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The fundamental importance of the steam engine to the Industrial Revolution.¹

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Abstract

This article argues, against the widespread and probably dominant view in the literature in recent decades, that the steam engine was indispensable to the Industrial Revolution in Britain. Without the steam engine the enormous increase in coal output over the eighteenth and nineteenth centuries would not have been possible. This would have stopped the Industrial Revolution in its tracks and, if population growth had remained unaltered, could have led to a Malthusian crisis. Moreover, the rotative steam engine enabled the creation of the first urban economy in world history. That created agglomeration effects which were likely a key contributor to the first achievement of high and sustained rates of economic growth in human history.

The importance of the steam engine to the Industrial Revolution in Britain has been the subject of profound scholarly disagreement. Arnold Toynbee, T.S. Ashton, Tony Wrigley and Bob Allen, to name but four, all regarded it of central importance.² However, other historians including Nick von Tunzlemann, Nick Crafts, Greg Clark and David Jacks have argued that during the classic period of the Industrial Revolution the contribution of the steam engine was of only minor significance and that the Industrial Revolution could have taken place without it.³ Cormac O' Gráda has argued that the steam engine was of little importance during the height of the Industrial Revolution.⁴ Phyllis Deane and W.A. Cole took an intermediate position arguing that the contribution of the steam engine to economic growth was modest between 1760 and 1830.⁵ Thus there is fundamental disagreement about the causation of the first transition to sustained economic growth in history. This paper reviews the available evidence, most of it historiographical, and argues that the steam engine played a critically important role in the Industrial Revolution. Space precludes a proper discussion of the importance of the development of railways which were entirely dependent on steam and coal.⁶ So the assessment provided here, of the importance of the steam engine to the Industrial Revolution, does not represent a complete account of the economic benefits.⁷

¹ I am very grateful to Yiming Cai, John Kanefsky, Sean Bottomley and Martin Daunton for helpful suggestions, comments and information. Any remaining errors and all opinions expressed are my own.

² Toynbee, *Industrial Revolution*; Ashton, *Industrial Revolution*; Wrigley, *Continuity*; Allen, *Industrial Revolution*; Wrigley, *Energy*; Wrigley, *Sustained growth*.

³ Von Tunzlemann, 'Steam'; Crafts, 'Steam'; Clark and Jacks, 'Coal.'

⁴ O' Gráda, 'Science.'

⁵ Deane and Cole, *British economic growth*, pp. ??? Elsewhere Deane suggested a fundamental role for the steam engine: Deane, *Industrial Revolution*, pp. 137-8. She also suggested the steam engine was crucial for the development of the iron industry. *Ibid*, pp.104-5, 109, 111, 118.

⁶ However, on the economic effects of railways see: Bogart et al, 'Railways'; and You et al, 'Transport development.'

⁷ Kander et al, *Power*, p. 197.

Early writers on the Industrial Revolution attributed a central causal role to the steam engine. Arnold Toynbee, who popularized the term 'Industrial Revolution' in the English speaking world in a book published posthumously in 1884, and ascribed it to the years 1760-1820, famously declared that 'industrial life was suddenly broken in pieces by the mighty blows of the steam engine and the power-loom.'⁸ T.S. Ashton, who regarded the Industrial Revolution as taking place between 1760 and 1830, described the steam engine as 'the pivot on which industry swung into the modern age.'⁹

Tony Wrigley, the most insightful thinker about the nature and causes of the Industrial Revolution, suggested 'that the development of the steam engine was arguably the single most important technical advance of the whole industrial revolution period.'¹⁰ More generally he argued that the fundamental cause of the shift from economies capable of only very limited economic growth to economies capable of very long run high rates of growth was the shift from what he termed an organic economy to a mineral-based energy economy.¹¹ In an organic economy the possibilities for long-run economic growth were subject to fundamental limits.¹² This was true for three key reasons. First, the great bulk of raw materials for industry had to be grown in the soil and their supply was therefore limited by the fertility of the soil and the share of agricultural land that could be devoted to growing raw materials. Second, the vast majority of energy used to do mechanical work in the organic economy came from either human or animal muscle power. Both humans and animals had to be fed from the products of the soil. That too imposed fundamental limits to the growth of organic economies. Third, the thermal energy required for industrial processes had to come overwhelmingly from wood, which also had to be grown, and that also imposed fundamental limits to growth. The crucial invention in relation to the second limitation of the organic economy was, of course, the steam engine which was in turn fuelled by coal. The ever-increasing use of coal was the key to escaping the third limitation.¹³ Wrigley stressed the indispensable role of steam pumping engines to the expansion of the coal industry.¹⁴

The first successful steam engine was built by Thomas Newcomen in 1710 or 1712.¹⁵ The original engine was remarkably inefficient and converted only around one half of one percent of the thermal energy used into mechanical energy.¹⁶ The Newcomen engine was so expensive a way to produce mechanical energy that its use was largely confined to pumping water, mostly out of coal mines, where waste coal generally provided a free and inexhaustible supply of fuel and Cornish tin and copper mines where, although coal from South Wales was very expensive, there was no alternative viable technology. Thanks to the painstaking work of John Kanefsky and his collaborators over more than four decades, we now have a very comprehensive and detailed knowledge of the diffusion of steam engines in England and Wales in the eighteenth century.¹⁷ A brief discussion of the diffusion of the Newcomen

⁸ Toynbee, *Industrial Revolution*, p. 58.

⁹ Ashton, *Industrial Revolution*, p.19.

¹⁰ Wrigley, *Energy*, p. 44.

¹¹ This idea was first fully articulated in Wrigley, *Continuity*, though elements of the idea can be found in earlier work. The thesis was developed at greater length in Wrigley, *Energy* and Wrigley, *Sustained growth*.

¹² *Ibid*, p. 10.

¹³ More recently the centrality of coal has been stressed by Bob Allen: Allen, *Industrial Revolution*.

¹⁴ *Ibid*, p. 45.

¹⁵ The usual dating is 1712 but Nuvolari suggests the actual date is more likely to have been 1710: Nuvolari, *Making*, p. 50.

¹⁶ Singer et al, *Technology*, p.184.

¹⁷ I am very grateful to John Kanefsky for making this invaluable dataset publicly available. For details, and a full list of those who contributed to the creation of the dataset, see: <https://coalpitheath.org.uk/engines/history> With colleagues we geo-referenced an earlier version of this dataset: Bogart et al, 'Kanefsky dataset.' It is this version of the dataset which is used in this paper. Since then, the publicly available Kanefsky dataset, which lists

engine prior to 1781, when the rotary steam engine was patented by James Watt follows. Of the 655 known steam engines installed before 1781 whose purpose has been identified 549, or 84 percent of the total were used to pump water.¹⁸ Of these 427 or 65 percent of the total were used to pump water out of coal mines.¹⁹ A second reason why Newcomen engines were largely used for pumping water was that they were, with some very minor exceptions, incapable of directly producing rotary motion and could not be used to power machinery. They were therefore of limited use for anything except pumping water. However, Newcomen engines were sometimes used to pump water uphill to secure a reliable source of water for water powered mills. In total 192 recirculating engines, mostly Newcomen engines, were installed in the eighteenth century.²⁰ This is around 10 percent of the engines with a known purpose. Sixty-one of these were installed before 1781. The use of recirculating engines points to problems of water supply for water mills in some locations where power was needed.²¹

Watt's famous invention of the separate condenser in 1769 brought about a major improvement in efficiency. In the 1760s two Newcomen engines capable of producing rotary motion were built at coal mines in Northumberland for winding.²² One further rotary engine was built at a coal mine in 1780.²³ The rotative Newcomen engine did not produce power with sufficient regularity to operate textile machinery.²⁴ It was Watt's patenting of the sun and the planets mechanism in 1781 that led to the widespread diffusion of rotary engines capable of driving machinery. However, initially the rotary motion was not sufficiently smooth to power machinery and further improvements were required but by 1785 the engines were capable of running machinery.²⁵ By 1800 424 of the new engines had been installed.²⁶

The rest of this article is structured as follows. Section one discusses the economic reasons for the adoption of steam engines before they were generally price competitive with water power. Section two presents the highly influential claim of von Tunzelmann that steam engines were of minor importance to the Industrial Revolution. Section three introduces the similarly sceptical work of Crafts. Section four discusses problems with data on which Crafts relied. Section five sets out the problems in von Tunzelmann's and Crafts' use of the social savings methodology. Section six presents evidence for the crucial importance of the steam engine in coal mining. Section seven outlines the relationship between urbanisation and modern economic growth. Section eight argues that the rotative steam engine was crucial to urbanisation from the late eighteenth century. Section nine identifies the importance of steam engines to the iron industry, shipping and agriculture. Section ten considers the problems with the arguments of Clark and Jacks. Section eleven consider the difficulties with the arguments of Section twelve concludes.

I

The economic reasons for the early installation of steam engines

a number of additional engines, has also been georeferenced. The first engine listed in the Kanefsky database is dated to 1710: Bogart et al, 'Kanefsky dataset.'

¹⁸ Bogart et al, 'Kanefsky dataset.'

¹⁹ *Ibid.*

²⁰ *Ibid.*

²¹ Recirculating engines may have been more common in the nineteenth century. See: Jonell et al, 'Limited waterpower', p. 6.

²² Bogart et al, 'Kanefsky dataset.'

²³ *Ibid.*

²⁴ Von Tunzelmann, *Steam*, p.142.

²⁵ Kanefsky, 'London', p. 98.

²⁶ Kanefsky, 'Watt', p. 7.

Stanley Chapman published an important but under cited article in *Midland History* in 1971 on the cost of power in the textile industry. Chapman began by noting that the relative cost of water power and steam power will have varied very considerably from one site to another.²⁷ This means that it is simply not possible to identify a single date at which the cost of steam power fell below that of water power. This is partly because the cost of water power varied from one riparian environment to another but more fundamentally because, until a late date, the cost of coal varied enormously between one part of the country and another. This is discussed at greater length below. However, Jeremy Attack, with much better data available, suggests that in the United States it was not until the 1850s that steam power became generally cost competitive with water power.²⁸ Chapman went on to note that 'the cost of water power on remote country sites should also take account of workers' housing, apprentice housing, markets, schools, roads, and other communal requirements which did not have to be provided at urban mills.'²⁹

Despite this Chapman suggested that in the 1780s 'steam was more expensive than the costliest water power installations.'³⁰ Yet this is the period when steam power began to be applied in the textile industry. Clearly then this was not because of *general* cost advantages and the reasons need to be sought elsewhere. The key advantage of the early steam engines for the textile industry was locational. Steam engines could be erected both at sites with other advantages where water power was simply not available, was insufficient, or where, for reasons specific to particular sites, the cost of water power did exceed the cost of steam power. Chapman argued that the reason that the first Boulton and Watt engine was installed at an Arkwright style mill, at Papplewick in Nottinghamshire in 1785, was a shortage of water power at the site.³¹ He went on to note that in:

Manchester and Leeds, the other urban centres of the late eighteenth-century English cotton industry, there is ample evidence that other pioneers of mill spinning faced a comparable problem of rapidly rising costs. William Walker's large-scale maps of Manchester (c. 1789-1795) suggest that, as in Nottingham and other industrial towns, the eligible local sites were all occupied before the era of Arkwright.³²

A further locational advantage of steam engines was that far more power could be generated at a single site than was possible with water power.³³ Beyond the textile industry there is evidence that in Birmingham, the leading centre for all kinds of metal goods, all of the available water power was being exploited by 1760.³⁴ The reason why specifically urban locations were so attractive to entrepreneurs will be discussed further below.

