BRILL

Historical Materialism 21.1 (2013) 15–68

historical materialism
research in critical marxist theory

brill.com/hima

The Origins of Fossil Capital: From Water to Steam in the British Cotton Industry*

Andreas Malm
Human Ecology Division/LUCID, Lund University
Andreas.Malm@lucid.lu.se

Abstract
The process commonly referred to as business-as-usual has given rise to dangerous climate change, but its social history remains strangely unexplored. A key moment in its onset was the transition to steam power as a source of rotary motion in commodity production, in Britain and, first of all, in its cotton industry. This article tries to approach the dynamics of the fossil economy by examining the causes of the transition from water to steam in the British cotton industry in the second quarter of the nineteenth century. Common perceptions of the shift as driven by scarcity are refuted, and it is shown that the choice of steam was motivated by a rather different concern: power over labour. Turning away from standard interpretations of the role of energy in the industrial revolution, this article opens a dialogue with Marx on matters of carbon and outlines a theory of fossil capital, better suited for understanding the drivers of business-as-usual as it continues to this day.

Keywords
Fossil fuels, steam power, water power, cotton industry, labour, space, time, carbon dioxide, capital accumulation

> In those spacious halls the benignant power of steam summons around him his myriads of willing menials, and assigns to each the regulated task, substituting for painful muscular effort on their part, the energies of his own gigantic arm, and demanding in turn only attention and dexterity to correct such little aberrations as casually occur in workmanship.
> – Andrew Ure, *The Philosophy of Manufactures*[1]

> The chemical changes which thus take place are constantly increasing the atmosphere by large quantities of carbonic acid [i.e. carbon dioxide] and other

* Many thanks to Alf Hornborg, Stefan Anderberg, Rikard Warlenius, Max Koch, Wim Carton, Vasna Ramasar and other LUCID colleagues, and two anonymous reviewers for very helpful comments at various stages of this work.

1. Ure 1835, p. 18.

DOI: 10.1163/1569206X-12341279

> gases noxious to animal life. The means by which nature decomposes these elements, or reconverts them into a solid form, are not sufficiently known.
> – Charles Babbage, *On the Economy of Machinery and Manufactures*[2]

Introduction

Global warming is the unintended by-product par excellence. A cotton manufacturer of mid nineteenth-century Lancashire who decided to forgo his old water wheel and, at long last, invest in a steam engine, erect a chimney and order coal from a nearby pit did not, in all likelihood, entertain the possibility that this act could have any kind of relationship to the extent of Arctic sea ice, the salinity of the Nile Delta soil, the intensity of the Punjab monsoon, the altitude of the Maldives, or the diversity of amphibian species in Central American rainforests. Nonetheless, sporadic forebodings appear in the literature of the time. One notable flash of apprehension about the atmospheric consequences of employing steam power in factories can be found in the first chapter of Charles Babbage's classic treatise *On the Economy of Machinery and Manufactures*. Babbage is credited with being the father of the modern computer, and his book is considered the first to introduce 'the factory into the realm of economic analysis'.[3] He made his fleeting remark, quoted above, some two-and-a-half decades before John Tyndall explained the greenhouse effect, and more than half a century before Svante Arrhenius first calculated the rise in surface temperature of the Earth following an increase in the emissions of carbon dioxide (called 'carbonic acid' by Arrhenius as well).[4]

But the environmentally concerned enquiry of the pioneer economist was truncated, due to sheer lack of knowledge. Babbage was verging on yet uncharted territory. Instead, his book continued as one long encomium to the wonders of machinery – first and foremost 'the check which it affords against the inattention, the idleness, or the dishonesty of human agents'.[5] With that turn of phrase, Babbage established a leitmotif for mid nineteenth-century bourgeois thinking on the triumphant powers of the machine. It evolved on the basis of the operating procedures of manufacturers, continuously checking the idiosyncrasies of human agents with ever more machinery impelled by ever more powerful steam engines, unsuspecting of any particular noxious effects.

As the world teeters on the brink of unimaginable catastrophe due to global warming, it is about time we revisit the origins of our predicament. How, simply

2. Babbage 1835, p. 18.
3. Rosenberg 1994, p. 24. See also Schaffer 1994.
4. See Weart 2003; Arrhenius 1896.
5. Babbage 1835, p. 54.

put, did we get caught up in this mess? Why were modern economies put on the track of perpetually increasing consumption of fossil fuels? This is the question of the emergence of *the fossil economy*: an economy characterised by self-sustaining growth predicated on growing consumption of fossil fuels, and therefore generating a sustained growth in emissions of carbon dioxide. Thus defined, the concept refers to an expansion in the scale of material production realised through expansion in the combustion of coal, oil and/or natural gas.

In the lexicon of climate change discourse, the term 'business-as-usual' is commonly employed as a stand-in for the fossil economy. As usual as this business now appears, it is not a fact of nature, nor the product of geological or biological history. The fundamental ontological insights of climate science tell us as much, and moreover, fossil fuels should, by their very definition, be understood as a social relation: no piece of coal or drop of oil has yet turned itself into fuel. No humans have yet engaged in systematic large-scale extraction of either to satisfy subsistence needs. Rather, fossil fuels necessitate commodity production and waged or forced labour as components of their very existence. A primary scientific task should therefore be to write a social history of business-as-usual or – synonymously – the fossil economy, and yet it is sorely neglected, in a field awash with data on the disastrous effects of the process but comparatively poor on insights into the drivers of the danger. Most climate science still dwells in the noiseless atmosphere, where everything takes place on the surface, rather than entering the hidden abode of production, where fossil fuels are actually produced and consumed. What follows is a modest contribution to the filling of this gap.

The birth of the fossil economy

The obvious birthplace of the fossil economy is Britain. As late as 1850, this single country was responsible for more than 60 per cent of global CO_2 emissions from fossil fuel combustion. It raised three-and-a-half times more coal than the US, France, Germany, Belgium and Austro-Hungary combined, the lion's share of it for combustion on the British Isles; per capita consumption was more than ten times higher than in France and Germany.[6] For quite some time, Britain was the sole economy of its kind, the place of origin of business-as-usual, from which it eventually spread to other advanced capitalist countries.

