drastic increase of "constant capital", to use a Marxist term, which led to total cost increasing proportionally to mean annual output (see Table 5.2). This stalling of productivity began in the 1760s and is associated with three developments. On the

Table 5.2: The evolution of ATC, Total Cost, and Mean Annual Output among Coke Furnaces

Decade	*ATC (£)*	*Mean annual output*	*Total cost (£)*
1750s	4.1	600	2,460
1760s	3.6	766	2,758
1770s	3.7	800	2,960
1780s	3.6	900	3,240

Note: The table presumes typical values when it comes to ATC and mean annual output per furnace for the specified decades.

one hand, there was a substantial increase in the size of furnaces.[34] The coke furnaces erected at Coalbrookdale (1715), Horsehay (1755), and Ketley (1755) were not much larger than contemporary charcoal furnaces standing at c. 25 ft high and having an inside capacity of 600 cubic feet. But when the Coalbrookdale furnace was rebuilt in 1777 it had a capacity of 1,750 feet. Larger furnaces improved efficiency by driving down capital and labor costs in several respects. To begin with, they had a lower construction cost per given capacity; the cost of related investments (e.g., sinking of mines, building roads and tramways, construction of housing) would increase slower compared to the increase of output; and managerial cost would remain stable when a larger furnace was erected. But while larger furnaces put a downward pressure on ATC, the wider diffusion of two technologies which made possible a stronger blast, and hence the larger furnaces, increased substantially total cost and stalled the decline of ATC. These two technologies were the cast-iron blowing cylinder, introduced first at Carron c. 1760, and the wider

[33] Davies, *The economic history of South Wales*, p. 139.
[34] Chambers, *The Vale of Trent*, p. 17; Landes, *The unbound Prometheus*, p. 90; Kitsikopoulos, *Innovation and technological diffusion*, p. 164; Hyde, *Technological change*, pp. 73-4.

adoption of steam engines which accelerated in the 1780s and continued through the 1790s; simply put, these two technologies were far more expensive compared to wooden bellows and water power.

The mean annual output of charcoal furnaces also scored improvements, particularly through the late 1780s before trending downwards during the last decade of the century (Figure 5.10). The modest increase in physical productivity was due to the gradual closure of the smaller and less efficient furnaces and benefits derived from certain technological innovations (e.g., the substitution of cylinder blowing machines in the place of wooden bellows).[35] But the physical productivity gap between the two techniques became wider: mean annual output of charcoal furnaces stood at 75% of the respective figure of coke furnaces in 1750; by 1796 it was a mere 44%. The fatal drawback of charcoal furnaces was the cost of fuel. The increase in demand for iron fed back to the production process increasing the demand and price for charcoal; the latter was already 50 % higher in the 1760s compared to 1740s.[36] Given the rising factor prices and the modest output growth, there was bound to be a flow of resources towards the production of coke iron.[37] But the market exit of charcoal furnaces was a slow process since the industry was fragmented due to high transportation costs in many places, composed of clusters of regionally separated producers insulated from outside competition. The blast furnaces that stuck to the use of charcoal the longest were located in the Scottish Highlands, the reason being that the scarcity of wood was still not acutely felt; Goatfield and Bunawe in Argyllshire were such examples, in this case sticking to charcoal until well into the 19th century. Another 10, of the 26 charcoal furnaces surviving by 1788, were located in the Glamorgan-Monmouth-Gloucester district.[38]

Despite the undisputed cost advantage of coke furnaces which developed during the second half of the 18th century, there was a potential obstacle when it comes to their wider adoption: the initial expense of erecting one, along with a steam engine, and the time it would take to defray this cost. Figure 5.11 provides estimates on the levels at which marginal costs met marginal revenues for two distinct years, 1780 and 1800. Both years present similar gaps between the price of coke iron and its ATC. The main difference lies in the dramatic increase of the erection cost of such furnaces. There were several reasons: more costly blowing apparatus, increases in the prices of inputs and, most importantly, the greater