Chapman suggested that in Lancashire, where the English cotton industry was overwhelmingly located, the steam engine overcame a shortage of available sites for water mills. He cited the Rees Cyclopaedia, from around 1815, to the effect that 'upon most rivers in this country all the falls of water are fully occupied, and at every mill there is a weir which pens up the water as high as the mill above can suffer it to stand without inconvenience.'³⁵ Edward Baines in 1835 claimed that if alternative sources of power had not been found, the expansion of the Lancashire cotton industry

²⁷ Chapman, 'Cost', p. 1.

²⁸ Attack 'Fact in fiction', p. 422.

²⁹ Chapman, p. 1.

³⁰ *Ibid*, p. 13.

³¹ *Ibid*, pp. 4-5.

³² *Ibid*, p. 9.

³³ On this point see also: Bottomley, 'Steam', p. 845.

³⁴ Pelham, 'Water power', p. 64.

³⁵ Chapman, 'Cost', p. 19.

would have ground to halt in the late eighteenth century.³⁶ However, Robert Gordon argued that many sites suitable for water powered mills in Lancashire remained unoccupied during the Industrial Revolution and that less than seven percent of water power potential was in fact in use in cotton mills in 1838.³⁷ He went on to suggest this undermined the claims of Pelham and Chapman that water power was fully utilised at an early date in the history of mechanisation.³⁸ If we accept Gordon's estimates of the amount of water power available, and this is questionable as will be discussed below, two major problems remain with his claims. First, by 1838 many water powered sites for cotton production had been abandoned in favour of steam, so the amount of water power in use in 1838 is an entirely unreliable guide to the amount in use in 1780 just before Watt patented his rotative engine.³⁹ Secondly this does nothing to address the claims made by Pelham and Chapman about the shortage of water power in *urban* areas. Gordon's suggestion that the continuing use of water power in some urban locations undermines the water shortage argument is logically fallacious. No-one disputes that *some* water power remained in use in urban areas after the widespread adoption of the steam engine. The key point is that the total amount of water power was insufficient to meet demand in many urban locations. Were that not the case there would have been no reason to adopt steam power until the point, perhaps towards the middle of the nineteenth century when steam power became generally cheaper than water power.⁴⁰

In the second quarter of the nineteenth century a third non-cost advantage for steam engines in the textile industry developed. Chapman argues that 'the perfection of Roberts' 'self-acting' mule in the 1830s encouraged a growth in size [of mills], for one skilled spinner could work 1,600 spindles as easily as he previously worked two 300 spindle hand mules, and power looms were increasing rapidly in numbers as they became efficient with the finer counts of yarns. The best sites might generate 100 h.p., but 10 or 20 h.p. was a typical limit, and there was little chance of meeting the power requirements of the new cotton mills on such slender natural resources.⁴¹

Tara Jonell and her co-authors have recently published the most thoroughgoing assessment to date of the role of limited water power availability in the early use of steam engines in the cotton industry.⁴² They began by creating a dataset of water power availability covering the whole of Britain from modern water flow data at high spatial resolution.⁴³ One interesting finding is that 99 percent of watermills were located below the 300m contour line. This is clear evidence of abundant water power not being utilised where locational disadvantages were too strong.⁴⁴ The new data, which are far less dependent on assumptions, lead to water power availability estimates between 29 and 44 per cent of Gordon's estimates.⁴⁵ The data also suggest that by 1838 there was insufficient water power to run Manchester's cotton mills, although Chapman had, of course, already demonstrated this for a period more than 40 years earlier without the same technical sophistication.⁴⁶ However, Jonell and her co-authors go on to suggest this was not the case in most other industrial centres in

³⁶ Gordo, 'Cost', p.242.

³⁷ Gordon, 'Cost', *passim*, p. 258.

³⁸ *Ibid*, p. 259.

³⁹ Crafts and Wolf, 'Cotton', p. 1130. The same interpretational error is made by Jonell et al: 'Limited waterpower', p. 5.

⁴⁰ Crafts, 'Steam', p. 342.

⁴¹ Chapman, 'Cost', p. 19.

⁴² Jonell et al, 'Limited waterpower.'

⁴³ *Ibid*, p. 2.

⁴⁴ *Ibid*, p. 3.

⁴⁵ *Ibid*, p. 4.

⁴⁶ *Ibid*, p. 5.

Britain.⁴⁷ Unfortunately, none of these are named so the importance of this doubtful claim is difficult to assess.

As long ago as 1967 J.R. Harriss argued that:

the great value of the steam engine was in its mobility to any point where coal could be supplied at reasonable prices, its capacity to carry out tasks to which horses could not be applied or which were out of the reach of water powered machinery, its removal of bottlenecks which had held up technical development, especially in mining, its influence in concentrating hitherto dispersed industrial units and processes. The relatively high cost of engines down to 1800 meant that they were used where it was thought they would solve hitherto intractable problems, enable a breakthrough into high profits, allow development on a scale otherwise impossible.⁴⁸

Von Tunzelmann provides some instructive estimates of the approximate number of steam engines installed in various towns at a number of dates: London, 290 in 1825; Manchester, 240 in 1825; Leeds, 130 in 1825; Bolton, 83 in 1825; Birmingham, 60 in 1820 and 169 in 1835; Glasgow 242 in 1825; Belfast, 50 in 1838; Dublin 29 in 1838.⁴⁹ In all these urban locations steam power must have been generating far more energy than would have been possible from water power. However, von Tunzelmann did not draw this obvious conclusion. Kanefsky notes London was very poorly endowed with sites suitable for watermills.⁵⁰ No doubt this explains why, by 1805 there were a minimum of 138 steam engines installed in London.⁵¹

II

The work of Nick von Tunzelmann

Von Tunzelmann undertook a social savings exercise which was intended to establish the cost savings attributable to the steam engine up to the cessation of Watt's patent in 1800 by comparing the cost of steam power to water power.⁵² He estimated the social savings attributable to James Watt as worth a mere 0.11 percent of national income in 1800 and then suggested that this figure was 'excessively high.'⁵³ Von Tunzelmann considered, and dismissed the significance of water mills being subject to a variable water supply.⁵⁴ He argued that by 1800 most of the really large textile mills were still water powered.⁵⁵ However, he noted the 'extensive' use of steam engines in watermills to provide power when there was not enough water available.⁵⁶ In the conclusion he suggested that it is 'highly probable that the ratio of social savings to national income would be higher in 1830' or 1850.⁵⁷ He also suggests that the steam engine allowed expansion to 'go ahead largely unchecked by power limitations, at more or less constant costs.'⁵⁸ This point, which is centrally important, is discussed nowhere else in the book and is in tension with the general tenor of von Tunzelmann's argument. It should be also noted that the comparison with water power is only partially appropriate. Two thirds of steam engines installed by 1780 were pumping water out of mines and

⁴⁷ *Ibid*, p. 6.

⁴⁸ Harris, 'Employment', p. 148.

⁴⁹ *Ibid*, pp. 31-35.

⁵⁰ Kanefsky, 'London', p. 97.

⁵¹ *Ibid*, p. 102.

⁵² Von Tunzelmann, *Steam*, p. 116.

⁵³ *Ibid*, p. 149.

⁵⁴ *Ibid*, pp. 154, 170-173.

⁵⁵ *Ibid*, p. 159.

⁵⁶ *Ibid*, p. 233.

⁵⁷ *Ibid* p. 287

⁵⁸ *Ibid*, p. 284.

most of these were probably replacing horse gins rather than water power and horses were probably significantly more expensive than steam.⁵⁹ I will defer the rest of my critique of von Tunzelmann's work until I have discussed Crafts' social savings calculations below because they suffer from identical problems.

In a 2013 review of the literature since von Tunzelmann, Kristine Bruland and Keith Smith declared that 'in our view von Tunzelmann's conclusions definitively break the nexus between steam, industrialization and capitalist development which, established by Toynbee, had sustained so much of British economic historiography.'⁶⁰ They go on to suggest that 'the main point of this work is that steam was not the driving causal factor that has been found in so much economic history.'⁶¹ In the rest of this article I will argue this is misconceived and that the particular econometric approach adopted by von Tunzelmann was inappropriate and largely irrelevant and that his interpretation of the results led to fundamentally misleading conclusions.

III

The work of Nick Crafts

In a 2004 article in the *Economic Journal* Crafts argued, based on a social savings methodology, that steam power contributed very little to economic growth before 1830 and only really realised its potential after 1850 with the widespread diffusion of the high pressure engine.⁶² Crafts' scepticism about the role of the steam engine during the Industrial Revolution may have been very long-standing. His 1985 book *British economic growth* hardly discussed steam engines at all and the index to his 1985 book contains only three references to the steam engine.⁶³ If Crafts were right, it fundamentally undermines a central plank of Tony Wrigley's arguments about the role of steam engines in escaping from Malthusian constraints during the Industrial Revolution.⁶⁴ In what follows I argue that Crafts fundamentally underestimated the critical importance of the steam engine during the Industrial Revolution.

Joel Mokyr has also dismissed the impact of the steam engine before 1830:

It is important to stress, however, that during the classic years of the Industrial Revolution the immediate impact of steam power on industry and productivity was fairly limited. Much of what steam did before 1830 could have been (and to a large extent was) readily carried out by alternative sources of inanimate power, especially water power.⁶⁵

Again, I will argue this is entirely mistaken.

IV

The omissions in the Factory Returns

Crafts adopted the then widely accepted view that, despite some omissions in the Factory Returns, John Kanefsky's work provided a fairly full account of installed stationary steam horse-power in the

⁵⁹ Flinn, *Coal*, p. 113; Kitsikopoulos, *Economic*, pp. 55-7.

⁶⁰ Bruland and Smith, 'Assessing', p. 1722.

⁶¹ *Ibid*, p.1722.

⁶² Crafts, 'Steam.'

⁶³ Crafts, *British economic growth*, p. 193. One of these references is to a discussion which is not present on the page on question. The length of the other two discussions is one paragraph and one sentence.

⁶⁴ Wrigley, *Continuity*, pp. ;Wrigley, *Energy*, p. 44.

⁶⁵ Mokyr, *Enlightened*, p. 125.

nineteenth century.⁶⁶ As a result of fundamentally important recent work published in the *Economic History Review* by Seam Bottomley we now know this assessment is seriously wide of the mark.⁶⁷ In a case study of Suffolk, based on a wide variety of sources, Bottomley created a 'census' of steam engines between 1800 and 1870. This showed that the figures derived from the Factory Returns under-counted steam power by the remarkable factor of almost two-thirds.⁶⁸ Whilst this is only data for one county, it is clear that the Factory Returns must substantially undercount stationary steam engines nationally by a very substantial margin.⁶⁹ Bottomley estimates, conservatively, that the Factory Returns generate estimates of installed stationary steam power in the UK as a whole in 1870 that are only 60 percent of the real total. For manufacturing his estimate is less than 50 percent.⁷⁰ As Bottomley makes clear it was always inevitable that the Factory Returns would understate the installed stationary steam horse-power because the returns did not cover all establishments using steam engines and were never intended to. In particular prior to 1860 they only covered textile mills and the intended coverage, though broader, was still incomplete in 1870.⁷¹ Moreover, as Bottomley documents for Suffolk, even in 1870, the Factory Returns failed to report on many establishments they were meant to cover.⁷² Finally, he shows, again with respect to Suffolk, that the Factory Returns were internally inconsistent.⁷³

Crafts argued that on Kanefsky's figures, installed stationary steam horse-power did not come to equal water power until 1830. The implication of Bottomley's findings is that this equality was reached significantly earlier. Kanefsky himself had noted that it was possible that installed steam power came to exceed water at an earlier date.⁷⁴

Again, based on Kanefsky's data, Crafts argued that as late as 1870, 'almost half of all steam power was used in mining and in cotton textiles while important sectors in the economy including agriculture and services (apart from transport) were virtually untouched by steam.'⁷⁵ As discussed further below, the claim about agriculture is at variance with compelling evidence in a long-standing literature. In sharp contrast to Crafts, Bottomley estimates, on the basis of the Suffolk evidence, that there might have been as much as 560,000 horse-power in steam engines in agriculture by 1870 including portable steam engines used for threshing.⁷⁶

V

Crafts' use of the social savings methodology and its limitations

As noted above, Crafts used the social savings methodology to measure the importance of the steam engine to the British economy. Crafts' paper was the first to attempt to measure the steam engine's

⁶⁶ Crafts, 'Steam', p. 341; Kanefsky, 'Motive power.'

