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Lessons from the age of coal

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From the vantage point of the 1550s, few, if any, could have predicted the dramatic growth of Britain's coal industry – and the profound effect that it would have by making energy so abundant. Coal was an ancient but relatively insignificant fuel, especially as compared to wood. It had been used for centuries for some specific blacksmithing tasks and was occasionally used in the making of lime, for mortar.[1] In some places, where coal that was especially lacking in impurities could be found – like in Aachen (Germany), south-western Wales, the Scottish Lowlands, Nottinghamshire and near Wigan — it was also occasionally used to heat people's homes. The highest-grade Scottish coal, found in Fife, was so pure that it was preferred to both peat and wood: the fuel of choice in the hearths of the rich and the royal.[2]

In the mid-sixteenth century, however, the demand for *lower*-grade coal very suddenly and dramatically began to increase. Coal of all grades, wherever it could be found in England, Wales or Scotland, whether inaccessibly inland or conveniently by a river or the sea, was within just a few decades being exploited at a scale never before seen. By 1700, the output of essentially every coal region in Britain had ballooned to easily ten or more times the size it had been in 1550. The output of Northumberland and Durham, despite producing some of the smokiest and most sulphurous coal in the country, grew especially large, by fourteen times.[1] Even as early as 1640, on the eve of the English Civil War, Britain was perhaps mining some 1.5 million tons of coal each year[3] – an estimated three times as much as the rest of Europe combined.[4]

The initial demand for all this coal came from ordinary people of modest means, to heat their homes. By installing chimneys and purpose-built iron grates, and mixing the coal with other materials into briquettes, even sulphurous Northumbrian coal could be burned within the home without leaving its inhabitants crying and coughing from the fumes. Wood or charcoal fires, by contrast, had involved a central hearth, their light smoke swirling through the rafter and exiting through gaps in the roof.[5] The spread of new methods of burning lower-grade coal – far cheaper than all other fuels – thus unleashed the coal industry's extraordinary growth. Any surface seams within 12-15 miles' walk of population centres were rapidly exploited, and the search was on for mines that could be dug within easy reach of navigable rivers or the sea. The seams along the rivers Tyne and Wear in Northumberland and Durham, which could most easily fuel London – already by far the largest city in the country, and growing further still – saw the most dramatic expansion in activity.[2]

The rapid expansion in the supply of this already-cheap fuel provoked the growth of many other industries, particularly near the coal pits themselves, where it was cheapest. The lowest-grade coal – a byproduct of the mining, unfit for burning in any homes – was increasingly used to make salt. Up until the late sixteenth century, the only cost-effective way to make salt in Britain was to locate a natural brine spring, like those at the various -wich towns (Droitwich, Nantwich, Northwich, Middlewich, etc.), and then boil the water away. Hotter countries, like France, had the major competitive advantage of being able to more reliably use the heat of the sun (the absolutist monarchy of the "Sun King" Louis XIV, funded by the *gabelle* duties on salt, was thus quite literally often powered by the sun). But the sheer increase in the availability of low-grade coal, especially along the eastern coast of England and Scotland, made it cost-effective to boil even sea-water, which was far less saliferous than spring brine, requiring 3-6 times as much fuel. Salt production thus not only expanded at the salt springs that were in reach of coal supplies but was also able to take place all within much easier reach of major population centres like London and the cities of the Netherlands. The salt pans all along the Firth of Forth became a major salt exporter to the Low Countries: one of the main foundations of the Scottish Lowlands' wealth going into the eighteenth century.[2]

The rapid expansion in the availability of the lowest-grade coal, fit only for boiling things in pans, likewise stimulated a host of other more niche industries: starch, soap for the cloth industry, candles (the chief source of lighting), saltpetre (the key ingredient in gunpowder) and alum and copperas (both used in fixing dyes in cloth). With a little adaptation, that same coal could also be applied to dyeing and brewing.

