9 Conclusion

This thesis began by setting out four questions posed by J.R. Harris, as to how much iron was made in England, why the domestic industry failed to satisfy home demand, why the cost of production was lower in Sweden and Russia than in England, and why it took so long after the time of the first Abraham Darby for most iron to be made with coke.[1] Clear answers have been provided to the first and last of these, but only partial ones to the others. On the other hand for the first time a credible series of statistics over several centuries has been provided not only for the production of bar iron, but also for the consumption of wrought iron. However figures on the production and consumption of cast iron goods remain somewhat unsatisfactory. It has also been shown how the organisation of the industry changed over the period. Furthermore, an overview has been provided of how water-power was gradually applied to manufacturing processes. In addition, technological innovations have also been linked with the places where they were used. This has enabled those processes that were viable, and were widely employed, to be distinguished from those that were impracticable or mere curiosities, particularly in the case of patented processes.

The estimates for the amount of iron manufactured and consumed in England and Wales provide data, which will enable the current figures of Crafts and Harley of the output of 18th century industry as a whole to be revised,[2] and in the case of iron to be extended back to the two preceding centuries. However research is still needed to estimate the value added by manufacturing bar iron into finished goods. The price paid by the Navy Board was generally between 28 and 32 shillings per *cwt.* in the early 18th century for 'weight work', that is smith's work that was paid for by weight rather than by the piece. This probably included about 13*s.* 6*d.* for the smith's labour,[3] and suggests that manufacture could almost double the value of the iron. However this is merely an example, for the amount of labour required to produce each different iron good must have varied considerably, and with it the value added by the manufacturing process.

The new consumption estimate for the 18th century shows the same general trend as the estimates of industrial output by Crafts and Harley, by indicating a gradual growth in each during the latter part of the 18th century. This also conforms in general terms with the views of Eversley, McKendrick, and others on the importance of

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1. Harris 1988, 19-40.
2. *Cf.* Crafts & Harley 1992.
3. P.R.O., ADM 49/120, 72-4 112-4 140. The prices are respectively for 'new iron' (supplied by the smith) and 'old iron' (supplied by the dockyard for reuse).

Figure 9.1

Consumption and Crafts-Harley/Chart1

the home market, though over a longer period than they suspected. My figures suggest that there was generally a growth in the economy during the early 18th century, not the deceleration suggested by A.J. Little. Modern research on consumption has indicated that the new demand for manufactured goods came from those engaged in manufactures in towns and elsewhere. Such manufactures provided the 'middling sort of people' and skilled industrial workers with sufficient income to spend on new consumer 'decencies',[4] which is no doubt why there is a correlation between the growth of iron consumption and that of industrial production generally (see figure 9.1).

Older researchers (such as Deane and Cole) suggested that there was a take-off into sustained growth from about 1780. Such a take-off certainly occurred in leading sectors, such as cotton and iron, but they have now been shown to be atypical.[5] However the identification of the recession preceding it sets this expansion in a new light. The new estimates of iron manufacture and of consumption reveal a marked recession during the American War of Independence, due to a decline in manufactured exports to America and difficulties caused by the war in other markets. During the war, there was a pause in the growth of domestic consumption and a temporary decline in iron manufacture, and also in the production and import of bar iron. This recession requires further investigation in order to determine how other industries were affected. J. Hoppitt emphasised the importance of financial crises, including the banking crisis of 1772-3,[6] but this is unlikely to have caused more than a temporary loss of confidence in commercial credit, while merchants reassessed financial soundness of one another. The banking crisis preceded the recession, but it was the war (and not that crisis) that caused the export markets to shrink.

Crafts and Harley have now shown that economic growth at the start of the Industrial Revolution was less rapid than Deane and Cole believed, because leading sectors such as cotton and iron were less representative of the economy than they assumed. However the identification of these two as leading sectors is no mistake. In this thesis I have identified the start of the extraordinary growth of iron production quite precisely in 1785 or 1786, when new processes for making bar iron came into use: the use by others (than the patentees) of Wright & Jesson's 1773 'potting and stamping' process was probably first permitted about then (after Jesson patented an improvement), and Henry Cort was certainly licensing his patented puddling process not long after. Unfortunately it has only been possible to provide good estimates of iron production by these new processes for the first few years, because the amount of new plant built for them after about 1790 remains largely unknown. A major new research project would be needed to resolve that problem.