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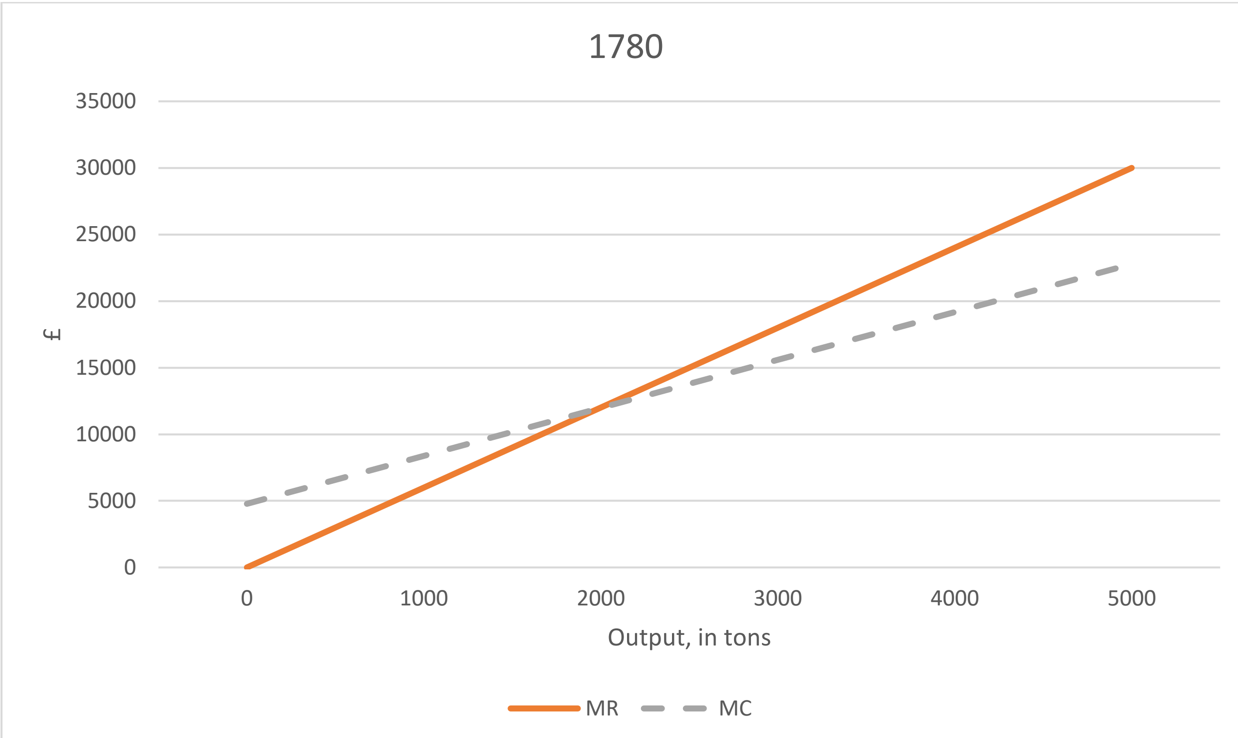
[35] Riden, "The output of the British iron industry," p. 448; Ure, *A dictionary of arts*, p. 1067; Hyde, *Technological change*, p. 198.