By the mid-nineteenth century, however, coal had been regularly utilised as a source of heat in Britain for almost two millennia. Stumbling upon outcrops of the black stone, the Romans began to burn it for heating military garrisons and villas, working iron in smitheries, and keeping the perpetual fire alive at the

6. Boden, Marland and Andres 2011; Church 1986, p. 773; Cameron 1985, p. 12.

temple in Bath.[7] Coal fell into disuse with their departure, only to reappear in the thirteenth century – primarily in the smitheries – and experienced a surge in the late sixteenth, when it spread rapidly as a fuel for domestic heating. By 1800, most people in towns probably bought coal to heat their homes and cook their meals.[8] The household continued to be the chief hearth for combustion. It could not give rise to a fossil economy: as long as coal was mostly used in the domestic production of heat, fossil fuels remained unattached to an engine of self-sustaining economic growth. No matter how much coal British households burnt, consumption levels were constrained by the slow march of population growth, rather than boosted by the exponential expansion in the scale of material production we associate with business-as-usual. It would be absurd to date its onset to the Roman occupation or the thirteenth century.

But long before 1850, coal had also made inroads into manufacturing, as a fuel in the production of salt and soap, lime and ale, bricks and glass, copper and pottery and a range of other commodities. Most importantly, the owners of blast furnaces shifted from charcoal to coke in the last quarter of the eighteenth century, ushering in a boom in iron production. By 1800, the iron sector took some 10–15 per cent of all coal – a rapidly rising share, though still rather small in relation to that of domestic heating (somewhere between a half and two thirds).[9] In furnaces, kilns and breweries, coal served the same purpose as in cottage stoves: it provided heat for smelting, boiling or distilling the matters in hand. A substitute for wood, it was confined to the processing of substances whose properties required heating. For coal to be universalised as a fuel for *all* sorts of commodity production, it had to be turned into a source of *mechanical energy* – and, more precisely, of rotary motion.

Only by coupling the combustion of coal to the rotation of a wheel could fossil fuels be made to fire the general process of growth: increased production – and transportation – of all kinds of commodities. This is why James Watt's steam engine is widely identified as the fatal breakthrough into a warmer world.[10] Newcomen's engine had managed to force a piston up and down, up and down, in a vertical motion well suited for the pumping of water in mines, but not for driving machinery. That was the feat of the device patented by Watt in 1784, when he finally 'adapted the motion of the piston to produce *continuous circular motion*, and thereby made his engine applicable to all purposes of

7. Dearne and Branigan 1995.
8. Nef 1966; Flinn 1984; Hatcher 1993.
9. Nef 1966; Flinn 1984; Hatcher 1993; Buxton 1978; Hyde 1977; Humphrey and Stanislaw 1979.
10. See, for example, Crutzen 2002; Crutzen and Steffen 2003; Steffen, Crutzen and McNeill 2007; Zalasiewicz, Williams, Smith, Barry, Coe, Bown, Brenchley, Cantrill, Gale, Gibbard, Gregory, Hounslow, Kerr, Pearson, Knox, Powell, Waters, Marshall, Oates, Rawson and Stone 2008.

manufacture.'[11] But a patent cannot by itself spark off something like a fossil economy. The mere existence of a steam engine as certified in the legal rights of the inventor tells us nothing about the extent to which such engines were actually installed, their function in the economy, or the propensity to emit carbon dioxide. History is replete with inventions petrified into objects of exhibitions or fantasies da Vinci-style, including in the annals of steam power, the basic principles of which were known long before Watt, including in China.[12] The question of the steam engine is therefore the question of *why it was adopted and diffused* – in Britain, and, first of all, in the cotton industry.

The most advanced branch of industrial production, following Richard Arkwright's establishment of the factory system, the cotton industry was eyed by Watt as the natural outlet for his product. The assembling of machines under one roof demanded a regular, smooth and dependable propulsive force, posing the technical challenge Watt wrestled with, and promising a vast market for him and his business partner Matthew Boulton once he succeeded. And indeed, the promise was eventually realised. The steam engine owed its coming position as the defining prime mover of industrial production to its success in the cotton mills.[13] But that was by no means an automatic or predetermined affair. In fact, as we shall see, cotton manufacturers preferred another prime mover for at least four decades after Watt's patent: the water wheel.

A traditional source of mechanical energy, leaving no traces of CO_2 behind – 'carbon-neutral', in today's parlance – water was the foundation of the early cotton industry.[14] Water, not steam, carried the first generations of cotton manufacturers to their super-profits, even as Boulton & Watt did everything to advertise the advantages of their engine. The water wheel proved extraordinarily resilient to the challenge of steam, and when it finally gave way, the shift was contingent upon developments in which neither Watt nor Boulton played any role.

Water power was a barrier that had to be knocked down for the fossil economy to emerge. The British cotton industry was the historical gateway, on the other side of which the steam engine spread to other major industries, other countries, completely different applications – such as on the seas – and

---

11. Farey 1827, p. 13; emphasis in original.
12. On steam engines in China, see Pomeranz 2000, pp. 61–2.
13. See, for example, von Tunzelmann 1978; Lord 1965; Hills 1970; Hills 1989; Briggs 1982.
14. See, for example, Aspin 2003; Fitton and Wadsworth 1958; Chapman 1972; Chapman 1992; Tann 1970; Cooke 2010; Ingle 1997. Insofar as the wheels were built using iron, which they increasingly were in the first half of the nineteenth century, they were not completely carbon-neutral or independent of fossil fuels – compare a bicycle, a windmill or a solar panel today. However, since depreciation rates were extremely low for water wheels made of iron, the embedded carbon element in every horsepower delivered must have been all but negligible.