⁶⁷ Bottomley, 'Steam.'

⁶⁸ *Ibid*, p. 836.

⁶⁹ One knock on consequence of this is the implication that Kanefsky's estimates of the growth of stationary steam power between 1870 and 1907, when the first census of production was undertaken, which Kanefsky put at a 3.9 fold growth is almost certainly far too large: Kanefsky, 'Diffusion', p.345. Unlike the earlier Factory Returns, the 1907 census of production was intended to be a complete census of steam engines employed in manufacturing: *Ibid*, p. 343. Kanefsky himself noted the possibility that the comparison between 1870 and 1907 might not be accurate: *Ibid*, p. 343. The returns do not include portable steam engines such as were used for threshing machines and more important do not record steam engines installed in trains and ships.

⁷⁰ Bottomley, 'Steam', p. 845.

⁷¹ *Ibid*, p 829.

⁷² *Ibid*, p. 830.

⁷³ *Ibid*, pp. 830-831.

⁷⁴ Kanefsky, 'Diffusion', p. 337.

⁷⁵ Crafts, Steam, pp. 341-342.

⁷⁶ Bottomley, 'Steam', p. 840.

contribution to economic growth.⁷⁷ Crafts calculated that the annual contribution of steam power to labour productivity growth was: 0.2 percent for 1760-180, 0.02 percent for 1800-1830, 0.3 percent for 1830 to 1850, 1.2 percent for 1850-1870, and 1.8 percent for 1870-1910.⁷⁸ These figures are the basis of Crafts' claim that the steam engine made only a very minor contribution to the Industrial Revolution. An obvious problem, which neither von Tunzelmann or Crafts addressed, is how to explain, on Kanefsky's figures, the increase in installed stationary steam power from 30,000 hp in 1800 to a 165,000 hp in 1830.⁷⁹

Charles Hyde, in a generally favourable review of von Tunzelmann's book published in the *Journal of Economic History* suggested that the social savings exercise was pointless because it did 'not take into account structural changes that steam power may have produced in the British economy in the second half of the eighteenth century, like the *relocation and concentration of industry in a few urban centres* or the rise of the factory system itself.'⁸⁰ He went on to suggest that if von Tunzelmann were right it would be very difficult to explain the irrationality of British entrepreneurs in installing so many steam engines before 1800.⁸¹ These points are unarguable.

Bottomley discusses the use of the social savings methodology to quantify the importance of the steam engine to the economy as a whole. He argues out that the methodology assumes that other sources of energy could be substituted for steam power albeit at somewhat higher costs and that it is this assumption that drives the erroneous result that steam engines made only a modest contribution to the Industrial Revolution.⁸² This is a fair criticism of von Tunzelmann, but isn't quite right for Crafts. Whereas von Tunzelmann's calculations of social savings were made by comparing the estimated costs of water power and steam-power, Crafts' calculations were based on how much the cost of steam power fell in each period.⁸³ It is not clear why Crafts' proceeded on this basis since it means he was not in fact measuring the contribution of the steam engine to the economy as he claimed but the contribution of changes in the efficiency of the steam engine over time. This is not to suggest that if he had used the price of water power as his comparator it would have significantly altered his findings.

Bottomley concludes the discussion, based on compelling evidence, by suggesting that:

the improvements in urban mortality seen in the second half of the nineteenth century could not have been fully realized without steam powered water supply and sanitation. Similarly, industrial concentration and the agglomeration economies this entailed could not have been achieved without steam. If this applies to a relative backwater such as Ipswich, then it would certainly apply to Manchester or London.⁸⁴

This provides a further example of the importance of the steam engine's locational advantages discussed above. This does hit home with both Crafts and von Tunzelmann not least because here Bottomley is identifying something of crucial importance, which is not captured by TFP, labour productivity or GDP and which could not have been effected without steam power. Most of the evidence on this point provided by Bottomley comes from the period where Crafts argued steam

⁷⁷ Crafts, 'Steam', p. 338.

⁷⁸ Crafts. 'Steam', p. 344.

⁷⁹ *Ibid*, p. 342.

⁸⁰ Hyde, 'Steam power', p. 1057.

⁸¹ *Ibid*, p. 1058. My italics.

⁸² Bottomley, 'Steam', p. 841.

⁸³ Crafts, 'Steam', p. 345.

⁸⁴ *Ibid*, p 846.

power had finally become economically significant or shortly before that.⁸⁵ However, there is evidence of much earlier usage for water supply. J.R. Harris pointed to the use of steam engines for pumping water at water works as early as the 1760s.⁸⁶ The Kanefsky dataset identifies the first such engine as early as 1714 and records 34 during the eighteenth century. Twenty-four of these engines, or 71 percent of the total were urban. As early as 1805 there were ten steam engines installed in waterworks in London.⁸⁷

One obvious problem with the social savings methodology as applied by both von Tunzelmann and by Crafts is that if the logic is accepted then as Hyde suggested, it makes it very difficult to explain the widespread diffusion of steam engines before the middle of the nineteenth century and implies economic irrationality on a large scale. The obvious explanation is that steam engines were adopted because of other economic advantages. Harris suggested that 'the simplest and best guide to the importance of steam is how often industrialists called for its aid.'⁸⁸ Neither von Tunzelmann nor Crafts actually cite any historian suggesting that early steam engines were adopted because they were cheaper than other forms of power and I have not been able to find any examples of such a claim.

VI

The crucial importance of steam power in coal mining

Coal mines tend to fill with water unless measures are taken to remove it.⁸⁹ In the seventeenth century there were four methods of pumping water out of mines. First, it could be drained directly to the surface by means of a sloping tunnel called an adit or sough from the bottom of the mine.⁹⁰ However, this technology could only be deployed where the lowest part of the pit was higher than some nearby location on the surface. It was thus of little use in deeper mines or outside hilly parts of the country. Second, it could be pumped out by wind power. But wind power's availability was erratic which was far from satisfactory in this context.⁹¹ Third, water power could be used to pump water out of mines. This was much more widely used than wind-power. However, this depended on 'the availability of an adequate flow of water at the requisite elevation and sufficiently close to the pit-head to be brought in easily by a leet' and, crucially, this requirement was not satisfied 'in many if, not most mining situations.'⁹² The fourth, and probably the most common method, was to use horses turning gins to raise large buckets singly or chains of buckets on ropes.⁹³ As the depth of mines or their horizontal extent increased, the weight of buckets full of water would rise in proportion to the depth eventually reach the point where neither horses nor water power were capable of lifting the weight. Mines of greater areal extent would also increase the weight to be lifted.⁹⁴

Michael Flinn, the leading authority on the eighteenth-century coal industry, suggested that 'by the end of the seventeenth century most fruitful [surface] outcrops of coal had been discovered and

⁸⁵ *Ibid*, pp. 842-846.

⁸⁶ Harris, 'Employment', p.143.

⁸⁷ Musson, 'Motive power', p. 426.

⁸⁸ Harris, 'Employment', p. 148.

⁸⁹ Flinn, *Coal industry*, p. 109.

⁹⁰ *Ibid*, pp. 110-11.

⁹¹ *Ibid*, p. 112.

⁹² *Ibid*, p. 112.

⁹³ *Ibid*, p. 113.

⁹⁴ I am grateful to John Kanefsky for this point.

worked into the seam as far as drainage and haulage technology would allow.⁹⁵ He concludes his summary of the four drainage technologies then available by stating that these were:

capable of only a very modest contribution to the drainage of mines. If drainage technology were to stand still at the point reached at the beginning of the eighteenth century, mining in Britain could scarcely have expanded and must probably have begun to show diminishing returns. At depths of between *ninety and 150 feet* the influx of water almost invariably created problems *insuperable* by the technology of the day, so that when seams of lesser depths were exhausted *mining must cease*. Most British coal-reserves, of course, lay at greater depths. *There was a future for [coal] mining in Britain only if some more efficient drainage techniques became available.*⁹⁶

The solution to the problem of draining deeper mines, and hence expanding production, was, of course, Thomas Newcomen's development of a successful atmospheric steam engine, the first of which, to the best of our knowledge, was probably built at a tin mine in Cornwall in 1710.⁹⁷ The earlier invention of a vacuum pump by Thomas Savery, patented in 1698, was of limited practical use for mine drainage because it could not pump water to a height of more than 32 feet.⁹⁸ Seventy-eight Newcomen engines had been installed in coalmines by the time Savery's patent expired in 1733.⁹⁹ By 1775, the year before the first installation of a Boulton and Watt engine, 321 engines are known to have been installed.¹⁰⁰ Flinn suggested that by the 1770s steam-pumping was a virtually ubiquitous feature of 'all but the smallest and shallowest of British coal mines.'¹⁰¹ John Kanefsky and John Robey identified 828 steam engines installed at coal mines by 1800 and estimated the true figure at between 950 and 1,000, some two-thirds of all steam engines installed in the course of the eighteenth century.¹⁰²

By the mid-eighteenth-century coal mines of up to 250 feet deep were present in Scotland, Yorkshire, South Wales, Derbyshire, Lancashire and Staffordshire. In three coalfields: Cumberland, Somerset and the North-East mines were much deeper and in 1739 one Whitehaven pit, said to be the deepest in England, was reported to be 630 feet deep. By the early 1800s pits in the North-East were as much as 800 feet deep and in 1828 the average depth of North-eastern pits of known depth was 543 feet with a range from 120 feet to 1,080.¹⁰³ Flinn concludes that by the early nineteenth century deep mines produced the 'overwhelming proportion of coal mined. It is clear that the large-scale adoption of steam engines for pumping water out of mines instead of water during the Industrial was not driven primarily by any cost advantage over water. The crucial factor was that the Newcomen engine could drain deeper mines. However, costs probably played a role too. Most pre-steam drainage was probably undertaken by horses not by water power.'¹⁰⁴ Steam engine costs compared favourably with horsepower from an early date. Haris Kitsikopoulos cites evidence from a Tyneside steam engine in 1780 to the effect that the cost of steam per horsepower generated was 75 percent that of horses for small engines and only 25-30 percent for large engines.¹⁰⁵

⁹⁵ Flinn, *Coal industry*, p. 68.

⁹⁶ *Ibid*, p. 114, my italics. This emerging problem is also acknowledged in Nuvolari et al, 'Diffusion', p. 293.

⁹⁷ Bogart et al, 'Kanefsky dataset.'

⁹⁸ Flinn, *Coal*, pp. 114-5. They were useful for pumping water back up the hill above a watermill where water supply was inadequate, *Ibid* p. 115.