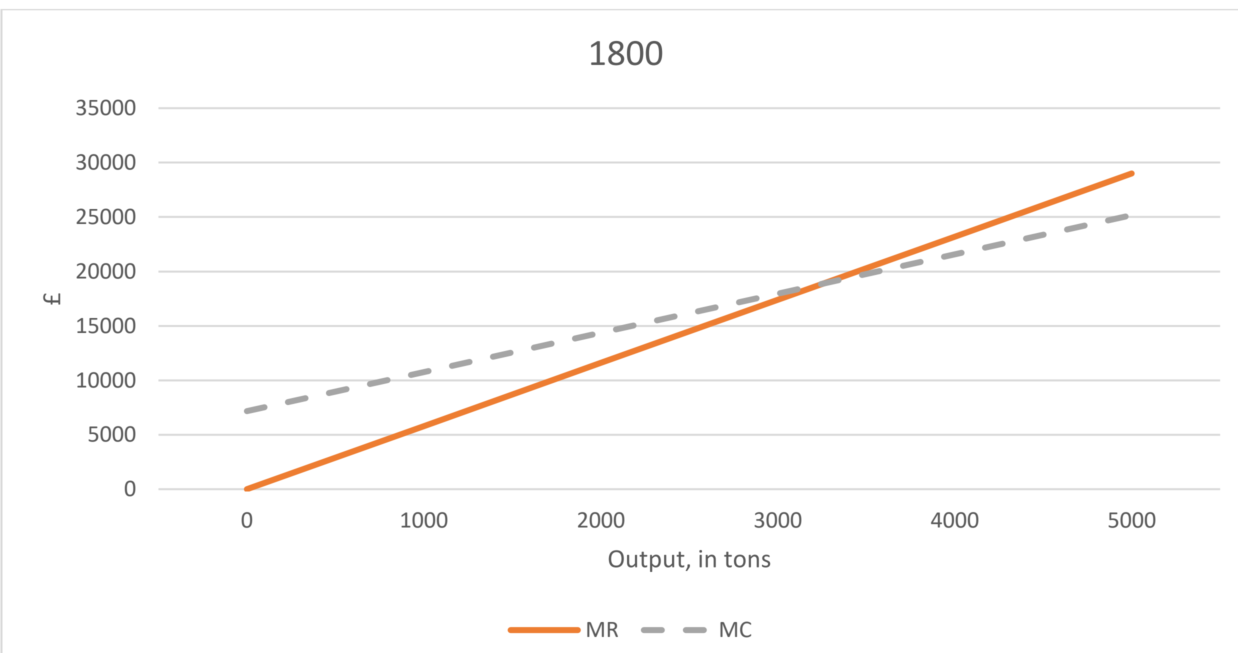
[36] Hyde, *Technological change*, pp. 204-5. Records from Coalbrookdale referring to 1718 cite a price of 14s per stature cord of wood, this figure going up to 17s by 1791 in Shropshire. To produce one ton of pig iron 6 cords of wood are needed; see Mott, "The Coalbrookdale Group Horsehay Works," p. 283.

[37] Output growth among charcoal furnaces could not imitate developments among their coke counterparts by, for example, increasing the size of furnaces since charcoal crushed and thus could not support a heavy charge. See Rosenberg, *Inside the black box*, p. 85.

[38] Clow and Clow, "The timber famine," p. 97; Birch, *The economic history of the British iron and steel industry*, p. 46.

***Figure 5.11*: Threshold levels of output defraying the cost of erection of a coke blast furnace and the installation of a steam engine**





capacity of furnaces. Coke ironmasters started experimenting with larger furnaces in the late 1770s but the first noticeable increase in size came in the 1790s among producers in south Wales. According to Davies and Pollard, the erection cost of coke blast furnaces increased from c. £4,000 in 1780 to c. £6,000 by 1800, the latter figure being more representative of the 1790s. Given these configurations, the threshold level of output at which MC=MR was 1,991 tons in 1780 rising to 3,259 tons in 1800. Given these thresholds, it would take 2.3 and 3.2 years respectively to defray the joint capital costs of a new coke furnace and steam power. The heavier investment burden, along with the greater output capacity of furnaces built in the 1790s may partially explain the absolute decline in the number of furnaces during 1794-98.

