Coal and the Industrial Revolution, 1700-1869

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How important was coal to the Industrial Revolution? Despite the huge growth of output, and the grip of coal and steam on the popular image of the Industrial Revolution, recent cliometric accounts have assumed coal mining mattered little to the Industrial Revolution. In contrast both E. A. Wrigley and Kenneth Pomeranz have made coal central to the story. This paper constructs new series on coal rents, the price of coal at pithead and at market, and the price of firewood, and uses them to examine this issue. We conclude coal output expanded in the Industrial Revolution mainly as a result of increased demand rather than technological innovations in mining. But that expansion could have occurred at any time before 1760. Further our coal rents series suggests that English possession of coal reserves made a negligible contribution to Industrial Revolution incomes.

Introduction

Coal has played a curious role in the history of the Industrial Revolution. In the popular imagination the Industrial Revolution *is* coal, steam, iron, cotton mills, and railways. And for an earlier generation of economic historians—T. S. Ashton, Fernand Braudel, Roy Church, J. H. Clapham, Phyllis Deane, Michael Flinn, and John Nef—coal was indeed at the heart of the Industrial Revolution.[1] Roy Church notes in his history of the coal industry, for example, "It is difficult to exaggerate the importance of coal to the British economy between 1830 and 1913."[2]

Yet "cliometric" accounts of the Industrial Revolution, produced from the 1980s on, — those of Deirdre McCloskey, Nick Crafts, Knick Harley, and Joel Mokyr, for example—make coal only a bit actor.[3] Despite enormous increases in output, the coal industry is credited with little of the national productivity advance either directly, or indirectly through linkages to steam power,

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[1] See Ashton (1948), Braudel (1981), Church (1986), Clapham (1926), Deane (1965), Nef (1932).
[2] Church, 1986, p. 758.
[3] McCloskey (1981), Crafts (1985), Crafts and Harley (1992), Mokyr (1990).

metallurgy, or railroads. McCloskey (1981) does not even list it among the revolutionized sectors of the Industrial Revolution.

But the partisans of coal as the key transformative element of the Industrial Revolution have not conceded, and in recent accounts of the Industrial Revolution, most noticeably in the work of E. A. Wrigley and Kenneth Pomeranz, coal is still the key actor.[4] Both argue that the switch from a self-sustaining organic economy to a mineral resource depleting inorganic economy was central to the British Industrial Revolution. Indeed, Pomeranz's account of the Industrial Revolution was recently dubbed "Coal and Colonies" by one reviewer.[5] Pomeranz argues that Britain, in contrast to China, had accessible deposits of coal near population centers. That, rather than differences in innovative potential, explains British success and Chinese failure. The exploitation of the coal in the Industrial Revolution did, however, required dramatic technological advance: "technological expertise was essential to Europe's coal breakthrough." This was supplied by the arrival of steam power in the form of the Newcomen engine in 1712. Steam engines "spread rapidly and transformed an entire industry within a few decades."[6]

These contrasting views of the role of coal in the Industrial Revolution can be portrayed in figures 1-3. Figure 1 shows estimated cumulative output in millions of tons from the north east coalfields in England compared with the estimated real price of coal in London, supplied by the north east, measured in the prices of the 1860s.[7] In real terms the price of coal to consumers in London fell by 40% over the course of the Industrial Revolution, at a time when coalfield annual output expanded 18-fold.

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[4] Wrigley (1988), Pomeranz (2000).
[5] Vries (2001).
[6] Pomeranz, 2000, pp. 66-68.
[7] Thus the price in London in the 1700s was 18 s. in nominal terms, compared to the 1860s nominal price of 19 s. 8 d. But between the 1700s and 1860s all prices rose by 61%, so in real terms the 1700s price was higher at 32 s. per ton.

The "cliometric" account of coal in the Industrial Revolution can be represented in figure 2. The horizontal axis shows cumulative output since the beginning of extraction in the north east coal field, and the vertical axis a hypothetical real cost of extraction per ton, which rises slowly as total extraction increases. But real extraction costs are only moderately higher at the cumulative output of the 1860s than at cumulative output of the 1700s. Also plotted are actual cumulative outputs by the 1700s and 1860s. In this portrayal the supply of coal is elastic. When demand increased so did output, with little increase in the price at the pithead. But the same expansion of output could have occurred earlier or later had demand conditions been appropriate. The movement outward in the rate of extraction was caused by the growth in population and incomes, and by improvements in transport and reductions in taxes which reduced the wedge between pithead prices and prices to the final consumers. Coal experienced a mere 'shift along the supply curve, rather than outward movement of the curve'; that is, output soared because of increased input utilization and not due to the development of 'new techniques allowing existing resources to produce cheaper or better' (Mokyr, 1990, 110).

The alternative picture, favored by Wrigley and Pomeranz, where the industry was subject to major efficiency gains is that of figure 3, where the cost of extraction in 1700 increased sharply with increased output. Greater extraction with the technology of the 1700s would have caused sharp increases in real coal prices. As Michael Flinn notes,

> The increase in the supply of coal at prices that in real terms were constant or even diminishing was, of course, made possible by an unceasing flow of technical advances. The number and economic significance of these developments have been much underrated by historians in the past. (Flinn (1984), p. 442).

In the northeast, for example, there were coal seams at various depths from the surface. By the 1700s the shallowest, most easily worked seams had been largely exploited and further output depended on sinking deeper shafts, with greater associated costs of excavation, haulage, drainage, and ventilation. Technological advances in the coal industry from 1700 to 1860 shifted the extraction cost curve downwards. The coal industry was only able to respond to increases in demand in the Industrial Revolution era because of this technological advance. With the technology of the 1700s energy costs would have been radically higher by the 1860s, and much of the Industrial Revolution growth would have been choked off.

If we just consider pithead prices and output then these very different accounts are observationally equivalent. Table 1 shows our calculated price of coal at Newcastle, which is close to the pithead price, from the 1700s to the 1860s. The sources are listed in the appendix. Since coal varied greatly in quality we set the level of the Newcastle series calculated for 1700 to 1869 to be equivalent to the pithead prices for the northeast reported by Church for 1882-1913 (Church (1986), pp. 58-9). Figure 4 shows what happened to this prices, expressed as a real price by deflating by the average price level, as cumulative output rose. This picture is consistent with *either* a slowly rising cost of extraction and no significant technological advance between the 1700s and the 1860s *or* a steady and dramatic advance in the efficiency of the extraction technology. For the decline in real prices in London, as is well known, was caused by declining shipping and distribution costs coupled with a decline in taxation of the coal trade. In real terms the costs of coal close to the pithead actually increased moderately.

Thus discriminating between these stories of what happened in the coalfields requires further information. Below we develop a test of whether the supply curve for coal was believed to be close to horizontal in the eighteenth and early nineteenth century by looking at the behavior of mineral rents.

The Coal Supply Curve in 1700

What was the coal supply curve with the technology of the 1700s? Was it steeply upward sloped? We consider this from two aspects. First are the technological constraints.

The quantity of the unexploited coal reserve in the northeast was vast in the eighteenth century. Stanley Jevons estimated in 1865 that the northeast coal field originally contained 8,550 million tons of coal.[8] In 1755 it was being extracted at the rate of 2 m. tons per year. At that rate there were reserves for 4,000 years or more.

However the coal seams lay at various, up to 2,000 feet. In 1700 the deepest mines were already about 300 feet. By the 1750s they reached 600 feet. By the 1820s some pits reached nearly 900 feet underground. Table 2 shows the distribution of mine depths on the Tyne in 1828. Two thirds of the mines then were below the 300 foot maximum of 1700, one third below the maximum of 600 feet in the 1750s. Another feature table 2 reveals, which was characteristic of the industry throughout the years 1700-1860, is that pits were always spread across a wide range of depths. The shallowest pits listed in 1828 were Blaydon Main and Baker's Main, both at only 150 feet. In the 1750s when the deepest pits were 600 feet, the average depth was less than 200 feet.

Could the deeper coal reserves have been reached with the technology of 1700 at only modestly greater cost? Deeper seams involved greater costs in the form of shaft sinking, in hauling coal out, and in pumping out seepage water. Would costs in deeper pits have been radically higher in 1800 or 1860 if miners had been forced to reach deeper seams without steam power?

Hauling (winding) costs themselves were not the major obstacle, since here the cost advantages of steam did not appear till quite late. The haulage in even the deepest mines was still done using horse power up until at least the 1760s. Thus in the Walker colliery in 1765, the deepest mine at that point at 600 feet, coal was lifted from the mine by a gin powered by 8 horses. So while

[8]Jevons (1865), pp. ---.

winding costs rose with depth there was no technological constraint on depth imposed by haulage costs with the technology of the 1700s, and no advantage gained from steam here before the 1760s.

By the 1760s, however, mine drainage was mainly accomplished using Newcomen steam engines.[9] However there was no technological barrier to using horse powered gins for drainage. The advantage of steam power was purely one of cost. Thus the engineers at the copper mine in Middleton Tyas, faced with a coal cost of 11/- per ton in 1750, double the cost of coal at the pithead, opted to drain the mine using "a battery of pumps worked by horses."[10] This implies that in 1750 steam engines were only about 40 percent cheaper than horse powered pumps (since coal costs were only 70 percent of the costs of steam drainage).

The cost advantage of steam versus horse winding and pumping depended mainly on the cost of steam engines, the cost of coal at the pithead, and the cost of horse fodder. Nicholas von Tunzelmann gives enough information in his book on steam power in the Industrial Revolution to make a rough calculation of the cost per horse-power hour of horses versus mine steam engines over the years 1700-1869. This calculation is shown in table 3. In the 1720s steam had, as expected modest advantages. The introduction of steam power certainly did not revolutionize the industry then. But by the mid-nineteenth century steam cost only 25-30% as much as horse power.

Table 4 calculates how much the absence of coal would have raised costs of production in each epoch. The method here is to calculate how many lbs of the equivalent of best coal were used at the colliery per ton of coal raised, using the share of mining costs reported as coal consumed in winding or pumping. These lbs of coal were then translated into horse-power hours per ton of coal, shown in column 3 of the table. The extra cost of supplying this energy as horse power as opposed to steam power is given in column 4, and the percentage increase this would imply in production

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[9]Smeaton found 57 Newcomen engines at work in the northeast coal field in 1767, with an aggregare horse power of 1,200 (Farey, 1827, 233-7).
[10]Raistrick, (1938), p. ---.

costs in the last column. The implication is that production costs in the nineteenth century would have risen by 10-20 percent absent the introduction and development of steam power in collieries. The absence of the new steam technology would not have crippled the industry even late into the Industrial Revolution.

This demonstration deals, however, with only one aspect of technological advance in the coal mining industry, steam power. If there was a steeply rising extraction cost curve in 1700, the introduction of steam power on its own did little to flatten that curve. While it will cast serious doubts on the statements by Pomeranz on the key role of steam, however, it does not demonstrate that in a wider sense other less heralded technological advances were not indispensable to the expansion of the industry. Might the absence of an "unceasing flow of technical advances" - safety lamps, gunpowder in shaft excavating, improved winding gearing, ventilation systems, and so on – have driven up costs in the nineteenth by hundreds of percent?

To get a more general test of the shape of the supply curve in the early eighteenth century, before the potential onslaught of the flow of innovation, we employ information on the site rents per ton of coal extracted paid to the owners of the land under which the coal seams lay compared to the pithead price of coal. Table 5 shows average, minimum and maximum site rents per ton by decade for the north east as a percentage of the average pithead price of coal, calculated on the basis of a sample of 203 coal leases from the northeast from 1715 to 1864. Coal rents averaged only 10% of the selling price at the pithead over these years. But also there was little range in the site rents paid. The standard error of rents as a share of output costs averaged 3.4%, so that 95% of site rents would fall in the range 3-17%. The maximum site rent at any time was 31% of the estimated average pithead price of coal. In contrast in the modern world the mineral rent paid for some oil reserves in the Middle East is close to the whole of the wellhead price. That is why their were so few coal millionaires in eighteenth and nineteenth century England, in contrast to the oil billionaires of today.

Figure 5 shows the range of lease values across time. From 1715-1833 there was little trend in the level or the variation in lease values across time. But after 1833 there appears to be a break in the series, with both the level of rents relative to output prices and the variance dropping. But throughout both average coal rents and their variance remained small as a share of the pithead price.

For a given price of output, the variance in the rents at one time mainly reflected the variance in the extraction costs. In general, if we take the price at the Tyne as the same for all pits, then

$$Rent_i = p - excost_i - trancost_i$$

where *p* is the price at the Tyne for a standard quality of coal, *q* is the quality of the coal, *excost* the cost of extraction and *trancost* the costs of getting the coal to the water, and *i* indexes the individual pit. Extraction costs, rather than transport costs, seem to dominate in the determination of rent. If transport costs to water were a substantial cost relative to rents then we would expect to see that after the introduction of rail travel c. 1830 there would be substantially greater dispersion of the pits from the Tyne. In fact average distances changed little. We calculated how close each pit was to the water, which varied from 0.25 miles to 18 miles. In 1727 to 1829 the average distance to the Tyne was 5.4 miles, in 1831-1864 6.4 miles. But this difference is not even close to statistically significant. Presumably the existing network of wagon ways in the Tyne area was a fairly cost effective way of getting coal down to the Tyne. Second if transport costs to the Tyne were substantial we would expect to see lower rent at more distant pits, since there transport costs would absorb all the site rents. There was, however, no correlation between rent and distance to water, even before the arrival of the railroad. The implication of this is that the transport costs to the water were generally low, so that they did not have much impact on mineral rents. Thus the site rents measure mainly differences in extraction costs.