thereby suffused the process of self-sustaining growth with fossil energy.[15] The adoption of steam power in the British cotton industry was, so to speak, a *rite de passage* for coal, a qualitative leap into the spiral of ever expanding commodity production. Had the cotton industry – the very spearhead of industrial capitalism – stayed with water, the fossil economy would not have come about the way it did (and the first task for history-writing is to account for what actually transpired). A central question in the writing of the social history of business-as-usual will therefore be: *why did the British cotton industry switch from water to steam?*

False starts in energy studies

While global warming accords novel significance to the energy aspects of the industrial revolution, interest in them is not, of course, entirely new.[16] The doyen of modern research in the field is E.A. Wrigley. In a path-breaking article in 1962, he first broached ideas later developed into a grand narrative of the industrial revolution and, more generally, of modern economic growth.[17] In what he would come to call an 'organic economy', all forms of material production are based on the land. Raw materials, as well as thermal and mechanical energy – human and animal bodies used to put things in motion – are all drawn from the yield of present photosynthesis. But that yield is restricted. There is no way to enlarge it beyond the constant supply of land. A growing organic economy will inevitably get trapped in fierce competition for scarce resources, making 'a permanent, radical increase of industrial raw material supply' – a necessary condition for modern economic growth – 'very difficult to obtain.'[18] The dependency on the land puts a low ceiling on industrial production. Fossil fuels shatter that ceiling.

In a series of subsequent articles and books, culminating in the 2010 magnum opus *Energy and the English Industrial Revolution*, Wrigley elaborated on these theses, whose influence on the study of energy in the industrial revolution now deserves the epithet of a paradigm.[19] That paradigm, however, has deeper sources than Wrigley himself, as he developed it in continuous engagement

15. For some aspects of the transition to steam power in the British imperial navy, see Malm 2012a.

16. For an excellent overview, see Barca 2011.

17. Wrigley 1962.

18. Wrigley 1962, p. 1. See further Wrigley 1972; Wrigley 1988; Wrigley 1990; Wrigley 2000; Wrigley 2004; Wrigley 2010.

19. For applications of Wrigley's theories, see for example Thomas 1985; Mayumi 1991; Malanima 2001; Malanima 2006; Sieferle 2001; Andrews 2008; Jones 2010. On Wrigley's centrality and influence, compare Barca 2011.

with two of the classical political economists: David Ricardo and Thomas Malthus. For Ricardo, a growing economy would lay claim to more land. Inferior soils would have to be taken into cultivation: wetlands, steep slopes, fields in the mountains hitherto left untouched because of their natural infertility. Higher inputs of capital and labour into such land would inescapably produce diminishing returns, decreasing profits, falling wages, and an end to growth; in a Ricardian formulation repeatedly quoted by Wrigley, a state of stagnation will 'necessarily be rendered permanent by the laws of nature, which have limited the productive powers of the land.'[20] But coal offers a 'chance of escaping the Ricardian curse'.[21] At the end of the eighteenth century, the British economy emancipated itself from the land constraint. Digging into the stores of past photosynthesis, bypassing the restricted surface area of inflowing solar radiation, it finally broke the spell of stagnation.

One method used by Wrigley and his followers to illustrate this logic is to convert coal into acres of land required to generate the same amount of energy. In 1750, all coal produced in England would have equalled 4.3 million acres of woodland, or 13% of the national territory. In 1800, substituting wood for all coal would have required 11.2 million acres, or 35% of the British land surface; for 1850, the figures rise to 48.1 million acres and 150% respectively. A hypothetical total conversion from coal to wood in the British economy would thus, even in the year 1750, have 'represented a significant proportion of the land surface for which there were many other competing uses'; in 1800, it would have been 'quite impractical', while in 1850 it was 'self-evidently an impossibility'.[22] In a similar computation inspired by Wrigley, Rolf Pieter Sieferle, in his aptly titled *The Subterranean Forest: Energy Systems and the Industrial Revolution*, concludes that 'British coal production freed an area that was equivalent to the total surface of Britain' already in the 1820s, while Paola Malanima, likewise standing on the shoulders of Wrigley, estimates that without fossil fuels, Europe would have needed a land area more than 2.7 times its entire continental surface in 1900, rising to more than 20 times in 2000.[23]

But the pressures undone by coal were not only Ricardian in character. They emanated from reproduction as much as from production. According to Wrigley, Malthus's theorem of geometrically growing population and arithmetically growing food supplies, generating a tendency for output per head to fall with population growth, is indeed valid in an organic economy. As long as all material production derives from land, living standards will decline

20. Ricardo quoted in Wrigley 2010, pp. 10–11. The quotation also appears in Wrigley 1988, p. 36; Wrigley 1990, pp. 49–50; Wrigley 2000, pp. 128–9; twice in Wrigley 2004, pp. 55, 72.

21. Wrigley 2010, p. 174.

22. Wrigley 2010, p. 99.

23. Sieferle 2001, pp. 102–3; Malanima 2006, p. 104.

when more people divide the fixed supplies into smaller pieces. Perpetual stagnation is ensured – until coal blazes a new trail, allowing population and economy to grow hand in hand.[24]

The Malthusian component of the paradigm has received its most articulate expression in a study by Richard G. Wilkinson. In *Poverty and Progress: An Ecological Model of Economic Development*, appearing in 1973, Wilkinson – fortunately now better known for his work on the unhealthy impacts of social inequality – constructed a model of technological and economic development in general, and of the industrial revolution in particular. People do not invent new methods of procurement because they are affluent, but because – and only when – they are poor. Poverty is a symptom of resource scarcity. Such a condition comes about when a human population succumbs to its innate tendency, common to 'every animal population', to reproduce beyond the bounds of its resource base.[25] This is, Wilkinson argued, what happened on the eve of the industrial revolution: the self-restraint of English couples broke down, fertility rose sharply, hitherto existing ecological equilibria collapsed and gave way to acute scarcity.