And the increased availability of coal of a middling or higher grade was also soon being applied – after some technical adaptation – to drying malt, baking bread, tiles, pottery and bricks, forging and working iron (though smelting iron with coal at any scale came later) and making copper, brass, lead, silver and tin. It was even used for the heat-assisted bending of wooden staves and beams for barrels, buildings and ships.[2]

The fuel-hungry glass industry, which was often blamed for the spoiling of the country's forests, by the 1610s had shifted to burning the highest-grade anthracite or "stone coal" found in Scotland, Wales and Nottinghamshire, and by the mid-1620s had managed to use even the lower-grade coals available from Newcastle. England's glass industry, having been scarcely existent in the mid-sixteenth century, was by 1700 the envy of Europe – especially as the fragile material could now be produced where it had the readiest and largest market, in the burgeoning metropolis of London itself.[2]

The rapid expansion of coal's availability also, in turn, increased the availability of some other energy sources – particularly, muscle. Lime, for example, anciently made with coal, was from the late sixteenth century produced at a dramatically expanded scale. As well as being used for mortar, lime was used as a soil acidity regulator, directly increasing the productivity of the same farms that were now served by coal as a heating fuel.[2] The grain that fed humans, and especially horses, was thus also made more available. Indirectly, too, the coal-fuelled expansion of British salt production meant that more food – especially fish and meat – could last longer, increasing the effective productivity of its pasture, rivers and seas. Indeed, wherever coal became more available it displaced traditional home-heating fuels – the peat found in fen and marsh, the furze or gorse of the heaths, and the wood of the forests – so that those lands could be converted to arable or pasture. Having been useful landscapes for centuries, marsh, heath and fen were recategorised as "wastes".[5] Coal thus, through a number of indirect channels, enabled the substitution of combustible fuels with food, effectively converting heat into muscle power.

The increased availability of muscle – particularly in the form of horses – was what powered much of the early machinery of Britain's cities, especially when what was needed was reliability (wind could be unreliable, and even water was prone to drought and frost. And both wind and water were only available in certain limited locations). Horses increasingly were put to work grinding the pigments for dyes and paints, tobacco for snuff, charred bones for shoe polish, tannin-rich oak bark for leather, flint for glass and ceramics, and grain for flour, beer and spirits. Horses fulled cloth, pounded rags into paper, flatted metal into sheets, and bored pipes, guns and even cannon.[6]

Only in the eighteenth century were horses gradually displaced by coal, especially in London. This began with the Newcomen steam engine replacing horses in the pumping of the city's water supply. And from the 1780s, once James Watt had reliably adapted the steam engine to direct rotary motion, coal was able to start displacing horses in the city's largest and most capital-intensive industries like flour milling and brewing.[6]

Horses would last even longer as the primary energy source for essentially all of Britain's early inland transportation and haulage, by road and canal (most early canals in Britain were in turn built with the explicit aim of extending the reach of coal, or coal-fuelled products, to more parts of the country). Even after horses were gradually displaced by the steam engines in factories, they were immediately needed in even greater numbers to haul those factories' increased output. London, despite decades of displacement by steam engines, by 1815 employed an estimated 31,000 horses, largely for haulage or transportation – one for every 45 of the city's inhabitants. They clogged the roads to such an extent that in the 1760s and 70s all of the city's old gates had to be removed.[6] England, as a seventeenth-century saying went, was infamously a "hell for horses".[7]

The growth of muscle power in humans was just as pronounced. Not only did Britain's population itself expand dramatically but its workers ate much more than anywhere else in the world. They generally ate far more, and especially far more meat, than other Europeans – something that all foreign visitors commented on in wonder. Recent estimates suggest that average calories per capita in Britain by the mid-eighteenth century was somewhere between 2,400 and 3,800 kcal, compared to the French 1,800 or so (some estimates even place English calories per capita as high as over 5,000 kcals in 1770). The average Englishman towards the end of the eighteenth century appears to have been about five centimetres taller than the average Frenchman. British workers thus had the added fuel to work harder, and given the lower chances of malnutrition during childhood, perhaps even smarter. An "industrious revolution" posited by some historians, whereby the English population seems to have worked more days in order to be able to afford more luxury goods, may partly be the result of the abundance of human muscle energy.[8]

Having newly abundant energy sources was one thing, but they also had to be connected to the places where energy was needed. The emerging British muscle- and coal-powered economy went hand in hand with the extension of transport infrastructure.