Accidental factors, such as the fact that large numbers of mines in the eighteenth century were leased for "dead rents" in order to be kept out of production, meant that at any time mine leases were for very varied points on the long run supply curve. Thus in 1770 while there were 31 collieries selling coal to the London market through the Tyne, another 11 collieries were being rented by the "Grand Allies" for a dead rent to keep their production out of the market. One, for example, was St Anthony's colliery, close to the Tyne. The Grand Allies paid £300 a year to keep this colliery out of production for 42 years from 1734 to 1776. In another case the Grand Allies took Stanley colliery out of production in 1793, while paying the mineral owners again a rent of £300 per year until 1817 to keep it closed (Cromar, 1978). The variance of rents thus indicates the steepness of the slope of the supply curve.

If the advocates of significant technological advance in the industry in the years 1700-1860 are correct, there would be substantial variance in mineral rents in the early eighteenth century, reflecting differences in transport costs. As figure 5 shows, the variance was in fact small. From 1715 to 1749 90% of the site rents were between 5 and 14% of the average price of coal at the pithead.

A second test for a steeply sloped supply curve in the early eighteenth century would be the size of the average share of rents in the pithead price. If mine owners believed the curve was steeply sloped then rents would be a large share of the price for the pits currently worked. No one would want to lease coal land now for the very modest rents being paid if they believed that soon the cost of extracting coal on new seams would drive up prices substantially.

The owner of an exhaustible asset such as a coal seam can leave the coal in the ground and extract it later if prices are assumed likely to increase. The owner of a seam with extraction cost c per ton should delay mining as long as

$$E(p_{t+1} - c) \geq (p_t - c)(1 + r) \tag{1}$$

where p_t is the price of coal in year t, and r is the rate of return on capital. $(p_t - c)$ is the amount the seam can be leased for per ton in year t, and $E(p_{t+1} - c)$ the expected site rent in year $t+1$. If coal seam owners expect site rents to increase at above the rate of return on capital they should just keep the coal underground and wait for more favorable prices. If real extraction costs from new mines and deeper seams were expected to be much higher in the early eighteenth century, then the market price of coal would be expected to rise also.

The incentive of the owners of the low cost seams would then be to conserve their assets for exploitation at a more favorable time unless the current coal price was already high enough to offer them large profits. Coal left in the ground would increase in value faster than the mineral rents obtained from its extraction could compound if invested in a mortgage or in landed property. What would persuade owners to exploit now would be a situation where enough owners deferred exploitation so that current prices rose sufficiently to make even current exploitation profitable. But this would imply that some owners received high site rents as long as extraction costs were expected to be increasing rapidly.

Figure 6 shows, for example, a simulated extraction path for the coal industry in the northeast, starting in 1700, where extraction costs then on the seams being exploited are assumed to be 4.5 s. per ton (the actual costs in the 1730s for best coal). But costs were expected to rise as new seams were brought into production, with extraction costs per ton given by

$$Cost(Q) = 4.5 + 0.0026Q^2$$

where Q is cumulative output from 1700 on. With this specification the cost curve with cumulative output is as shown in figure 6. By 50 years from 1700, at the extraction rate of that decade, costs would be 23/- per ton with this assumption.

Assume that land owners have no market power and simply decide when to start working their seams. The price of coal at Newcastle is then the extraction cost plus the site rent. The price at London is the Newcastle price plus 17/- shipping and tax cost to the London market. The price in London (in shillings) is assumed to be

$$p_t = 40 - 10q_t \qquad (2)$$

where q_t is the million tons of the Newcastle reserves mined in that period. This demand curve is set so that at the actual annual output of the 1700s (q = 1.8 m tons per year) the price in London is close to the actual price that prevailed in that decade, 23/-. This implies that the maximum price that would be paid in London for coal is 40/-, and that demand for Newcastle coal in London was relatively elastic with respect to price (the price elasticity at the London price of the 1740s is 1.22 with this demand curve).[11] The return on capital (*r*) is assumed to be 4.5%.

With just these specifications, we can calculate an implied extraction path (prices and quantities) for the decades following the 1700s, if the coal owners expected the technology and the demand to remain the same, and price path which meets condition (1) for the owners of the coal reserves. This is the path is shown in figure 6.

What is interesting for our purposes is that with these realistic specifications of initial costs the coal rents of the 1700s on the easily worked seams in use then are, at 3.5/- per ton, about 42 percent of the implied Newcastle price of 8.3/-. These rents are about 10 times as great as the rents per ton actually being charged in coal leases in the 1710s-1740s (see table 2). Yet the history of this

[11]Thus at the point where Newcastle output was 1% of the total reserves per year the price elasticity for Newcastle coal in London would be 12.5.

period is that mineral rents in the north east were low despite persistent attempts to restrict production. The payment of dead rents to keep mines out of production made no sense if future coal production was expected to come from seams with inherently much higher costs. Coal owners in the eighteenth century behaved as though they believed their currently worked seams, generally those close to the surface, had little cost advantage on coal seams not yet worked. And among the seams being opened up in any decade there is little sign of much variation in the costs of production.

Thus both the low level of coal rents in the early eighteenth century, and their low variance, indicates that the cost curve at that time was only very modestly upward sloped.

Total Factor Productivity in Coal Mining, 1700-1869

The evidence from consideration of the technological barriers, and from coal rents, is that extraction costs rose only modestly with cumulative output. Here we use this result to establish upper and lower bound estimates of the gains in total factor productivity (TFP) in coal mining over the Industrial Revolution era.

Lower Bound Estimate on Productivity Gains

If we assume that the long run supply curve was in fact flat, then the TFP of the coal mining industry can be estimated reasonably well using the ratio of average input costs (C) to average extraction costs (EXCOST). Costs at any time t we measure as

$$C_t = \prod_j \omega_{jt}^{\theta_j}$$

ω_j is the factor price paid to input *j*, and θ_j is the share of input *j* in the total payments to inputs (other than the land owners). The extraction cost is just the pithead price minus rents paid to the land owners. That is

$$EXCOST_t = p_t - \text{site rents}_t$$

Productivity can thus be approximated as

$$A_{\min,t} = \frac{C_t}{EXCOST_t} = \prod_j \frac{\omega_{jt}^{\theta_j}}{p_t - rent_t}$$

This is labeled as A_{min} since it is a lower bound on the estimated productivity gains, because it assumes that coal seams were of equivalent quality over time.

Upper Bound Estimate on Productivity Gains

We can also derive an upper bound productivity estimate. Since depth was the obstacle to exploiting the huge reserves of the deeper seams in the coal field, we can include a specific allowance for costs that increased with depth in the productivity calculation. These costs were pit sinking, winding and pumping. This is done by increasing the cost factor of the productivity calculation by a factor dependent on depth so that

$$A_{\max} = \prod_j \frac{\omega_{jt}^{\theta_j}}{p_t - rent_t^{\,i}} \left[(1+\phi) + \phi\left(\frac{h_t}{h_{1700}}\right) \right]$$

where h is the average depth of pits, and ϕ is the share of costs that were dependent on the depth of pits in 1700. This measure of productivity will be the same in 1700 as before, but will increase as h increases relative to average depths in 1700. This productivity measure will overstate the gains in productivity between 1700 and 1860, since again it assumes all coal seams were equivalent apart from their depth. But in reality deeper mining was undertaken only when the lower seams justified the extra costs by being thicker, or having higher quality coal (the thickness of the seams economical to exploit in the northeast coal field varied between 6.5 feet and 2 feet). The above formula does not take into account the potential improvement in working costs and coal quality with deeper mining, and thus overestimates productivity gains.

The share of costs that were proportionate to depth, ϕ, can be estimated from the studies of Sidney Pollard and Michael Flinn of coal mine accounts in the early eighteenth century at about 9 percent (6 percent of costs were for fuel for winding and pumping, and 16 percent of capital costs were devoted to shaft sinking and to engines for winding and pumping, both of which were depth dependent). Average depth of pits increased from about 150 feet circa 1700 to the 450 feet seen in table 2 by the late 1820s. We assume depth moved up in a linear fashion so that average depth by the 1860s was 550 feet, nearly four times the average depth of 1700. With these two assumptions we can generate a cost function for mining as a function not just of input costs, but also of average mine depth.

We take as our best estimate of the true gains in coal mining productivity between 1700 and 1860 the average of these two measures. Tables 1, and 5-9 show the data necessary to calculate TFP in coal mining in the north east on either assumption. While the north east was a minority of the English industry, it was the single most important coalfield throughout this period, so productivity growth in the industry as a whole was unlikely to have differed much for England as a whole from the north east.[12]

Mining labor was the most important cost, being more than 45% of all costs including rents of capital. The royalties paid for access to the seams were about 9%, which is very much in line with our estimates for the northeast shown below in table 6. Returns on capital were about 20% of costs. Coal used for pumping and winding operations was 4% of costs, horse fodder 5%. The final 17% was a miscellany of craftsmen's wages, and supplies such as timber, rope, candles, and oil.

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[12] Pollard (1983) places the share of the Northumberland and Durham coalfields at one-third for the beginning of the period and one-fourth for its closing. McCord and Rowe (1971) report that the region supplied London with nearly 95% of its coal requirements as late as 1826.

Pithead Prices. Coal is anything but a homogenous good, varying widely—both among *and* within mines—in such qualities as thermal content, length and type of burn, and 'sootiness.' So pithead prices were estimated from a variety of printed and archival sources on Newcastle prices and true pithead prices for individual mines from 1730 to 1869 (detailed in the appendix). They were combined in a regression of the form

$$\ln p_{it} = \sum_i \alpha_i LOC_i + \sum_t \beta_t DUM_t + \varepsilon_{it}$$

where p_{it} is the quoted price from source i in year t, LOC_i is an indicator variable for each of the sources we have on prices of types of coal (such as Wallsend), and DUM_t is an indicator variable for the year. Then the prices obtained were linked to the pithead prices of coal from the northeast reported by Church (1986) for the years 1882 on using export prices as the linking series. The resulting estimated prices, controlling for differences in coal quality, are those shown in the last column of table 1. To extend these back to the 1710s, when we have no actual northeast prices, the ratio of pithead to London prices was assumed to be the same as in the 1740s.

Wages. There is no series available for coal miners' wages in the northeast in the years 1740 to 1869. Instead we have 38 scattered estimates and measures of hewers wages per shift reported by authors such as Ashton and Sykes, Flinn and Church. These estimates are shown in figure 6. Hewers wages should be a good index of mining wages in general since the wages of some other workers, especially putters (those employed in transporting the coal from the face to the pit bottom or head), were set explicitly in terms of hewers' wages and also there are indications of strong correlation between hewers' wages and the whole of those employed in mining, including some lower-level management type positions such as overman (Church, 1986; Griffin, 1977). When we compare these scattered quotes of wages over time to farm wages in the north of England we find that, while there are short run deviations, over the long run of 1740 to 1869 they increase by exactly the same amount. Thus when we regress the ratio of hewers' wages to farm wages (W_H/W_A) on a constant plus a time term, T, measuring as years since 1740, we find that the time trend term is both statistically and quantitatively effectively 0. Thus,

$$\frac{W_H}{W_A} = 2.108 - 0.00024T \qquad (3)$$

with the standard error on the coefficient estimate for T being 0.00141. Figure 6 shows also hewers wages as predicted from equation (3), shown as the bold line. As can be seen, for the long run, hewers' wages can be reasonably well approximated by farm wages. Since the major recruitment for labor for the coalfields was farm workers this result is not surprising. Notice also that the hewer in the northeast earned more than double the agricultural wage, as compensation for the danger and unpleasantness of underground working.

Hewers in the northeast also received free housing and coal allowances which are not incorporated in these wage estimates. The housing is included under the capital costs of the mine. The coal allowance is subsumed under the coal consumed at the pithead for pumping and other purposes when estimating TFP. Table 7 shows the resulting decadal estimate of northeast daily coal wages. Also shown are the average daily wages of building craftsmen and their helpers in the northeast. In the productivity estimates we assume that such workers maintaining pit structures and equipment were 10% of total costs.

We assume half of the 18% spent for craftsmen and supplies was for labor. The wage used here is that of northern building craftsmen from Clark (2004).

