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Stationary steam power in the United Kingdom, 1800–70: An empirical reassessment

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Industrialization – and with it the breakthrough to modern economic growth – is traditionally associated with steam power and factory production. Although this association has been queried, this paper argues emphatically that it stills holds: steam power was adopted more widely than previously thought, and we have barely started to grasp the myriad contributions it made to economic and social developments during the nineteenth century. Once developed, the steam engine meant that humanity could access essentially limitless mechanical energy. Although data remains limited, this paper argues that steam consequently sustained the British industrial revolution, and so the global transition to modern economic growth.

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Abstract

The conventional view that the industrial revolution was premised on the unprecedented supply of mechanical power delivered via steam engines has been undermined by econometric work, purporting to show that their adoption outside the cotton and mining sectors was extremely limited until at least 1870. This was largely because water and wind power remained viable and cost-competitive substitutes long into the nineteenth century. Using evidence from a newly compiled ‘census’ of stationary power installations in Suffolk, this paper demonstrates instead that the adoption of steam power was far greater than previously thought, especially in manufacturing. Moreover, the assumption that steam could be invariably substituted with environmental forces is untenable. Depending on circumstances, even very modest power requirements could only be met with steam. Although the quantitative picture remains incomplete, steam power was likely an indispensable sustentative factor for industrialization.

KEYWORDS
energy, industrial revolution, steam engine, steam power, Suffolk, United Kingdom

I | BACKGROUND

Steam power was conventionally believed to have been indispensable for industrialization and the development of the factory system. Unlike animate power sources such as human and animal muscle, or environmental power sources such as water and wind, power from steam never tired, was not contingent on weather conditions, and provided that coal was available, was essentially inexhaustible.[1] The first historians of the industrial revolution were unanimous on its importance. In 1884, Toynbee wrote that the pre-industrial system of domestic manufacture and the social system it underpinned 'was shattered by the power-loom and the steam engine'.[2] Sixty years later, Ashton described the steam engine 'as the pivot on which industry swung into the modern age'.[3]

More recently, Wrigley re-stated this view, emphasizing the fundamental constraints inherent to any organic economy, wherein virtually all energy inputs are derived from what can be grown from the land, be it firewood to provide heat energy or feed for men and animals to provide mechanical energy.[4] The latter might also be obtained by exploiting environmental forces, namely water and wind, although power generation from these sources was strictly limited in both scale and concentration.[5]

The constraints in generating heat and mechanical energy could only be overcome by adopting inorganic sources of energy – in the first instance, coal, which by 1600 was already the primary source of heat in a growing range of industries such as brewing and brick making. However, 'without a parallel breakthrough in the provision of mechanical energy to solve the problem associated with dependence on human or animal muscle to supply motive power in industry and transport, energy problems would have continued to frustrate efforts to raise manpower productivity'.[6] This breakthrough was achieved with the steam engine, which converted the heat energy produced from burning coal into mechanical energy. The first economically viable engine was developed by Thomas Newcomen in the 1700s. A rudimentary design produced a simple reciprocal motion with a poor fuel economy such that it could only be deployed where fuel was essentially free (draining coal mines) or where the economic value of their work was sufficient to cover operating costs (draining tin and copper mines in Cornwall).[7]

As the mechanical energy produced by the steam engine could be generated without drawing on the annual stock of energy generated through photosynthesis, the constraints of the organic economy could now be demolished. Over the next 200 years, as new designs were developed yielding improvements on every point of operation, such as capital expense, operating expense, form of motion, regularity of action, reliability, and ease of maintenance, the steam engine was profitably adopted for an ever-growing range of tasks. The British economy would be supplied with essentially inexhaustible mechanical power, a vital input in any manufacturing process and transport.

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[1] Wood could also fuel steam engines, although given that it has roughly half the energy density of coal and has to be collected from wide areas, its use was limited to locomotives that could collect wood as they travelled, classically, railways and steamships in virgin North America. Even there, however, deforestation increasingly forced the transition to coal from the 1850s. Hunter, *Steam-power*, pp. 403–20.

[2] Toynbee, *Lectures*, p. 148.

[3] Ashton, *Industrial revolution*, p. 58.

[4] Wrigley, *Energy*.

[5] Chandler, 'Anthracite coal'.

[6] Wrigley, *Energy*, p. 45.

[7] Bottomley, *British patent system*, pp. 233–47.

This was an unprecedented achievement and one which enabled the breakthrough to modern economic growth. Wrigley concludes that 'the steam engine was arguably the single most important technical advance of the whole industrial revolution period'.[8]

However, despite the conceptual clarity of this account, it has been contradicted by social savings exercises which look to quantify steam's contribution to economic development. Social savings represent the additional costs incurred by replacing an optimal production method with a second-best method while still producing the same volume of output. They are popularly used to estimate the economic contribution of a new technology (the optimal method) relative to a pre-existing technology (the second-best method) and were pioneered by Robert Fogel's work on the American railroad. Contrary to prior consensus, Fogel concluded that the railroads had not made an indispensable contribution to American economic growth – in 1890, they could have been replaced with the second-best transport method available (canals and roads) at a cost equivalent to only 5 per cent of GDP. If this was the case with the American railroad, Fogel concluded that 'no single innovation was vital for economic growth during the nineteenth-century'.[9] Although the specifics of Fogel's exercise drew significant and varied criticism, his starting premise that the railroad could invariably be substituted with alternative means of transport was generally uncontroversial, as was his final conclusion concerning the railroad's dispensability.[10]

Social savings have also been used to estimate the contribution of stationary steam engines to the British economy. Assuming they could invariably be substituted with alternative power sources (water and wind), and that the point of difference between these alternatives and steam was solely one of cost, von Tunzelmann estimated that all stationary steam engines in Britain in 1800 could have been replaced at a cost equivalent to only 0.2 per cent of national income.[11] Moreover, given the social diseconomies associated with steam (pollution and loss of life from industrial accidents), he considered this 'computation [to be] an upper bound'. von Tunzelmann was more tentative for the nineteenth century, conscious that the quantitative picture was far from complete. He speculated that, while the social savings attributable to steam engines would be higher in 1830 or 1850, given that steam power remained relatively expensive into the 1840s, it would still 'tend towards zero', encouraging 'a very different assessment of the economic effects of Watt and other [steam engineers]'.[12] von Tunzelmann's analysis also encompassed some of the linkages between steam engines and other industrial sectors that would not be so easily captured in a social savings analysis, for instance, how steam power might improve the quality of cotton spun, or how steam-engine manufacturing acted as a source of demand for iron. Nonetheless, until 1847, he considered these to be 'minor foreshadowings' of what would occur later in the second half of the nineteenth century.[13]

[8] Wrigley, *Energy*, p. 44.

[9] Fogel, *Railroads*. p. 234.

[10] See for instance, Gunderson, 'Social saving', p. 217. Alternatively, White ('Social saving', pp. 88–9) observed that the 'calculation of social saving can never take account of developments which would have been impossible without transport improvement', noting in the Russian case that it would be 'nonsense to consider an alternative transport cost of moving Donbas coking coal to the Krivoi Rog iron-ore deposits'.

[11] von Tunzelmann, *Steam-power*, pp. 27, 157. For this exercise, von Tunzelmann used figures prepared by Harris, 'Steam-power', although these were soon superseded by Kanefsky and Robey, 'Steam engines'. In particular, whereas the former estimated there had been 1330 engine erections during the eighteenth century, the latter estimates 2500.

[12] von Tunzelmann, *Steam-power*, pp. 287–8.

[13] Ibid., p. 292.