The growing population initially resorted to the 'available slack in the resource-base'.[26] But by the eighteenth century, the combined Ricardian-Malthusian curse had, according to Wilkinson, reached intolerable levels, forcing England into 'the substitution of mineral resources for landbased ones.'[27] The stimulus to the industrial revolution came 'directly from resource shortages and other ecological effects of an economic system expanding to meet the needs of a population growing within a limited area.'[28] Coal was the natural resolution of the crisis, taking the place of wood in cottages and smitheries under the dictates of 'population growth and the consequent extension of the economic system'.[29] Like every other change the industrial revolution brought about, the turn to fossil fuels was the outcome of 'a valiant struggle of a society with its back to the ecological wall', a decision 'made under duress'.[30]

We may designate this the *Ricardian-Malthusian paradigm* for studying the role of energy in the industrial revolution.[31] Another Wrigley-inspired

24. For example, Wrigley 2010.
25. Wilkinson 1973, pp. 4–5, 19–52. 'Every animal population': Wilkinson 1973, p. 20.
26. Wilkinson 1973, p. 76.
27. Wilkinson 1973, p. 101.
28. Wilkinson 1973, p. 112.
29. Wilkinson 1973, p. 115.
30. Wilkinson 1973, pp. 126, 134.
31. Robert Brenner speaks of a 'Malthusian-Ricardian model' in the closely related context of the debate on the origins of capitalism (see Brenner 2007). The terms have been swapped here, since the Ricardian component appears determinant, primarily in Wrigley. An ironic illustration

scholar, Brinley Thomas, sums up its basic tenets: 'The industrial revolution was Britain's response to *an energy shortage* which afflicted its economy in the second half of the eighteenth century. A population explosion intensified the need to change its energy base from wood fuel to fossilized fuel.'[32]

How, then, does the Ricardian-Malthusian paradigm account for the rise of the steam engine? In his original 1962 piece, Wrigley noted the delay between Watt's invention and its diffusion in the cotton industry, concluding that 'only after a generation of expansion had caused the need for power to outstrip the capabilities of the human arm and the water wheel was the steam engine brought into use'.[33] The great advantage of the engine was its independence from 'the annual round of plant photosynthesis', as hitherto embodied in human or animal muscle.[34] According to Wilkinson, 'the use of water power was limited by the number of streams with suitable sites for mills: new sites became scarce in many parts of the country during the *seventeenth* century.' By the time of the late eighteenth, the rise in British fertility had created a situation where 'good mill sites were no longer available', whereas 'coal to fuel the steam engine was plentiful – especially at the pit head. *The spread of steam power was ecologically favoured*.'[35] For Kenneth Pomeranz, whose magisterial and extremely influential *The Great Divergence: China, Europe, and the Making of the Modern World Economy* is based on Ricardian-Malthusian – and Smithian – conceptions of growth, 'water power, no matter how much the wheels were improved, simply did not have the same potential to provide energy inputs that would significantly outpace a rapidly growing population'.[36] In this version of events, water wheels and other traditional prime movers were discarded in favour of the steam engine *because they could not deliver the requisite absolute quantities of energy*.

Critique of the paradigm

The Ricardian-Malthusian paradigm has a number of conspicuous short-comings. Wrigley's terminology is imprecise, to begin with: fossil fuels are no less organic than wood or people, which is why their combustion releases carbon dioxide. Denoting our current economy 'inorganic' or 'mineral-based' –

---

of the power of the Ricardian-Malthusian paradigm is the apparently thoughtless recent endorsement of it by Timothy Mitchell, who is, of course, sharply anti-Malthusian. Mitchell 2011, pp. 12–15; compare p. 238; Mitchell 2002.

32. Thomas 1985, p. 729; emphasis added.
33. Wrigley 1962, p. 12.
34. Wrigley 2010, p. 100.
35. Wilkinson 1973, p. 120; emphases added.
36. Pomeranz 2000, p. 61.

Wrigley's antitheses to 'the organic economy' – makes little sense; both terms would encompass the Bronze Age as well as the Iron Age.

Semantic pedantry aside, the paradigm fits ill with the transition we are concerned with here. Prime movers derived from photosynthesis – animal and human bodies – were never capable of delivering mechanical energy to large-scale industry. In eighteenth-century British factories, they were certainly experimented with, but quickly abandoned as useless.[37] Not land but *water* was the element on which Britain's industries, cotton foremost among them, first developed. Products of present photosynthesis are eminently suitable for the generation of thermal energy, human beings having burnt wood for heat since time immemorial, but not for powering machinery: coal was never an alternative to wood, humans or animals *as fuels for rotary motion.* Thus a Ricardian exigency could not possibly have triggered the one transition we have identified as epoch-making. Ironically, Wrigley himself professes awareness of the diffusion of steam engines in industrial production as the watershed event – and yet it is an anomaly to the paradigm, since the crucial victory of steam power came at the expense of a prime mover that did not grow from plants.[38] There is still, of course, the possibility that scarcity in a more general sense, along the lines suggested by Wilkinson and Pomeranz, afflicted water power, and that steam offered relief from it. We shall see presently how that proposition chimes with the data.

A more fundamental problem of the Ricardian-Malthusian paradigm, however, lies in its form of explanation. It runs something like this: *there is a constant appetite for more energy inherent in all societies, and in the eighteenth and nineteenth centuries, Britain finally managed to satisfy it.* To construct such an explanation for the emergence of a fossil economy, the paradigm's exponents need to invoke a transhistorical factor, an urge shared by all societies finding its wanted object in Britain's mines. For Wrigley, that factor is simply the drive to perpetual economic growth. 'The move away from an exclusively organic economy was a *sine qua non* of achieving a capacity for exponential growth', he writes, or: 'The land surface of the earth was a fixed quantity and formed a barrier to indefinite growth', or: 'The energy bottleneck which set limits to growth in organic economies was widened progressively as fossil fuels replaced organic [*sic*] fuels.'[39] Similar statements are repeated *ad infinitum* in Wrigley's writings.

37. See, for example, Tann 1970.

38. For Wrigley's awareness of the centrality of mechanical energy and rotary motion in particular, see for example Wrigley 1990, pp. 6, 78, 90; Wrigley 2004, pp. 35, 78; Wrigley 2010, pp. 42–5, 100, 177–8, 190–1.