Coal Rents. The rental payment per ton of coal in table 1 is calculated from leases of coal land. Since mine operators had to undertake large fixed investments in mines coal leases were generally for 21 years or more. The form of the lease in the north east was generally that the lessee paid a fixed rent for all coal extracted up to a certain minimum quantity, and then a payment per unit of output—

known as the tentale rent—for all output above the allowance. Often the tentale rent was the same as the fixed payment divided by the allowance. Thus it is possible to estimate from these leases the average coal rents paid per ton of output. A sample of over 203 leases from the 1710s to the 1860s was collected (see Appendix I). From this sample, estimates were made of the general course of lease payments in each decade. In estimating these we again used a regression of the form

$$\ln rent_{it} = \sum_i \alpha_i LOC_i + \sum_t \beta_t DUM_t + \varepsilon_{it}$$

where $rent_{it}$ is the quoted tentale rent from source i in year t, LOC_i is an indicator variable for the location or the colliery, and DUM_t is an indicator variable for the year.

These rental payments we assume to reflect the value of coal land in free competition. Throughout this period, however, colliery owners in the north east attempted, through the 'limitation of the vend', for example, to restrict output and bolster prices. If limitation of output was present earlier in the history of the industry, but not later, it would bias upwards the estimated movement of productivity over these years (see Harrison, 1994). Various studies of competition and monopoly in the industry in these years, however, have generally concluded that the attempt to limit output was generally unsuccessful, due to a poorly designed system of positive and negative incentives (Sweezy, 1938), indifferent enforcement (Hausman, 1984a, 1984b), and an inability to erect substantial barriers to entry (Cromar, 1977; Hausman, 1984a, 1984b).

Fodder. Fodder costs were assumed to be half those of oats and half those of hay. These prices are available from Clark (2004) for England as a whole and are shown in table 7.

Supplies. These we assume to be 9% of costs. There is no clear breakdown of these in the accounts of the industry. We know timber, iron, ropes, candles, and oil all were components. Table 7 shows the estimated prices for timber, iron and candles, which we assign weights of 5%, 2% and 2% respectively in total costs.

Capital Costs. Capital costs in the productivity calculation will be

$$(r+d)p_k$$

where r is the rate of return on mining capital, d the depreciation rate of capital, and p_k the cost per unit of the capital goods employed in mining.

To estimate the cost of mining capital, p_k we used five price series: estimated northeast hewers wages (50%), estimated northern builders wages (20%), the price of bricks (10%), the price of iron (10%), and the price of timber (10%). The weights were those suggested by Roy Church for circa 1850 (Church (1986), p. 175). The major capital goods in mining were the shaft, the pithead structures and buildings, and railways and wagons. Table 8 shows estimated brick prices for England as a whole. The other prices necessary to construct capital costs are all shown in table 7. Table 8 shows the resulting index of the price of mining capital in the northeast per unit. For comparison Church's index of capital costs for the 1830s to 1860s is also shown. These two series both move little for this interval and are quite consistent.

For the years before the 1850s there are no direct measures on the long-term return on capital in mining, or on the cost of the capital involved. The records needed to calculate an industry-wide average rate of return are no longer extant. Even in the fragmentary records that have survived, accounting practices, especially for the earlier parts of the period, seem to be a jumbled confusion of entries. There is little delineation between charges for, say, circulating and fixed capital, depreciation, and returns and little concern for consistent and fundamental accounting principles (Flinn, 1984).

Given this we estimated the return on capital in mining as the average rate of return on bonds and mortgages in the same interval. Most coal mine owners were landowners or merchants in addition (Buxton,1978; Flinn, 1984; Griffin, 1974). Thus the return on investing in mines cannot have strayed too far in the long run from investments in other assets such as mortgages. We took as our rate of return proxy the rate of return on bonds and mortgages in England from Clark (1998). These returns are shown in table 8. They were not much lower than the return reportedly earned in coal mining in the 1850s and 1860s when we get accounts good enough to estimate returns. Table 9, for example, shows some estimates of the net return on mining capital in the UK in the 1850s and 1860s. As can be seen these returns exceed those on bonds and mortgages in the same period by less than 1%. So while we do not have direct measures of the return on capital in mining, it did not exceed the mortgage rate by much. We calculate the rental cost of capital in mining thus as

$$(r + 0.05)\, p_k$$

where r is our measure of the interest cost of capital, 0.05 is allowed for depreciation and for a risk premium, and p_k is the price of capital goods. The allowance for depreciation is in line with estimates in the nineteenth century by Church of the gross return on mining capital compared to the net return. Gross returns, which incorporate capital consumption and depreciation as part of the return, were about double estimated net returns. Table 8 also shows the resulting estimated rental cost of capital in mining by decade.

Total Factor Productivity. Table 10 shows as an index the extraction cost of coal at the pithead in the northeast by decade (price minus coal rents). Also show is an index of the input costs of mining coal, under the lower bound assumption that all seams were equivalent, and under the upper bound assumption that a set of costs were directly proportional to depth. The associated Total Factor Productivities are then just the index of costs divided by the index of extraction costs. These are shown as the fourth and sixth columns of the table. These productivity indices are shown in figure 8.

Even though mining wages rose much faster than the extraction costs, overall input costs rose only very slightly more than extraction costs because so many other elements of cost increased much more slowly – coal rents, iron, timber, bricks, and candles in particular. Thus between the

1730s and the 1860s measured productivity rose by only about 6% overall on the measure that assumes the seams were unchanged over time. When we overcorrect for higher costs through deeper seams, the measured productivity gain was still modest, at about 25%. This still implies a productivity growth rate of less than 0.2% per year over the Industrial Revolution period, slower than for the economy as a whole.

Given that these two productivity estimates are upper and lower bound estimates of productivity growth, the best estimate is an average of the two. These estimates are all subject to error. From the standard errors of the individual components we estimate that the productivity estimates for any decade relative to the 1860s have a standard error of 10%. But since we observe many decades for the overall trend we have much less error than this. From the four decades 1710-1749 to 1830-1869 for example, our best estimate is of a growth rate of 0.14% per year, with a standard error of about 0.04% on either side. This estimate is quite consistent with the estimate made above of the benefits from the addition of steam power to mines by the 1860s of a productivity gain of 10-20 percent. This implies that we can say with 95% confidence that productivity in coal mining grew at less than 0.22% per year from the early eighteenth century to the mid nineteenth century.

Coal and the Industrial Revolution

This productivity result above is entirely consistent with the cliometric interpretation of the coal industry. Output expansion was driven by factors external to the industry – increased urban demands for coal, increased demand from iron production, and reduced taxation and transport costs. In contrast to the estimated 0.14% productivity growth rate of coal mining, productivity in cotton textile production increased by 3.1% per year (Clark (2001b)). TFP in iron and steel manufacturing is estimated to have increased in the same years by about 0.9% per year (McCloskey

(1981), p. 114). Further productivity growth in coal mining is much below the 0.55% per year productivity growth for the economy as a whole found by Crafts and Harley (1996). Coal mining really was a bit actor in the productivity advances of the Industrial Revolution drama. The aggregate productivity growth rate in an economy is the sum of productivity growth rates in each sector, weighted by the share of output in that sector in GDP. Thus

$$g_A = \sum_i \theta_i g_{Ai}$$

where g_A is the overall productivity growth rate, θ_i is the share of each industry in GDP, and g_{Ai} is the productivity growth rate of each industry. If we calculate sectoral productivity growth rates on a value-added basis, then the weights θ_i will be value-added in each sector relative to GDP. If we calculate productivity growth rates treating intermediate inputs as factors of production in each industry, then the weights will be the ratio of gross output of each industry to GDP, and these weights will add to more than 1. Over the years 1760-1869 the average share of GDP produced in coal mining was only 1.6%. Thus the contribution of coal **mining** productivity growth to overall TFP growth in the Industrial Revolution era was 0.003% per year. Had there been no productivity growth in coal mining output in the economy in the 1860s would only have been 0.2% less than actually observed. In contrast cotton textiles alone contributed about 0.20% per year to productivity growth. Had the entire textile revolution never occurred output per capita would have been at least 23% lower in the 1860s.

Transport Improvements and Coal Consumption

The major reason for the huge increase in consumption of coal per capita in England in the Industrial Revolution period seems to have been a combination of increased demands for coal from greater populations and higher incomes, increased demands following on improvements in iron smelting technology, reduced taxation of coal used for domestic purposes in cities like London, and declining real transport costs.

The top line in figure 9, for example, shows the price of best coal in London, in shillings per ton, measured in real terms compared to the 1860s. Also shown are the costs of coal of this quality in real terms at the pithead in Newcastle as calculated above, as well as the real transport cost and the real tax burden on the coal trade. 'Transport costs' here mean all the costs in getting coal from the pithead to the final buyer, exclusive of taxes. They thus include insurance costs, the costs of transferring coal between the land and the ships, and of delivering coal to the customers in London. For the 1860s these costs are estimated at 8.21 s. per ton, compared with 6.36 s. per ton for the actual sea freight rate as reported by Harley (Harley (1988), p. 875). For the years 1740-1829 we used Beveridge's data for coal transported to Greenwich Hospital. We link this series to the difference between Newcastle and London prices for best coal for 1830-1869. The real price of coal in London falls by nearly 50% from the 1740s to 1860s as a result of the decline in the tax burden and in transport costs. Had the costs of shipping coal from the coalfields to places like London been the same in real terms in 1740 as in 1860 then production would have been many times greater in 1740.

The Industrial Revolution without Coal?

Above we have implicitly considered the counterfactual "what would Industrial Revolution growth have looked like had there been no productivity advance in coal mining?" The answer has been "very little different." A much more radical counterfactual to consider would be what would have happened had the available coal supply been limited so that after 1770 Britain had depleted its coal reserves. What would the Industrial Revolution have looked like absent British coal?

It depends crucially here what exactly the counterfactual is. A narrower version is that the Dutch or the Irish, instead of being left coal poor, had received instead the British coal reserves. How would that have changed the Industrial Revolution in England? One thing is clear. The income derived in England from the actual possession of the coal reserves was always an extremely modest share of national income. If we assume all coal mined in England paid the same site rents to land owners as for our sample of leases reported in table in the northeast then the share of national income paid to coal reserve owners would only be 0.1% in the 1710s, rising to about 0.2% in the 1860s. Had the same coal been located only in Scotland, in Ireland, or in the Netherlands the losses to English national income from loss of mineral rents would have been insignificant.[13]

The much more important cost from having to rely on coal imports would have come from higher coal prices to final consumers as a result of greater transport costs. But much of the coal mined in England was already shipped considerable distances to final consumers. Between 20% and 33% of all coal mined in England before 1870 reached consumers after a sea voyage, and other coal was carried some distance by canal and rail. Suppose we assume that coal consumption 1740-1869 was as we observe, but all of it had to bear the expense of a sea voyage from another country whose cost was the same as the Newcastle-London voyage. In that case the additional cost of coal to consumers would be a fairly consistent 3.9% of English GDP throughout the years 1740 to 1869 (much more coal was consumed in later years but the transport costs had fallen). This reduction in GDP would not fundamentally change the course of the Industrial Revolution.

Since the coal costs for industries such as iron making or salt making which were very energy intensive and located close to the pits would have been much greater the growth of these industries might have been much more limited. But even if England had not developed a substantial iron

[13] The situation was very different with coal than with Middle Eastern oil producers such as Saudi Arabia where the extraction cost for the oil can be well below 10% of the market price, leading to massive rental payments to producing countries.

industry in the Industrial Revolution era, the productivity gains from iron working were again a minor contributor to the Industrial Revolution.[14] And the less coal was imported for iron making, the lower the extra transport cost identified above. Textiles were where the major productivity gains occurred. And the share of energy costs in textile production was small. In a counterfactual world where the coal reserves were located in Ireland or Scotland or elsewhere in northwest Europe the history of Industrial Revolution England need not have resulted in much slower economic growth.

Equivalently the absence of coal in Ireland, the Netherlands or northwest France does not explain why the Industrial Revolution did not occur there. Throughout this period coal from the Tyne went not just to London but to the rest of northwest Europe. Ireland was the recipient of supplies from Cumbria and other West Coast English coal fieds. Thus countries like the Netherlands and Ireland had access to coal at prices little higher than those of most of southern England through most of the Industrial Revolution period.

A more sweeping counterfactual would have been to suppose that there was no available coal in Europe. This is the counterfactual Kenneth Pomeranz effectively considers when he asserts that the location of accessible coal was one of the two vital factors allowing Europe to have an Industrial Revolution when an equally qualified China did not (Pomeranz (2000)). It is also implicitly the counterfactual of E.A. Wrigley, who characterizes the Industrial Revolution as most importantly a switch from a self-sustaining organic economy to a mineral resource depleting inorganic economy. Since this takes us further away from the actual events, the counterfactual is correspondingly more difficult to evaluate.

Without coal, water power, wind power and firewood would have alone served the energy needs of the Industrial Revolution economy. In England by the 1860s 22 million tons of coal was used for domestic purposes – heating, cooking and lighting (Church (1987), p. 19). The value of this

[14] See McCloskey (1981), Crafts (1985).

coal at the point of consumption was about 2% of GDP. All of that would have to have been replaced by firewood and oils. This is the energy equivalent of 2,350 m. cubic feet of wood per year.[15] The average reported annual yield of coppiced wood of different species in England in recent years, including an allowance for the small branches which would be bundled into faggots, is 1.27 tons per acre of dried wood, or 97.5 cubic feet of wood.[16] Each acre of managed woodland in England could thus produce the equivalent, in energy terms, of only 0.87 tons of coal per year. To produce firewood in the 1860s equivalent in energy terms to domestic consumption of coal would have required 25 m. acres of land per year, nearly the entire farmland area of England of 26 million acres. Thus if England had to depend only on its own supplies of energy, costs would soon have soared, and the economy taken a very different path.