⁹⁹ Newcomen's engine was covered by Savery's patent.

¹⁰⁰ Bogart et al, 'Kanefsky dataset.'

¹⁰¹ Flinn, *Coal industry*, pp. 121-122.

¹⁰² *Ibid*, pp. 127.

¹⁰³ *Ibid*, pp. 78-9.

¹⁰⁴ *Ibid*, p. 113.

¹⁰⁵ Kitsikopoulos, *Economic*, pp. 55-7; Tann, 'Steam engine' pp. 157-60.

By the late eighteenth century the great majority of collieries had adopted steam pumping.¹⁰⁶ Collieries often consisted of clusters of pits which were either shafts or shallow open-cast workings. In the late eighteenth century the great majority of collieries, but not pits, had an installed steam engine. One engine could drain multiple shafts. Shallow pits may or may not have required steam drainage. The dominance of steam pumping is clear on every coal field except the Forest of Dean and the southern edge of the Glamorgan coalfield. Collieries and pits were identified from a number of sources. The main source was county maps 1770-1800. Further collieries were identified from the National Mines Research Group database and John Farey's published list of mines from 1810. Steam engines were identified from the county maps. For England and Wales this exercise identified a total of 550 collieries, 2997 pits and 1,166 steam engines. That the great majority of collieries adopted steam drainage suggests there were overwhelming advantages to doing so.

No-one has done more than Tony Wrigley to document that the massive expansion of coal was necessary both for the success of the Industrial Revolution and for the escape from Malthusian constraints.¹⁰⁷ The output of the British coal industry rose from an estimated, 2.6m tons in 1700-09 to 15m tons in 1800-09 and 74m tons in 1850-9.¹⁰⁸ This spectacular growth was very largely dependent on the steam engine for which there was no substitute. By 1800-09 coal consumption in Britain was 22 times larger than firewood consumption and 79 percent of all the energy (including human and animal muscle power) came from coal.¹⁰⁹ Wrigley estimates that by 1800 to replace coal with wood in England would have required around 11m acres of woodland, something over one-third of the entire surface area of the country.¹¹⁰ To take so much land out of agricultural production would have provoked a Malthusian crisis. Industrial dependence on coal was overwhelming and without the expansion of the coal industry during the eighteenth century the Industrial Revolution would have been stopped in its tracks.¹¹¹

VII

The relationship between urbanisation and modern economic growth

Urbanisation in nineteenth century Britain was spectacular and the period saw the emergence of the first urban society in human history. This involved a radical spatial restructuring of the economy, not least the increasing share of industrial employment in towns. In England and Wales, the percentage of the population living in settlements of 2,500 or more inhabitants increased from 34 per cent to 54 per cent between 1801 and 1851 and by 1911 had reached 79 percent.¹¹²

Table one shows the urbanisation rate of England excluding Monmouthshire from 1700-1851 using a higher population threshold of 5,000 to identify urban settlements in the third column. The fourth column indicates the decadal increases. As can be seen urbanisation proceeded much more rapidly in the early nineteenth century than in the eighteenth century.

¹⁰⁶ I am grateful to Alan Rosevear for undertaking the work summarised in this paragraph.

¹⁰⁷ Wrigley, *Continuity*; Idem, *Energy*; idem, *Sustained growth*. The view that the pre-industrial economy was Malthusian has been challenged recently. For a review of this literature, the argument that the pre-industrial economy was indeed Malthusian, and the misconceptions underlying the contrary view, see Shaw-Taylor, 'Escape.'

¹⁰⁸ Wrigley, *Energy*, p. 37. The figures in the rest of this paragraph derive ultimately from Warde, *Energy*.

¹⁰⁹ *Ibid*, p. 35.

¹¹⁰ *Ibid*, p. 36.

¹¹¹ *Ibid*, pp. 40-41.

¹¹² Law, 'Growth', p.150.

It should be noted that this level of urbanisation was only possible because of profound improvements in urban mortality in the period 1750-1820.¹¹³ Astonishingly, the vast secondary literature on towns and on urbanisation does not contain a single serious attempt to *explain* nineteenth century urbanisation though the importance of anterior rises in labour productivity in agriculture has often been noted as a necessary pre-condition.¹¹⁴

Table 1

The urbanisation rate of England excluding Monmouthshire 1700-1851 using a threshold of 5,000

		%	%
1700	850,000	17.0	
1750	1,125,000	21.0	0.8
1801	2,432,591	29.5	1.7
1811	3,047,215	32.1	2.6
1821	3,835,969	34.2	2.1
1831	4,933,917	38.0	3.7
1841	5,946,865	40.0	2.0
1851	7,302,030	43.6	3.5
Sources: the urban figures for 1700 and 1750 derive from Wrigley, 'Urban growth' p. 681. The urban figures for 1801-1851 derive from Bennet, 'Urban. The national population figures derive from Shaw-Taylor, 'Population.'			

Simon Kuznets, who pioneered national accounting and invented the term modern economic growth, by which he meant high rates of GDP per capita growth sustained over long periods of time, went so far as to argue that a decline in mortality was 'an indispensable prerequisite for modern economic growth.'¹¹⁵ It is possible to go further and suggest that the escape from the urban graveyard effect, which refers to the situation where the number of deaths in urban areas exceeded the number of births and which prevailed in even very small urban settlements in eighteenth century Britain, and indeed elsewhere, was a precondition for modern economic growth. Without the escape from the urban graveyard phenomenon the spectacular urban growth of the nineteenth century would have been impossible.

Town and cities are characterised by agglomeration effects. Alfred Marshall was the first to identify agglomeration effects. He noted three key benefits: knowledge spillovers, specialised labour pools, and the presence of supporting industries.¹¹⁶ On knowledge spillovers Marshal argued that 'great are

¹¹³ Davenport, 'Mortality'; Shaw-Taylor, 'Infectious diseases.'

¹¹⁴ See for instance: Devine, 'Scotland', p. 161; 'Wrigley, 'Urban'; Wrigley, *Energy*, p. 35; Brunt and Garcia-Penalosa, 'Urbanisation', p. 512.

¹¹⁵ Kuznets, 'Population', p. 136.

¹¹⁶ Marshall, *Principles*, p. 225.

the advantages which people following the same skilled trade get from near neighbourhood to one another. The mysteries of the trade become no mysteries but are as it were, in the air.¹¹⁷ On pools of specialised labour he suggested 'employers are apt to resort to any place where they are likely to find a good choice of workers with the special skill which they require; while men seeking employment naturally go to places where there are many employers who need such skill as theirs and where therefore it is likely to find a good market.'¹¹⁸ On supporting industries he suggested that 'subsidiary trades grow up in the neighbourhood, supplying it with implements and materials, and organizing its traffic, and in many ways conducing to the economy of its material.'¹¹⁹ There can be little doubt that these three agglomeration benefits are real and that they existed during the Industrial Revolution. It is equally clear that none of them were available in rural areas. The modern field of economic geography derives from Marshall's initial insights. Paul Krugman, in an address to the Association of American Geographers in 2010, made the point that without agglomeration effects there would be no urban areas.¹²⁰ There is historiographical evidence of urban agglomeration effects by the early sixteen century.¹²¹ Urban agglomeration effects must have been present even in the Middle Ages or, as Krugman observes, towns would not have existed.

In a 2021 paper in the *Economic Journal*, Liam Brunt and Cecilia Garcia-Penalosa argue 'that agglomeration can cause economic growth through its impact on technological change.'¹²² There is direct evidence on this point. During the Industrial Revolution the vast majority of patentees were urban.¹²³ Christine Macleod found that London's share of national patents in the eighteenth century was twice its share of the national population and that provincial patents were overwhelmingly urban.¹²⁴ She went on to suggest that urbanisation was partly responsible for the increasing number of patents over the eighteenth century.¹²⁵ Not all towns were equally prone to patenting and patenting was dominated by manufacturing towns plus Bristol and Liverpool.¹²⁶ Whilst not all inventions were patented, and not all patents were for inventions of any importance, we can safely infer that invention was overwhelmingly urban.

Brunt and Garcia-Penalosa observe that urbanisation rates in Europe and in Britain in particular before the Industrial Revolution were unusually high and far higher than they were in China.¹²⁷ They go on to develop a model 'consistent with the idea that urbanisation precedes industrialisation.'¹²⁸ They note that there is a very large literature in economic geography which suggests that urbanisation is crucial for modern economic growth.¹²⁹ Vernon Henderson in the *Handbook of Economic Growth*, provides a survey of the relationship between urbanisation and economic growth.¹³⁰ At the beginning of the survey Henderson notes that 'in growth theory, endogenous growth is based on knowledge spillovers

¹¹⁷ *Ibid*, p 225.

¹¹⁸ *Ibid*, p. 225.

¹¹⁹ *Ibid*, p.225.

¹²⁰ Krugman, 'New economic geography', p. 1. For the pioneering explanation, based on the competing influences of urban disamenities and agglomeration effects, see Henderson, 'Sizes and types.'

¹²¹ Cesaretti et al, 'Increasing returns.'

¹²² Brunt and Garcia-Penalosa, 'Urbanisation', p. 512.

¹²³ Macleod and Nuovalari, 'Patents', p. 12.

¹²⁴ MacLeod, *Inventing*, pp. 118, 125, 128.

¹²⁵ *Ibid*, p. 125.

¹²⁶ *Ibid*, p. 128.

¹²⁷ Brunt and Garcia-Penalosa, 'Urbanisation', p. 512-513.

¹²⁸ *Ibid*, p. 514.

¹²⁹ *Ibid*.

¹³⁰ Henderson, 'Urbanisation.'

and sharing, and evidence suggests that much of that interaction must occur at the level of individual cities.¹³¹ Henderson's view is that urbanisation is a necessary but not sufficient condition for growth.¹³²

As is well known as a result of pioneering work by Crafts and Knick Harley in the 1980s it is now generally accepted that Britain achieved the world's first transition to modern economic growth in the second quarter of the nineteenth century.¹³³ This occurred during a period of historically unprecedented urbanisation which entailed a very large-scale relocation of industry from the countryside to the towns. I will now turn to consider the role of the steam engine in driving urbanisation during the Industrial Revolution.

IIX

The rotative steam engine as a driver of urbanisation

Much of the textile industry had been in rural areas since the late medieval period. The extent to which this was driven by the need for water power for fulling mills has been a subject of dispute.¹³⁴ Prior to the development of rotative steam engines, patented in 1781 by James Watt, virtually all textile mills were essentially water powered.¹³⁵ In the great majority of cases this necessitated a rural, and not infrequently, remote location.¹³⁶ Agglomeration benefits would not have been available. In particular, this posed problems for labour supply.¹³⁷ Katriona Honeyman argued that it was this locational drawback which was largely responsible for the widespread use of child pauper apprentices, mostly recruited from urban areas, in early textile mills.¹³⁸ The first steam powered mill was a cotton mill at Papplewick, a village, near Nottingham, built in 1785.¹³⁹ There is a very long-standing claim in the literature that the rotative engine allowed the textile industry to shift over time from rural locations, where it was located by the need for water power for mills, to a predominantly urban location.¹⁴⁰ This is a testable proposition. To identify which of the stationary engines in the Kanefsky dataset were urban and which rural it was necessary to combine a GIS (Geographical Information System) version of the Kanefsky dataset with a GIS of actual urban areas. The urban areas were derived from cartographic sources created or published between 1790 and 1830.¹⁴¹ That means there may be some misidentification of urban engines especially earlier in the eighteenth century when the towns may have been smaller. However, any such misidentified engines would have been on the fringes of an urban area. The Kanefsky dataset includes 781 stationary steam engines installed before 1781. Of these 526, or 67 per cent of the total were rural (defined as more than two hundred meters from one

¹³¹ *Ibid*, pp. 1544, 1546.