Managing the pre-electric grid

Both grain and coal had especially low values compared to their bulk, so they were only worth transporting when transportation costs were low. Overland haulage of coal was only cost-effective at a range of about 12-15 miles at the very most – it was significantly cheaper to float it in a barge downriver or in a ship along the coast. The navigation of rivers, digging of canals and building of railways were thus all akin to extending a modern electrical grid. They did not just convey goods for sale but extended access to power.

This process of grid extension began with making rivers more navigable by boat. In 1635 the River Thames was made navigable all the way from London to Oxford, making it easier to bring more grain from the inland counties to London and more coal to Oxford. The same was done for its tributary the Wey from 1651 onwards, extending coal further into the Surrey countryside and thereby swelling the size of towns like Guildford, while London gained access to more grain.[9]

Once the number of rivers that were worth making navigable had begun to dwindle, in the eighteenth century, attention then turned to digging canals. The Sankey Canal of 1757 – the opening salvo of the canal age — was dug to connect the growing port of Liverpool to the coal fields at Haydock and Parr, because its traditional supply of coal from Prescot had become too expensive. And the inspirational Bridgewater Canal of 1761, which even flowed over a river through an aqueduct and under hills through tunnels, was dug to supply Manchester from the coal mines of Worsley.[10] The Bridgewater Canal even helped to drain the mines, while relieving the region's roads from the excessive strain of coal-hauling carts and waggons.[11]

Yet such projects also sometimes came at the expense of an older, less connected, but still important energy source: water power. Getting sufficient water from a river to power a wheel often required collecting it into reservoirs with dams and weirs or channelling it into mill races, to divert it directly onto the wheels. But this could reduce the navigability of the river by boat, and increase the risks of surrounding land getting flooded.[12] Choosing water power – while it gave a big advantage in terms of very local energy production – thus sometimes came at the expense of a wider region's production of grain and its connection to the waterborne network for both grain and coal. The proprietors of the seventeenth-century Wey Navigation, for example, had to pay mill-owners along the river to keep the water penned up so that it was deep enough for barges, rather than letting it flow to turn their wheels. Despite these payments, it took almost two centuries of on-and-off disputes until the proprietors and mill-owners reached a proper agreement.[13]

Despite these occasional tradeoffs, water power was still used intensively in Britain, and on the whole acted as a complement to human muscle power. Waterwheels fed by aqueducts or other artificial channels had been used since ancient times, largely for milling flour or raising water for irrigation – in other words, as a means of enhancing the production and processing of grain to obtain more muscle power. Water power was thus mainly used initially to supplement the overwhelmingly important muscle energy needs of agrarian societies. Over the course of the seventh to thirteenth centuries, waterwheels were then adapted to more and larger watercourses, as well as to a wider variety of industrial uses – much like those mentioned above for horse power.[12]

They also helped give rise to the great mediaeval orders of monasteries. Saint Benedict, founder of the Benedictine order of monasteries in the sixth century, recommended the use of mills so that the monks would not have to be economically reliant on contact with the outside world. And Saint Bernard, founder of the Cistercian order, rebuilt Clairvaux Abbey in 1136 by applying the force of its stream to milling and bolting the monks' flour, fulling their cloth, and grinding the tannins for their leather shoes, as well as to irrigation, washing and clearing away their waste. The stream, which one impressed visitor described as though it was the monks' robotic servant – "it never shrinks back or refuses to do anything that is asked of it", freed them from various menial tasks to leave more time for prayer.[12] Just as countries today try to ensure some degree of energy self-sufficiency, water power provided the means for monasteries to insulate themselves from the outside world.