There was, however, in the Baltic region alone a lot of wood available to the English economy throughout the Industrial Revolution era. Baltic timber for construction had been imported to England even in the middle ages, and the Baltic was also from early on supplying timber for the Netherlands. By the nineteenth century the Baltic was a major supplier of timber to England. Table 11 shows the areas, modern timber areas, modern wood production and wood yield per acre of the countries or regions bordering the Baltic. This shows that at current production rates, based on smaller forested areas than in the nineteenth century, the Baltic regions could have easily supplied enough wood to completely replace the energy supplied by coal for domestic purposes even as late as the 1860s.[17]

This alternative energy, however, would have been more expensive than coal, in large part because of its higher transport costs. Figure 11 shows the cost per ton of coal to domestic

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[15] Assuming that a lb. of coal contains 12,000 btu., that the dried weight of wood is 29.2 lbs per cubic foot, and that each lb of wood contains the 8,600 btu.

[16] See Begley and Coates (1961), Evans (1984), Rollinson and Evans (1987). Hammersley (1973), pp. 604-5, notes that woodland can produce "up to 100 cubic feet per year."

[17] These current production rates are generally below the estimated sustainable production of woodlands in these countries.

consumers in England, the cost of domestic firewood per ton of coal-equivalent, and the cost of shipping from St. Petersburg a wood volume equal to a ton of coal-equivalent in energy, all normalized by the average day wage of a building worker. Thus the figure shows how many days a building worker had to work to get the fuel equivalent to a ton of coal. As can be seen imported fuel, just based on transportation costs from the Baltic, would have been more expensive than coal. If the costs of production of firewood in the Baltic had equaled that for domestic firewood, then fuel costs in the Industrial Revolution era for domestic consumers of coal would have been about doubled throughout these years. This would have represented in any year a loss of at maximum about 2% of GDP by the 1860s, which is not a dramatic difference. Also with higher energy costs there would have been more efficient use of fuel for heating, cooking, and lighting.

This just looks at the extra costs to domestic consumers. The other 65% of coal went into industrial uses by the end of the Industrial Revolution era – iron and steel making, salt pans, and brick making. If all of these sectors had used as much energy as before then we would need to add at least another 4% of GDP to the losses in the 1860s from not having coal. Also the demand would have reached the upper limit of sustainable output from the Baltic region, raising production costs at the source. Thus by the 1860s England would be reaching the upper limits of energy use using sustainable wood sources in Europe, had it tried to replicate its history exactly as with coal. But higher energy costs would again have led to more economical usage of energy in production and for domestic purposes. The Cornish mining industry, for example, developed much more fuel efficient steam engines in the nineteenth century in response to the high coal costs there.

One result of such substitutions would be that most likely here these energy intensive industrial uses of coal would not have located in England – iron as in earlier years would have been imported from the Baltic - with modest costs to the productivity growth of the economy. The strength of these counterfactual calculations gets weaker the further we move from the actual economic circumstances of England in the Industrial Revolution era. So this last conclusion is no more than an interesting suggestion. But it certainly suggests that Pomeranz's and Wrigley's conclusions on the vital role of English coal in the Industrial Revolution are, equivalently, just speculations. Certainly the Industrial Revolution in textiles would have been well under way in the 1820s and 1830s before energy constraints became even a significant issue for the English economy given the fuel supplies of the Baltic.

Conclusion

Productivity growth in English coal mining in the Industrial Revolution era was extremely modest even under upper bound assumptions on productivity gains. The enormous expansion of coal output owes to factors external to the industry: increased demands for coal from greater populations and higher incomes, increased demands following on improvements in iron smelting technology, reduced taxation of coal used for domestic purposes in cities like London, and declining real transport costs.

This conclusion is based in part on the behavior of the owners of coal reserves in the northeast. They did not act as though they believed at any time that there was, with current technology, an impending increase in extraction cost as the seams of coal closer to the surface were exhausted. Instead they consistently leased coal lands for very modest rents per ton, as though they expected little rise in the price of coal in the coming years from the 1710s onwards. Making the assumption that even up to the 1860s there were still large reserves of coal in the northeast unexploited, all of which had roughly the same cost of extraction except for differences in depth, we estimate a lower bound increase in the total factor productivity of the industry in the northeast from 1710 to 1869 and find that there were only very modest gains. Alternatively we estimate an upper bound gain in productivity by assuming that deeper mining was required to reach the same quality reserves over time. This suggests about a 25% gain in productivity. Our best estimate is thus of a gain of about 12% in coal mining productivity over the Industrial Revolution era. There is little sign of a technological revolution in coal mining. English coal reserves, known and exploited since medieval times, simply found a much larger market in Industrial Revolution England.

As we saw the low coal rents, and the importance of transport and tax costs in the final cost of coal imply that England gained little advantage from actually possessing the coal reserves. An Industrial Revolution based on coal reserves which gave the same pithead price but were located in the Netherlands or Ireland would not have involved a much slower growth rate.

The more radical counterfactual of a Europe that completely lacked accessible coal reserves, or was unable to utilize the deeper English coal seams after the 1760s, is more difficult to analyze. Certainly there were plenty of energy supplies available in the forests of the Baltic and more remotely in the Russian Arctic. The costs of getting these supplies to English consumers were falling as a result of improvements in sailboats, and the end of the Anglo-French struggle in 1815. Energy for domestic purposes could have been supplied to English consumers at a less than prohibitive cost as late as the 1860s. But this more expensive energy would have resulted in a very different pattern of location for energy intensive industries such as iron production. The effects of this relocation of industrial activity are difficult to analyze. But since, as noted before, the estimated contribution of coal and iron and steel to productivity growth is Industrial Revolution England is so small, the effects before 1870 would still potentially have been modest. These last estimates are very speculative, but by implication so also are the alternative claims of Pomeranz and Wrigley that English possession of coal was a vital component of the Industrial Revolution.

APPENDIX: DATA SOURCES

COAL LEASES:

Hughes (1963); Durham Record Office: D/Br/B 1, 79, 122, 141, 180, 186, 195; D/CG 6/365, 1450, 1455-57, 1460, 1462; D/DD 140; D/Lo/E 303, 304; D/St/Bl/3/4, 5, 25, 39-40, 66, 69, 72, 108-9, 119; D/X 651/3; Durham University Special Collections: GB-0033-SHA 393, 423, 431/1a, 3289, 3314, 3327, 3351, 3402, 3403, 3572-4, 3581, 3586; Newcastle City Library: L347.2 230743, 230745; L622.33; L622.33 63943; Northumberland Record Office: 2/DE/1/14; BELL/14; BUD/18, 32, 50, 53; JOHN/6/26; JOHN/7, 8; LES 2/30, 32-3, 40; LES/3/34, 44, 46, 50, 56, 62-3, 61, 77-8, 83; WAT/1/5; WAT/3/30, 41, 45, 51, 58, 72, 103-4, 110; WAT/4/21; WAT/5/2, 6, 7, 11-2; ZGR dm/12/n; ZRI/35/24; Tyne and Wear Archive Service: 3415 CK/8/60, 65; 3415 CK/9/106, 122; DF/WF/29; DS/CAR/11/1-4; DX 973/5/1.

PITHEAD PRICES:

Beveridge (1966), pp. 294-5; Dunn (1844), pp. 73, 85; Harley (1988); Hausman, William J. (personal communication), Newcastle prices from "Brief Against the Petition of Glassmakers."

Porter (1851), pp. 277-8; Durham Record Office: NCB/I/JB/2435, 2444, 2454, 2457, 2462, 2466. Morpeth Records Centre: NRO 1073/1-55; Newcastle City Library: SL 622.33; Northumberland Record Office: 2/DE/7/10/1-22; 725/C/2; BUD/32; BUD/53; BUD 54/18-9, 132; FOR/3; WAT/1/26/9; WAT/3/41, 84; ZAN/M13, B3-4; Tyne and Wear Archive Service: 35/167

LONDON PRICES:

Beveridge (1966) (Greenwich Hospital, Chelsea Hospital, Lord Steward, Navy Victualling, Westminster); United Kingdom, Board of Trade (1902) (Greenwich Hospital, Bethlem Hospital);

Guildhall Library: Brewers' Company, Dame Alice Owen's Almshouses, Islington. 5478/1-3. 5473/1-5.

WORKS CITED

Ashton, T. S. 1948. *The Industrial Revolution*. Oxford: Oxford University Press.

Ashton, T. S. and Joseph Sykes 1964. *The Coal Industry of the Eighteenth Century.* Manchester: Manchester University Press.

Begley, C. D. and A. E. Coates. 1961. "Estimating Yield of Hardwood Coppice for Pulpwood Growing." *Forestry Commission Report on Forest Research 1959/60*, pp. 189-196. London: Her Majesty's Stationary Office.

Beveridge, W.H. 1966. *Prices and Wages in England from the 12th to the 19th Century, Vol. I.* London: Frank Cass & Co.

Braudel, F. 1981. *The Structures of Everyday Life*. New York: Harper & Row.

Buxton, N.K. 1978. *The Economic Development of the British Coal Industry*. London: Batsford-Academic.

Church, R. 1986. *The History of the British Coal Industry, vol. 3, 1830-1913*. Oxford: Clarendon Press.

Clapham, J.H. 1926. *An Economic History of Modern Britain*. Cambridge: Cambridge University Press.

Clark, Gregory 1998. 'Land Hunger: Land as a Commodity and as a Status Good in England, 1500-1914,' *Explorations in Economic History,* 35 (1), (Jan.), 59-82.

Clark, Gregory 2001a. 'Farm Wages and Living Standards in England, 1670-1869,' *Economic History Review*, 54 (3), (August): 477-505.

Clark, Gregory 2001b. "The Secret History of the Industrial Revolution." Working Paper, UC-Davis.

Clark, Gregory 2004. "The Price History of English Agriculture, 1209-1914" Forthcoming, *Research in Economic History, 22*.

Clark, Gregory 2005. "The Condition of the Working-Class in England, 1209-2004" *Journal of Political Economy, 113(6)* (December): 1307-1340.

Crafts, N.F.R. 1985. *British Economic Growth during the Industrial Revolution*. Oxford: Clarendon Press.

Crafts, N.F.R. and C.K. Harley. 1992. 'Output Growth and the Industrial Revolution: A Restatement of the Crafts-Harley View.' *Economic History Review* 45:703-730.

Cromar, P. 1977. 'The Coal Industry on Tyneside, 1771-1800: Oligopoly and Spatial Change.' *Economic Geography* 53, 79-94.

Cromar, P. 1978. 'The Coal Industry on Tyneside, 1715-1750.' *Northern History*, 14, 193-207.

Deane, P. 1965. *The First Industrial Revolution*. Cambridge: Cambridge University Press.

Dunn, M. 1844. *An historical, geological and descriptive view of the coal trade of the north of England*. Newcastle upon Tyne: Garrell.

Evans, J. 1984. *Silviculture of Broadleaved Woodland*. Forestry Commission Bulletin 62. London: Her Majesty's Stationary Office.

Farey, J. 1827. *Historical Account of the Steam Engine*.

Flinn, M.W. 1984. *The History of the British Coal Industry, vol. 2*. Oxford: Clarendon Press.

Griffin, A.R. 1977. *The British Coalmining Industry*. Buxton: Moorland Publishing.

Hammersley, G. 1973. "The Charcoal Iron Industry and its Fuel, 1540-1750." *Economic History Review*, *24*: 593-613.

Harley, C. K. 1988. 'Ocean Freight Rates and Productivity 1740-1913: The Primacy of Mechanical Invention Reaffirmed.' *The Journal of Economic History*, 48 no. 4 (1988) 851-876.

Harrison, A.E. 1994. 'Productivity, imperfect competition and trade reform: Theory and evidence.' *Journal of International Economics*, 36, 53-73.

Hausman, W.J. 1984a. 'Cheap Coals or Limitation of the Vend? The London Coal Trade, 1770-1845.' *Journal of Economic History*, 44, 321-328.

Hausman, W.J. 1984b. 'Market Power in the London Coal Trade: The Limitation of the Vend, 1770-1845.' *Explorations in Economic History*, 21, 383-405.

Hausman, W.J. 1987. 'The English Coastal Coal Trade, 1691-1910: How Rapid was Productivity Growth?' *Economic History Review*, 40(4), 588-596.

Hausman, W.J. 1993. 'Freight Rates and Shipping Costs in the English Coastal Coal Trade: A Reply.' *Economic History Review* 46(3), 610-612.

Hughes, M. 1963. *Lead, Land, and Coal as Sources of Landlord Income in Northumberland between 1700 and 1850*. Ph.D. thesis, Durham University.

Jevons, W. S. 1865. *The Coal Question: An inquiry concerning the progress of the nation and the probable exhaustion of our coal mines*. London.