¹³² *Ibid* 'Urbanisation', p. 1160 and personal communication.

¹³³ Crafts, *British economic growth*; Crafts and Harley, 'Output growth.'

¹³⁴ Carus-Wilson, 'Industrial Revolution.' Carus-Wilson's original argument that the textile industry relocated to rural areas in search of waterpower for fulling mills has been criticised by John Munro and Adam Lucas and others, but it remains clear that much of the late medieval textile industry was rural.

¹³⁵ Some Newcomen engines were used to pump water back up the hill in locations suffering from inadequate water supply. Note that Kanefsky dataset records seven pre-1781 rotative engines. These must have used the (patented) crank not the sun and planets mechanism patented by Watt.

¹³⁶ Hills, *Power*, p. 6; Gordon 'Water', p. 242.

¹³⁷ Pollard, *Genesis*, pp. 171-172.

¹³⁸ Honeyman, Child workers, FIND PAGE REFERENCES.

¹³⁹ Tann, 'Steam power', p. 249.

¹⁴⁰ Ashton, *Industrial Revolution*; Toynbee, *Industrial Revolution*; Mokyr, *Lever of riches*; Crafts and Harley, 'Output growth'; Allen, 'Industrial Revolution'; Wrigley, *Energy*; Wrigley, *Sustained growth*. This list is far from exhaustive.

¹⁴¹ The dataset is Litvine et al (BUA). For a description of this dataset and its construction see: Litvine et al, 'Built-up areas.'

of the urban areas). Of these early rural engines 442 or 84 percent of the total were pumping engines, nearly all of which were pumping water out of mines. Only 32 per cent of the pre 1781 engines were urban. The dataset contains 489 rotative engines installed between 1781 and the end of the eighteenth century.¹⁴² Of these 270, 56 percent of the total, were in urban areas or within 200 metres of the urban footprint dataset, i.e. on the edge of an urban area.

There were 169 rotative steam engines installed from 1781-1800 in textile works of one kind or another. This is 34 percent of the total rotative steam engines installed and 109 of the textile engines, 66 percent of the total were installed in an urban area or on their outskirts. The online notes describing the Kanefsky dataset note that 'the biggest gap in all these information points is the huge number of small engines erected in textile and other factories from the late 1780s onwards.'¹⁴³ Since two-thirds of the textile engines we know about were urban in 1800 it is likely that most of the missing engines were urban too. It follows from this that the overall proportion of eighteenth century rotative engines that were installed in urban areas may have been considerably higher than the 56 percent suggested above.

A.E. Musson in a 1976 article that was generally concerned to stress the ongoing importance of animals, wind mills and water mills for motive power in industry in the early nineteenth century, reported that 'in the Manchester area, for example, there were only two spinning-mills in the early 1780s, but there were 52 by 1802, 64 by 1809, and 99 by 1830, nearly all of them driven by steam engines' and that there 'were very few water powered factories in towns such as Manchester, Salford, and Bolton by the 1830's'.¹⁴⁴ This is clear evidence of the crucial role of steam engines in the urbanisation of textile mills. Musson went on to cite the 1838 factory returns to the effect that 'in the textile industry there were 3,053 steam engines with a total of 74,084 horse-power in U.K. textile factories, mostly for spinning; but there were still 2,230 water-wheels, with a total of 27,989 h.p.'¹⁴⁵ So, by the 1830s, well before steam power had become generally competitive on cost per horsepower generated, steam was supplying three-quarters of all motive power in the textile industry and the average steam engine employed was supplying twice as much energy as the average water mill. This clearly implies that at this date the locational advantages of steam engines in the textile industry were overwhelming. The locational advantages can only have been the agglomeration effects.

The rotative steam engines were not restricted to the textile industry. There were 67 rotative steam engines installed in the metal industries, predominantly iron works, in the period, some 14 percent of the total. Of these 49 or 73 percent of the total were either in urban areas or on their outskirts. Thirty-one rotative steam engines, some six percent of the total, were installed for milling grain in this period. Of these 20 or 60 percent of the total were in urban areas or their outskirts. Thus, the steam-driven urbanisation of industry was not restricted to the textile industry.

The rotative steam engine was clearly driving a shift of industry into urban areas from 1785. Over the course of the nineteenth century the share of steam engines that were urban must have increased massively. A strong claim can be made that the stationary rotative steam engine was a centrally

¹⁴² Bogart et al, 'Kanefsky.' I am very grateful to Alan Rosevear for undertaking the GIS work necessary to distinguish urban from rural locations: The relationship between stationary steam engines and nineteenth century urbanisation will be explored much more thoroughly in Bottomley et al, 'Rotative steam engines.' I have excluded a number of earlier Newcomen rotative engines and a number of others predating 1781 whose type is not clear.

¹⁴³ <https://industrial-archaeology.org/EarlyEngines/history.php> Accessed on 31.3.2026.

¹⁴⁴ Musson, 'Motive power', pp. 417, 420.

¹⁴⁵ *Ibid.*

important causal factor in urbanisation in the nineteenth century and possibly as early as the mid-1780s. This claim is not new but has never been more than a passing suggestion and has not been subject to any rigorous empirical testing.¹⁴⁶ However, no-one has ever argued against this claim, or proposed another reason for industry to become increasingly urban and it is reasonable to accept the proposition even though we cannot yet quantify it.¹⁴⁷ The hypothesis advanced here is that the diffusion of the rotative steam engine was the primary reason why the speed of urbanisation in the nineteenth century was so much higher than in the eighteenth century.

Moreover, it is clear from recent work that steam powered railways also played a very major role in nineteenth century urbanisation in the second half of the nineteenth century and they may well have played a significant role in the 1830s and 1840s.¹⁴⁸ It is likely that the main channels through which railways effected urbanisation was by lowering the price of coal at locations distant from the coalfields leading to major increases in the use of steam power in these locations. Railways were discussed by Crafts in a single paragraph with no attempt to estimate their contribution to the growth of GDP.¹⁴⁹ This is surprising given the rapid spread of railways in the second half of the nineteenth century, was temporally coincident with the initial achievement of modern economic growth by Crafts and Harley.

Alan Rosevear and the present writer have shown that the rotative steam engine played a critical role in the explosive growth of Manchester from around 1795 as the cotton spinning industry shifted from rural areas into Manchester.¹⁵⁰ The only explanation for this shift is that entrepreneurs shifted into Manchester because of the perceived agglomeration effects.

The steam engine thus appears to be a crucial determinant of urbanisation during the Industrial Revolution and there are reasons for suspecting that this role dates back to the mid-1780s. Since there are grounds for thinking that urbanisation contributed directly to economic growth a strong claim can be made for the proposition that the emergence of modern economic growth in the second quarter of the nineteenth century was heavily dependent on the rotative steam engine.

X

The importance of steam engines in iron manufacturing, shipping and agriculture

Neither Crafts nor von Tunzelmann discussed the use of steam engines in the iron industry. The use of steam engines to power bellows in blast furnaces producing iron in the late eighteenth century allowed a stronger blast which led to a reduction in the cost of iron and allowed an increase in the scale of production. Firstly, steam engines reduced downtimes which could previously last for months and result in keeping expensive capital equal idle. Second, steam engines provided a stronger blast which produced a higher annual output. Third, by freeing blast furnaces from the locational constraints of riparian locations, steam power allowed blast furnaces to be sited where there were deposits of both coal and iron. This reduced transport costs.¹⁵¹

¹⁴⁶ For instance, see: Toynbee, *Industrial Revolution*, Ashton, *Industrial Revolution*; Devine, 'Scotland'; Ellis, 'Regional.'

¹⁴⁷ Bottomley et al, 'Role', in progress.

¹⁴⁸ Bogart et al, 'Railways.'

¹⁴⁹ Crafts, 'Steam', p. 343.

¹⁵⁰ Rosevear and Shaw-Taylor, 'Urbanisation.'

¹⁵¹ For all these points see Tylecote, *History*. CHECK. See also, Harris, 'Iron', p.35

Crafts suggested that the triumph of steam shipping over sailing ships was not achieved until the 1880s. It is true that the registered tonnage of steam ships did not come to exceed sailing ships until 1883.¹⁵² However, this neglects a number of important earlier developments. First, steam tugs became important as early as the 1820s, for getting sailing ships out of harbour. Before that sailing ships often had to wait for days and sometimes weeks to get out of harbours. As a result of the spread of steam tugs the number of journeys a sailing ship could make in a year increased. Faster journeys reduced labour costs per voyage. The amount of dock labour required was also reduced.¹⁵³ Second, steam ships came to exceed sailing ships in speed in the 1850s and 1860s. Hence steam ships could make more journeys in a year than sailing ships. It therefore follows that the amount of freight moved by steam ships probably came to exceed that moved by sail some time significantly before 1883 and that the productivity of shipping increased at an earlier date than Crafts suggested. Crafts cites von Tunzelmann to argue that the price of steam power did not fall between 1800 and 1830.¹⁵⁴

Crafts argued that as late as 1870 steam power had virtually no impact on agriculture.¹⁵⁵ Early threshing machines were mostly powered by horses, but some were powered by water.¹⁵⁶ Some farms continued to use water powered threshing machines after the development of steam powered threshing machines. However, on the great majority of farms there would have been no available source of water. Thus, the only available power source for mechanized threshing was steam. While the first steam powered threshing machine in England was installed in Northumberland in 1783, the more general diffusion of the machines began in the 1840s following the invention of the portable steam powered threshing machine.¹⁵⁷ Ransomes, the famous agricultural engineering company, built the first portable steam threshing machine in 1841 and by 1849 there were at least 12 manufacturers of portable steam powered threshing machines.¹⁵⁸ By 1880 steam powered threshing had almost entirely replaced hand threshing in lowland Britain.¹⁵⁹ According to Ted Collins at this date, 'steam power predominated in southern, midland and eastern England, south Wales and the large-farm districts of south-east Scotland and north-west England.'¹⁶⁰ By 1850 horse-operated threshing machines were associated with a five-fold increase in labour productivity.¹⁶¹ The productivity gain for steam powered machines must have been considerably larger or they would not have been adopted on such a large scale given the significantly higher capital costs involved.¹⁶² Threshing machines also yielded ten percent more grain than threshing by hand which means they made a significant contribution to the productivity of arable agriculture.¹⁶³ Portable threshing machines also allowed threshing in the fields thus saving the labour and expense entailed in carting the stalks and husks to the barn.¹⁶⁴ So, not only was steam threshing very widespread on farms by the third quarter of the nineteenth century but it made a significant contribution to raising both land and labour productivity in agriculture. Most farms would have had no source of running water so the general diffusion of steam powered threshing machines from the 1840s was very largely dependent on the use of steam power.

¹⁵² Mitchell, *Historical statistics*, p. 536.

¹⁵³ Jackson, *Ports*, pp.?

¹⁵⁴ Crafts, 'Steam', p. 343.

¹⁵⁵ Crafts, 'Steam', pp. 341-342.

¹⁵⁶ McDonald, 'Early threshing machine', p.65.

¹⁵⁷ Collins, 'Diffusion', pp. 16, 19; Agnew, 'Evolution of the threshing machine', p. 153.

¹⁵⁸ Collins, 'Diffusion', p. 19; McDonald, 'Early threshing machine', p.76

¹⁵⁹ Collins, 'Diffusion', p. 20.