How much of a burden were these investment figures in relation to firm sizes and capitalization rates? There is no doubt that there were firms, both in the smelting and other stages of iron production, which found the cost quite burdensome. But these were probably the exception rather than the rule. Lord provided a list of companies which inquired early on for the purchase of a Watt engine but did not proceed speculating that the main reason was the lack of sufficient capital, though other factors may have played a role. Very few of the companies in the list come from the iron industry. Profits were often extraordinary with early coke furnace producers realizing a £2-3 per ton of pig iron and having a rate of return on capital in the range of 40-70%. Continuous data referring to Carron from the period 1770-1800 reveal that annual profits averaged £14,445. Such high profits were both a precondition and the main source of capital for the expansion of the industry given the very high cost of entering this sector. But there was another factor which rendered investment on coke furnaces and steam power a not so burdensome affair. According to Pollard, the close proximity between coal and iron in many parts of Britain as well as technological innovations (e.g., the spread of coke smelting beyond Coalbrookdale as well as of puddling in the 1790s) facilitated the growth of firms through horizontal and vertical integration. Firms were involved not only in the production of pig and bar iron but also rod and wire, castings and even steam engines. This growth was reflected on the size of employment with typical figures being 200-300 workers getting up to 700 in places like Shropshire.[39] At the top of the pyramid were companies which reached extraordinary sizes for the standards of the time, rivalling those of the great northeastern collieries. Dowlais, one of the most efficient producers of coke pig iron, begun in 1760 with an initial investment of £4,000 reaching a value of £61,000 by 1798; Carron's capital was £12,000 in 1759 when the company came into being but grew to

[39] Pollard, *The genesis of modern management*, pp. 75-6. See also Hyde, *Technological change*, p. 198; Campbell, *Carron*, pp. 330-1.

£150,000 when it was incorporated in 1773; Walkers' firm had a capital value of £600 in 1745, reaching £213,393 by 1795; Coalbrookdale's capital was c. £100,000 by 1800.[40]

The above developments were tied directly to the diffusion of steam power. Hyde expressed the view that in many cases water power was adequate in powering blast furnaces, steam power being more likely to be chosen when a second furnace was added; nevertheless "while the steam engine was not a prerequisite for the adoption of coke-smelting, it served to speed diffusion of the new technique."[41] This is putting it mildly. The number of acting coke blast furnaces added during the last quarter of the century slightly exceeded 100. The total number of steam engines added to power these furnaces during the same time reached 65, a figure which certainly underestimates the degree of penetration of this technology since there are engines in the database whose function is not known and others which are specified as "water-returning" some of which must have been used in blast furnaces. In light of the fact that many engines powered more than one furnace, one appreciates the nearly complete dominance of this power source in iron smelting.[42] Steam engines offered several advantages. First, they made possible the drastic reduction of the time furnaces remained idle for maintenance, from 4 months or longer when water power was used down to about a month. Steam engines also made possible a stronger blast, along with various blowing cylinders that came to replace the leather bellows, leading to an increase in the size of furnaces. The combined outcome of these developments was the increase of annual output. Another major advantage offered by the steam engine was that it allowed the relocation of firms closer to ore and fuel supplies thus reducing their overall operating cost. The fact that firms had to abandon free water power was not much of an issue since coal near the pit was very cheap. As an illustration, the Black Country (South Staffordshire) was a region having very limited water supplies. It was only through the use of steam power that its production of iron flourished.

When it comes to the precise model chosen to install in blast furnaces, the revised Kanefsky database reveals that of the 65 engines installed in the period 1774-1800 whose type is known, 24 of them were

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[40] But Coalbrookdale also had a debt of a little over £50,000; Raistrick, *Dynasty of ironfounders*, p. 244. See also Raistrick,"The south Yorkshire iron industry", p. 158; Mathias, *The first industrial nation*, p. 125; Pollard, *The genesis of modern managemen*t, p. 76; Ashton, *Iron and steel*, pp. 40-52. The growth of the Walkers' firm by leaps and bounds was based, among other things, on the willingness of the partners to take out small sums as profits and it was further boosted by massive orders for ordnance from the government, a cause of growth that was also relevant for other firms. For some brief histories of the top four iron firms/families in the country during the 18th century (the Darbys, Wilkinsons, the Walkers, and the Carron company) see pages in Ashton's citation.

[41] *Technological change*, pp. 70-3, quote from p. 71.