McCloskey, D. 1981. 'The Industrial Revolution: 1780-1860, A survey,' in R. Floud and D. McCloskey, *The Economic History of Britain since 1700*, pp. 103-128. Cambridge: Cambridge University Press.

McCord, N. and D.J. Rowe 1971. *Northumberland and Durham: Industry in the Nineteenth Century*. Newcastle upon Tyne: Frank Graham.

Mitchell, B.R. 1984. *Economic Development of the British Coal Industry, 1800-1914*. Cambridge: Cambridge University Press.

Mokyr, J. 1990. *The Lever of Riches*. Oxford: Oxford University Press.

Nef, J.U. 1932. *The Rise of the British Coal Industry, vol.s I & II*. London: Routledge.

Pollard, S. 1983. 'Capitalism and Rationality: A Study of Measurements in British Coal Mining, ca. 1750-1850.' *Explorations in Economic History*, 20, 110-129.

Pollard, S. 1988. 'Coal Mining, 1750-1850" in Charles Feinstein and Sidney Pollard (eds.), *Studies in Capital Formation in the United Kingdom, 1750-1920*, pp. 35-72. Oxford: Clarendon Press.

Pomeranz, Kenneth 2000. *The Great Divergence: China, Europe and the Making of the Modern World Economy*. Princeton: Princeton University Press.

Porter, G. R. 1851. *The Progress of the Nation*. London: John Murray.

Raistrick, A. 1938. "Mine Drainage in the 18th Century," *Mine and Quarry Engineering*, Sept.

Rollinson, T. J. D. and J. Evans. 1987. *The Yield of Sweet Chestnut Coppice*. Forestry Commission Bulletin, 64. London: Her Majesty's Stationary Office.

Sweezy, P.M. 1938. *Monopoly and Competition in the English Coal Trade, 1550-1850*. Cambridge: Harvard University Press.

United Kinggdom, Board of Trade 1902. *Wholesale and Retail Prices.*

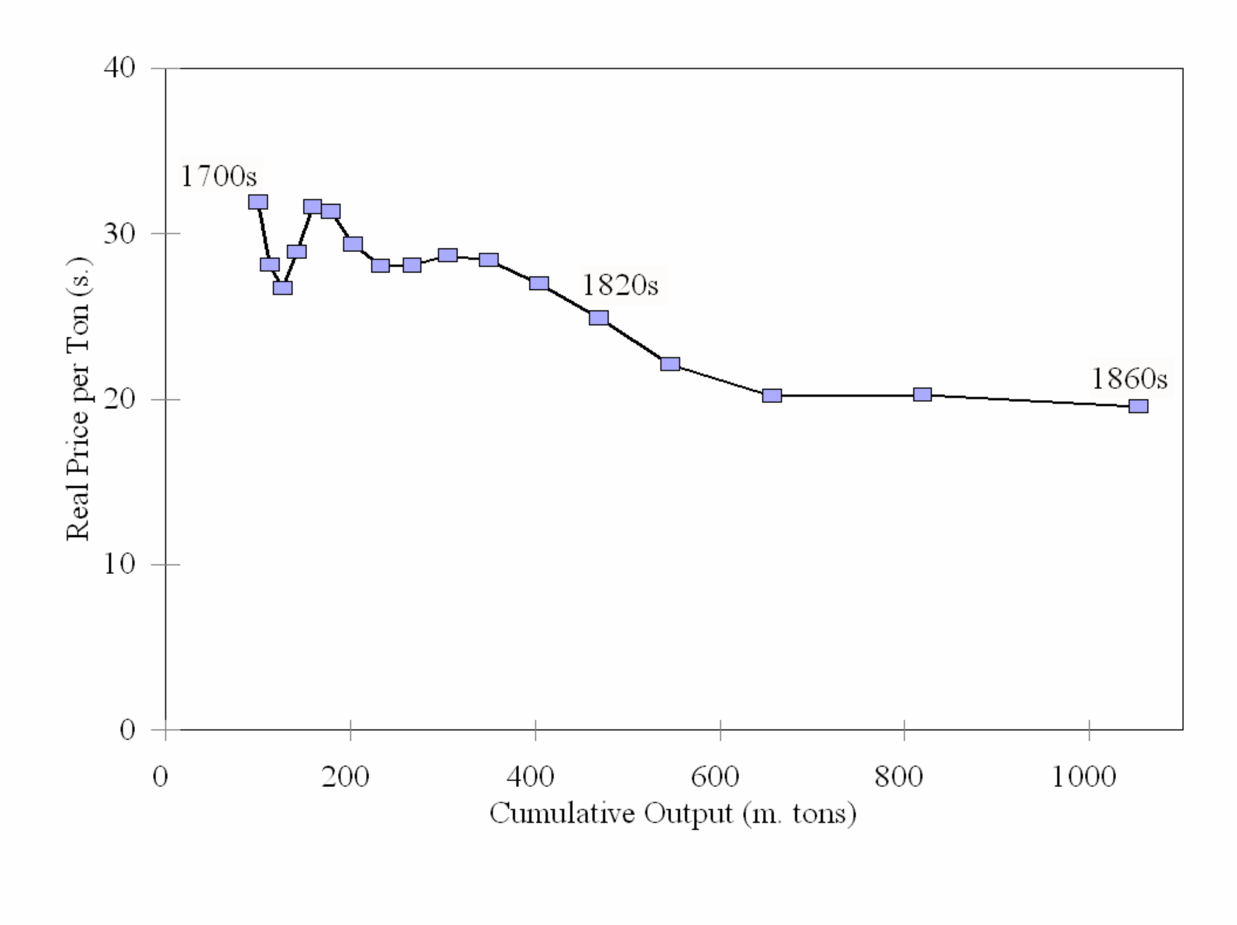
von Tunzelmann, Nicholas. 1978. *Steam Power and British Industrialization to 1860*. Oxford: Clarendon Press.

Vries, P. H. H. 2001. 'Are Coal and Colonies Really Crucial? Kenneth Pomeranz and the Great Divergence,' *Journal of World History, 12(2), 407-446.*

Wrigley, E.A. 1962. 'The Supply of Raw Materials in the Industrial Revolution,' *Economic History Review* 15(1), 1-16.

Wrigley, E.A. 1988. *Continuity, chance and change.* Cambridge: Cambridge University Press.

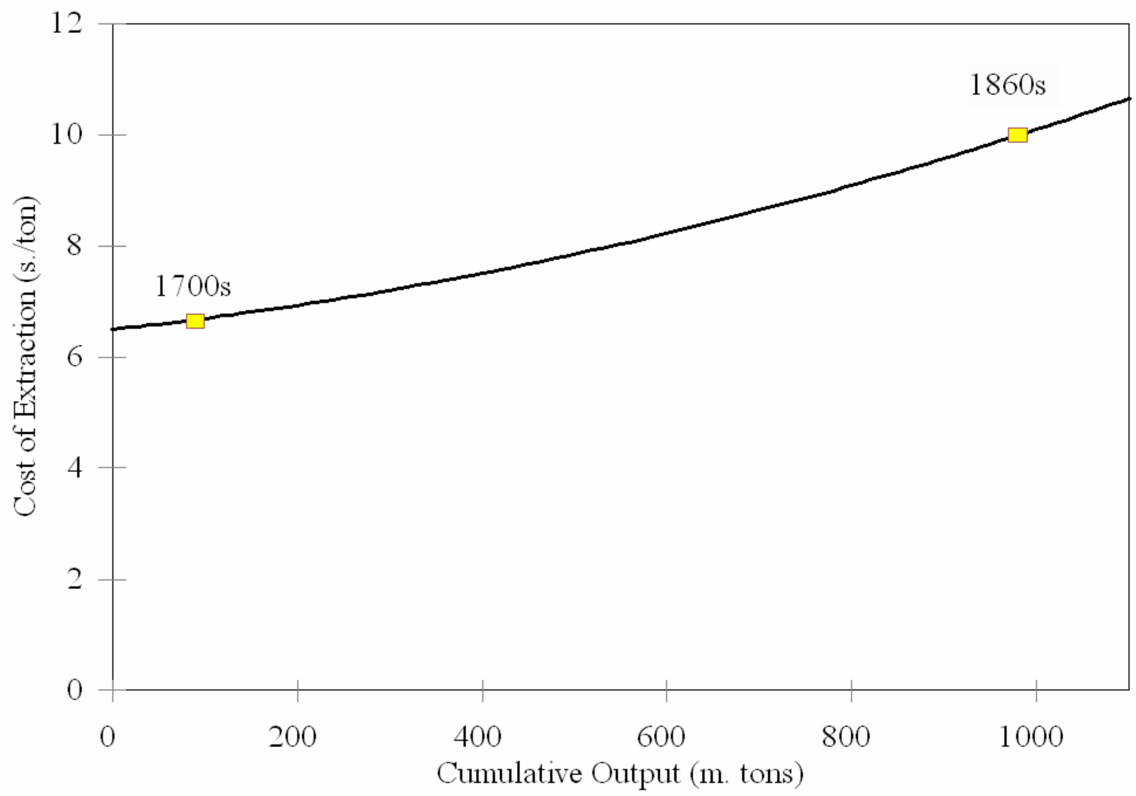
Figure 1: Real prices in London and cumulative output from the north east coalfields, 1700s-1860s



Note: The cumulative output in 1700 from the north east is assumed rather arbitrarily to be 100 million tons. It would not affect the picture shown here if it were made higher or lower. Prices are deflated by a price index for the economy as a whole.

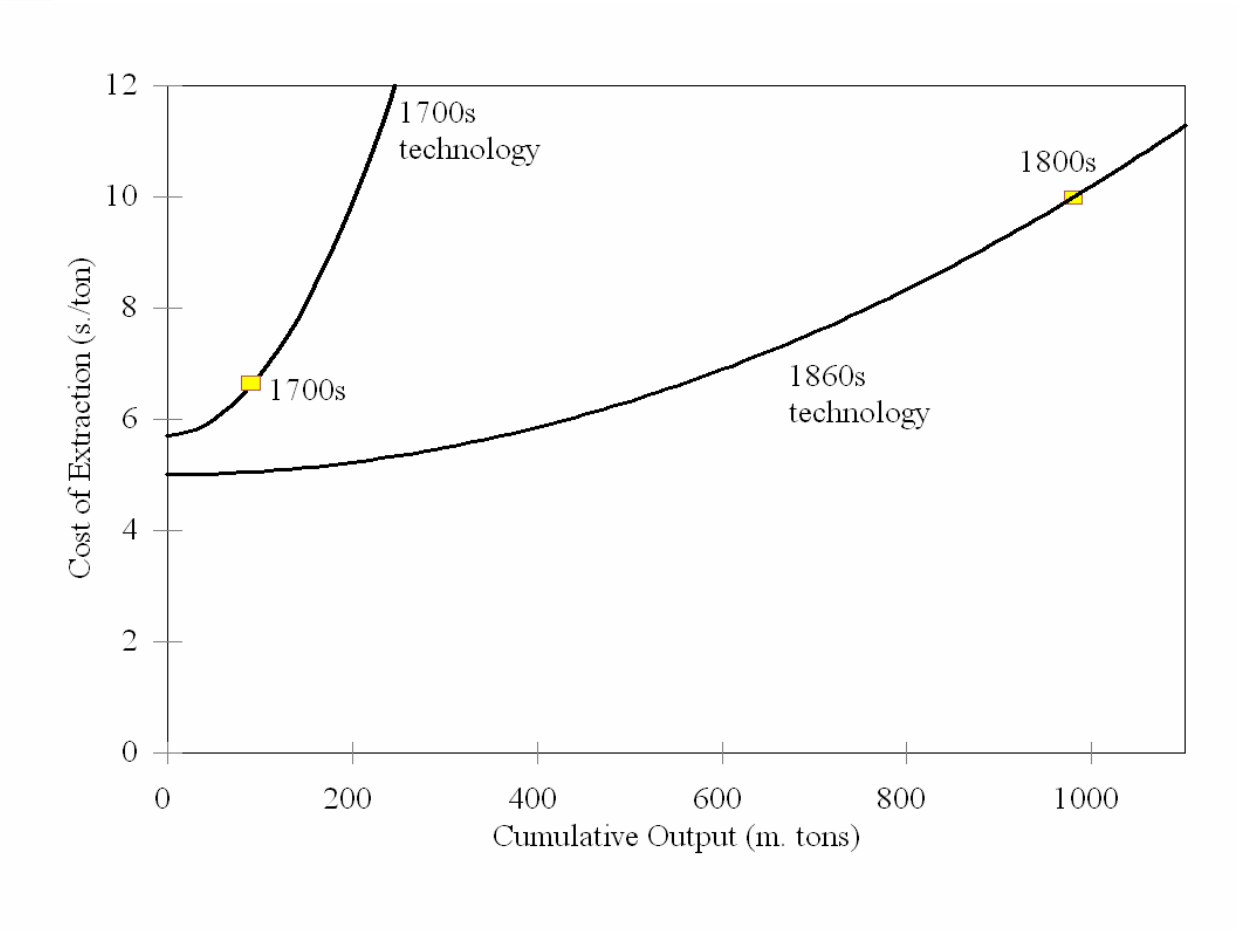
Sources: Outputs, Flinn (1984), p. 26, Church (1986), p. 3. London Prices, see appendix. General price level, Clark (2006).