Subsequent work by Crafts applying the same social savings methodology confirms this outline. He finds that the social savings attributable to the adoption of steam power declined to 0.02 per cent of GDP over the period 1800–30 before increasing again to 0.3 per cent in 1830–50 and 1.2 per cent in 1850–70.[14] Crafts also reports commensurately modest contributions by steam to total factor productivity (TFP) growth, peaking at 0.06 per cent per annum during 1850–70. These results are attributed to the limited diffusion of steam power outside of mining and cotton, with some important sectors such as agriculture remaining 'virtually untouched by steam' until at least 1870.[15] As with von Tunzelmann, this in turn is attributed to the relatively high operating costs of low-pressure engines, and it was only with the transition to more fuel efficient, with higher working pressures starting in the third quarter of the nineteenth century, that steam had a wider economic impact.

Even then, Crafts concludes that, while 'the contribution to growth made by the stationary steam engine … was considerably bigger in the second half of the nineteenth century than during the industrial revolution, it was always quite modest'.[16] This conclusion is now widely accepted,[17] although the applicability of social savings is contingent on three assumptions: that the only significant point of difference between steam and other power sources was cost, that steam could invariably be substituted with other power sources, and that we have a tolerably accurate quantitative picture of the adoption of steam power during the nineteenth century. This paper argues that these assumptions are untenable. The following section critically assesses the Factory Returns, contemporary government reports which constitute one of the primary source bases for estimating power adoption in British manufacturing during the nineteenth century. Although the figures in the Factory Returns have been substantially updated and supplemented by the subsequent work of Kanefsky (and it is these figures which Crafts used),[18] unfortunately, the Returns remain internally inconsistent and demonstrably incomplete. As an alternative, a 'census' of stationary steam engines erected in Suffolk from 1800 to 1870 has been compiled, described in section II. Section III outlines results from this census, showing that power provision from steam was significantly greater than has been previously estimated, especially in manufacturing, and presents new national estimates for the adoption of steam power in 1870. Section IV turns to the first two assumptions mentioned above, arguing that, even in an agrarian county such as Suffolk, there were industrial processes where only steam could provide the power required: steam was not substitutable. Section V concludes.

II | THE FACTORY RETURNS

Prior work estimating the contribution of steam to economic growth during the nineteenth century has relied, in part, on figures available in the Factory Returns.[19] Produced on an intermittent basis between 1838 and 1870 by the state Factory Inspectorate, the Returns reported on

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[14] Crafts, 'Steam', p. 344.

[15] Ibid., pp. 341–2.

[16] Ibid., p. 345.

[17] See, for example, McCloskey, 'Ideas and ideologies', pp. 58–9; Ó Gráda, 'Science', p. 230.

[18] In particular, Crafts, 'Steam', used the figures Kanefsky prepared for his PhD ('Diffusion of power technology', p. 338) which are substantially the same as those which appeared in print the same year (Kanefsky, 'Motive power', p. 373).

[19] We have a much more accurate picture for the eighteenth century due to the census of stationary steam engine installations compiled by Kanefsky, a methodology akin to the one adopted in this paper. On the basis of this census, Kanefsky

the employment of women and children in manufactories that came under the provisions of the Factory Acts, legislation passed to improve their working conditions. The Returns also reported on power provision in manufactories and it is these figures which have been previously used. However, the sectoral coverage of the Factory Acts was limited. Until 1860, they only extended to textile mills,[20] at which point legislation was passed to include all bleaching and dyeing works.[21] A second, much more ambitious extension was enacted in 1867 when all manufacturing establishments that employed women and children or that employed more than 50 men for 100 days a year were included.[22] Also included, even if they did not meet these employment criteria, were all earthenware manufacture (excluding bricks and tiles), lucifer match-making, percussion cap and cartridge trades, paper-staining and fustian cutting, metal trades (excluding works with less than six men employed in casting and founding metals), rubber- and gutta-percha-making, glassmaking, papermaking, tobacco, letterpress printing, and bookbinding.

Consequently, the Factory Returns only pertain to textiles until 1860, and only the final return in 1870 has the most complete coverage. Even then, given the distribution of firm size and the preponderance of males in manufacturing, this means the 1870 Factory Return excluded up to half of all British manufacturing by employment, and the scale of omission varied by sector and location.[23] For instance, while the 1870 Factory Return (conducted in November and December of that year) recorded 94 men employed in ship-building in Suffolk, the 1871 census, conducted 2 April, records 418 men employed in ship-building in Suffolk.[24] Another limitation with the Factory Returns is that they omit sectors that were not deemed to constitute manufacturing, specifically grain milling, public utilities, and mining.

Musson tried to compensate for these omissions by using contemporary local surveys of power provision in industry and inferring from these what a national picture might have looked like. He arrived at a ‘very shaky’ upper bound estimate that total ‘industrial steam power’ in 1850 was 300 000 nominal horsepower (nhp), of which 108 113 nhp was accounted for in the Factory Return of the same year. Given that the latest local survey used for this estimate was from 1838, Musson was rightly diffident about this estimate.[25] Moreover, as working pressures in steam engines increased, so also did nhp, the conventional means of reckoning horsepower, understate ‘true’ power output (the next section will detail these various horsepower measurements). Indicated horsepower (ihp) was the direct and more accurate measurement, and Musson’s figure of 300 000 nhp has been variously rendered as 487 500[26] or 500 000 ihp.[27]

von Tunzelmann undertook essentially the same exercise using similar surveys. For 1838, assuming (implicitly) that the Factory Return of that year faithfully recorded installed power from all sources in the textile sector (59 800 nhp), he estimated that this constituted a quarter of installed

estimates that total power output of installed stationary steam engines in England in 1800 was approximately 35 000–40 000 nhp (‘Diffusion of power technology’, p. 277), and further refinements indicate that the total is nearer the latter figure than the former. (‘Newcomen engines’, p. 169).

[20] 3 & 4 William IV, c.103 (1833).

[21] 23 & 24 Vict. c.78 (1860).

[22] 30 & 31 Vict c.146 (1867).

[23] Kanefsky, ‘Motive power’, p. 363.

[24] ‘Return of number of manufacturing establishments’, p. 155. ‘Census, 1871’, vol.3, p. 191.

[25] Musson, ‘Industrial motive power’, pp. 425–34.

[26] Crafts, ‘Steam’, p. 344.

[27] Greenberg, ‘Power patterns’, p. 1253.

power in the United Kingdom, so 239 200 nhp, although as with Musson, he acknowledged that the data were 'sketchy'.[28]

Potentially more reliable is Kanefsky, who used the most sectorally extensive 1870 Factory Return. Conscious that only eight counties in England reported a full return in 1870, Kanefsky [29] also supplemented the Return with data available from the Coal Supply Commission to estimate a total of 1 400 000 ihp of stationary steam power installed in British manufactories.[30] He also prepared estimates for sectors omitted from the 1870 Factory Return, including mining (565 000 ihp, of which coal mining used 500 000 ihp), grain mills (25 000 ihp), utilities (55 000 ihp), and 'other' (20 000 ihp). Kanefsky arrived at a final estimate of 2 065 000 ihp steam power in Britain in 1870 (see table 3 below for details).