Previous attempts have been made at estimating the output of pig iron (but not that of bar iron). However those estimates are unsatisfactory until the 18th century, because of the difficulty in providing a convincing estimate of the average annual output of a blast furnace. I have here broken new ground by estimating bar iron

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4. Little 1976. Eversley 1967, esp. 220-9; John 1965, 24; McKendrick 1974; Little 1976; Weatherill 1988.

5. Deane & Cole 1967, ch. 2.

6. Hoppitt 1986, 50-4.

output year by year from the end of the 15th century. That has got around the difficulty with furnace output, and has indeed provided a credible objective answer to that problem. The new estimate has indicated that bar iron production reached a peak of 18500 tons per year around the year 1620. This peak was not surpassed until the 1750s, except briefly around 1720. The existence of such a peak has hardly been suspected before.[7] It marks the end of a long period of rapid growth that had started about 1540 when the Wealden iron industry began its great expansion. The maximum output from the Weald (at 9600 tons of bar iron) was probably reached about 30 years before that for England and Wales as a whole. The 80 years of growth coincide with the period identified by Joan Thirsk as 'the Age of Projects' and by J.U. Nef as 'an early industrial revolution'.[8] Nef's view has been heavily criticised on the basis that there was no revolution in the largest sector, the production of woollen textiles.[9] Important though cloth was, growth in other sectors is likely to have reduced its overwhelming dominance among manufactures, thus beginning a significant trend that has continued to this day.[10]

The estimate for the consumption of iron also depends on data on imports. I have for the first time documented the decline during the 16th century of the import of iron from the Biscay region of Spain, from perhaps 75% of English consumption to under 7%.[11] Spanish iron imports held up well in quantitative terms until about 1540. Their decline thereafter thus mirrors the advance of the Wealden industry. My research into the import of iron from the North (Sweden and Russia) largely confirms what was already known from the work of S-E. Åström, K-G. Hildebrand, and others.[12] However attention has been drawn to the importance of imports of Swedish iron from entrepôts in Holland and Germany between 1630 and the outbreak of the Third Dutch War in 1672. The existence of this trade points to a difficulty in trading with Sweden direct while the Eastland Company retained its monopoly on Baltic trade, and while its regulations required an outward cargo to be shipped to their staple at Danzig (and earlier at Elbing). England therefore (unlike Holland and Scotland) did not see a sharp increase in its imports from Sweden shortly after Louis de Geer and others invested in building new ironworks in Sweden between 1615 and 1630.

The embargo in 1717-19 on trade with Sweden (and thus on the direct import of Swedish iron) was probably the most traumatic period for the iron industry during the period considered in this thesis. It probably increased the price of iron, and certainly stimulated investment in new ironworks. However the expansion proved unsustainable when imports resumed, and even more so a few years later when Russia began exporting

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7. Schubert 1957, 334-35; H.R. Schubert suggested a peak of output around 1630, but this was based on the claim made during Richard Foley's prosecution that there were about 300 ironworks in England, which Schubert interpreted as 100 furnaces and 200 forges. He then multiplied the former by 250 tons of pig iron. G. Hammersley, counted furnaces found 89 them in the 1600s. His figures were interpreted by P. Riden, who believed that the record output in that decade was overtaken in the 1620s by renewed growth. I estimate there were 109 furnaces, but only 129 forges operating around 1630. I also estimate there were 120 and 134 respectively in the year 1620: Hammersley 1973, 595; *cf*. Riden 1977, 443.

8. Thirsk 1978; Nef 1934.

9. Coleman 1956.

10. As note 8; note also Gough 1969.

11. The work of W.R. Childs (1981) relates only to the 15th century.

12. Hildebrand 1957; Åström 1963; for earlier periods note also Hinton 1954; Zins 1972; Fedorowicz 1980; Millard thesis.

iron. The new production estimates thus confirm (and add detail to) the case I made in an article a few years ago.[13]