¹⁶⁰ *Ibid*, p. 20.

¹⁶¹ *Ibid*, p. 20.

¹⁶² *Ibid*, p. 25.

¹⁶³ *Ibid*, p. 28.

¹⁶⁴ *Ibid*, p. 29.

Another important contribution of the steam engine to agriculture was the drainage of the fens and the consequent large-scale conversion to arable. The fens covered 3,900 square miles, about three percent of England but, once drained, a much higher percentage of arable land. There were also other extensive wetlands to which the same considerations apply. Overton suggests that fen drainage may have increased arable land in England by as much as ten percent.¹⁶⁵ The drainage of the fens had begun in earnest in the seventeenth century. Windmills were used to pump water out of the fens. However, this was only partially successful and much of the fens remained vulnerable to flooding. It is not possible to grow grain crops on land that floods seasonally because standing water kills the grain. Thus, the fens remained predominantly pastoral until the nineteenth century despite having some of the best soils in the country for arable agriculture. Steam drainage was introduced between the 1820s and 1870s. This definitively solved the drainage problem. In consequence, there was a wholesale switch from pastoral to arable agriculture.¹⁶⁶

Crafts' claim that in 1870 that agriculture was 'scarcely touched' by steam is, as Bottomley argued, clearly mistaken.¹⁶⁷ If steam drainage made the major contribution to increasing the arable acreage by perhaps as much as 10 percent and steam threshing increased yields by around ten percent then it is possible that by 1870 steam power had raised arable output by perhaps fifteen percent or more.

X

The argument of Clark and Jacks

Clark and Jacks published an article in *The European Review of Economic History* in 2007 in which they argue that both steam engines and coal were unnecessary for the Industrial Revolution.¹⁶⁸ Curiously they discuss neither the arguments of von Tunzelmann nor of Crafts though they do make use of data from the former.

Clark and Jacks assert that 'there was no technological barrier to using horse-powered gins for drainage. The advantage of steam power was purely one of cost.' They go on to cite a single example of a coal mine in 1750 using horse gins for drainage but provide no evidence as to the depth or areal extent of this mine so this proves nothing.¹⁶⁹ Ignoring the passages from Flinn discussed above, and perhaps entirely unaware of it, Clark and Jacks labour under the misapprehension that the key issue was solely one of cost rather than one of technical feasibility. They make comparisons using data from von Tunzelmann's book to suggest that in the early eighteenth-century steam power was only very marginally cheaper than horse gins though by the middle of the nineteenth century the cost of steam power was one third that of horse gins. This exercise is based on assuming that the steam engines used 'best coal' throughout the period i.e. the most expensive coal and costing this accordingly. This assumption obviously pushes the calculations in the direction of the argument they make. However, Newcomen engines used much cheaper coal at pit-head prices.¹⁷⁰ In many perhaps most mines waste coal that could not be sold was used. In other words the fuel was essentially free. It follows that Clark and Jacks seriously overestimate the costs of steam power across the eighteenth and early nineteenth centuries. On this basis, which in any case misses the key benefits of the steam

¹⁶⁵ Overton, *Agricultural revolution*, p.9.

¹⁶⁶ Ash, *Draining*, pp. ??; Overton, *Agricultural revolution*, pp. 89-90. I think Mark gets it wrong and I should drop the citation. Derby, *Draining*. Derby, Changing Fenland.

¹⁶⁷ Crafts, 'Steam', pp. 341-342.

¹⁶⁸ Clark and Jacks, 'Coal.' Surprisingly this article does not reference Crafts' earlier paper downplaying the role of the steam engine.

¹⁶⁹ Clark and Jacks, 'Coal', p. 46.

¹⁷⁰ Inferior coal for Newcomen engines p.124.

engine before the middle of the nineteenth century, they make the mistaken argument that 'the absence of the new steam technology would not have crippled the industry even late into the Industrial Revolution.'¹⁷¹

Clark and Jacks go on to estimate total factor productivity growth in coal mining between 1730 and 1860 at a mere six percent.¹⁷² Leaving aside any issues with the reliability of the calculations, and these are significant, this does nothing to undermine the arguments made by Flinn upon which Wrigley depended. The key point about Flinn's argument about that the steam engine is not that it raised productivity but that allowed an enormous increase in output without prices rising very substantially. Neither Flinn nor Wrigley claimed that steam engines led to large declines in the price of coal.

Crafts and Jacks then go on to question whether coal was in fact of any importance to the Industrial Revolution.¹⁷³ They posit a world in which Britain imported all its coal from elsewhere.¹⁷⁴ They build this imaginary world on the basis of three very problematic assumptions. First, they do not consider whether steam engines might have been necessary for drainage for the massive expansion of European coal output that would have been necessary, as it almost certainly would have been. Second, they assume that the imaginary coal from these European coalfields could have produced coal at Newcastle prices, but no evidence is provided. Third, they make the specious assumption that the transport costs of importing coal would have been the same as the transport costs of shipping coal from London to Newcastle.¹⁷⁵ If this were correct along much of the south-coast of England, all coal would have come from European coalfields, since it was obviously more expensive to ship coal from Newcastle to the south coast than it was to ship coal from Newcastle to London. This was not the case. We can safely assume that the cost of imported coal would have been very much higher than Clark and Jacks imagine.

On the basis of these implausible assumptions Clark and Jacks estimate that the extra cost of imported coal between 1740 and 1869 would have been only 3.9 percent of GDP. They therefore conclude that the absence of coal deposits in Britain would not have fundamentally changed the course of the Industrial Revolution.¹⁷⁶ There is a fourth problem here, common to much counterfactual history not least Robert Fogel's work on the importance of railways to nineteenth century economic growth.¹⁷⁷ It is simply assumed that the output of coal-using industries would have continued at the same levels in the face of increased costs. This is unrealistic. The increased costs faced by individual producers making heavy use of energy would have been very much larger than 3.9 percent, even if that were the correct figure for the reduction in GDP attributable to the increased cost of fuel, and it is therefore likely that much productive activity would in fact have been quite significantly lower and that the counterfactual consequences for GDP would have been very substantially larger. As is well known virtually all heat-using industries, as well as nearly all industries

¹⁷¹ Clark and Jacks, 'Coal', p. 46.

¹⁷² *Ibid*, 'Coal', p. 62.

¹⁷³ Clark and Jacks, 'Coal', p. 63. There have been other claims in the literature that coal was not important to the Industrial Revolution. For reasons of space these will be addressed elsewhere.

¹⁷⁴ *Ibid*, 'Coal', p. 64-5.

¹⁷⁵ *Ibid*, 'Coal', p.65.

¹⁷⁶ Clark and Jacks, 'Coal', p. 65.

¹⁷⁷ Fogel assumed that in the face of increased transport costs farmers in the United States would have continued to produce and sell the same amount of grain as they in fact did. This is clearly an unrealistic assumption: Fogel, *Railways*. More recent econometric work has shown that without railways the value of agricultural land in the United States would have been 60 percent lower. This makes it clear that Fogel's counterfactual estimates were fundamentally unrealistic: Donaldson and Hornbeck, 'Railroads.'

using steam engines for driving machinery, were located on the coalfields during the Industrial Revolution, precisely because it was not economic to produce elsewhere.

In the paragraph succeeding this calculation they acknowledge that heat using industries such as glass and iron might have been significantly smaller in the absence of coal. However, they then argue that 'even if England had not developed a substantial iron industry in the Industrial Revolution era, the productivity gains from iron working were again a minor contributor to the Industrial Revolution.' This is a surprising claim. It overlooks a number of crucial facts. First, on Crafts' estimates, the iron industry accounted for just under 7 percent of value added in industry throughout the Industrial Revolution.¹⁷⁸ According to Broadberry et al industry accounted for 32 percent of GDP by 1851. Without the growth of the iron industry, GDP could have been two percent lower. Second, the iron industry supplied crucial inputs to other industries not least railways, which required many millions of tons of iron, and iron beams necessary for building fire-resistant textile mills.¹⁷⁹ Third, from the 1740s, as a result of the invention of crucible steel by Benjamin Huntsman, Britain was able to produce steel of much higher quality than anywhere else in the world.¹⁸⁰ This was suitable for watch springs ... high quality edge tools, dies, hammers and small pairs of rolls.¹⁸¹ Harris suggests that high quality cutting surfaces were 'essential to the growing engineering industry of the late eighteenth and early nineteenth century' and goes on to note that the contribution of good quality steel tools to the Industrial Revolution has been overlooked.¹⁸² Fourth, they fail to mention a whole series of other heat using industries: lime-burning, brewing, malting, brick making, tile-making, chemicals, glass, pottery, lead, copper, tin, gun-powder, starch, sugar, railways, steam shipping all of which were entirely dependent on coal and all of which would have been much smaller without coal. Fifth, they ignore the enormous consumption of coal used for domestic heating and the much higher heating bills that would have been incurred in its absence, not to mention much colder homes.¹⁸³ Sixth, they ignore entirely the agglomeration effects that resulted from industrial concentrations which were in turn driven by the need for coal and from the late eighteenth century by the spread of rotative steam engines. Both Daniel Defoe and Adam Smith identified coal as a crucial locational factor in the concentration of the textile industry in the north-west of England.¹⁸⁴

Clark and Jacks go on to suggest that because fuel was only a minor cost in the textile industry coal cannot have been very important.¹⁸⁵ It is no doubt true that fuel costs were modest but cotton mills were almost universally located on coal fields where fuel was cheap. If the cost of fuel was not important it is very puzzling that the industry was almost exclusively located on coal fields by the late eighteenth century.¹⁸⁶ In contrast Crafts and Niko Wolf concluded, on the basis of a statistical exercise based on empirical data that 'cheap coal apparently put a clear limit on the growth of the [cotton] industry.'¹⁸⁷ They also found that the disappearance of earlier water powered cotton mills by 1838 was strongly correlated with coal being relatively expensive in these locations.¹⁸⁸ Moreover, Clark and Jacks'

¹⁷⁸ Crafts, *British economic growth*, p. 22.

¹⁷⁹ Harris, 'Iron', p. 57.

¹⁸⁰ *Ibid*, pp. 45-46.

¹⁸¹ *Ibid*, p. 46.

¹⁸² *Ibid*, p. 41.

¹⁸³ Cheap coal was a major factor driving the early concentration of the textile industry in the North-West long before the adoption of steam power in textile mills from 1785. See Sugden et al, 'Adam Smith.'

¹⁸⁴ *Ibid*, pp. 165-166.

¹⁸⁵ Clark and Jacks, 'Coal', p. 65.

¹⁸⁶ Crafts and Wolf, 'Cotton.'

¹⁸⁷ *Ibid*, p. 1124. This point was also made by von Tunzelmann, *Steam*, p. 66.