Using the Factory Returns back to 1838 and, courtesy of his own census of steam engine erections for Britain in the eighteenth century, an evidentially secure estimate for 1800, Kanefsky interpolated the rate of steam power adoption for the period 1800–70, figures which are now considered to be 'broadly accurate' and are generally cited.[31] Nonetheless, it remains likely that Kanefsky understated the scale of omission in the 1870 Factory Return. While there were manufacturing establishments which met the criteria for inclusion in the Return, they were missed, and this occurred even in a county which claimed a full return such as Suffolk. The silk industry, for example, had been included in the Returns since the original Factory Act of 1833. One might therefore expect factory inspectors to have been familiar with silk mills in their district and to include them in the Returns. Moreover, silk mills had a predominantly female workforce. Given the remit of the Factory Acts, they ought to have been of especial interest. However, while the 1870 Factory Return recorded three silk manufacturing establishments in Suffolk, employing a total of 630 (of which 554 were women), the 1871 census records 1708 employed in silk manufacture (1159 of which were women).[32] This discrepancy cannot be attributed to an (undocumented) boom in the Suffolk silk industry in the first 3 months of 1871. The Post Office Directory of 1869 lists 14 silk mills in the county, whereas 10 are listed in the 1875 Directory, nine of which had the same owners as in 1869.[33] Instead, these establishments were omitted by a Factory Inspectorate that was overworked, underfunded, and riven by infighting. As the Inspectorate was failing to prevent widespread flouting of Parliamentary safety legislation, its primary function and a critical actuating factor for the nascent labour movement, it is unrealistic to expect it to have accurately recorded power inputs in industry, a secondary function.[34]

Finally, the 1870 Return is riven with inconsistencies. For instance, the Factory Return recorded 1792 ihp of stationary steam power installed in Suffolk manufactories and 32 ihp of water. 'Extracted' from the county return for Suffolk is the return for Ipswich, recording 505 ihp of steam and 7 ihp of water. However, the return for Suffolk and the return for Ipswich are irreconcilable.

[28] von Tunzelmann, *Steam-power*, pp. 35–6.

[29] Matters were better in Scotland, where all but three counties reported a full return, although in Wales and Ireland not a single county return was complete, and 11 Irish counties failed to make any return at all. On Ireland and Scotland, see Kanefsky 'Motive power', p. 362. On Wales, see 'Return of number of manufacturing establishments', pp. 118–50.

[30] Kanefsky, 'Diffusion of power technology', p. 334.

[31] Kanefsky, 'Diffusion of power technology', p. 338. Quotation from Crafts, 'Steam', p. 341.

[32] 'Census, 1871', vol.3, pp. 192, 195.

[33] *Post Office*, 1869, pp. 1071–2; *Post Office*, 1875, p. 1065. These nine firms were Stephen Walters & Sons (Haverhill), Stephen Brown (Ipswich), Henry Eaton W. Sons (Glemsford, Sudbury), Thomas Kemp & Son, Charles Norris & Co., Salter & Whaiter, Joseph Seagrave, and Vanner & Sons (Sudbury).

[34] Bartrip, 'Government inspection'.

Whereas there were reported to be 15 metal foundries in Suffolk, using 47 ihp of steam and employing 167 (all men), in Ipswich there were four foundries, but using 234 ihp of steam and employing 1523 (again, all men). As Ipswich was a subset of Suffolk, it is unclear how it was able to employ more men and more steam horsepower.[35]

III | DATA DESCRIPTION

The 1870 Factory Return is:

(i) Internally inconsistent.
(ii) Geographically incomplete.
(iii) Omits steam engines that did not enter its legislative remit.
(iv) Omits steam engines that did enter its legislative remit.

Considering this, it forms an insecure basis to conjecture about the British economy and especially its adoption of steam power. Some of these shortcomings have been acknowledged in the past, although their extent has perhaps been underappreciated. Instead, this paper will present results from a census of all stationary power installations erected in Suffolk over the period 1800–70. Ideally, such a census would be national in scope, although given the sheer number of engines involved, this would be prohibitively time-consuming. Instead, a county-level census has been prepared. In some respects, Suffolk may appear an idiosyncratic choice. It was certainly a laggard adopting steam power, being the largest county by population without a single steam engine to be erected during the eighteenth century.[36] It was also entirely bereft of mining activity and remained a predominantly agricultural county long into the nineteenth century.[37] Nonetheless, Suffolk was chosen for four reasons:

(i) It was one of only eight English counties to report a full return for the 1870 Factory Return. If it is shown that the 1870 Return significantly understated the number and size of power installations for Suffolk (which it did), then it is more likely that the Return did so for the rest of the country and that the understatement for counties reporting an incomplete return were proportionately greater than for Suffolk. Indeed, it appears that the sub-inspector responsible for conducting the 1870 Return in Suffolk (a Mr. Lakeman) was particularly diligent, completing more inspections in the 6 months preceding the Factory Return than any of the 16 sub-inspectors reporting to Inspector Redgrave.[38]
(ii) The source base for Suffolk is especially rich. In particular, the agricultural implement makers Garrett & Sons and Ransome & Co. manufactured stationary steam engines, and production registers for both survive from 1850 to 1860 onwards, respectively. These have been used to compile the census in conjunction with a variety of other sources, including newspapers, local tax rates, trade directories and the work of R.H. Clark on steam

[35] 'Return of number of manufacturing establishments', pp. 226–27.

[36] Kanefsky and Robey, 'Steam engines', p. 176.

[37] In 1817, 56% of adult males were employed in agriculture (compared with a national figure of 37%), and in 1851, this figure remained at 47.7% (having fallen to 27.5% nationwide). Kiebek, 'Occupational structure', pp. 152, 646.

[38] Great Britain, *Inspectors of Factories*, 1870, pp. 131–47.

engineering in East Anglia.[39] Finally, Peter Dolman has compiled an equivalent census of water- and wind-powered installations.

(iii) If stationary steam engines performed functions for which there were no substitutes, even in an industrial backwater such as Suffolk, it is reasonable to suppose that the same would apply to the rest of the country.

(iv) Finally, it became clear at an early stage of the project that there would be a significant upward revision in the adoption of steam engines compared with what was recorded in the Factory Returns. This meant compiling the census was more time-consuming than originally planned, but still achievable. In an industrial county such as Yorkshire (which also claimed a full return in 1870, reporting 187 336 ihp of steam in use, over 100 times that of Suffolk), it would have been prohibitively time-consuming, involving the manual collation of details for tens of thousands of steam engines, rather than 'just' hundreds.[40]

The compilation of the census was modelled on prior work by Kanefsky for the eighteenth century, recording an engine's location, its industrial sector, operator, horsepower output, manufacturer, and any other available technical information such as whether it was worked at high pressures.[41]

The one distinction is that, whereas Kanefsky's census only recorded when a steam engine was installed, the Suffolk census also records if it ceased working before 1871, if it was replaced, or if it was moved to another site. By recording an engine's operational life span, it is possible to estimate the overall amount of installed steam power in Suffolk for any particular year and to compare those estimates with figures from the Factory Returns. This operational life span is not always documented, and it has sometimes been inferred by other means. Where an engine's start date is unrecorded, it has usually been dated to the first documentary record of the engine. This has two consequences. One, the estimate for total installed horsepower in Suffolk for any particular year will be an underestimate. There will certainly be engines which had been working for an (unrecorded) period of time prior to when they first appear in the documentary record. Two, more importantly, those engines that started work prior to 1871 but for which the first documentary evidence only survives from after 1870 are entirely omitted from the census. The estimation methods used here are purposively conservative, and the figures discussed in the following section are best considered as lower bound estimates rather than best guesses.

In terms of when an engine ceased operating, where this is unrecorded, provided that the engine owner's business is recorded in the 1869 Post Office directory, then it has been assumed that they had remained in business until the end of 1870 and that they had retained the engine. When they do not appear in the Post Office directory and there is no record of the business premises having been sold on, or a confirmed purchaser of the engine, it is assumed that the steam engine had ceased operating at the mid-point between the 1869 directory and the last recorded instance of the engine remaining in operation.

In the case of horsepower figures, these are only documented for two-thirds of the engines. In some cases, the power rating can be estimated using other information about the operator. For instance, when using steam power in milling, the standard requirement to drive each pair of

[39] Clark, 'Early engines'; Clark, *Steam-engine builders*.

[40] 'Return of number of manufacturing establishments', pp. 161–62.