Examination of data on trade through the Sound (from the Baltic) and that from Gothenburg has suggested that the growth of the heavily export-orientated Swedish iron industry ceased in about 1730. This throws new light on the limitation imposed on the production of the Swedish iron industry from 1747, and fits in well with the view of most modern Swedish historians that the object of the limitation was to prevent damaging competition between ironmasters for fuel.[14] Nevertheless the limitation did initially have a significant effect in England, as the price of iron there rose sharply. This stimulated the erection in Britain of new ironworks, the first since the embargo period 30 years before. In particular there were new forges in south Wales, new charcoal furnaces around the west coast of Britain, and perhaps most significantly the first blast furnaces to produce substantial quantities of forge pig iron using coke (of which more below). However this expansion is probably also related to an expansion in the demand for bar iron, whose consumers included new tinplate works in south Wales. Nevertheless further research into the output of the Swedish iron industry in the late 17th and early 18th centuries would be desirable. Swedish historians have tended to rely on export statistics, but the best series of these only starts in 1738. I have had to use Stockholm export data to estimate traffic through the Sound before 1710 in Swedish vessels (whose cargoes were not then recorded in the *Sound Toll Tables*), but that is not totally satisfactory, nor is the use of data that treats Ireland as a part of England. It ought to be possible to obtain further and more detailed export figures from Swedish Customs records, both those for crown and town dues. Further work on English overseas trade in the late 17th century would also be desirable, particularly that of London.[15]

I have for the first time provided a structure for analysing the various changes in the macro-economic organisation of the iron industry. The initial investment was usually undertaken by aristocrats, using it as a new means of exploiting unproductive woodland, by turning unsaleable wood into iron. However in the early 17th century landowners leased most ironworks to a new breed of professional ironmasters. By replacing their manager with a tenant, a landowner saved himself the trouble of overseeing a manager, while continuing to draw a substantial income from the ironworks from both rent and supplying wood. Such ironmasters often created large vertically-integrated enterprises that enjoyed a monopoly locally in buying wood to make charcoal. However in the Severn catchment, that system began to break down towards the end of the 17th century, for the availability of pig iron brought up the river Severn (initially from the Forest of Dean and subsequently from further afield) made vertical integration less important. When Philip Foley began in the 1670s to break up his ironmaking business in and around the Black Country, he and his contemporaries

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[13]. King 1996b.

[14]. The arguments are reviewed in Hildebrand 1997; and Floren & Ryden 1996.

[15]. The present estimates (Davis 1954) are based on a few sample years and concerned with trade as a whole and broad sectors within it. There is a great deal to be discovered as to how trade with particular countries and in individual commodities changed in the decades before the start of the Customs Ledgers. In respect of iron, the examination of more London import port books might enable something to be worked out concerning the period in the late 1670s when most Swedish exports were carried in (neutral) British vessels.

initially regulated their purchases of wood by bipartite agreements setting boundaries between them. However such agreements were for fixed terms and had to be renegotiated periodically. They also proved inflexible, being unable to respond quickly to changing market conditions. The long term solution was provided by a system of ironmasters' meetings that set a price for iron. That existed by 1720, and continued well into the 19th century. Various authors have described aspects of this organisation, but no overall discussion of it as a whole has appeared before.[16]

I have also in this thesis re-examined the technology of the iron industry, particularly by linking processes with sites. This has enabled effective and commercially viable processes to be distinguished from those that did not work and from those that were mere curiosities. It should also provide a resource for industrial archaeologists and historical metallurgists, by enabling them to identify significant sites for preservation or excavation and for metallurgical research into finds.[17] This relates both to the transition to coke in the production of iron (which will be discussed further below), and also to the application of water-power for processing iron before or after manual manufacturing processes. In addition I have elucidated how the use of slitting and rolling for reshaping bar iron in preparation for manufacture provided the experience to enable the rolling of puddled blooms to be adopted (in conjunction with puddling) in the production of bar iron. Their adoption marks the start of the Industrial Revolution so far as the iron industry is concerned.

One question still remains, the fourth of those posed by J.R. Harris and mentioned at the beginning of this chapter,[18] that of why it took so long for coke to replace charcoal as the main fuel for the iron industry. There were three important innovations in iron production during the 18th century. Firstly, Abraham Darby I smelted pig iron with coke at Coalbrookdale in 1709, following the example of his predecessor Shadrach Fox in the 1690s. Secondly, Abraham Darby II began regularly to supply coke pig iron to forges from 1754, perhaps more a commercial innovation than a technological one. Thirdly, Wright and Jesson in 1773 and 1783, and then Henry Cort in 1783 and 1784, patented new ways of making bar iron from pig iron without charcoal. Each of these brought significant changes to the iron industry. They will be examined in turn in the following paragraphs.