Figure 2: The Cliometric Account of the Coal Industry in the Industrial Revolution



Source: See the text.

Figure 3: The Traditional Account of the Coal Industry in the Industrial Revolution



Source: See the text.

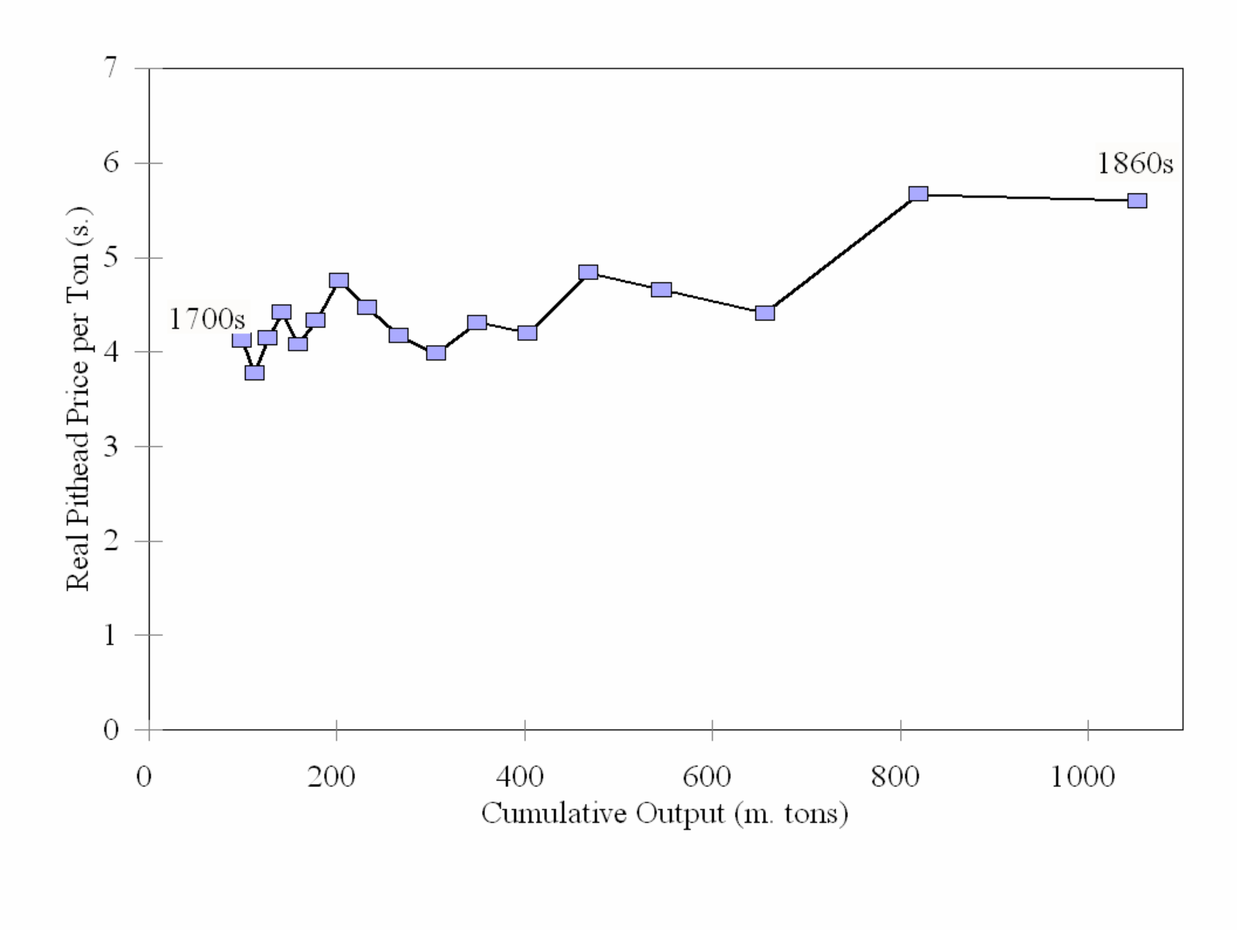
Table 1: Pithead coal prices in the northeast, 1700s-1860s (s./ton)

Decade	Wallsend	Mainteam	Percy Main	Tanfield Moor	"Best"	Exports – Newcastle	Exports – Shields, N & S	"Pithead" Average,
1700s								(2.31)
1710s								(2.25)
1720s								(2.46)
1730s					4.78			2.47
1740s		4.34			4.53			2.34
1750s		4.45			4.34			2.60
1760s		5.28			5.66			3.07
1770s		5.43			5.09			3.15
1780s		5.45			6.89			3.08
1790s		5.56		5.87	6.98			3.35
1800s	10.41	7.55		8.47	12.38			4.87
1810s	12.61			9.43	14.57			5.41
1820s	11.96		11.23	9.38	14.48			5.31
1830s	10.91		10.34	8.30	12.40	6.36		4.77
1840s			7.30		11.02	7.19	7.88	4.28
1850s						8.27	8.11	5.29
1860s						8.75	8.46	5.60

Note: For our method of estimating average Newcastle prices per ton see the appendix. Prices before the 1730s are not based on actual Newcastle prices, but are estimated assuming that they bore the same relation to London prices as in the 1740s. For the decades after this the standard error of the price relative to that of the 1860s is typically 5-8%.

Sources: See the appendix.

Figure 4: Real Newcastle Pithead Prices and cumulative output, 1700s-1860s



Note: Prices were deflated by a general price index derived in Clark (200-).

Sources: See the appendix

Table 2: Pit Depths in the Newcastle Area, 1828

Depth of Pit (feet)	Number in 1828
0-99	0
100-99	4
200-99	9
300-99	5
400-99	6
500-99	4
600-99	3
700-99	4
800-99	3
All	38

Source: Parson and White's *History, Directory, and Gazetteer, of the counties of Northumberland and Durham, 1827-28*, Vol II, pp. 119-20.

Table 3: The Comparative Cost of Steam and Horse Power

Decade	Horse Cost, d./hour	Engine Cost/hp (£)	Pithead coal price (s./ton)	Lbs coal per hph	Steam Cost (d./hph)	Steam cost advantage (d./hph)
1710	1.8		4.30			
1720		72	4.72	45	1.6	0.2
1730		69	4.73	45	1.6	
1740		73	4.48	45	1.5	
1750			4.98			
1760			5.88			
1770	2.5	37	6.03	25	1.0	1.5
1780			5.90			
1790	4.0	54	6.41	20	1.0	3.0
1800		80	9.32	12	1.1	
1810		78	10.35	12	1.1	
1820			10.16			
1830	3.5	60	9.13	12	0.9	2.6
1840		73	8.20	12	1.0	
1850	3.0	34	10.13	12	0.9	2.1
1860			10.72			

Notes: The steam engine is assumed to be a Newcomen until the 1760s, then a Newcomen as improved by Smeaton until the 1790s, then a Watt engine thereafter. The engine capital cost is calculated assuming a 70 percent mark up on the price of the engine itself for transport, erection, boilers, and engine house as suggested by von Tunzelmann. Steam engines are assumed to operate 4,000 hours per year, horses 2,400 hours. Coal prices are taken as those of best coal because this is what von Tunzelman assumes.

Sources: Price of best coals at the pithead in the northeast, Table 1. Horse cost, steam engine capital costs, and engine efficiency, von Tunzelmann (1978), pp. 48-55, 70-74, 117-121.

Table 4: Cost Increase from absence of steam in mining, by epoch

Period	Share of costs coal for winding, pumping (%)	hph/ton	Cost increase (d./ton)	Cost increase (%)
1720-59	6.0	1.6	0.4	1
1770-99	4.4	2.0	5.3	14
1800-39	4.9	4.8	12.2	20
1840-69	3.0	2.9	6.2	10

Source: Share of coal costs in mining, table 6.

Table 5: Coal site rents in the northeast as a share of pithead prices

Decade	Number of leases	Average site rent per ton (s.)	Site rent as % of Pithead price	Standard Error of Site rent (%)	Minimum site rent (%)	Maximum site rent (%)
1710s	3	0.28	(12.4)	(1.2)	(11)	(13)
1720s	10	0.30	(12.4)	(4.4)	(8)	(23)
1730s	10	0.24	9.8	2.7	5	14
1740s	14	0.34	14.4	6.5	6	31
1750s	9	0.33	12.8	3.8	4	17
1760s	12	0.43	14.1	8.4	4	30
1770s	10	0.34	10.9	2.6	9	15
1780s	7	0.33	10.8	3.4	7	16
1790s	12	0.36	10.6	3.2	6	16
1800s	28	0.48	9.9	4.2	6	20
1810s	9	0.43	7.9	4.0	4	18
1820s	41	0.46	8.8	2.6	5	16
1830s	19	0.43	9.0	3.4	3	16
1840s	10	0.44	10.2	1.5	7	13
1850s	4	0.42	8.0	0.9	7	9
1860s	5	0.42	7.4	1.2	6	9

Note: For our method of estimating average site rents per ton see the text. The minimum and maximum rents are just the minimum and maximum reported rents per ton. Pithead prices for the 1710s and 1720s are estimated from the London price by assuming they were in the same proportion as in the 1740s.

Sources: See the appendix.

Figure 5: Rents as a Share of Pithead Prices, 1815-1864

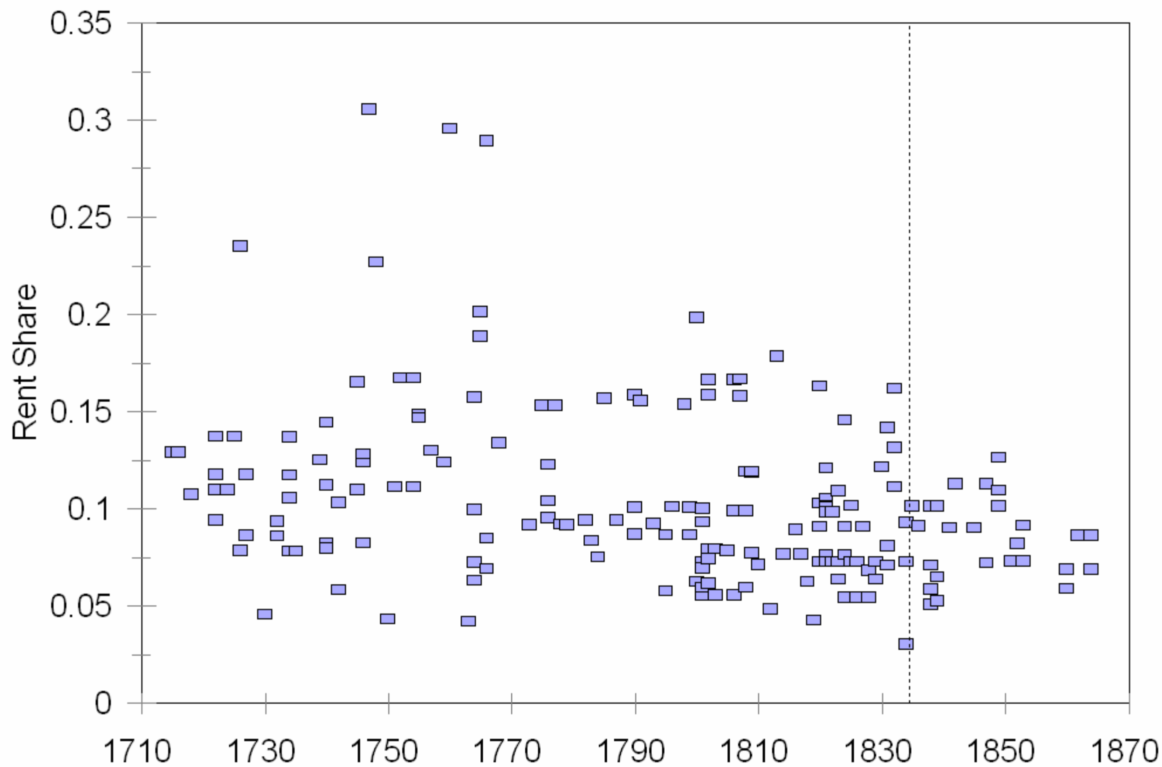
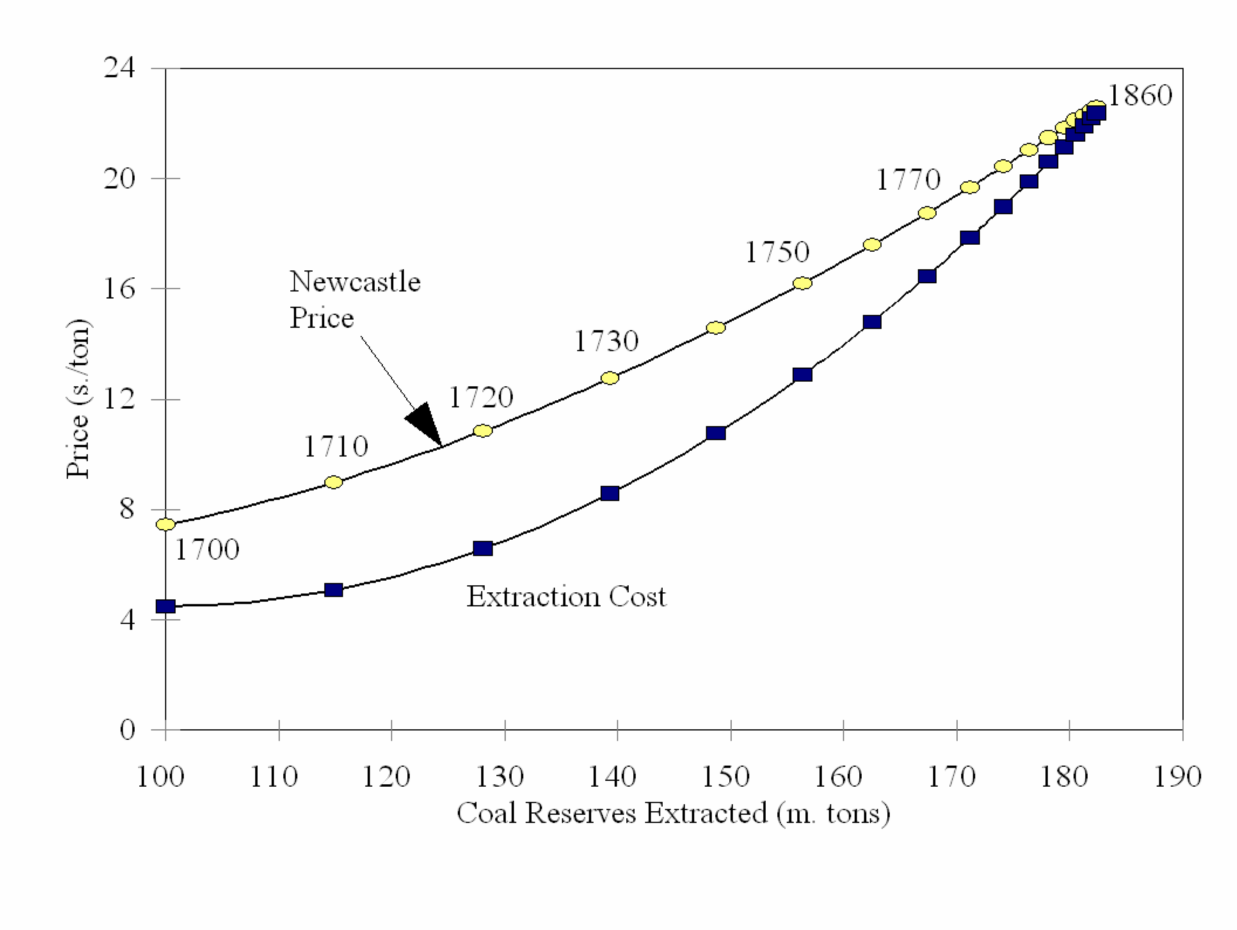