[41] Kanefsky, 'Diffusion of power technology'; Kanefsky, 'Newcomen engines'.

stones was 8 ihp[42] Accordingly, missing horsepower ratings for steam engines at grain mills have been estimated using the number of pairs of millstones they were driving. Employment information in the 1861 census has also been used to estimate power usage. For example, in 1861 Edward Greene employed 50 hands at his Bury St Edmunds brewery, using a 15 ihp steam engine.[43] It has been assumed that the steam engine used by the Beccles brewer Crisp & Son (employing 63 hands in 1861) had an equivalent power rating. Where there is no available rating for the engine and insufficient evidence to enable an estimate (accounting for less than a fifth of the engines in the database), it has been assumed that the engine was equivalent to 8 ihp. This rating has been adopted, as it is both the statistical mode for engines where there are documented power ratings and as there were only 25 engines rated at less than 8 ihp. Therefore, inputting 8 ihp reinforces the bias towards underestimating overall steam power adoption.

In a related matter, contemporaries usually measured horsepower in relation to the size of the cylinder, termed ‘nhp’. This was accurate enough for engines that worked at low pressures and where there was one single-acting cylinder (i.e. the steam worked once, on one side of the piston), but as working pressures increased and cylinders were increasingly compounded, nhp increasingly understated actual power output. These new engineering practices spread more quickly than the more accurate ihp measurement did, and the differential between the two horsepower measurements was both significant and inconsistent across different types of engines. In 1859, William Rankine estimated ihp to be anywhere from one and a half times the nhp (a multiple applicable to older-style engines) to five times the nhp (applicable to the latest high-pressure compound engines).[44] This variance in horsepower measures would not be a problem if both measurements were available for every engine, although this is rarely the case. Instead, nhp was most usually reported. An 1872 newspaper report describing steam engines at a Bramford fertilizer plant is illustrative. These were rated at a combined 147 nhp, which in conjunction with the engines at their Ipswich plant, rated at 70 nhp, meant that the firm (Packard & Co.) disposed of a total of 217 nhp at their two Suffolk plants. Only at the end of the report was it observed that this was equivalent to an ‘actual power … upwards of 600 horsepower’.[45] In a similar vein, it was only the 1870 Factory Return that reported ihp as opposed to nhp, and even then inspectors were confusing the two measures.[46]

It also needs to be emphasized that the census is composed of stationary steam engines only and therefore omits locomotive engines, specifically steamships and railway engines, and self-propelled traction engines. In practical terms, it would not make sense to count an engine which ranges across county boundaries in a county-level census. They could only be incorporated into a national census. Neither do they relate (directly) to the literature discussed in opening section. Of greater concern, and the least remediable of the limitations highlighted so far, is the omission of portable engines. These were smaller engines that could be moved around a worksite to provide power as and when required. They could also be cheaply hired from contractors. First adopted on a large scale in agriculture during the 1840s, by the 1860s, it was estimated that there was enough work to justify a portable engine for every farm of at least 50 acres,[47] a criterion which would

[42] Tann, ‘Corn milling’, p. 410.

[43] Clark, ‘Early engines’, p. 391.

[44] von Tunzelmann, *Steam-power*, p. 27.

[45] *Suffolk Chronicle*, 2 March 1872, p. 9.

[46] von Tunzelmann, ‘Coal’, p. 76.

[47] Bourne, *Steam-engine*, p. 371.

have applied to the vast majority of farms in the country.[48] Conceptually, portable engines are indistinct from the stationary steam engines recorded in the census. They delivered power in the same way as stationary engines did, but with the inconsequential difference that they could be moved around a worksite. Portable engines were used not solely in agriculture. They were also commonly used in construction and for ancillary power at water mills and windmills.

Omitted from the Factory Returns, we have vanishingly little quantitative evidence concerning portable engines' power contribution, although the (impressionistic) evidence is that this was considerable, certainly in an agricultural county such as Suffolk. For instance, it was estimated that, between 1855 and 1859, the combined horsepower of the portable engines manufactured by the five leading East Anglian manufacturers (including Ransomes and Garrett) equated to 40 000 ihp.[49] Of course, a lot of these engines were built for export from the region, and this figure also does not include smaller Suffolk firms that manufactured portable engines over this period, such as Turners (who employed 140 men and boys in 1861),[50] W.P. Wilkins (131 in 1861),[51] Whitmore & Binyon (60 in 1855),[52] William Bear (27 in 1861),[53] William Syrett (11 in 1861),[54] and Woods & Co., and who presumably supplied more local markets.

Despite their likely importance, portable engines have been excluded from the census prepared here for two main reasons. The first concerns the census's accuracy. Without a specific location to distinguish between engines, the likelihood of 'double' counting increases (and stationary engines without a location have been excluded from the census for this reason). Second, portable engines were not included in the Factory Returns (indeed, it is telling that the inspectors made no attempt to include them). Nonetheless, rough estimates from a comparative exercise with the United States are presented later. With these caveats in mind, we can now examine the Suffolk census of (stationary) steam engines.

IV | RESULTS

The Factory Return for 1850 records a total of 17 nhp of steam installed in Suffolk produced by three engines working at silk mills at Glemsford, Hadleigh, and Nayland.[55] By contrast, the census indicates that there were 66 stationary steam engines working in Suffolk, yielding a combined 697 nhp.

This discrepancy is almost entirely attributable to the sectoral coverage of the early Returns, which were limited to textile factories. The census only includes one engine that ought to have been included in the 1850 Factory Return, an 18 nhp engine installed at Glemsford silk mill in 1849, replacing the old one which had been recorded by the Factory Inspectorate.[56] The remaining 63 engines worked in sectors that were not covered by the Factory Return. Predictably, half of these

48 Shaw-Taylor, 'Agrarian capitalism', p. 32.

49 Collins, 'Power availability', p. 211.

50 TNA, RG 9/1162, p. 16. Turner manufactured its first engine in 1842, and its first portable engine in 1849. Clark, *Steam-engine builders*, p. 72.

51 TNA, RG 9/1165, p. 10.

52 Clark, *Steam-engine builders*, p. 77.

53 TNA, RG 9/1130, p. 33.

54 TNA, RG 9/1141, p. 9.

55 The horsepower figure is from Great Britain. *Return*, 1850, p. 8. The silk mills are identified using Great Britain *Reports of Inspectors*, 1850, p. 55.

56 Watkins, *Stationary steam engines*, p. 115.

TABLE 1 Stationary steam power in Suffolk, 1850.

Sector	1850 Factory Return (nhp)	Steam engine census (nhp)	Total number of engines
Textiles			
Silk	17	32	3
Metal manufactures			
Foundries	–	6	1
Manufacture of machinery	–	28	2
Chemical works			
Oil and oil cake	–	26	3
Miscellaneous chemical works	–	5	1
Manufactures connected with food			
Breweries	–	45.5	7
Miscellaneous	–	11.5	3
Manufactures connected with building			
Builders	–	8	1
Marble and stone mason	–	8	1
Carpenters, joiners	–	72	3
Paper manufacturing			
Papermaking	–	72	4
Miscellaneous manufactures			
Ropemaking	–	4	1
Shipbuilding	–	8	1
Letterpress printing	–	5	1
Coachbuilding	–	10	2
Milling	–	211	20
Municipal			
Sanitation	–	34	4
Land drainage	–	120	5
Port maintenance	–	32	2
Unknown		9	1
Total	17	697	66

engines were related to food processing, including 20 engines (producing 211 nhp) working at flour mills and seven at breweries (45.5 nhp) as well as five engines draining land for agriculture (120 nhp).