By the eighteenth century, essentially every available fall of water in Europe was being exploited to turn waterwheels. Some water power installations were vast. At Yekaterinburg in the Urals, a reservoir dammed in the 1720s eventually powered 50 waterwheels, producing an estimated 200-500 horsepower (in practice, equivalent to even more actual horses as the water never needed to rest), which in turn drove over a hundred bellows for blast furnaces, and dozens of machines for hammering, rolling, drawing and stamping metal.[12] Where there had scarcely been a village before, the region became the Russian Empire's industrial centre – Yekaterinburg is still Russia's fourth largest city. Abundant energy enabled urbanisation.

Even more dramatic was the exploitation of water power at the Harz mountains in Germany. From the late sixteenth century onwards, more and more of the region was dammed and canalled, such that by 1800 there were over 225 water wheels pumping water from mines, drawing up ore, stamping it and driving the bellows for lead, silver and copper foundries. In total, the complex probably produced more than 1,000 horsepower.[12]

Perhaps the earliest and largest water power complex in the world, however, was in the New World, at the largest silver mine in history – Potosi, in the Bolivian Andes. By the 1620s, dozens of Spanish-built dams were storing the water to power 132 ore-crushing mills, providing an estimated 600 horsepower.[12] This water-powered complex produced some 60% of the entire world's silver in the late sixteenth century. It enriched the Spanish Hapsburg Empire and allowed European long-distance merchants to trade for luxuries in the Indian Ocean and beyond, by being able to supply China's extraordinary demand for silver.[14]

Water power quickly hit upon constraints. Yet these were partly overcome in the eighteenth century as a result of John Smeaton's studies of the relative efficiencies of different kinds of wheels. The most common form of wheel was "vertical", with a horizontal axis, which itself came in two forms: undershot wheels whereby water pushed it at the bottom, typically hitting blades; and overshot wheels whereby water fell on them from above, filling buckets. Undershots were driven by impulsion, whereas overshots exploited gravity, being pulled by the weight of the water. The choice of using either an overshot or undershot wheel largely depended on the topography of the site where it was installed. But despite being ancient technologies, it was widely assumed before the 1750s that overshots and undershots were about equally effective.

What Smeaton showed, after years of experimentation with model waterwheels, then tested at scale, was that undershot wheels had an average efficiency of just 30%, whereas overshots had an average efficiency of 67%. He also established that their theoretical maximum efficiencies could also be increased, to 50% for undershots and 100% for overshots. These were important results, because they showed how to improve the waterwheel's efficiency. Smeaton argued the potential "mechanical power" from a stream was being wasted in impulse wheels, from the water having to change its figure when it hit the blades, manifesting as turbulence and splashes. (To illustrate, using impulse to drive a wheel was like trying to close a door by hitting it with a hammer, rather than applying a slow, smooth force.) Slowly and smoothly pouring water into the buckets of an overshot wheel, to let gravity do the work, was far more efficient.

Smeaton, as one of the most prolific engineers of the age, was personally responsible for converting many of Britain's waterwheels to take account of the superiority of gravity. Overshot wheels were adopted wherever practicable (e.g. where the fall of the water was sufficiently high), and where they were not, the undershots were adapted into "breast-shot" wheels, by pouring the water onto them more smoothly and as high as possible, so that at least some gravity was exploited. By 1800, it seems that essentially no undershot wheels were being installed in England, unless there was no other choice. Indeed, the work led to further experimentation on waterwheels. The application of iron to waterwheels meant they could be made much larger than wood alone would allow, and in the nineteenth century further experimentation led to the invention of highly efficient water turbines (which, having since been adapted to steam, are today used to generate nearly all the world's electricity.)[12]

The power output of water power thus continued to expand in Britain well into the late eighteenth century and beyond, despite the advent of coal and the increased availability of grain for muscle. Water was even, increasingly, complemented by coal.