39. Wrigley 2000, p. 139; Wrigley 2010, pp. 193, 191.

For Wilkinson, a rather more avowed Malthusian, the transhistorical factor is the biological urge to breed, shared not only by all societies but by all animal populations. Since the dawn of time, it aroused a unilinear 'growth of need' that forced man 'to involve himself in more and more complicated processing and production techniques'; in hyper-fertile Britain, it finally impelled him to enter the age of fossil fuels.[40] According to Pomeranz, the English economy diverged from an equally growth-prone China because the turn to coal – via the steam engine – 'enabled it to break through the fundamental constraints of energy use and resource availability that had previously limited *everyone's* horizons.'[41] Such formulae rest precisely on the assumption that the impulse to expansion was permanently present in pre-fossil economies, bottled up throughout history, on everyone's horizon, from the Yangzi to the Thames. The growth imperative was always there, though frustrated by the dependency on land – and this explains why fossil fuels were introduced in the end.[42]

The transition then becomes a mere formality. Since that which requires explanation – the dynamics of business-as-usual – is postulated a priori as biding its time, there is not much to uncover in the passage from one form of economy to another. In Wrigley and his peers, the fossil revolution resembles the fulfilment of historical destiny, rather than a rupture separating two distinct orders from each other. There are no laws of motion specific to the fossil economy, no emergent imperatives that compel economic agents to combust fossil fuels, only an opportunity to realise age-old, universal forces – laws of nature, in effect. And hence there are no social antagonisms. 'Capitalism', according to Wrigley, 'is an elusive concept' unworthy of application; no relations of power between labour and capital appear on his radar.[43] In claiming that 'the spread of steam power was ecologically favoured', Wilkinson elevates the agents of steam to representatives of the common interests of their biological population, while Sieferle similarly refers to humanity as an undifferentiated whole: 'Fossil energy *liberated humans* from their ties to area size.'[44] As if the fossil economy was the work of humans in general, of a species in action, united and harmonious.

40. Wilkinson 1973, pp. 90, 102.
41. Pomeranz 2000, p. 207; emphasis in original.
42. This critique is derived from that developed by Ellen Meiksins Wood and Robert Brenner in the context of the debate on the origins of capitalism. See Meiksins Wood 1995; Meiksins Wood 2002; Brenner 1986; Brenner 1987a; Brenner 1987b; Brenner 2007.
43. Wrigley 2010, p. 209.
44. Sieferle 2001, p. 121.

The puzzle of superior water

In actual history, the decision to replace water with steam was not, of course, democratically taken. Choice of prime mover was the prerogative of capitalists. It presupposed the separation between the direct producers and the means of production; only when operatives were gathered under the eye of a manufacturer, who paid them to perform labour on his machines, did he have reason to weigh the relative merits of different non-human motive forces for the propulsion of machinery. Choice of prime mover, in other words, was a corollary of the factory system, and though its instigator Richard Arkwright failed in his early experiments with steam, it did not last long before cotton-mills puffed out black soot. In 1786, the brothers Robinson erected the first rotative steam engine to drive machinery for spinning cotton in their Papplewick factory on the River Leen. But they soon became disappointed. In a complaint that would long haunt steam power, the brothers faulted the engine for excessively high fuel costs: coal commanded a price of 11 to 12 shillings, to be measured against the free running water of the Leen. Instead of pursuing steam further, they fell back on the natural supply of the river, augmented it with reservoirs, and continued to spin by water.[45]

The rotative steam engine first made a home in the mills of Manchester in 1790.[46] By the middle of the decade, the technical capability of the prime mover had been thoroughly demonstrated, knowledge of steam was widespread, and cotton capitalists in some Lancashire towns eagerly embraced it. Yet water power reigned supreme, its dominance in the cotton industry barely dented.[47] Frustration surfaced in the sales efforts of Boulton & Watt. In 1791, one manufacturer explained why he turned down their offer: 'The Expense of a small engine as well as the consumption of coal and water being much greater than I apprehended would be required for our work, it seems more advisable to place our machines on a stream of water about a mile from our house'.[48] Watt himself offered a sober assessment in the same year: 'I hear that there are so many mills resting on powerful streams in the North of England that the trade must soon be over-done.'[49]

---

45. Marshall 1957; Chapman 1971, pp. 5–6. On Arkwright and steam, see Fitton 1989; Tann 1973a.

46. Chaloner 1954–5.

47. See Chapman 1969; Chapman 1971; Chapman 1972; von Tunzelmann 1978; Musson 1976; Kanefsky 1979; Hills 1970; Hills 1989.

48. Letter quoted in Tann 1973b, p. 220. This particular manufacturer was in the woollen industry, but his objections summarised those 'of many small clothiers to steam power at the turn of the century' (ibid.). Compare Musson and Robinson 1959, pp. 423–4; Hills 1970, p. 145.

49. Quoted in Briggs 1982, p. 57.

By 1800, 84 Boulton & Watt engines in British cotton mills were still overshadowed by around one thousand water wheels. Water remained the foundation for the capitalist factory system, and not merely as a relic of the past: wheels were enlarged and perfected, dams and reservoirs excavated *en masse*, new and extended mills – particularly in the great cotton boom of 1823–5 – equipped with the latest wheel-models of gargantuan dimensions. More than four decades passed from Robinsons's first installation to the decisive triumph of steam. Some time between the mid-1820s and the late 1830s – no exact date can be pinned down – steam power reached parity with and, in quick succession, dethroned water in the cotton industry. This was the time of the transition, in at least three senses. New or extended mills were now only rarely fitted with water wheels, in a sharp break with the past. For the first time, the bulk of horsepower came from steam engines. But perhaps most importantly, a range of decisions were taken over the 1830s by manufacturers and legislators that, for all practical purposes, ended water power expansion in the cotton industry and cleared the way for steam, not only there, but throughout British manufacturing.[50]

The time-lag has long been considered a puzzle: 'Explaining the slow adoption of steam power in the cotton industry is an important problem for the historians of its technology', in the matter-of-fact words of a recent account of the industrial revolution.[51] But the problem could just as well be formulated in the reverse terms. The very slowness of the process – four or five decades are a blink of an eye in geological time, but they can be an aeon in the annals of capitalism – raises the question not only of why it happened so late, but *why steam power was adopted at all.* We need an explanation that can account for the adoption that took place before the mid-1820s, but *particularly* thereafter, with the 1830s standing out as the decade of the most concentrated shift.