Critically, as can be seen in table 2, the 1870 Factory Return has the same shortcomings despite its much broader sectoral coverage. The first column provides the sectoral categorization, which for comparability is the same as the one used in the 1870 Factory Return (and the same as in table 1). In the bottom quarter of the table are those sectors which were not included in the Return. The second column provides the sectoral distribution of indicated horsepower in Suffolk, as reported in the 1870 Return. The third column provides the sectoral distribution of ihp, as recorded by the steam engine census. To ensure these are comparable with the results of the

1870 Return, two adjustments have been made to horsepower figures from the census which were not necessary for the 1850 Return. Firstly, figures in the 1870 Factory Return were reported in ihp, which is not always recorded for engines in the census. Where it is not recorded, for engines erected before 1850, it has been assumed that an engine's ihp was 1.5 times that of its reported nhp (consistent with Rankine's lower bound mentioned in section I). As working pressures increased, for those engines erected during the 1850s (or earlier engines if they were specifically recorded as working at higher pressures), an engine's ihp is assumed to be 2.5 times nhp and for those engines erected during the 1860s and 1870, 3.5 times. These are intended to be cautious adjustments. In 1865 the engineer John Bourne noted that 'in the average class of modern engines the actual power may be taken at 4 to 4½ times the nominal power'.[57]

A second adjustment was also necessary. Contemporaries during this period usually rated horsepower at capacity (that is, an engine's maximum working capacity), a convention that has been adopted for the engines in the census and, unless stated otherwise, applies to the horsepower figures cited in this paper. However, the 1870 Factory Return recorded power in use, that is, an engine's usual working load. Consistent with Kanefsky, it has been assumed that power in use in manufacturing (i.e. those sectors entering the Factory Return's remit) was equivalent to 80 per cent of capacity and, in other sectors, 60 per cent.[58] The fifth column reports the total number of engines in each sector.

The first point to make is that, although the 1870 Return had a much broader sectoral coverage than its 1850 counterpart (essentially all manufacturing), there were still significant omissions, especially flour milling (accounting for 1059 ihp), comparable with the largest sector included in the Return itself, manufacture of machinery (996 ihp).

Second, even in those sectors that were covered by the Factory Return, there remained significant omissions. While the Return reported 17 ihp in silk mills, the census indicates there was actually 134 ihp. In total, whereas the Factory Return reports a total of 1792 ihp in Suffolk, the census reports 3618 ihp in these same sectors. Especially important were the manufacturing of machinery (996 ihp) and artificial manures (706 ihp).

Third, there are some minor sectors where steam-powered installations have been missed by the census but recorded in the Factory Returns (serving as a reminder that the census also omits engines and that these results should be seen in this light). For instance, the latter records that there were 10 ihp installed in a cotton manufactory in Suffolk, but there is no record of such an engine in the census. In those sectors where the Factory Return records more installed ihp than the census and there is no ambiguity over which sector to assign an engine, this has been used to produce a final estimate for total installed horsepower in Suffolk in 1870, as reported in the fourth column of table 1. Those sectors where the Factory Return has been used are highlighted by a dark border. This produces a final estimate of 3643 ihp in use in those sectors covered by the Factory Return, and a total of 5171 ihp in use – nearly three times the 1792 ihp in use recorded in the Factory Return.

[57] Bourne, *Catechism*, p. 40. And if we reduce the multiplier to two for engines installed in the 1850s and 2.5 times for the 1860s and 1870, the results do not change significantly, yielding a total of 4627 ihp. in use in 1870, as opposed to 5186 ihp in the main text.

[58] Kanefsky, 'Motive power', p. 373. To illustrate these various adjustments, we can take the 10 nhp engine installed at Edward Greene's brewery in Bury St Edmunds in 1836 and which remained operational until 1926 (Clark, 'Early engines', p. 391). As it was erected before 1850 and there is no indication that it worked at high pressures (i.e. above 7 pounds-force per square inch), it has been assumed to be equivalent to 15 ihp capacity. This figure has in turn been adjusted to 12 ihp in use, and it is this figure which has been used to compile the third column of table 2.

TABLE 2 Stationary steam power in use in Suffolk, 1870.

Sector	1870 Factory Return (ihp)	Census (ihp)	Combined (ihp)	Total number of engines
Textiles				
Cotton	10	–	10	1
Flax	90	109	109	4
Silk	17	134	134	6
Hair and fur	–	13	13	1
Bleaching and dyes	14	13	13	2
Handloom weaving	9	–	9	1
Hatters	–	7	7	1
Others	30	30	30	2
Metal manufactures				
Foundries	47	83	83	7.5[a]
Manufacture of machinery	445	996	996	21
Miscellaneous articles of metal	88	–		
Leather				
Tanners and curriers	21	47	47	4
Miscellaneous articles	4			
Chemical works				
Oil and oil cake	113	97	97	3.5
Artificial manures	309	706	706	15.5
Miscellaneous chemical works	40	70	70	8
Manufactures connected with food				
Bakehouses, biscuits, confectionary	6	27	27	4
Breweries	72	246	246	22
Sugar refineries	50	234	234	8
Miscellaneous	136	106	106	11
Manufactures connected with building				
Builders	100	56	56	1.5
Carpenters, joiners	51	178	178	19
Miscellaneous	–	70	70	3
Paper manufacturing				
Papermaking	64	185	185	4
Miscellaneous manufactures				
Ropemaking	10	11	11	2
Bricks and tiles	10	13	13	2
Shipbuilding	16	56	56	1
Letterpress printing	55	70	70	10
Coachbuilding		34	34	3
Tobacco and cigars	6	–	6	1
Miscellaneous	6	27	27	2
Subtotal	1792	3618	3643	171

(Continues)

TABLE 2 (Continued)

Sector	1870 Factory Return (ihp)	Census (ihp)	Combined (ihp)	Total number of engines
Milling	N/A	1059	1059	96
Agriculture	N/A	179	179	15
Land drainage	N/A	167	167	8
Utilities				
Sanitation	N/A	88	88	8
Port maintenance	N/A	29	29	3
Street lighting	N/A	5	5	1
Services	N/A	6	6	2
Unknown	N/A	12	12	1
Subtotal		1543	1543	134
Total	1792	5161	5186	305

[a]Where an engine was used as a power source for two different sectors, it has been divided between them, explaining the '0.5' in some of the column entries.

Even though the figures in tables 1 and 2 are lower bound estimates, the census still confirms that the Factory Returns offer a wholly inadequate basis from which to estimate total installed power in the United Kingdom during the nineteenth century. Before 1870 it says nothing about the economy outside of textiles, and the suggestion that large parts of the economy 'were virtually untouched by steam' is an artefact of this.[59] But it also omits the majority of engines that should have entered its remit. Compounding this is that Suffolk was one of only eight English counties in 1870 that reported a full return of factories and workshops. All this means that, when we estimate national steam power adoption for 1870 by extrapolating from the results of the Suffolk census (table 3), these estimates almost certainly understate the adoption of steam power.

For comparability with the secondary literature, the discussion here returns to steam power capacity. In particular, whereas Kanefsky estimates a total installed capacity in the United Kingdom (including Ireland) of 2 065 000 ihp for steam, here the estimate is 60 per cent higher at 3 297 150 ihp. The most important reason for this discrepancy is the new estimate for steam power in manufacturing, which was omitted from the Factory Return. Kanefsky estimated that 195 347 ihp of steam and water power was used in manufacturing but had been omitted (inadvertently or otherwise) from the Factory Returns. Here, the figure for steam alone is 1 009 000 ihp. Given that the steam engine census figures are lower bound estimates, this indicates there was at least twice as much steam power in British manufacturing in 1870 than previously thought.