¹⁸⁸ *Ibid*, p. 1130.

argument neglect the role of coal-fired steam engines in allowing the textile industry to urbanise during the Industrial Revolution and the likely importance of the agglomeration effects this entailed. The secondary literature suggests agglomeration effects were important in the cotton industry in the nineteenth century.¹⁸⁹ Crafts and Wolf concluded on the basis of their own econometric analysis that agglomeration effects were an important locational factor for the nineteenth century cotton industry.¹⁹⁰

Next Clark and Jacks suggest that the absence of coal in Ireland, the Netherlands and France does not explain why these other countries did not industrialise because coal prices there were no higher than in southern England.¹⁹¹ As an aside it is well known, there were abundant coal reserves in France. The comparison between Ireland, north-eastern France, the Netherlands and *southern* England is misguided because industrialization based on coal fueled steam engines did not occur in southern England precisely because coal was too expensive there until railways reduced the price of coal. Industrialisation occurred on the coal fields where coal was very much cheaper than in southern England. Moreover, when France, the Netherlands, and also Belgium and Germany did industrialise, the process was fundamentally dependent on coal and steam engines.¹⁹²

Next it is suggested that England could have sourced all of its fuel needs from Baltic firewood up to about 1860 and that coal was not therefore necessary to the Industrial Revolution. For no obvious reason Scotland and perhaps Wales are ignored here as elsewhere in the article. More importantly, the fundamental historical importance of the British Industrial Revolution is that it was the world's first transition to high and *sustained* rates of economic growth. It would not have that global-historical significance if it had ground to halt around 1860 once it had exhausted the supplies of Baltic firewood as is implied by this argument. This implication of the paper is not discussed. However, the problems with the argument are more fundamental than that and arise from the use of simplistic counterfactual reasoning without thinking through the real-world implications.

It is claimed that the price of this imported firewood would have been about twice the price of coal.¹⁹³ On this basis it is suggested that GDP in 1860 would only have been six percent lower than it actually was. There are a number of problems here. First, Clark and Jacks do not indicate from which part of Britain the coal prices they use come from.¹⁹⁴ Coal prices in different parts of Britain varied enormously during the Industrial Revolution although the variation declined over time as a result of transport improvements. For instance, in 1700 the price of coal in London was nearly eight times that in the north-east even though London had the very considerable advantage of being connected to the north-eastern coal field by water. A few miles by road from London and the price differentials would have been substantially greater. By 1750 the ratio had declined to a little under 5.5.¹⁹⁵ In 1842/3, when there is a parliamentary paper reporting coal prices by poor law unions and covering the whole of England and Wales, a much fuller and more accurate picture of the spread of prices emerges. Prices differed by a factor of ten between the cheapest and most expensive locations.¹⁹⁶ By 1912 the railways had massively reduced the price of coal in most locations distant from the coal fields and in a parliamentary paper with cost data for various towns in England and Wales that year

¹⁸⁹ Crafts and Wolf, 'Cotton', p. 1119.

¹⁹⁰ *Ibid*, p. 1128. See also, Jonell' et al., 'Limited waterpower', p. 2.

¹⁹¹ Clark and Jacks, p. 64

¹⁹² Wrigley, *Industrial growth*.

¹⁹³ Clark and Jacks, p. 68.

¹⁹⁴ Nor is this clear in either of the articles by Clark cited as sources.

¹⁹⁵ Allen, *Industrial Revolution*, p. 98.

¹⁹⁶ Crafts and Wolf, 'Cotton', p. 1117.

the cost of coal in the most expensive location was only 171 percent of the cost in the cheapest location.¹⁹⁷ Since the coal price data used by Clark and Jacks appear to have originally collected by Clark for use in a price index used to deflate farm wages nationally presumably the data reflect some kind of average price for England.¹⁹⁸ This is, of course, the wrong comparator, which would be the much lower coal prices on the coal fields where industries were in fact concentrated. Second, the price of the Baltic wood they use for all of England is based on Knick Harley's data which are based on the price in London of imports from St Petersburg, which was entirely reasonable for Harley's work which was looking at *ocean* freight rates, but does not capture the cost of onward movement to other locations in the UK.¹⁹⁹ Like coal, wood had a high ratio of transport costs to initial value and moving it any distance from navigable water prior to the introduction of railways from 1825 was very expensive. The average cost of Baltic firewood in Britain as a whole would have been significantly higher than the London price.²⁰⁰ The ratio of Baltic wood costs to coal costs would therefore have higher than Clark and Jacks suggest.

There are further problems with the assumption that production of Baltic woodland could be scaled up without increasing costs. Firstly, virtually all of the Baltic woodlands were inland, not on navigable waterways and in fact mostly in locations far from the sea and nowhere near a road. Given the expense it is safe to assume that the wood imported from St Petersburg had not travelled far by land. In other words, costs would have increased astronomically if the entirety of the Baltic woodland areas had been harvested for wood. Second, large parts of continental Europe industrialised in the nineteenth century on the basis of coal. Presumably, we would need to assume in this counterfactual world that some parts of Europe would also have used Baltic wood rather than coal. If they did the entirety of Baltic output would not have been available to Britain and costs would have been pushed up further. Third, the argument also rests on the fallacy that production of all other goods in the economy would have remained the same given a doubling of fuel costs. The cost to enterprises with large fuel needs would have been much more than 3.9 percent of turnover. All this implies that the fall in GDP would have been significantly larger than is suggested.

XI

The arguments of Cormac O' Gráda

Cormac O' Gráda has also argued against the centrality of steam for most of the Industrial Revolution.²⁰¹ His first argument is that most textile mills continued to be dependent on steam until relatively late.²⁰² Exactly when he means is unclear but he probably means before around 1830. He depends for this largely on von Tunzelmann's claim that up to the mid 1830s most power for cotton mills was provided by water.²⁰³ However, this is clearly wrong. As noted in the discussion of Musson's work above, by 1838 steam power provided three times as much power to textile mills as water wheels. It is inconceivable that most power for cotton mills was provided by water in the mid 1830s. Steam must

¹⁹⁷ Smith, *Cost*. Note that this may understate the differences between the lowest and highest price locations slightly because the highest cost location was Southampton on the coast. This would have been about the most expensive place in England and Wales for coastal shipping to deliver coal either from the north-east or from South Wales. However, coal prices would have been a somewhat higher inland from Southampton. I am very grateful to Dan Bogart for making these data available to me.

¹⁹⁸ Clark, 'Farm wages.'

¹⁹⁹ Clark and Jacks, 'Coal' pp. 67-8.

²⁰⁰ Harley, 'Ocean', p.871.

²⁰¹ O' Gráda, 'Science.'

²⁰² *Ibid*, pp. 228-9.

²⁰³ *Ibid*, p. 229; von Tunzelmann, p. 224.

have become more important than water significantly before the 1830s. The second claim is that 'steam's role at the height of the Industrial Revolution, both as a source of energy relative to waterpower and in terms of its contribution to overall economic growth was distinctively secondary.'²⁰⁴ There are three problems with the first claim and one with the second. The first of these claims is based on data which show that steam only came to equal water power around 1830. First, as discussed above, Bottomley has made clear that these data radically undercount the amount of steam power which must therefore have come to exceed waterpower some time before 1830. Secondly, it is implicitly assumed here that the share of all power provided by steam is a reliable indicator of its importance to the Industrial Revolution. However, as we have seen steam power, regardless of how much was being used, was crucial to the expansion of the coal industry on which the Industrial Revolution depended while the freeing up of locational constraints generated significant agglomeration effects which probably drove high exceptionally rapid urbanization and played a major role in achieving economic growth regardless of what fraction of all power this represented. Third, the key cumulative achievement of the Industrial Revolution, the thing that makes it of fundamental global importance, was the achievement of high rates of sustained GDP per capita growth in the second quarter of the nineteenth century, a period in which steam provided more, probably much more, than half of all power. The second part of the claim rests on the work of von Tunzelmann and Crafts which has been shown to be unreliable.

XII

Conclusion

The steam engine was essential to the Industrial Revolution in Britain, the world's first transition to modern economic growth. The massive expansion of coal output during the Industrial Revolution was essential to the Industrial Revolution and could not have taken place without the steam engine. The emergence of the world's first urban economy was fundamentally dependent on the steam engine. The arguments based on the cost of steam power put forward by von Tunzelmann and Crafts are largely irrelevant to understanding the importance of the steam engine before the middle of the nineteenth century. The key benefits of the steam engine were first that it could be used to do things that were otherwise impossible and second that it allowed economic activities to be concentrated in locations with other advantages and third that it was cheaper than using horses to drain the vast majority of mines. Without the steam engine the urban agglomeration effects achieved would not have been possible and it seems likely these made critical contributions to the rate of technological change and to the achievement of modern economic growth. The steam engine also made major contributions to shipping, the iron industry and even agriculture (though only at the end of the Industrial Revolution). Finally, without the steam engine there would have been no railways which might have been fatal for the achievement of modern economic growth in the second quarter of the nineteenth century.

Bibliography

Agnew, J., 'The nineteenth century evolution of the threshing machine in Britain', *The International Journal for the History of Engineering and Technology* (2024), 94, 2, 152-177, <https://doi.org/10.1080/17581206.2024.2391455>

Allen, Robert C. *The British Industrial Revolution in global perspective* (Cambridge, 2009), pp. 164–165.

²⁰⁴ Ibid, p. 230.

Ash, E., H., *The draining of the fens: Projectors, popular politics, and state building in early modern England* (Baltimore, 2017).

Ashton, T. S. *The Industrial Revolution, 1760–1830* (Oxford, 1948).

Atack, J. (1979). 'Fact in fiction? The relative costs of steam and water power: an approach', *Explorations in Economic History*, vol. 16, pp. 409–37.

Bennett, R. J. *Urban population database, 1801-1911* (2012). [data collection]. Robson, B., University of Manchester, Department of Geography. UK data service. SN: 7154, DOI: <http://doi.org/10.5255/UKDA-SN-7154-1>.

Bogart, D., Rosevear, A., Satchell, M., and Shaw-Taylor, L., 'A GIS of the Kanefsky eighteenth century steam-engine dataset.'

Bogart, D., You, X., Alvarez-Palau, E.J., Satchell, M., Shaw-Taylor, L., 'Railways, divergence and structural change in C19th England and Wales', *Journal of Urban Economics*, 128 (2022).

Bottomley, S., *The British patent system during the Industrial Revolution, 1700-1852* (Cambridge, 2014).

Bottomley, S., 'Stationary steam power in the United Kingdom, 1800–70: An empirical reassessment', *Economic History Review*, 78 (2025), pp. 825–848. <https://doi.org/10.1111/ehr.13375>

Bottomley, S., Bogart, D., and Shaw-Taylor, L., 'The role of rotative steam engines in urbanisation' (in progress).

Bridbury, A. R., *Medieval English clothmaking: An economic survey* (London: Heinemann, 1982).

Bruland, K., Smith, K., 'Assessing the role of steam power in the first industrial revolution: The early work of Nick von Tunzelmann', *Research Policy*, 42, 10 (2013), pp. 1716-1723.

Carus-Wilson, E.M., 'An Industrial Revolution of the thirteenth century', *The Economic History Review*, 11, 1 (1941), pp. 39–60.

Cesaretti, R., Lobo, J., Bettencourt, L.M.A., Smith, M.E., 'Increasing returns to scale in the towns of early Tudor England', *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 53, 3 (2020), pp. 147–165. <https://doi.org/10.1080/01615440.2020.1722775>

Chapman, S.D., 'The cost of power in the Industrial Revolution in Britain: The case of the textile industry', *Midland History*, 1, 2 (1971), pp. 1-24. <https://doi.org/mdh.1971.1.2.1>

Clark, G., 'The condition of the working class in England, 1209–2004', *Journal of Political Economy*, 113, 6 (2005), pp. 1307–1340. <https://doi.org/10.1086/498123>.

Clark, G., Jacks, D., 'Coal and the Industrial Revolution, 1700–1869', *European Review of Economic History*, 11, 1 (2007), pp. 39–72, <https://doi.org/10.1017/S1361491606001870>

Collins, E.J.T., 'The diffusion of the threshing machine in Britain, c 1790-1800', *Tools and Tillage*, 2, 1 (1972), pp.16-33.