Was steam resorted to because water was scarce by the time of the 1830s? The hypothesis of an energy crisis – a wall of water shortage confronting cotton manufacturers, leaving them no choice other than steam – was submitted to rigorous testing by Robert B. Gordon in 1983. 'If it can be shown', Gordon wrote, 'that nearly all the water power physically available in the industrial regions was exploited before steam power was much used, the energy crisis hypothesis would be proved.' But if the recoverable data rather indicated that 'there were unused water power resources throughout this period, it would be necessary to appeal to the social factors for support of this hypothesis' – or, to be exact, the

50. See, for example, Kanefsky 1979; Rose 1986; Taylor 1949; von Tunzelmann 1978; Chapman 1972; Chapman 1969, p. 75; Crafts 2004. More extensive empirical support for the claims in this article, with full sourcing, will be found in the dissertation in progress of the present author.

51. Allen 2009, p. 172.

hypothesis would be disproved, and a completely different explanation would be needed.[52]

Gordon proceeded with a scrupulous reconstruction of the meteorological, geological and topographical conditions in the industrial areas of both England and New England. To assess the potential power supply, he identified the available watersheds and computed their drainage areas, falls and stream slopes, but excluded sites where the initial costs of establishing a mill would have been prohibitive. The results for both regions were unambiguous. As for England, in the year 1838, mere fractions of the potential water power in eleven major rivers running through the textile districts were utilised. For Irwell, that fraction was 3.4%; for Derwent, 1.7%; for Dove, 0.8%; for Ribble, 3.0%; for Spodden – the most heavily exploited watercourse on the list – 7.2%. 'More water power could have been obtained by continued geographical extension of the industrial districts without encountering either high initial costs or excessive variable, transportation, or other costs. It follows', Gordon concluded, 'that physical bounds on the availability of water power at low cost was not a limitation on the development of industry.'[53] The energy-crisis hypothesis demolished, he stopped short, however, of exploring alternative explanations.

For Scotland, a cotton district second in importance only to Lancashire, the picture is similar. 'The potential of water power in Scotland was never fully realised, except in a few localities favoured by other attributes', runs the conclusion of John Shaw in his *Water Power in Scotland, 1550–1870*. 'The end of the Age of Water Power came about not so much on account of any inherent weakness as through changes in the scale of industrial units, in work patterns, populations distributions and economic goals' – factors which, again, Shaw left without further examination.[54]

Did the transition happen because steam engines had become more powerful and reliable – in short, technologically superior? In the early decades of the nineteenth century, the average output of both an iron breast-wheel and a Boulton & Watt steam engine was 20 horsepower, or slightly less. But the most powerful prime movers were invariably water wheels. In the 1820s, steam engines of 60 horsepower were considered unusually powerful, while a string of giant water mills in northern England and Scotland had a capacity of between 300 and 500 horsepower. Indeed, as late as in the early 1840s, the most imposing wheel constructions generated more power than the mightiest steam engines – a situation that would not remain for much longer, the engines

52. Gordon 1983, p. 243.
53. Gordon 1983, p. 256.
54. Shaw 1984, p. 544.

leaping ahead in the latter decades of the nineteenth century, but by then the transition in the cotton industry had long been completed.[55]

One of the greatest obstacles for Boulton & Watt was the perceived irregularity and frailty of their engines, compared to the robust wheels. Not until the mid-1830s could the finest workshops deliver steam engines capable of producing a motion as smooth and even as that of water.[56] In 1840, *The Civil Engineer and Architect's Journal* reported that factories at Stockport erected two engines to work the same machinery in order to equalise the action of steam, 'yet the motion is not so regular as that of an overshoot water-wheel, where the supply of water is uniform.'[57] In his unpublished PhD thesis from 1979 – the authoritative compilation of statistics on water and steam in British industry – John Kanefsky reckoned that 'cotton produced by water mills was still regarded as being generally superior to that produced by steam power', due to the unequalled evenness of motion in the former, all through the 1830s.[58] Well into the second half of the century, water wheels were less prone to mechanical glitches and breakdowns.[59]

Was steam cheaper than water? This is, at first sight, the most plausible explanation: cotton capitalists opted for steam because one horsepower thereof was cheaper than one of water. A water wheel represented a substantial investment. The wheel itself had to be purchased, positioned in a wheel-house, and, in most cases, supplemented with a dam to secure a regular supply of water. Then the mill-owner would have to build a system of conduits – canals, leats, sluice-gates – to lead the water onto the wheel in proper amounts, presuming that it was of the standard overshot or breast type. A steam engine, on the other hand, consisted of iron, brass and copper, fly-wheel, boiler and pipes; fixed on a solid framing in a special engine-house, its construction required skilled labour. Then there was the occasional need for extensive repairs following breakdowns and the spectacularly high depreciation rates, whereas water wheels could function with only minor maintenance for decades or even a century. Water came flowing for free. Once the capitalist had secured a lease from the landowner, paying rent for the right to utilise the stream, there were no further fuel costs. Coal had to be constantly purchased on the market. The sum of these relations is widely accepted in the literature: *water wheels were consistently cheaper per horsepower than steam engines* in

55. Musson 1976; Reynolds 1983; Hills 1970; von Tunzelmann 1978.
56. Chapman 1971, p. 12.
57. *The Civil Engineer and Architects' Journal* 1840, p. 8; emphasis added.
58. Kanefsky 1979, p. 141.
59. Kanefsky 1979, p. 142.

the early nineteenth century.[60] 'It is difficult to resist the conclusion', writes cotton historian Stanley Chapman, 'that steam was more expensive than the costliest water power installations.'[61]