The first, the production of coke pig iron at Coalbrookdale by Shadrach Fox in the 1690s and by Abraham Darby I from 1709, enabled coke to replace charcoal as the fuel for making foundry pig iron.[19] This coke pig iron was initially only used to produce small cast iron goods such as pots and kettles, a purpose for which it was particularly suitable. It initially made little difference to the far larger sector that supplied pig iron to forges, for the production of bar iron which was manufactured by smiths. My new compilation of figures

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[16]. Johnson 1950; 1951; 1952; 1953; 1954; Awty 1957; Schafer 1973; Ashton 1924, ch. 177-83; Birch 1967, ch. 6; Rowlands 1975, ch. 4; and many local studies.

[17]. This view was expressed by David Cranstone, an industrial archaeologist and past president of the Historical Metallurgy Society, at their conference at Seaford in September 2002: *HMS News* 52 (Winter 2002), 3.

[18]. See note 1.

[19]. For Shadrach Fox see King 2002a.

from the Coalbrookdale accounts (by the massive accountancy exercise described in chapter 5) has confirmed the correctness of C.K. Hyde's case concerning pig iron production costs. He correctly showed that the fuel costs of the Coalbrookdale furnaces were comparatively high, so that the inherent cheapness of the fuel was counterbalanced by an excessive amount of it being used.[20] On the other hand, his other argument (concerning forges) has definitively been shown to be unsound, thus confirming the doubts raised about it by J.E. Rehder and L. Ince.[21] Hyde used a counterfactual argument to suggest that the silicon content of coke pig iron meant that the fuel consumption in forges fining it was excessive. However my examination of the production at Coalbrookdale Forge itself between 1720 and 1738 has shown that it was an inefficient little forge, which could hardly make a profit, however the Coalbrookdale Company used it. It is possible that there was a technological difficulty in the use of coke pig iron in the forge at Coalbrookdale in the early 1720s, and that this caused the temporary abandonment of its use. That is not clear; but if there was a problem, it was evidently overcome later. In the early 1730s, the cost problems in producing coke pig iron from the blast furnace seem to have been overcome, probably by increasing the blast into it (and thus its operating temperature). However, the economic conditions were not ripe for the introduction of a new variety of forge pig iron to the market, as appears from the wider examination (in this thesis) of the iron trade in the second quarter of the 18th century.

The second innovation, the first significant use of coke pig iron in forges, did not occur until the mid 1750s. By then the fuel efficiency of coke furnaces had improved still further, and the price of iron was high. Its price had risen at the end of the 1740s (as mentioned above), partly as a result of the limitation imposed on Swedish production a few years before and partly due to increased demand. Rising prices had stimulated considerable investment in new ironworks, and the decision of Abraham Darby II to construct a new furnace at Horsehay was part of that. A successful trial of coke pig iron in the forges of Edward Knight & Co. in 1754 resulted in Horsehay Furnace (then under construction) being mainly used to produce forge pig iron, and likewise several of the other coke furnaces built in Shropshire in the following years. From that time onwards, coke pig iron was a usual part of the feedstock of many forges, but they still relied on charcoal as the fuel for all their fineries.

The key breakthrough was the third one, the invention of a means of producing bar iron without charcoal. As described in chapter 3, its development took several decades. This was discussed by Morton and Mutton and by R.A. Mott,[22] but by identifying people and processes with places, I have added significant details to what they said. Several difficulties had to be overcome. Firstly sulphur in the coal had to be prevented from contaminating the iron. This was achieved by using a reverberatory furnace that kept them separate, and coke as fuel rather than raw coal. Secondly the iron had to be desiliconised and decarburised. Early processes for doing that involved potting and stamping, but they were later replaced by Henry Cort's puddling process.

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[20]. Hyde 1977, 32-8.

[21]. Hyde 1977, 38-41; Rehder 1987; Ince 1991a.

[22]. Morton & Mutton 1967; Mott 1959b; 1983, 27-39; Tylecote 1991, 233-44; *cf.* Evans 1993, 74-6 and *passim*.

Shortly before Wright and Jesson's potting and stamping process came out of patent in 1787, it began to be widely adopted, particularly in the Midlands. This allowed a very sudden and rapid increase in iron production from 1785. Cort's puddling process was used in a few works from the late 1780s, notably Cyfarthfa Ironworks at Merthyr Tydfil, but its widespread adoption may have been deferred until Cort's patents expired in the late 1790s. Cort's other innovation was also very important. Rolling blooms into bars (instead of forging them) produced a more homogeneous and stronger product, which was able to replace imported Swedish and Russian iron for most purposes (though not for converting to steel). The iron was also good enough to enable the Navy to replace imported Swedish oregrounds iron with English (and Welsh) puddled iron in 1809.[23] James Watt's development in the early 1780s of the rotary steam engine was also important for driving forges and rolling mills, but its role was probably not as crucial for the expansion of the iron industry as the new fining processes.