In the decades before James Watt reliably adapted the steam engine to direct rotary motion, the much older Savery and Newcomen engines – which proliferated in the opening decades of the eighteenth century – had begun to be applied indirectly to mechanical functions by raising water into reservoirs, to then pass over waterwheels. These re-circulating or "returning" engines made pre-existing water-powered factories more reliable, supplementing the flow of water during times of drought or frost, as well as more generally keeping the reservoirs that fed them topped up. They replaced the backup role usually played by horse power.

In 1749 a large returning engine powered the brassworks of William Champion at Warmley, near Bristol. When it was replaced in 1761, it used the largest steam engine that had ever been built. Returning engines were also used to drive the bellows at various ironworks in the 1750s, and at Bersham Isaac Wilkinson used a returning engine that "shook the buildings and ground to a considerable distance" to power the blowing cylinders he had invented to supersede leather bellows for blast furnaces.[15] By the 1770s, James Watt would write that almost all the furnaces throughout the rapidly industrialising Midlands had their bellows worked with the aid of returning engines.[16]

Re-circulating engines gave the edge to many of the rapidly expanding woollen mills of West Yorkshire, and especially the cotton factories of late eighteenth-century Lancashire and Derbyshire: Richard Arkwright installed a returning engine at Cromford mill in 1780, and many more simplified Savery-type returning engines were installed by Joshua Wrigley throughout the region. Some of the water raised by the engines could also be applied to putting out fires – a constant threat in cotton mills, where the air itself could become so full of fibres that they were at risk of catching alight with even the slightest spark.[17] Returning engines were in the 1770s also being used in the Staffordshire potteries for grinding flint, at various mines to raise ore and coal. These alliances of coal and water were so widespread and successful that the first ever order for James Watt's revolutionary rotary steam engine, for the Deptford Naval Victualling Yard flour mill in 1781, was countermanded in favour of a returning engine because the great Smeaton doubted that directly using steam could ever be as reliable as a waterwheel.

Returning engines continued to be built well into the 1790s because, despite the growing fame of Watt's improvements. They were cheaper to build, and only burned as much coal as was needed "to make up temporary deficiencies in the reservoir or stream." They also had all the advantages that water power in general had, of smooth and constant operation, in a way that horses could not quite achieve. As late as 1834, much of the engine work at Boulton and Watt's own Soho Manufactory, just as at many other factories, was being provided by a returning engine – by an overshot waterwheel only supplemented by steam.[15]

The Dutch golden age of wind and peat: a cautionary tale

Britain's growing abundance of energy, with muscle, coal, and water all tending to reinforce the advantages of the other, was unprecedented in world history. The only society to come close, with a similar self-reinforcing combination of energy sources, was the Dutch Republic of the late sixteenth and early seventeenth centuries. Just as London became increasingly reliant on coal, the cities of the Low Countries – already highly urbanised – came to use peat.

The exploitation of peat began in the low-lying bogs of Holland and western Utrecht, during the dry season when the upper layers were more exposed and could be stripped away. This method soon exhausted much of the immediately available peat, but the development of the *baggerbeugel*, or dredging hoop, in around 1530 allowed peat to be cut below the water level and hauled up. This left behind a landscape pitted with lakes, but these could then be drained – if the underlying soil was of clay, rather than sand – to be converted into agricultural land. Peat-digging and drainage by the citizens of Utrecht, for example, created entirely new towns like Veenendaal (in English, it would be Fendale).

From 1551 the search for peat turned northwards, to the high-lying bogs of Friesland, Groningen, and Drenthe. Exploiting these peat bogs required digging canals to connect them to the network of Dutch rivers and coastline.