Figure 6: Simulated path of prices and output from 1740 to 1860 with rapidly increasing extraction costs



Source: See the text.

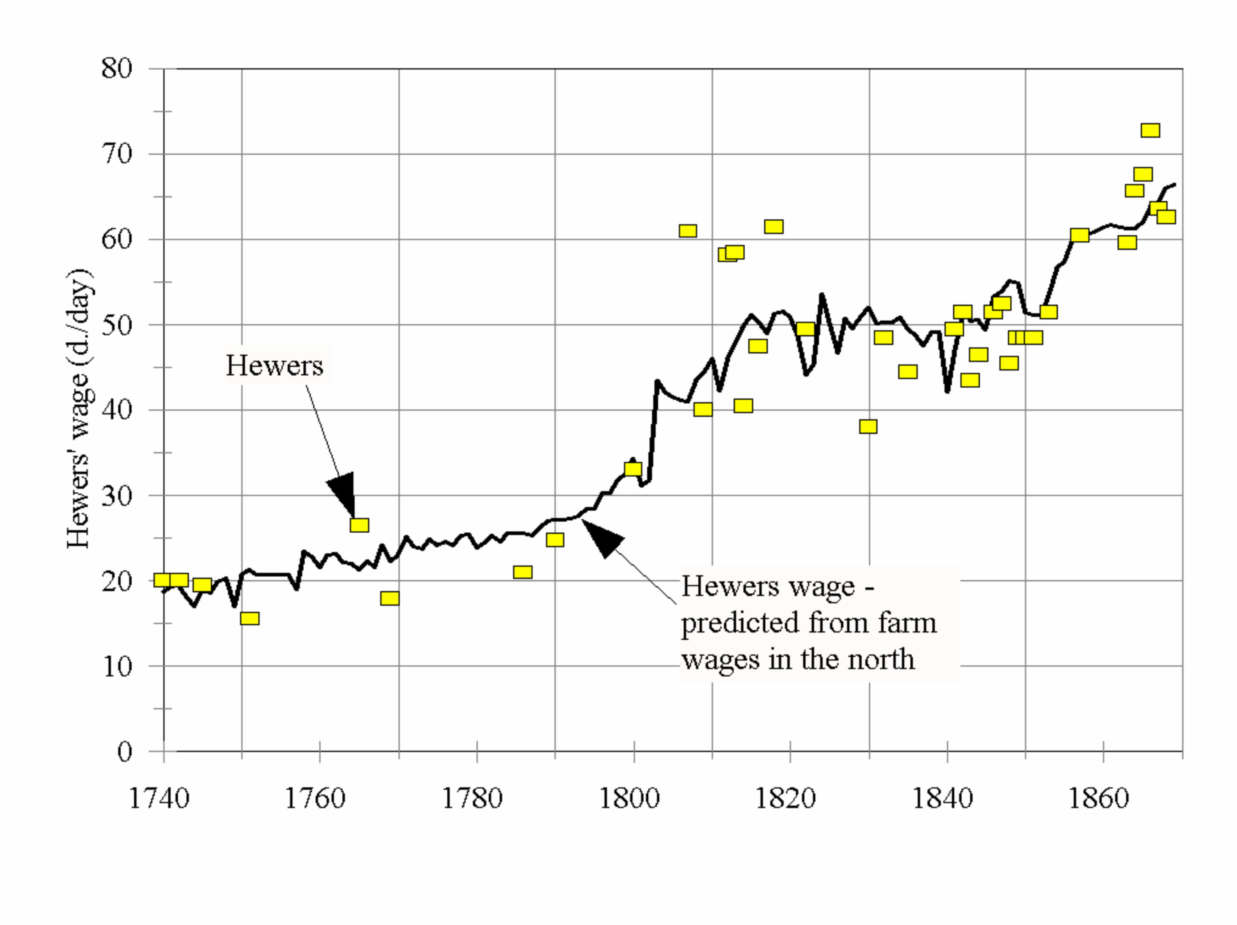
Table 6: The Composition of Costs in Coal Mining, 1700-1869 (%)

Period	Coverage	Mining Labor (including coal)	Horse Fodder	Pumping, winding coal	Craftsmen and supplies	Ground rents	Capital
1717-59	Northeast	40.7	-	6.0	26.6	13.0	13.5
1760-99	Northeast	40.6	-	4.4	24.1	6.2	26.5
1800-1830	Northeast	45.4	6.3	4.9	17.5	7.3	21.5
1830-1860	Britain	51.0[1]	-	-	-	-	20.0
Colliery Guardian, 1871	Britain	56.8[1]	3.3	2.5	9.6[2]	7.8	(20.0)
Assumed, 1700-1869		45.0	5.0	4.0	17.0	9.0	20.0

Notes: Costs were calculated net of taxes. [1]Labor costs including craftsmen, and miners' coal. [2]The costs of supplies only.

Sources: Flinn (1984), pp. 34-5, 292-3, 324-5, Church (1986), p. 502, 521-2,

Figure 7: Estimated hewers' wages in the northeast, 1740-1869



Notes: The solid line shows hewers wages in Northumberland and Durham as predicted from northern farm wages.

Sources: Hewers wages in Northumberland and Durham, Ashton and Sykes (1964), pp. 135-141, Flinn (1984), pp. 387-392, Church (1986), pp. 642-5. Farm workers wages in the north of England, Clark (2001).

Table 7: Estimated costs in north eastern coal mining, 1700s-1860s

Decade	Predicted Hewers' wages (d./day)	Northern Craftsmens' Wages (d./day)	Oats (s./bushel)	Hay (s./ton)	Timber (d./ft^3)	Bar Iron (d./lb)	Candles (d./lb)
1700s	16.2	17.7	1.46	41.6	10.0	4.34	4.95
1710s	15.5	18.2	1.47	42.7	9.5	4.16	6.08
1720s	17.2	17.5	1.48	41.5	8.8	3.83	5.76
1730s	18.6	18.0	1.42	44.1	8.0	3.95	5.42
1740s	17.5	18.4	1.49	46.9	7.8	3.50	6.54
1750s	19.6	19.1	1.62	47.8	8.9	3.36	6.33
1760s	20.9	21.3	1.74	48.9	9.3	3.83	6.82
1770s	22.8	21.9	1.91	60.4	9.9	3.76	7.15
1780s	23.6	22.7	2.01	69.3	9.6	3.83	7.54
1790s	27.0	26.2	2.60	75.1	13.0	4.59	8.36
1800s	36.7	36.7	3.50	96.1	22.2	5.05	10.73
1810s	45.1	45.0	3.74	109.7	25.3	4.67	11.46
1820s	45.5	43.0	2.85	91.1	17.1	3.37	7.13
1830s	46.4	42.0	2.74	81.3	15.5	2.92	6.18
1840s	47.2	42.3	2.65	74.2	12.4	2.25	5.93
1850s	52.5	44.9	2.76	72.5	9.1	2.54	6.27
1860s	58.6	50.2	2.89	82.3	9.4	2.23	6.40

Sources: Farm wages, Clark (2001). Building wages, candles, Clark (2005). Oats, hay and timber, Clark (2004).

Table 8: Estimated capital costs, 1700s-1860s

Decade	Brick Prices (d./100)	Capital Price (p_k) (1860s = 100)	Capital Price, Church (1860s = 100)	Bond and Mortgage Rate (%)	Capital Rental Costs (1860s = 100)
1700s	22.3	43.9	-	5.00	44.9
1710s	24.6	43.2	-	4.87	43.7
1720s	23.8	44.3	-	4.86	44.8
1730s	23.3	45.8	-	4.67	45.4
1740s	22.0	43.8	-	4.14	41.0
1750s	26.1	48.0	-	4.11	44.8
1760s	28.9	52.1	-	4.30	49.6
1770s	28.7	54.8	-	4.39	52.7
1780s	32.0	56.8	-	4.69	56.4
1790s	44.4	67.8	-	4.71	67.4
1800s	60.9	92.9	-	4.85	93.7
1810s	68.9	109.3	-	4.86	110.3
1820s	64.1	100.5	-	4.69	99.7
1830s	58.3	97.6	96.7	4.69	96.9
1840s	53.4	93.2	93.9	4.75	93.0
1850s	45.6	96.0	95.7	4.62	94.6
1860s	35.0	100.0	100.0	4.76	100.0

Notes:

Sources: Capital costs, Church (1986), p. 177.

Table 9: Net Returns on Coalmining Capital, UK, 1850s, 1860s

Year	Net UK Coal Profits (£ m.)	Estimated Mining Capital (£ m.)	Net Rate of Return (%)
1854	[a]1.29	[a]25.6	5.04
1856	[a]1.32	[b]21.6	6.11
1860	[a]1.52	[c]28.0	5.42
1866	[a]2.14	[a]39.5	5.42
1866	[a]2.14	[b]34.3	6.24

Sources: [a]Church (1986), pp. 103, 530-1, [b]Mitchell (1984), [c]Buxton (1978).