[42] Blowing engines in ironworks ranged from 20 hp (Walker's Milton furnace near Rotherham) to 30 hp (Wilkinson's engine at New Wiley) and reaching sizes up 70 hp (such as the ones at Dowlais and Pen-y-Darren) and occasionally beyond. See database K and Tann, *The development of the factory*, p. 35.

Newcomen engines, 13 B & W, 4 made by other makers, while the relevant information is not specified for another 24. Atmospheric engines offered the advantage of familiarity with their mode of operation given their longer history and, most importantly, were somewhat cheaper than B & W engines when the ironworks were located near coalfields which was often the case. On the other hand, B & W engines were the preferred choice when an engine was called to serve more than one furnace given their ability to generate a more powerful blast.[43]

Bibliography

Aiken, J., *A description of the country from thirty to forty miles round Manchester* (London, 1795)

Allen, Robert, *The British industrial revolution in global perspective* (Cambridge, 2009)

Allen, G. C., "An eighteenth century combination in the copper-mining industry", *Economic Journal*, XXXIII (1923), pp. 74-85

Ashton, T.S., *Iron and steel in the industrial revolution*, 2nd ed. (Manchester, 1951)

Ashton, T.S., and J. Sykes, *The coal industry of the eighteenth century* (New York, 1967)

Bell, I.L., *Principles of the manufacture of iron and steel, with some notes on the economic conditions of their production* (London, New York, 1884)

Birch, A., *The economic history of the British iron and steel industry, 1784-1879; essays in industrial and economic history with special reference to the development of technology* (New York, 1968)

Blakey, W., *A short historical account of the invention, theory and practice of fire machinery* (London, 1793)

Campbell, R. H., *Scotland since 1707: the rise of an industrial society* (New York, 1965)

Campbell, R.H., *Carron company* (Edinburgh and London, 1961)

Chambers, J. D., *The Vale of Trent, 1670-1800: a regional study of economic change* (London and New York, 1957)

Clow, Archibald, and Nan L. Clow, "The timber famine and the development of technology", *Annals of Science*, 12 (1956), pp. 85-102

Davis, R., "English foreign trade, 1700-1774", *Economic History Review*, 2nd ser., 2 (1962), pp. 285-303

[43] This statement was confirmed through NVT's econometric results which revealed that having one more blast furnace resulted in increasing the number of Watt engines by 0.35. See Nuvolari et al., 'The early diffusion of the steam engine," p. 314.

Davies, D. J., *The economic history of South Wales prior to 1800* (Cardiff, 1933)

Davies and Pollard, "The iron industry, 1750-1850" in Feinstein and Pollard, eds., *Studies in capital formation*, pp. 73-104

Dickinson, H. W., and R. Jenkins, *James Watt and the steam engine; the memorial volume prepared for the Committee of the Watt Centenary Commemoration at Birmingham 1919* (Oxford, 1927)

Duckham, Baron F., *A history of the Scottish coal industry, volume I: 1700-1815* (Newton Abbot, 1970)

Dunn, Matthias, *An historical, geological, and descriptive view of the coal trade of the north of England* (Newcastle upon Tyne, 1844)

Fairbairn, William, *Iron: its history, properties and processes of manufacture* (Edinburgh, 1865)

Fang, H. T., *The triumph of the factory system in England* (reprint, Philadelphia, 1978), originally published in Tientsin, 1930)

Farey, John, *A treatise on the steam engine, historical, practical and descriptive* (London, 1827)

Feinstein, C. H., and S. Pollard, eds., *Studies in capital formation in the United Kingdom, 1750-1920,* (Oxford, 1988)

Flinn, Michael W., *The history of the British coal industry, vol. 2, 1700-1830: The industrial revolution* (Oxford, 1984)

Flinn, M. W., "The growth of the English iron industry, 1660-1760", *Economic History Review*, 2nd ser., XI (1958), pp. 144-53