But had not the balance swung in favour of steam by the time of the 1830s? Could water wheels still put up with the challenge, in pure cost terms? The 1833 Factories Inquiry, carried out by a Parliamentary commission under the leadership of Edwin Chadwick, provides some answers. One proprietor of a steam-powered mill in Manchester declared that a manufacturer with water power enjoyed an 'advantage over his competitors'. Curious, his interviewer wondered:

> Why do you think he has till now enjoyed an advantage over his competitors in trade? – Because it is a well-ascertained fact that water-power is cheaper than steam.
>
> Then if a mill-owner wishes to set up a manufactory, he can always do it cheaper by purchasing a waterfall than a steam-engine? – Yes; if he does not pay too high for his water.
>
> Suppose he does not pay too high for his steam-engine, would he be in the same condition? – No; because the price of fuel is a greater object than the price of a steam-engine.
>
> Why is it cheaper to purchase a waterfall than a steam-engine? – On this ground – *the constant supply of water is much cheaper to turn an engine with than the supply of coal.*[62]

'If I wanted to hire power to-morrow', announced Thomas Worsley, a Stockport shopkeeper, 'I can procure it in the country parts round Manchester' – i.e. along rivers – 'one-third under what I should have to give for it in Manchester or any of the manufacturing towns'. Therefore 'the owners of water power can work cheaper than the owners of steam power.'[63] One commissioner alluded to a 'jealousy of the water-mills' on the part of steam-dependent manufacturers in the cotton industry.[64] Factory philosopher Andrew Ure referred to the 'cheapness' of water 'as compared to that of steam'.[65] In 1849, the manager of Quarry Bank mill, the water-powered jewel of Samuel Greg & Co. – known as the largest cotton empire in all of Britain – calculated that running an engine of

---

60. See, for example, Chapman 1971; Kanefsky 1979; von Tunzelmann 1978; Tann 1970; Hills 1970; Hills 1989; Briggs 1982; Musson 1976.
61. Chapman 1971, p. 13.
62. Parliamentary Papers 1833a, p. D2.132; emphasis added (John Cheetham).
63. Parliamentary Papers 1833a, p. D1.16.
64. Parliamentary Papers 1833a, p. D2.99.
65. Ure 1835, p. xlvii.

100 horsepower instead of the current wheel of the same capacity would burden the factory with a cost of £274 per annum.[66] The computation was repeated in 1856, now against a water wheel of 172 horsepower; again, the manager found that 'our waterpower is worth about £280 a year' due to 'the saving in coal.'[67]

Such evidence dovetails with all modern reconstructions of power costs in the period. Chapman estimated the cost per unit of horsepower in a cotton mill in the year 1840 as £86 for steam and £59 for water.[68] In *Steam Power and British Industrialization to 1860*, Nick von Tunzelmann inferred that water wheels 'cost far less per horsepower for purchase and erection than did steam-engines' in the 1850s; 'for large wheels the cost was around half that of steam-engines of equal power.'[69] But the decisive factor remained the difference in fuel costs, underpinning 'the profitability of water-power up to at least the mid-nineteenth century'.[70] Kanefsky went even further. 'It is quite plain that throughout the period' – up to 1870 – 'water power was, when available, significantly cheaper in all but very exceptional circumstances and that where coal was expensive the difference could be considerable.'[71] The railways failed to close the gap, so that water was 'preferable to steam *even in 1870 if cost factors alone were under consideration*' – but then again, in 1870 the transition had been accomplished long ago.[72]

All of this points to a conclusion of rather startling implications for the history of the fossil economy. The transition from water to steam in the British cotton industry did not occur because water was scarce, less powerful, or more expensive than steam. To the contrary, steam gained supremacy *in spite of water being abundant, at least as powerful, and decidedly cheaper*. None of this is in serious dispute, *pace* Wrigley et al., but so far it has only served to deepen the mystery: then *why* did the transition occur? Was it irrational, or did it have another rationale, a different set of causes, hidden beneath the immediately visible differentials in economic and technological benefits? Neither Gordon, nor von Tunzelmann, nor Kanefsky or anyone else has systematically examined the actual motives for turning to steam. It is to this task we now turn.

66. Rose 1986, p. 42. On the size of the firm, see for example Ure 1835, p. 347.

67. Greg archive: C5:3/2, memorandum, 'Water Wheel Power at Quarry Bank, August 4th 1856'.

68. Chapman 1971, p. 18.

69. von Tunzelmann 1978, p. 130.

70. von Tunzelmann 1978, p. 136.

71. Kanefsky 1979, p. 175.

72. Kanefsky 1979, p. 176; emphasis added.

Power to visit labour

The steam engine could not explain or promote itself. Its way had to be paved by tracts and manuals, written for manufacturers and their right-hand men, teaching them how to properly handle the boilers and the pipes, the fly-wheels and the governors, and appreciate the superior principles of steam. The specimen of the genre today regarded as most accurate – and probably wielding most influence over manufacturers at the time – is the voluminous *A Treatise on the Steam-Engine*, written in 1827 by John Farey, owner of a consulting firm through which he advised capitalists on technical matters.[73] Here he wished to 'perfect the practice of those engineers and others who require to employ steam-engines', averring that the application of the 'power of the steam-engine' was of paramount importance for the well-being of the nation. The reason was simple: 'Unless the industry of the working class is systematically applied, and aided by the use of machines, there can be but little surplus wealth to maintain an educated class in society, and produce that state of general affluence which is conducive to the progress of civilization, and the development of the intellect.'[74] The steam engine was eminently conducive to this pursuit. In the Introduction to his *Treatise*, Farey juxtaposed water and steam, without hinting at any scarcity of the former: the advantage of steam lay not in its being uniquely plentiful, nor in its commanding a lower price. Instead, Farey argued, steam 'is often preferred, because a manufactory by steam power may be established in any convenient situation where fuel can be procured', whereas 'water power can only be obtained in particular situations, which are frequently unfavourable in other respects'. Of particular significance,

> natural falls of water are mostly found on rivers in the open country; but steam-engines can be placed *in the centres of populous towns, where labourers are easily procured*. Steam-power is frequently preferred, as a first mover for those mills which consist of a number of small machines, each performing some delicate operation; such machines require considerable assistance from work-people to direct their actions, and supply them with the materials upon which they are to operate. As all manufactories of this nature require many work-people, they are more advantageously carried on by steam-power in populous towns, than by water-power in the country: this is fully proved by the number of large manufactories in London, Manchester, Leeds, and Glasgow.[75]

73. On Farey and the *Treatise*, see Woolrich 1997; Woolrich 1998; Woolrich 2000; Nuvolari 2004.
74. Farey 1827, pp. v–vi.
75. Farey 1827, p. 7; emphasis added.