There are also significant adjustments made for estimates of steam power in milling and 'other' sectors, comprising mainly agriculture – and this latter figure would be much higher if portable engines were included. For a crude approximation of steam power adoption in British agriculture (stationary as well as portable), we can turn to the United States, where in 1880 there was reported to be 1 200 000 ihp in use on American farms (earlier figures are unavailable).[60] If we assume that the intensity of steam adoption by agricultural output was the same in Britain in 1870 as it was in America 10 years later (defensible given that the use of portable engines in American agriculture

[59] Crafts, 'Steam', p. 342.

[60] Wik, *Steam-power*, p. 84. The graph on the same page implies a total of 2 000 000 ihp, but we use the figure stated in the main text derived from US Department of Agriculture statistical bulletins.

TABLE 3 New estimates for total installed steam horsepower capacity in the United Kingdom (including Ireland).

	Factory Return (1870)			Kanefsky (1979)			Steam engine census			
	Steam in use	Water in use	Steam and water in use	Steam capacity	Water capacity	Steam and water capacity	Steam in use	Steam capacity	Water capacity	Steam and water capacity
Manufacturing (included in Factory Return)	976 802	55 600	1 032 560[a]	1 221 000[b]	100 000	1 500 000	976 802	1 221 000[b]	100 000	2 582 250
Manufacturing (omitted from Factory Return)			167 440	179 000			1 009 000[c]	1 261 250[b]		
Manufacturing (total)			1 200 000	1 400 000	100 000	1 500 000	1 985 802	2 482 250	100 000	2 582 250
Coal mines			300 000	500 000	–	500 000	300 000	500 000	–	500 000
Other mines			60 000	65 000	35 000	100 000	39 000	65 000	35 000	100 000
Utilities[d]			36 000	55 000	5000	60 000	23 100[e]	38 500[f]	5000	43 500
Grain mills			54 000	25 000	65 000	90 000	95 550[g]	159 250[f]	65 000	224 250
Others[h]			18 000	20 000	30 000	50 000	31 300[g]	52 150[f]	30 000	82 150
Total	976 802	55 600	1 668 000	2 065 000	235 000	2 300 000	2 435 750	3 297 150	235 000	3 532 150

[a]The reported total for steam and water power in use in the 1870 Factory Return is 1 032 402, although Kanefsky appears to have rounded this upwards to yield a total estimate for steam and water power in use in Factory Return sectors of 1 200 000 ihp.
[b]Estimated by assuming that 80% of steam capacity was in use.
[c]Estimated assuming that the rate of omission of steam power in the United Kingdom was the same as in Suffolk.
[d]Comprising sanitation, port maintenance, and street lighting.
[e]Estimated assuming that the adoption of steam power was proportional to urban population. For this exercise, urban population was taken to be equivalent to total population living in cities and towns with a population of at least 2000 as recorded in the 1871 census. This yields a total urban population in Suffolk of 80 751 (Price-Williams, 1880, p. 481), compared with a total of 15 305 466 for England (12 182 794), Scotland (1 919 528), and Ireland (1 201 344).
[f]Estimated by assuming that 60% of steam capacity was in use.
[g]Estimated assuming that the adoption of steam power in other sectors was proportional to overall population. In the 1871 census, the population of Suffolk was 349 000, while the overall population of the British Isles was 31 484 000. Thus the population of Suffolk comprised 1.1085% of the British total, and it is assumed that it also comprised 1.1085% of installed steam power used in 'other sectors' (especially agriculture and land drainage). If, instead, we assume it was proportional to the percentage of the installed steam power as reported in the original Factory Return, then this estimate increases 189 150 ihp in use.
[h]Comprising services and agriculture.

was largely experimental before the Civil War)[61] and that British agricultural output by value in 1870 was roughly 46.5 per cent that of America in 1880, this implies that there was roughly 560 000 ihp in use in British agriculture in 1870.[62]

Finally, given that there was no mining activity in Suffolk, there is no reason to alter Kanefsky's estimates for installed power in mining sectors. The same point applies for water power, although it is conceivable that the 1870 Factory Return omitted power inputs from water to the same extent as it did for steam.

However, observing that steam power was much more widely adopted in British manufacturing in 1850 and 1870 than the Factory Returns indicate is not equivalent to arguing that they played a causative role in the industrial revolution, conventionally dated to the period *c*. 1760–1830.

When we plot the adoption of stationary steam power in Suffolk between 1800 and 1870 (figure 1), we can see that steam was seldom used into the 1830s. As late as 1837, there were only 16 (documented) engines in the whole county, producing a combined 145 nhp (or approximately 229 ihp). After this, however, we enter the 'take-off' stage of technology adoption, with the amount of ihp in Suffolk doubling every 6–7 years until at least 1870. This 'take-off' precedes the widespread application of high-pressure steam to industrial purposes, which was previously thought to have been necessary for the increasing adoption of steam engines in the third quarter of the nineteenth century.[63] (And recall that the census does not report when engines started operating but rather when they are first recorded. Exponential growth in stationary steam power in Suffolk may have started earlier). Instead it is coincident with contemporaneous transport improvements. Given that Ipswich was a port town and the river Gipping was navigable to Stowmarket, this refers specifically to improvements in coastal shipping (even in the early 1860s, barely 30 per cent of coal in London was delivered by rail).[64] The period saw significant improvements in productivity in coastal shipping, and in 1842, the country's largest wet dock was opened at Ipswich.[65] Diminishing freight costs meant that coal prices converged to pithead levels and that steam engines were now cheaper to operate. We know certainly for the eighteenth century that coal prices were one of the critical determinants for the geographical distribution of steam engines, and tentatively the same process occurred in the first half of the nineteenth century.[66]

Of course, we are only looking at one atypically agrarian county with relatively expensive coal prices. While Suffolk is likely representative of other agrarian counties with high coal prices such as Hertfordshire and Sussex, it tells us less about the chronology of steam power adoption in industrial pioneers such as Lancashire or Yorkshire. However, given that these industrial counties already had low coal prices and that the wider sectoral adoption of steam power was not

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[61] Ibid., p. 21.

[62] This is a much higher estimate than one previously prepared by Collins for 1880 – 175 000 ihp – although he considered this figure to be 'largely guesswork' (Collins, 'Power availability', p. 212). Concerning the estimate that British agricultural output by value was equivalent to 46.5% of American output in 1880, the starting point is the estimate in Turner, 'UK agriculture', p. 42, specifically the revised 'Bellerby 2' figure for 1867–9, presenting an annual average for the 3 years of £220.7 million. By comparison, the nominal value of total US agricultural output in 1879 was $2 212 540 927 (United States, *Census of agriculture*, p. 4). Converting the figure for Britain from 1868 GBP to 1879 USD produces a figure of $1 030 000 000 (an average of two conversion methods on https://www.measuringworth.com/calculators/exchange/result_exchange.php (accessed on 23 November 2023).

[63] Crafts, 'Steam'.

[64] Hawke, *Railways*, p. 168.

[65] Bogart et al., 'Coastal shipping'.

[66] Nuvolari, Verspagen, and von Tunzelmann, 'Diffusion', pp. 313–4.