Peat, like coal, effectively needed to be connected to a kind of waterborne energy grid, because it was too costly to transport it even short distances overland. Despite the additional investment required to connect Dutch cities to these peat reserves, the bogs themselves lay above the water table, so could more easily be converted to agricultural land.[18] Indeed, it was Dutch expertise in creating these canals and performing these drainages that was then employed in England in the early seventeenth century when the rise of coal made it increasingly worthwhile to drain its marshes and fens.[19]

Abundant peat enabled the Low Countries as a whole to become one of the most urbanised regions in the world by the fifteenth century, and supported the Dutch Republic's extraordinary rate of urbanisation from the late sixteenth century too (when so many of the city-dwellers of modern-day Belgium emigrated north to the Netherlands). It also fuelled the seventeenth-century growth of the Dutch Republic's urban industries too: bricks, tiles, pottery, tobacco pipes, refined sugar, salt, soap, whale oil, glass, spirits and beer.[18] And just as coal in England increased the availability of land for agriculture, and thus of grain for muscle power, peat in the Netherlands did the same.

Yet the Dutch Republic was also supplied by another abundant and complementary energy source: wind.

On one level, the rise of the Dutch Republic to prominence in the first place was built on wind power: it was thanks to developments in ship design that the Dutch over the course of the sixteenth century became the dominant fishers and traders of northern Europe. The Dutch herring buss was essentially a floating factory, able to follow the fish wherever they migrated, immediately processing and salting them aboard the busses when they were freshly caught, rather than having to wait to get back to shore.[18] And Dutch ships – particularly the *fluyt* from 1595 onwards – were impossible to out-compete when it came to bulky cargoes. They were cheaper to build, required fewer sailors and were easier to handle. Their only disadvantage was that they were lightly armed, making them vulnerable during wartime.[20] Together, the herring buss and the fluyt allowed Amsterdam to become the grain depot of Europe, providing abundant imported grain to the Dutch too.

They bought up salt that had been evaporated with the heat of the French or Spanish sun and used it to buy up plentiful Baltic grain,[18] essentially using wind to convert solar energy into muscle. They also refined the salt further with the help of domestic peat and used it to preserve their buss-caught herring, which was exported throughout Europe.

And Dutch busses and fluyts were so cheap to make because they were themselves made with wind power. The Zaan river in Holland ran out into the coast just northwest of Amsterdam and had sites all along the river that were unobstructed from the wind. With the river itself making it easy to bring in timber, and with its rural situation meaning it had no guilds to drive up wages, the region was transformed by the invention of the wind-powered sawmill by Cornelis Corneliszoon van Uitgeest in the 1590s. The Zaan was soon overrun with wind-powered sawmills supplying planks to shipbuilding wharves all along its banks, and a major centre for sailmaking too. It became the Dutch Republic's chief source of ships – the wind-powered reason the Dutch could catch the wind so well at sea.[20]

In the 1650s-80s, however, demand in the Dutch economy began to fall. The reasons are not entirely clear, but its abundance of energy failed to save the country from a century-long decline. Population stagnated, the cities shrank, and the country as a whole both de-urbanised and de-industrialised. Contrary to popular belief, the Dutch Republic did not reach some energy-imposed limit by running out of peat. Instead, peat and grain prices plummeted,[20] as did the demand for many of the country's peat-fuelled or wind-caught exports. From bricks to herring to ships to beer, Dutch industries were forced to contract.

Indeed, the landscape itself appeared to decline. With peat and agricultural prices as low as they were, the incentives to drain the low-lying bogs and keep that land safe from flooding disappeared. In the eighteenth century much of the area between Amsterdam, Rotterdam and Utrecht "took on the appearance of a veritable Swiss cheese, with dozens of water-filled, exhausted peat bogs often separated from each other by nothing more than narrow, vulnerable strips of land on which were scattered the structures of what once had been farms."[20] And various schemes to create canals and reclaim high-lying lakes and bogs were also shelved. It was only when demand for both grain and peat picked up again from the late eighteenth century that the cycle of peat bog drainage and conversion to agricultural land got going again.