Crafts, N.F.R., *British economic growth during the Industrial Revolution* (Oxford, 1985).

Crafts, N.F.R., 'Steam as a general purpose technology: A growth accounting perspective', *The Economic Journal*, 114 (2004), pp. 338-351. <https://doi.org/10.1111/j.1468-0297.2003.00200>

Crafts, N. F. R., Harley, C. K. 'Output growth and the British Industrial Revolution: A restatement of the Crafts-Harley view', *Economic History Review*, 45, 4 (1992), pp. 703–730.

Crafts, N., Wolf, N., 'The location of the UK cotton textiles industry in 1838: A quantitative analysis', *The Journal of Economic History* 74, 4 (2014), pp. 1103–1139. <http://www.jstor.org/stable/24550695>.

Davenport, R.J., 'Mortality, migration and epidemiological change in English cities, 1600–1870', *International Journal of Paleopathology*, 34 (2011), pp. 37–49.

Deane, P., Cole, W.A., *British economic growth, 1688–1959*. (Cambridge, 1962).

Deane, P., *The first Industrial Revolution* (Cambridge, 1965).

Devine, T.M., 'Scotland', in Clark, P. (ed), *The Cambridge Urban History of Britain, Volume II, 1540–1840* (Cambridge, 2000), pp. 151–164.

Donaldson, D., Hornbeck, R. 'Railroads and American economic growth: A "market access" approach.' *The Quarterly Journal of Economics*, 131, 2 (2016), pp. 799–858.

Ellis, J., 'Regional and county centres 1700–1840', in Clark, P. (ed), *The Cambridge Urban History of Britain, Volume II, 1540–1840* (Cambridge, 2000), pp. 673–860.

Fischer, L.R., Nordvik, H.W., *Shipping and trade, 1750–1950*. (Oxford, 1990).

Flinn, M. W., with the assistance of David Stoker. *The History of the British Coal industry. Volume 2, 1700–1830: The Industrial Revolution*. (Oxford, 1984).

Fogel, R. W., *Railroads and American economic growth: Essays in econometric history* (Baltimore, 1964).

Gordon, R. B., 'Cost and use of water power during industrialization in New England and Great Britain: A geological interpretation.' *The Economic History Review*, 36, 2 (1983), pp. 240–259. <https://doi.org/10.2307/2595922>.

Harley, C. K., 'Ocean freight rates and productivity 1740–1913: the primacy of mechanical invention reaffirmed', *The Journal of economic history*, 48 (1988), pp. 851–76.

Harris, J.R., 'The employment of steam power in the eighteenth century', *History*, 52, 175 (1967), pp. 133–148.

Harris, J. R., 'The rise of coal technology', *Scientific American*,. 231, 2, (1974), pp. 92–97.

Harris, J. R., *The British iron industry, 1700–1850* (London, 1988).

Hatcher, J, *The history of the British coal industry: Volume 1, Before 1700: Towards the age of coal*, (Oxford, 1993).

Henderson, J. V., 'The sizes and types of cities', *The American Economic Review*, 64, 4, pp. 640–656.

Henderson, J.V., 'Urbanisation and growth' in Aghion, P., and Durlauth, S.N., (eds.) *Handbook of Economic Growth, Volume 1B* (2005).

Hills, R, L., *Power from steam: A history of the stationary steam engine* (Cambridge, 1989).

Honeyman, K. *Child workers in England, 1780–1820: Parish apprentices and the making of the early industrial labour force* (Aldershot, 2007).

Hyde C., *Steam power and British Industrialization to 1860*. By G. N. Von Tunzelmann (Oxford, 1978), *The Journal of Economic History*, 38, 4 (1978), pp. 1056-1058. doi:10.1017/S0022050700088021

Jackson, G., *The history and archaeology of ports* (Oxford, 1983).

Jonell, T. N., Jones, P., Lucas, A., Naylor, S. *Limited water power contributed to rise of steam power in British "Cottonopolis"*. *PNAS Nexus*, 3, 7 (2024), <https://doi.org/10.1093/pnasnexus/pgae251>

Kander, A., Malanima, Warde, P., *Power to the people: Energy in Europe over the last five centuries* (Princeton, 2013).

Kanefsky, J. W., 'The diffusion of power technology in British Industry 1760-1870', unpublished Ph.D. thesis, University of Exeter, (1979).

Kanefsky, J. W., 'Motive power in British industry and the accuracy of the 1870 factory returns', *Economic History Review*, 32 (1979), pp. 360–375.

Kanefsky, J., 'James Watt in context: steam engine building 1776–1800', *The International Journal for the History of Engineering & Technology* (2025), pp. 1-16. DOI: 10.1080/17581206.2025.2555356

Kitsikopoulos, H., *Innovation and technological diffusion: An economic history of early steam engines*. (New York, 2019).

Kitsikopoulos, H., *An economic history of British Steam engines, 1774–1870: A study on technological diffusion*. (Cham, 2023)

Kitsikopoulos, Haris. 'Steam power diffusion in the British cotton and woolen industries, 1774–1800: The role of firm size.' *Review of Evolutionary Political Economy* 5, 3 (2024), pp. 559–580. DOI: 10.1007/s43253-024-00129-x

Krugman, P., 'The new economic geography, now middle aged', address to the Association of American Geographers (2010). Available at: [Krugman. The new economic geography now middle aged 2010.pdf](#)

Kuznets, S., 'Population trends and modern economic growth: Notes towards a historical perspective', in Kuznets, S., *Growth, population and income distribution: Selected essays*, (New York, 1979), pp. 162-205.

Law, C. M., 'The growth of urban population in England and Wales, 1801-1911.' *Transactions of the Institute of British Geographers*, 41 (1967), pp. 125-143.

Litvine, A. D., Starzec, A., Younis, R., Faula, Y., Coustaty, M., Shaw-Taylor, L., & Églin, V., 'Built-up areas of nineteenth-century Britain. An integrated methodology for extracting high-resolution urban footprints from historical maps', *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 57, 1 (2024), pp. 1–19. <https://doi.org/10.1080/01615440.2024.2324163>

Litvine, A. D., Starzec, A., Younis, R., Faula, Y., Coustaty, M., Shaw-Taylor, L., & Églin, V., 'Nineteenth-century BUA of Britain dataset' (2024), 10.5281/zenodo.5534676

MacLeod C. *Inventing the Industrial Revolution: The English patent system, 1660-1800* (Cambridge, 1988).

Macleod, C., Nuovalari, A., 'Patents and industrialisation: An Historical overview of the British case, 1624-1907' (2012). Available at: <file:///C:/Users/lmws2/Downloads/ssrn-2019844-1.pdf>

- MacLeod C. *Inventing the Industrial Revolution: The English patent system, 1660-1800* (Cambridge, 1988).
- Marshall, A., *Principles of economics*, (London, 8th edition, 1920).
- McDonald, S., 'The progress of the early threshing machine', *Agricultural History Review*, 23, 1 (1975), pp. 63-77.
- Mitchell, B.R., *British historical statistics* (Cambridge, 1988).
- Michie, R.C. , 'London and the progress of economic growth since 1750', *London Journal*, 22, 1 (1997), pp. 63-90.
- Miller, E. 'The fortunes of the English textile Industry in the thirteenth century', *The Economic History Review*, 18 (1965), pp. 64–82.
- Mokyr, Joel. *The lever of riches* (Oxford, 1990).
- Mokyr, J., *The enlightened economy. An economic history of Britain 1750–1850* (New Haven, 2010).
- Nuvolari, A., *The making of steam power technology: A study of technical Change during the British Industrial Revolution* (Eindhoven, 2004).
- Nuvolari, A., Verspagen, B., von Tunzelmann, N., 'The early diffusion of the steam engine in Britain, 1700–1800: a reappraisal', *Cliometrica*, 5 (2011), pp. 291–321.
- Ó Gráda, C., 'Did Science Cause the Industrial Revolution?', *Journal of Economic Literature*, 54, 1 (2016), pp. 224–239.
- Overton, M., *Agricultural revolution in England* (Cambridge, 1996)
- Pelham, R.A., 'The water power crisis in Birmingham in the eighteenth century', *University of Birmingham Historical Journal*, 9 (1963-4).
- Pollard, S., *The genesis of modern management: A study of the Industrial Revolution in Great Britain* (London, 1965).
- Rosevear, A., and Shaw-Taylor, L., 'Urbanisation of mechanical power during the Industrial Revolution', in progress (2026).
- Satchell, M., Shaw-Taylor, L., 'Urban footprints of candidate towns in England and Wales c.1900' (2015).
- Shaw-Taylor, L., 'An introduction to the history of infectious diseases, epidemics and the early phases of the long-run decline in mortality', *Economic History Review*, 73, 3 (2020), pp. 1-19. <https://doi.org/10.1111/ehr.13019>
- Shaw-Taylor, L., 'The population of England and Wales: 1541-1796', *Local Population Studies*, 214 (2026).
- Shaw-Taylor, L., 'The escape from Malthusian constraints in England and Wales', in progress but will be online as a WP early in 2026.
- Singer, C.J., Holmyard, E. J., Hall, A. R., Williams, T.I. (eds.), *A History of technology, Volume IV: The Industrial Revolution, c. 1750–c. 1850* (Oxford, 1958).

Smith, H. W., *Cost of living of the working classes. Report to an enquiry by the Board of trade into working class rents and retail prices, together with the rate of wages in certain occupations in industrial towns of the United Kingdom* (London, 1913).

Solar, P. M., Lyons, J. S. 'The English cotton spinning industry, 1780–1840, as revealed in the columns of the *London Gazette*' *Business History*, 53, 3 (2011), pp. 302–323.
<https://doi.org/10.1080/00076791.2011.565510>

Sugden, K., Keibek, S., Wells, J., and Shaw-Taylor, L., 'Adam Smith revisited: the relationship between the English woollen manufacture and the availability of coal before the use of steam power, *Continuity and Change*, 38 (2023), pp.163-191.

Tann, J., 'Arkwright's employment of steam-power', *Business History*, 21, 2 (1979), pp.247–250,
[doi:10.1080/00076797900000030](https://doi.org/10.1080/00076797900000030)

Tann, J., 'The steam engine on Tyneside in the Industrial Revolution', *Transactions of the Newcomen Society*, 64 (1992–93), pp. 53–75.

Toynbee, A., *Lectures on the Industrial Revolution in England*, (Trowbridge, 1969).

Tylecote, R. F., *A History of Metallurgy* (2nd ed., London, 1976, 1992).

Von Tunzelmann, N., *Steam power and British industrialisation to 1860* (Cambridge, 1978).

Warde, P., *Energy consumption in England & Wales, 1560-2004* (Naples, 2007)

Wrigley, E. A. *Industrial growth and population change: A regional study of the coalfield areas of north-west Europe in the Later nineteenth century*. (Cambridge, 1961).

Wrigley, E. A., 'Urban growth and agricultural change: England and the continent in the early modern period', *The Journal of Interdisciplinary History*, 15, 4 (1985), pp. 561–779.

Wrigley E.A., *Continuity, chance and change: The character of the Industrial Revolution in England*' (Cambridge, 1988).

Wrigley, E.A., *Energy and the English Industrial Revolution* (Cambridge, 2010).

Wrigley, E.A. *The path to sustained growth. England's transition from an organic economy to an Industrial Revolution* (Cambridge, 2016).

You, X., Bogart, D., Alvarez, E., Satchell, A.E.M., Shaw-Taylor, L. 'Transport development and urban population change in the age of steam: A market access approach', in progress.