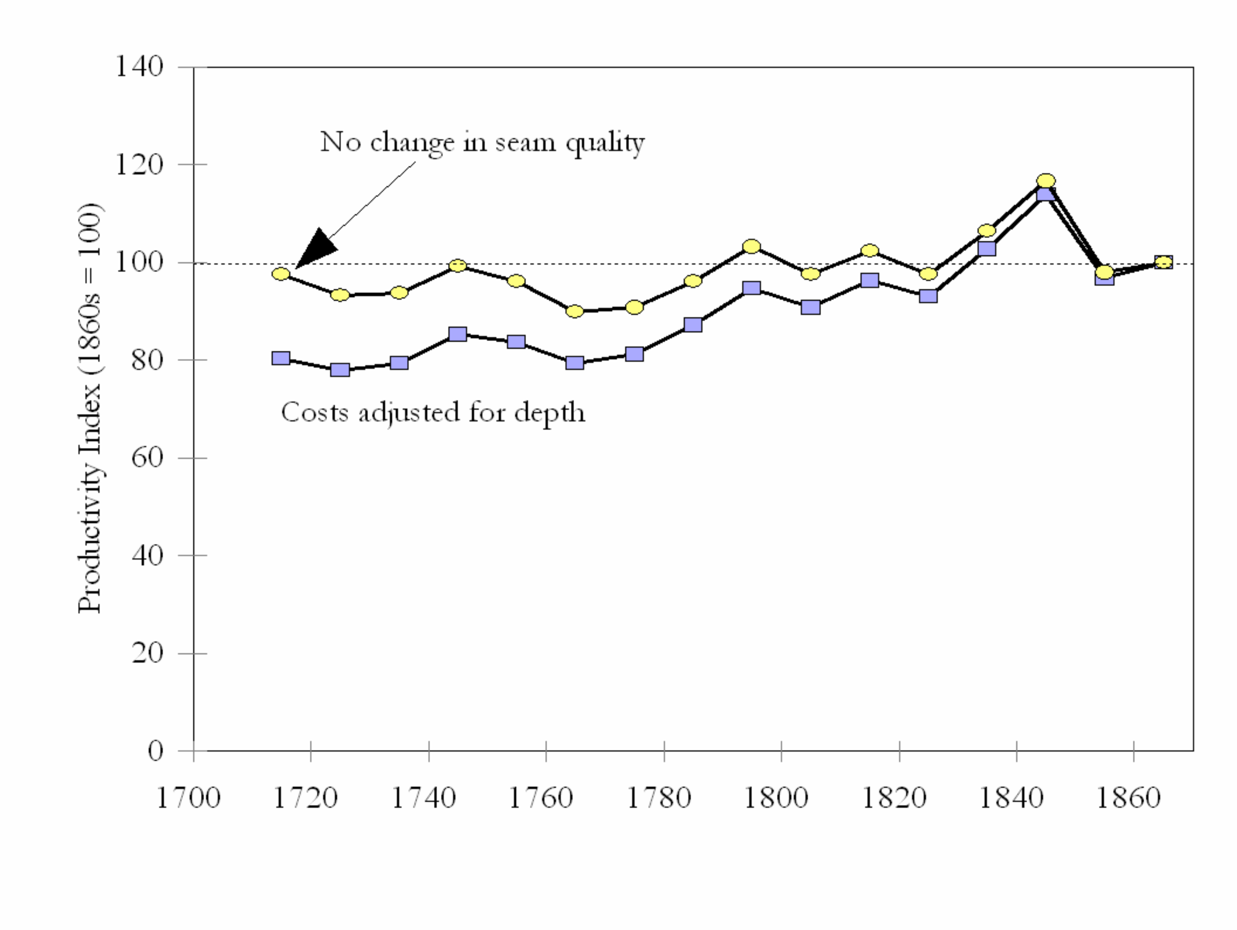
Table 10: Estimated extraction costs, input costs and TFP in the northeast, 1700s-1860s

Decade	Extraction Costs (Pithead Prices - Site Rents) (1860s = 100)	Input Costs (flat supply curve) (1860s = 100)	TFP (flat supply curve) (1860s = 100)	Costs – controlling for depth (1860s = 100)	TFP (allowing for depth) (1860s = 100)
1710s	38.0	37.0	97.6	30.5	80.4
1720s	41.7	38.9	93.3	32.5	78.0
1730s	42.9	40.3	93.8	34.1	79.5
1740s	38.6	38.4	99.4	33.0	85.4
1750s	43.8	42.1	96.1	36.6	83.7
1760s	50.9	45.8	89.9	40.4	79.4
1770s	54.1	49.1	90.8	43.9	81.2
1780s	53.1	51.1	96.3	46.3	87.3
1790s	57.7	59.6	103.2	54.7	94.7
1800s	84.7	82.7	97.6	76.9	90.8
1810s	96.1	98.3	102.4	92.6	96.4
1820s	93.4	91.2	97.6	86.9	93.1
1830s	83.7	89.1	106.5	86.0	102.7
1840s	74.2	86.6	116.7	84.5	114.0
1850s	93.9	92.0	98.0	90.9	96.9
1860s	100.0	100.0	100.0	100.0	100.0

Notes: The standard error of these estimates of TFP we estimate to be about 10% in each decade relative to the 1860s, assuming the errors in all the components independent.

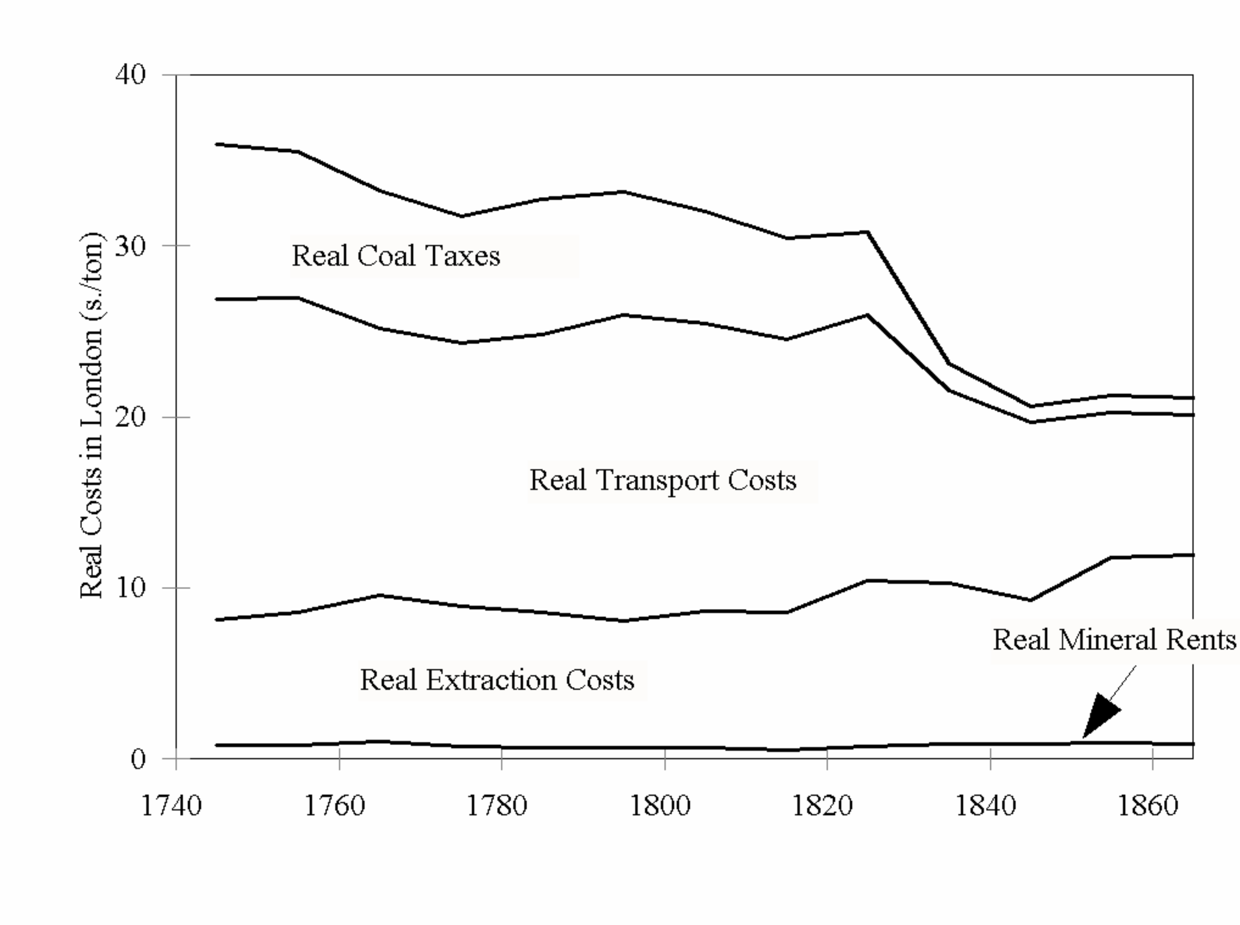
Sources: Tables 1, 5-9.

Figure 8: Total factor productivity in north east mining, 1710-1869



Source: Table 10.

Figure 9: The Elements of the Real Cost of Coal in London, 1740-1869



Source: See the text.

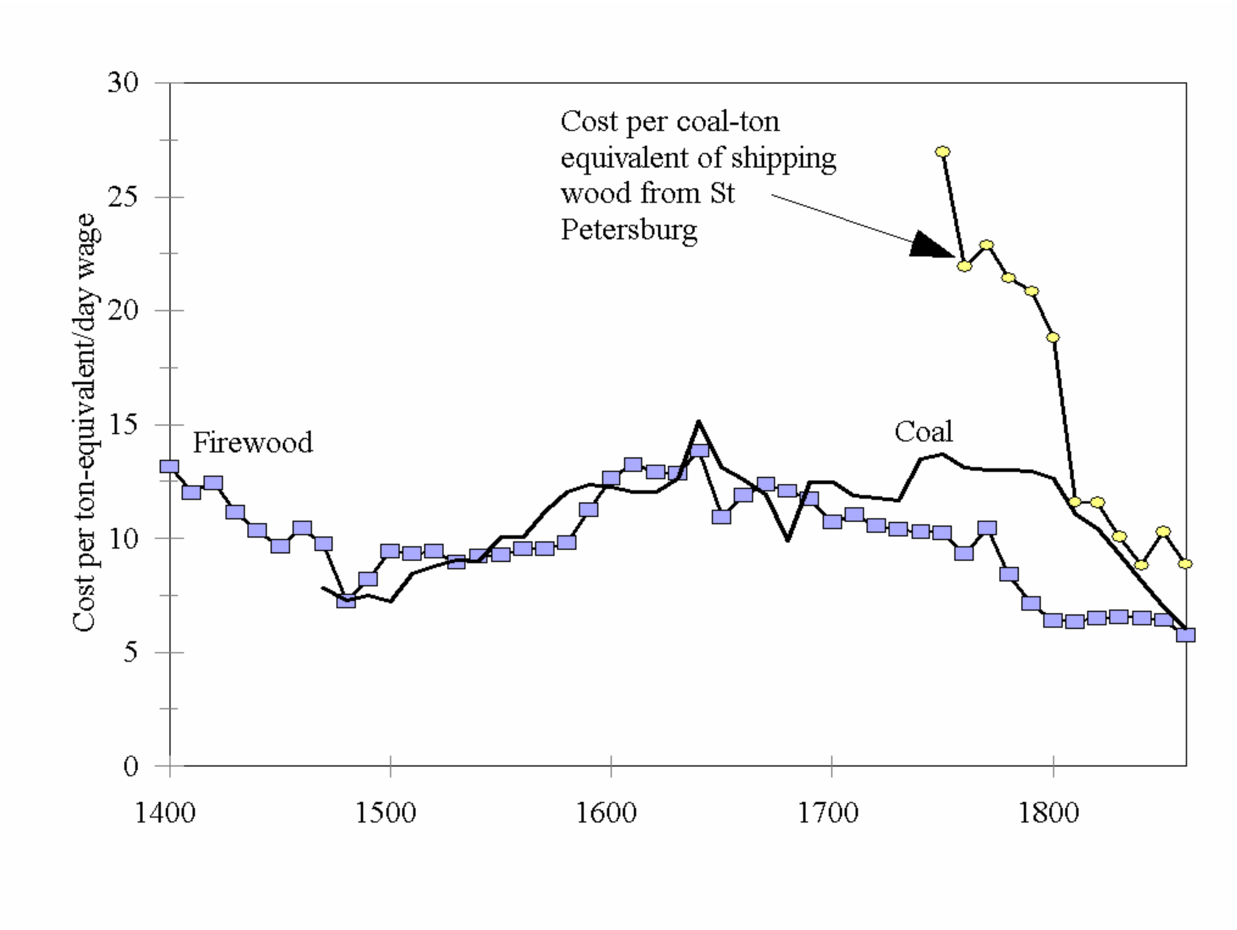
Table 11: Potential Fuel Supplies Available to England in the Industrial Revolution Era

Region	Area (m. acres)	Forest area 2000 (m. ac)	Forest output c. 2000 (m. ft^3)	Equivalent tons of coal (m)	Output/Acre 2000 (ft^3)
England	32.23	-	-		-
Baltic Republics	43.00	17.24	679	6.3	39.4
Belarus	51.30	23.23	627	5.9	27.0
Finland	83.26	54.20	1,784	16.7	32.9
Norway	80.06	21.91	291	2.7	13.3
Sweden	111.10	67.05	2,055	19.2	30.7
Poland	77.06	29.28	919	8.6	31.4
North West Russia	366.69	259.27	2,196	20.5	8.5
BALTIC/ARCTIC	**812.48**	**472.21**	**8,552**	**79.9**	-

Notes: North West Russia is taken as including the Arkhangelsk, Karelia, Komi, Leningrad, Murmansk, Novograd, Pskov, and Vologda Oblasts.

Sources: United Nations, Food and Agriculture Organization, Forest Products.

Figure 10: The Cost of Coal and Wood as Energy Sources, 1400-1869



Notes: This figure is drawn on the assumption that a standard hundred of deals in St Petersburg occupied 165 cubic feet (Lower (1973), p. 25).

Sources: Clark (2004), Clark (2005), Harley (1988)