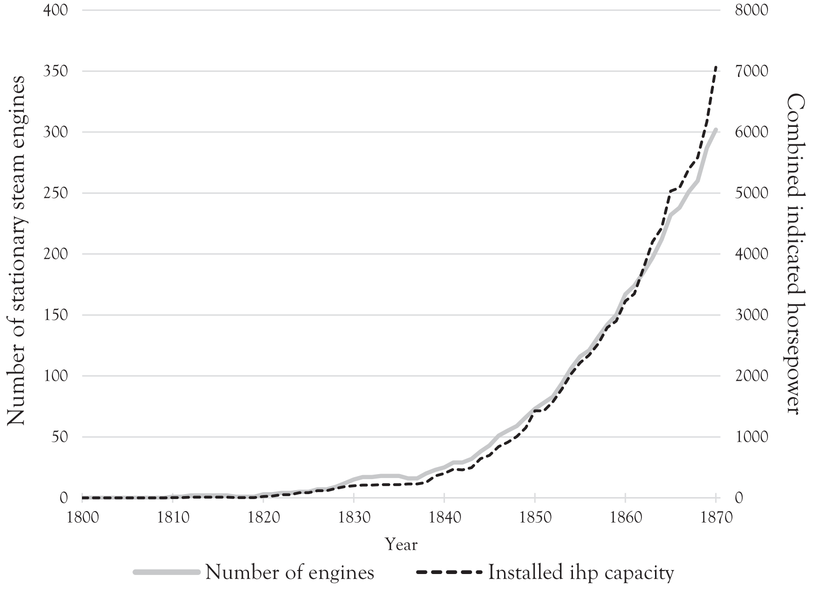

FIGURE 1 Stationary steam power capacity in Suffolk 1800–70.

contingent on the fuel efficiencies augured by high-pressure engines, it does resurrect the possibility that, nationally, steam was adopted at a wider level and at an earlier period than has been previously suggested.

V | SOCIAL SAVINGS

To this point, the paper has focused on estimating the power contribution steam made to the Suffolk/national economy. However, steam power's greatest significance was not so much that it resulted in an unprecedented quantitative contribution to the provision of mechanical power (although it did) but rather that it permitted entirely new processes of raw material extraction, manufacturing, and service provision – processes and services that were unachievable using other power sources available at the time (i.e. water and wind). This is not captured in a standard social savings analysis which assumes that power sources were ultimately substitutable with one another as only a matter of cost. It is this assumption which explains why social savings analyses have consistently concluded that steam power (and other technologies) made a modest contribution to economic development.

We can take the example of urban sanitation and water supply. The nineteenth century witnessed rapid and unprecedented urbanization. In 1801, approximately 34 per cent of the population of England and Wales lived in towns containing more than 2500 inhabitants (already an exceptionally high figure relative to other European countries), a figure which increased to just over 78 per cent by 1901.[67]

Although urban areas had conventionally been associated with higher mortality rates, the period saw significant advances in average life expectancy, increasing from 41 years during the

[67] Law, 'Urban population', p. 130.

1840s to 50.5 years during the 1900s.[68] This decline in mortality was achieved primarily through the increased provision of sanitation infrastructure. Chapman shows that up to 60 per cent of the urban mortality decline seen in England between 1861 and 1900 can be attributed to spending on sanitation infrastructure, which had in turn sharply reduced mortality due to water-borne diseases such as cholera, dysentery, typhoid, and polio.[69]

From a technical perspective, these improvements in sanitation were premised on the availability of steam power. In the case of London, from 1875, sewage was pumped out of the city by four massive pumping stations, generating a combined 2528 ihp. The largest station at Abbey Mills in the East End generated 1168 ihp.[70] This concentration of power output was not technically feasible using water power. An 'above average' vertical water wheel of the period generated 40 ihp. The world's most powerful waterwheel in New York state generated an estimated 280 ihp.[71] Rather than directly replacing water for steam at the four pumping stations, might it have been possible to use standardized water wheels of 40 ihp at around 60–65 sites (that is, the overall power requirement of 2528 ihp divided by 40)? These would have had to have been positioned along the course of the five main sewers which ran parallel to the Thames at a distance of roughly 1 mile until they discharged at Barking and Plumstead.[72] Therefore, the waterwheels would have been powered not by the Thames but rather by its London tributaries. In this case, it is doubtful there was a single site available that could have provided 40 ihp, let alone 60.[73] Instead, might it have been possible to alter the routes of the main sewers to maximize the advantage of what water power there was? The routes had been partly chosen to maximize the advantage of elevation changes in the Thames Basin (i.e. to use gravity to move sewage), so altering the routes would only have increased the power required.

The power required to supply fresh water to the metropolis was greater still. In 1869, London was supplied by eight water companies, using 93 steam engines producing a combined 10 566 ihp.[74] Ultimately, given the topography of London and the power requirements of urban sanitation, there was no alternative to steam. Moreover, the same limitations applied at the other end of the urban hierarchy. Returning to Suffolk, Bury St Edmunds is a medium-sized market town, which experienced relatively modest growth over this period (its population grew from 7655 in 1801 to 16 255 in 1901). In 1858, the town's Paving Commissioners solicited technical advice on supplying water to the town. Summarized by a Mr. Croft, the advice was emphatic: 'it was utterly impossible to raise water into the town by hydraulic power: there was not sufficient fall [of the river]'.[75] When a steam engine was installed for this purpose the following year, it was rated at a modest 3 nhp (approximately 8 ihp). It is revealing of the limitations of water power that it could not have been relied upon to produce 8 ihp consistently.[76]

[68] Office for National Statistics (ONS), https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/lifeexpectancies/articles/howhaslifeexpectancychangedovertime/2015-09-09 (accessed on 26 April 2023).

[69] Chapman, 'Infrastructure investment', p. 233.

[70] Douet, 'Pumping stations'.

[71] Rollinson, 'Castleford Mills', p. 58.

[72] Douet, 'Pumping Stations', p. 137.

[73] Blythman, *Mills of Middlesex*.

[74] Great Britain, *Water supply*.

[75] *Bury Free Press*, 10 July 1858, p. 7.

[76] *Bury and Norwich Post*, 8 November 1859, p. 2.

Conceivably, water could have been supplied to Bury using literal horse power. Four-horse mills had been common in the first half of the century,[77] and when technical advice had first been solicited in 1851, this was considered (albeit at a lower estimated power requirement of 1.5 nhp, which would have been equivalent to the power output produced by four horses).[78] The power requirements, though, for pumping sewage away were too great for horses to be feasible. By the mid-1860s, the rivers that ran through Bury (the Lark and the Linnet) had become 'polluted to an almost intolerable extent', and an attempt at deodorizing them had failed.[79] To resolve the problem, in 1867 the Paving Commissioners installed an 8 nhp engine (approximately 20 ihp) to lift sewage away from the town and to manure nearby fields. Unsurprisingly, there is no indication they considered alternative power sources. Water was clearly inadequate, and attempts elsewhere to use more than 16 horses in lifting water had encountered insurmountable technical issues.[80] The only technically feasible power source for pumping sewage away from Bury St Edmunds, not a large town by contemporary standards, was steam. To summarize, outside the most topographically advantageous locations, absent steam power, absent also was modern sanitation, and accordingly absent were the improvements in hygiene, mortality, and life expectancy this augured.

Not only did steam power ameliorate the (in)sanitary consequences of rapid urbanization, but it also was an essential enabling factor. Whereas power generation from environmental sources was available in only certain areas (and then power generation needed to be spatially dispersed), neither condition applies to steam, thereby removing a critical locational constraint on power output and industrial concentration. In the case of water power, a critical limitation was that power generation had to be dispersed along rivers. The most powerful waterwheels, those capable of producing 40 ihp, were overshot designs where the wheel was rotated by the weight of water falling into buckets just past the top of the wheel. However, overshot designs require a significant height drop ('fall') in the river to be practicable, at least equivalent to the height of the water wheel itself. Finding suitable sites was straightforward in upland areas – although these are usually those areas furthest from supplies of (non-mineral) raw materials and from centres of greatest (urban) demand. Conversely, those areas where the most 'useful' work might be accomplished (lower-lying urban areas) also had the fewest available sites for overshot wheels. Instead, less powerful designs, but ones which required less available fall in the river, had to be adopted, such as undershot wheels, where the wheel was powered by the flow of the river itself. Nonetheless, available sites using these designs were also soon exhausted in urbanizing areas. In Birmingham, it appears this point had been reached by 1700 when 'nearly all the available sites within a five-mile radius of Birmingham had been occupied'.[81]

In brief, water power had to be linearly dispersed along a river, and the river's gradient further constrained the density of power generation.[82] Generating wind power did not have the same locational constraint. While some locations were more advantageous than others, ideally an open plain or field, of which Suffolk had an abundance, siting a windmill at one spot did not preclude another windmill being built in close proximity. At one point in the 1820s, there were seven

[77] MacDonald, 'Early threshing', p. 75.