Just as there was a long period of growth in consumption, there was a long period of technological innovation, lasting almost a century. The two earlier innovations described above no doubt freed up some charcoal resources, enabling bar iron production by the traditional finery process to grow. Each of the three brought about profound changes, but it was the third that permitted the great expansion of iron production that constitutes the Industrial Revolution for the iron industry, as this freed the industry almost completely from reliance on charcoal (and thus on the speed of growth of trees).[24] All this throws a new light on technological change in the iron industry, and explains why it took about a century after the first coke pig iron was produced at Coalbrookdale for coke to replace charcoal. The last of these three great innovations in ironmaking technology just happens to have coincided approximately in date with the adoption of the new means of spinning yarn, the other leading sector in the Industrial Revolution. Whether this was a more than mere coincidence is a question which must be left for others to address.

I would suggest that before the Industrial Revolution ultimately iron production was limited by the fuel supply. G. Hammersley was right to point to the interaction between transport costs and fuel supply, which made wood growing outside ironmaking areas unavailable to the industry. However looking at the matter very broadly in terms of the sources of the iron used by manufacturers, perhaps a case can be made that the initial expansion of the English iron industry ended in around 1620, because the iron industry was consuming the available charcoal at about the rate that trees grew the wood from which it was made. Certainly ironworks accounts give the impression that most local woodland in ironmaking areas was managed with the primary object of producing charcoal.[25] Perhaps the older historians (who pointed to a charcoal shortage) were not so far off the mark after all. However it was not that the charcoal iron industry declined as its fuel became exhausted (as they thought),[26] but that the shortage of wood prevented the expansion of production. This is a hypothesis,

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[23]. King 2003 from P.R.O., ADM 106/2672, 31 Jan. 1809.

[24]. Small amounts of charcoal iron nevertheless continued to be made for special purposes for many years.

[25]. Foley a/c; SW a/c; BW a/c. I understand there has been a study on woodland in the Sheffield area, but I have not seen it.

[26]. [D. Mushet] in *Rees' Cyclopaedia* (1802-20), 'Blast Furnace - history'; Mushet 1840, 42; Flinn 1957, n.2; Crow 1956; refuted by Flinn 1957; 1959; Hammersley 1973.

which ought to be examined using the new production estimates in this thesis, but considerations of time and space have prevented this being done. Certainly in the period around 1600 there were ironworks in the uplands of Glamorgan and Gwent (and also around the west coast of Britain) in areas where there were few or none again until the early or mid 18th century.[27]

The peak in English output at 1620 was followed a decade or so later by the first arrival of Swedish iron in large quantities. The Swedish industry underwent a considerable expansion from about that time until around 1730, when Swedish wood resources were perhaps being fully utilised, but by then Russian iron had begun entering England. Finally the adoption of mineral fuel for fining iron in England from the mid 1780s largely freed English manufacturers from dependence on imports. Each of these developments involved the use of a new fuel resource. On the other hand the two great expansions of English iron production, starting in about 1540 and 1785, both resulted from the widespread adoption of new technology. These were the indirect process (of blast furnace and finery forge) in the first case and new coke-based fining processes in the second. Both also resulted in the substitution of home production for imports. There were also two periods of relatively rapid growth in the consumption of iron. The first coincided with the first expansion in production, but the second began early in the 18th century (perhaps about 1720), long before the start of the second expansion in home production. Growth was rather slower in the intervening century. Over the whole period under consideration consumption per head grew gradually, overall at the modest rate of about 1% per year, but at almost all dates the growth in the consumption of iron exceeded that of population.

[27]. Glamorgan and Gwent: see at the beginning of chapter 4. On the west coast there were early ironworks at Mathafarn, Nannau, somewhere in Cumberland (possibly Millom), and on Loch Maree in Scotland: Davies 1939, 64 from *Royal Commission on Ancient and Historic Monuments, Montgomeryshire*, no. 720 (but the date of the Mathafarn ironworks is indicated by 'raw iron in pigs' being shipped to Aberdovey in 1630 and 1634: *Gloucester Portbooks Database*); Parry 1963; King 1999a, 68; Lewis 1984. For later ones see Fell 1908; Awty 1957; Schubert 1961; Thomas 1984.