The only region in the Dutch Republic to stave off the decline – albeit temporarily – was the windy Zaan region. Although the demand for timber, sails, and shipbuilding collapsed, its abundant wind power was adapted to new uses. Since 1610, its windmills had been applied to pressing various vegetable oils, essentially putting the Dutch whaling industry out of business because it removed whale oil's only competitive advantage on cost.[20] The Zaan region also shifted towards papermaking. The invention of the "Hollander" to improve pulping in 1674 gave it an especial advantage in making the highest-quality white paper used for writing and printing, and it also expanded production of lower-quality grey and blue paper and cardboard. Papermaking, with the help of wind (and of water power in the Veluwe region), was one of the only industries in the Dutch Republic to buck the general trend of post-1670s decline, instead continuing to expand into the eighteenth century.[20]

Yet even the Zaan could not survive forever. By the 1730s its access to the sea – or in other words, its connection to the waterborne "grid" – had become silted up, and attempts to dredge it came too late. Although the Zaan had been one of the few regions in Holland to see any post-1670s population growth, after 1735 that stopped and it sharply declined.[20] Energy abundance thus gave the Dutch Republic significant advantages, much as it did in Britain, but maintaining the infrastructure to exploit it and to meet demand was essential too.

References

1. Hatcher, J. (1993) *The history of the British coal industry. Volume 1: Before 1700: Towards the age of coal*. Oxford University Press.
2. Nef, J.U. (1932) *The rise of the British coal industry*, Volume 1. London: George Routledge and Sons.
3. Nef, J.U. (1936) 'A comparison of industrial growth in France and England from 1540 to 1640: II', *Journal of Political Economy* 44(4).
4. Gough, J.W. (1969) *The rise of the entrepreneur*. London: Batsford.
5. Goodman, R. (2020) *The domestic revolution*. Michael O'Mara Books.
6. Almeroth-Williams, T. (2019) *City of beasts: how animals shaped Georgian London.* Manchester University Press.
7. Chamberlayne, E. (1671) *Angliae Notitia, or, the present state of England together with divers reflections upon the antient state thereof*. 5th edn. London: John Martyn.
8. Kelly, M., Mokyr, J. and Ó Gráda, C. (2014) 'Precocious Albion: A New Interpretation of the British Industrial Revolution', *Annual Review of Economics* 6(1).
9. Satchell, M. (2017) 'Navigable waterways and the economy of England and Wales: 1600-1835', working paper. Cambridge Group for the History of Population and Social Structure.
10. Fouquet, R. (2008) *Heat, power and light: revolutions in energy services*. Edward Elgar Publishing.
11. Brindley, J. (1769) *The history of inland navigations, particularly that of the Duke of Bridgwater*. 2nd edition. T. Lowndes.
12. Reynolds, T.S. (1983) *Stronger than a hundred men: a history of the vertical water wheel.* JHU Press.
13. Wardle, A.R. (2003) *The Wey navigations: an historical guide*. Surrey Industrial History Group.
14. Flynn, D.O. and Giráldez, A. (1995) 'Born with a "silver spoon": the origin of world trade in 1571', *Journal of World History* 6(2).
15. Kanefsky, J. and Townley, J. (2023) 'Keep that wheel a-turning: why and how the hybrid of steam pumping engine and water wheel combinations was appropriate technology in changing times', *Transactions of the 2nd International Early Engines Conference* 2.
16. Robinson, E. (1970) *Partners in science: letters of James Watt and Joseph Black.* Harvard University Press.
17. Aikin, J. (1975) *A description of the country from thirty to forty miles round Manchester*. John Stockdale.
18. de Vries, J. and van der Woude, A. (1997) *The first modern economy: success, failure, and perseverance of the Dutch economy, 1500-1815.* Cambridge University Press.
19. Ash, E.H. (2017) *The draining of the fens: projectors, popular politics, and state building in early modern england*. Johns Hopkins University Press.
20. van Royen, P.C. (1990) 'The first phase of the Dutch Straatvaart (1591–1605): fact and fiction', *International Journal of Maritime History* 2(2).