[78] Suffolk Record Office (Bury St Edmunds), Printed report to the Paving Commissioners by George R. Burnell on the supply of water to the town, EE 500/41/1, 4 October 1851.

[79] *Suffolk Chronicle*, 16 March 1867, p. 8.

[80] Brunner and Major, 'Water raising'.

[81] Pelham, 'Water-power crisis'.

[82] Chandler, 'Anthracite coal'.

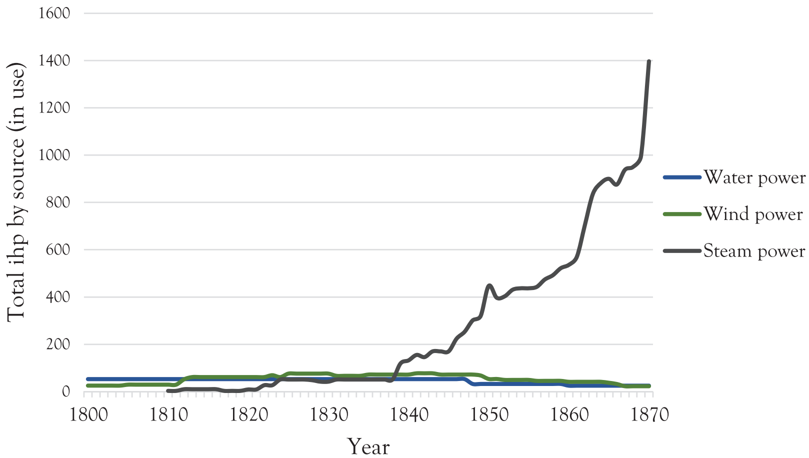

FIGURE 2 Stationary power supply in the borough of Ipswich, 1800–70. [Colour figure can be viewed at wileyonlinelibrary.com]

windmills clustered within 200 m of each other on the eastern outskirts of Ipswich.[83] However, power generation is contingent on weather conditions (the wind needs to be blowing), and this clearly cannot be managed in the way that water can be stored in reservoirs. Consistent, reliable power supply, critical for most industrial processes, is impossible to achieve with wind power. Moreover, maximum power output was far more limited than was the case even with water. One noteworthy instance illustrating both these points occurred in 1949 when the largest operational post mill in the country ground 40 coomb of grist in a single night during a gale storm – as much work as it done in the previous 12 months.[84] This also equates to a power output of roughly 30 ihp, which can be considered the absolute maximum power output achievable with wind during the nineteenth century.[85]

These constraints are illustrated in figure 2, plotting stationary power in Ipswich (defined by borough boundaries, a roughly 3 by 3 mile area) from all sources between 1800 and 1870. Starting with water power, Ipswich was poorly served by potential sites, located where the river Gipping becomes a tidal estuary, meaning there was not a continuous, unidirectional flow of water to power a wheel in the conventional manner. Instead, three tidal mills were erected in the eighteenth century, which worked by pooling water from the incoming tide and then releasing it with the outgoing tide. The limitation encountered was the lack of sites where enough tidal water could be stored, and no more tidal mills were built during the first half of the nineteenth century – this despite Ipswich's population almost trebling from 10 185 in the 1801 census to 28 863 in 1851.[86] As with Birmingham *c.* 1700, the potential for water power in the vicinity of Ipswich had been exhausted by 1800.

[83] Details of windmills in Ipswich are derived from the prior work of Peter Dolman, available at Mills Archive, Reading, Ipswich windmills, DOLM-12538.

[84] Freese, *Windmills* p. 112.

[85] Kanefsky, 'Diffusion of power technology', p. 78.

[86] Details of watermills in Ipswich are derived from the prior work of Peter Dolman, available at Mills Archive, Reading, Ipswich watermills, DOLM-12612 and available online at https://catalogue.millsarchive.org/ipswich-watermills (accessed on 26 April 2023).

Wind offered very limited scope for harnessing additional mechanical power, with the number of windmills in Ipswich increasing from 6 in 1800 (yielding an estimated 38 ihp capacity – as with the tidal mills, the in-use figure would be less than half this given potential working hours) to 17 (116 ihp) in 1841.[87] Moreover, all of these windmills were used exclusively for grain milling. Given that wind power was a relatively limited and intermittent source of power, it was unsuitable for other industrial purposes. And after 1841, coincident with the fall in coal prices and the increasing adoption of steam engines, the number of windmills in Ipswich declined to 5 (34 ihp) by 1870.

Of course, none of these constraints applied to steam power. Hundreds of horsepower could be generated at one site if necessary. The Eastern Union Mills erected in 1846 had 16 pairs of stones driven by two 18 nhp engines. Given that each engine drove eight pairs of stones each, they would have had an approximate 128 ihp. One steam-powered mill had roughly the equivalent power of all windmills in Ipswich – and of course, it could work all hours of the day.

And unlike water, the power generated at one site did nothing to curtail a neighbour's potential power output. An industrial area developed on the right bank of the River Orwell, where the wet dock had opened in 1842. By 1870, Packard, a fertilizer manufacturer, had two engines producing 193 ihp at their Ipswich plant. This did not prevent their Duke Street neighbour, the agricultural implement manufacturer Ransomes, from installing four engines, totalling 500 ihp, and a coterie of other power-hungry businesses developed in their vicinity. To labour the point, it is inconceivable using the technology of the period that water or wind could have reliably supplied the amount of power generated at a single worksite such as Packard or Ransomes, let alone in the entire borough of Ipswich.

VI | CONCLUSION

The belief that steam's contribution to economic growth was only 'modest' is contingent on three assumptions: that the only significant point of difference between steam and other power sources was cost, that steam could invariably be substituted with other power sources, and that we have a broadly accurate quantitative picture of the adoption of steam power during the nineteenth century.

This paper has demonstrated that each of these assumptions is untenable. In reverse order, the Factory Returns assuredly do not provide an accurate quantitative picture of power provision during the nineteenth century (as previously emphasized by Kanefsky). More likely, British manufacturing used at least twice as much steam horsepower in 1870 than prior estimates have indicated.

Similarly, steam was emphatically not interchangeable with water or alternative power sources. Even at relatively modest power requirements, depending on circumstances, steam was the only available solution, as evidenced by the case of sanitation in Bury St Edmunds. This also speaks to the first assumption: that the only major point of difference between water and steam was one of cost. This was assuredly not the case. Steam enabled far greater power output and at a far greater density than could possibly have been achieved with environmental power sources. Social savings' assumption of substitutability predetermines its results.

[87] Consistent with Kanefsky, 'Diffusion of power technology', pp. 77–78, 227, it has been assumed that post mills yielded an average of 4 ihp in use and smock mills 5.33 ihp.

The paper has offered less evidence on the positive side, that is, to demonstrate or quantify the contribution steam made to economic development during the nineteenth century and/or for the traditional industrial revolution period. It can be stated with confidence, though, 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.

Finally, there is now robust evidence for America concerning the importance of inanimate power generally and steam in particular for generating improvements in industrial productivity. Evidence from the US Department of Labor's 1899 *Hand and Machine Labor Study* shows that the transition from hand to mechanized labour was associated with an 85 per cent reduction in the time required to complete production tasks. One-third of this productivity gain was directly attributable to the adoption of inanimate power sources and the fact that the effect of adopting steam 'was much larger than water'.[88] In the event of future work, it is to be expected that the same would apply to the British case (Supporting Information).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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