Floud, Roderick, and Donald McCloskey, eds., *The economic history of Britain since 1700, vol. I* (Cambridge, 1981)

Fordyce, W., *A history of coal, coke, coal fields* … (London, 1860)

Harris, T. R., ""John Edwards (1731-1807) Cornish industrialist", *Transactions of the Newcomen Society*, XXIII (1942-3), pp. 13-21

Hart, I. B., *James Watt and the history of steam power* (New York, 1949)

Hyde, Charles K., *Technological change and the British iron industry, 1700-1870* (Princeton, 1977)

Hyde, C. K., "The adoption of coke smelting by the British iron industry, 1709-1790", *Explorations in Economic History*, 2nd ser., x (1973), pp. 397-418

Jacob, Margaret C., *Scientific culture and the making of the industrial west* (New York, Oxford, 1997)

Kitsikopoulos, Harry, *Innovation and technological diffusion: an economic history of early steam engines* (New York, 2016)

Landes, D., *The unbound Prometheus* (Cambridge, 1969)

Levy, H., *Monopoly and competition: a study in English industrial organization* (London, 1911)

Lord, J., *Capital and steam-power, 1750-1800*, 2nd ed. (London, 1966)

Mathias, Peter, *The first industrial nation: an economic history of Britain, 1700-1914* (New York, 1969)

Meade, Richard, *The coal and iron industries of the United Kingdom* (London, 1882)

Mott, R. A., "The Newcomen engine in the eighteenth century", *Transactions of the Newcomen Society*, xxxv (1962-3), pp. 69-86

Mott, R. A., "The Coalbrookdale Group Horsehay Works, Part I", *Transactions of the Newcomen Society*, XXXI (1957-9), pp. 271-87

Pollard, S., "A new estimate of British coal production, 1750-1850", *Economic History Review*, 2nd ser., XXXIII (1980)

Pollard, "Coal mining," in Feinstein and Pollard, eds., *Studies in capital formation*, pp. 35-72

Pollard, S., *The genesis of modern management: a study of the industrial revolution in Great Britain* (Cambridge, Mass., 1965)

Raistrick, A., "The south Yorkshire iron industry", *Newcomen Society Transactions*, 19 (1938-9), pp. 51-86

Raistrick, A., and E. Allen, "The South Yorkshire ironmasters, 1690-1750", *Economic History Review*, IX (1939), pp. 168-85

Rees, W., *Industry before the industrial revolution, vols. I and II* (Cardiff, 1968)

Riden, P., "The output of the British iron industry before 1870", *Economic History Review*, 2nd ser., XXX (1977), pp. 442-59

Roll, E., *An early experiment in industrial organization being a history of the firm of Boulton & Watt, 1775-1805* (London, 1930)

Rosenberg, N., *Inside the black box* (Cambridge, 1982)

Rowe, John, *Cornwall in the age of the industrial revolution* (Liverpool, 1953)

Porter, G.R., *The progress of the nation in its various social and economic relations, from the beginning of the nineteenth century*, a new edition (London, 1847)

Schumbert, H.R., *History of the British iron and steel industry from c. 450 B.C. to A.D. 1775* (London, 1957)

Scrivenor, Harry, *History of the iron trade, from the earliest records to the present period* (London, 1854)

Tann, J., *The development of the factory* (London, 1970)

Turnbull, G., “Canals, coal ad regional growth during the industrial revolution”, *Economic History Review*, 2nd ser., XL (1987), pp. 537-60

Von Tunzelmann, “Technical progress,” in Floud, and McCloskey, eds., The economic history of Britain

Watson, J. Y., *A compendium of British mining, with statistical notices of the principal mines in Cornwall* (London, 1843)

Wilson, Thomas, *A comparative statement of the effects of Messrs. Boulton and Watt’s steam engines with Newcomen’s and Mr. Hornblower’s* (Truro, 1792)

Ure, A., *A dictionary of arts, manufactures and mines, containing a clear exposition of their principles and practice, v. 1* (New York, 1851)