The edge of steam, in other words, was its unique suitability not for the generation of power per se, but *for the exploitation of labour*.

John McCulloch, a leading bourgeois economist of the period, had as his mouthpiece the *Edinburgh Review*, house organ of cotton capital. He hammered away at the point throughout the 1820s and '30s, dispelling misunderstandings and speaking the truth to his audience of manufacturing interests:

> The real advantage of the application of the power of steam to give motion to the machinery of a spinning mill, or of a number of power-looms, appears to be a good deal misapprehended. It does not consist so much in any direct saving of labour, as in permitting it to be carried on in the most proper situation. The work that is done by the aid of a stream of water, is generally as cheap as that which is done by steam, and sometimes much cheaper. But the invention of the steam-engine has relieved us from the necessity of building factories in inconvenient situations merely for the sake of a waterfall. It has allowed them to be placed *in the centre of a population trained to industrious habits*.[76]

The argument was echoed on both sides of the transition. In 1818, John Kennedy, partner in McConnel & Kennedy – among the largest fine-spinners in Manchester and pioneers of steam – deplored how the dependency on water caused manufacturers to be 'removed from the experienced workmen'. But the steam engine offered salvation: 'instead of carrying the people to the power, it was found preferable to place the power amongst the people.'[77] Almost half a century later, in 1866, William Stanley Jevons, in his classic *The Coal Question*, maintained that 'when an abundant natural fall of water is at hand, nothing can be cheaper or better than water power. But everything depends upon local circumstances.' Some circumstances worked to the detriment of this source of energy, however cheap it may be: the necessity of 'carrying the work to the power, not the power to the work, is a disadvantage in water power, and wholly prevents that concentration of works in one neighbourhood which is highly advantageous to the perfection of our mechanical system.'[78]

Statements of this kind can be multiplied over and over. In steam-engine manuals, essays on the factory system, testimonies from manufacturers and other contemporary sources, this is the single most salient motive: steam was a ticket to the town, where bountiful supplies of labour waited. The steam engine did not open up new stores of badly needed energy so much as it gave access to exploitable labour. Fuelled by coal instead of streams, it untied

---

76. McCulloch 1833, p. 323; emphasis added. Compare *The Circulator of Useful Knowledge, Literature, Amusement, and General Information* 1825; McCulloch 1835, p. 457.

77. Kennedy 1818, pp. 10, 15–16.

78. Jevons 1866, pp. 150–1.

capital in space, an advantage large enough to outdo the continued abundance, cheapness, and technological superiority of water. But before we accept this conclusion, we need answers to at least three questions. What determined the geographical mismatch between water and labour supplies? How did it affect cotton capitalists in their daily operations? And did the locality of water become particularly burdensome during the 1830s?

The centrifugal dynamic of water mills

Water power was not without its limitations. With electric transmission far into the future, streams had to be used right on the spot, and not all spots were, of course, equally generous in their supply of moving water. As William Fairbairn, the era's super-engineer and designer of several of the most stupendous water mills, pointed out in his *Treatise on Mills and Millwork*, water wheels received their 'energy from falling or flowing water, and their power or dynamic effect clearly depends upon the amount of water supplied and the height through which it falls, or its velocity at the point of application.' Thus the wheels had to be placed 'on the banks of rivers where a large body of water is at hand, and near some considerable natural or artificial fall in the bed of the stream.'[79] Riveted to the spot, the water supply was contingent on the varying attributes of the landscape. While profuse on the whole, cotton capitalists could not take for granted that it was present in the right amount where they so wanted it to be; near or inside towns, sites might become crowded.

But there was always an exit. Manufacturers could *move out* to eschew congested areas, or simply to find the best sources. In the 1780s, master spinners from Manchester and other cotton centres fanned out across the countryside of Lancashire, the Midlands, Scotland and Wales; penetrating deep into the Pennine and Rossendale valleys, into Derwent and its sister valleys or the upper Clyde, they found untouched, spurting flows of water. Not only were the banks unoccupied uphill, but the falls tended to be steeper, the rain more frequent, and the need for extensive dams lesser.[80] Reliance on water power generated *a centrifugal dynamic* in the localisation of cotton mills. The more capitalists used water, the stronger the push to search farther afield – but the farther they went, the smaller the likelihood of them encountering a pre-existing settlement. If the water resources were the chief reason for choosing the site, as was so often the case in the late eighteenth and early nineteenth centuries, the

79. Fairbairn 1864, p. 67.
80. See, for example, Chapman 1971; Ashmore 1969; Rodgers 1960; Taylor 1949; Ashworth 1951; Atwood 1928; Turner 1958; Foulkes 1964.

other prerequisites for factory production might have to be assembled from the ground up. First of all, that meant labour power.

In order to construct a viable factory at Cromford, where the swift streams of the Derwent could power his water-frames, Richard Arkwright had to collect operatives from towns and conjure up a whole village, establishing not only the first full-fledged factory, but also the blueprint for the factory *colony*, to be copied along the rivers of northern Britain. Once collected, the operatives – primarily young women – had to be accommodated in houses built for the purpose. A colony usually also included a church or a chapel, a Sunday school, a shop for groceries, perhaps roads and bridges, maybe also an inn, and certainly a mansion for the manager. Without assistance from any authority or public budget, all of this had to be financed from the pocket of the manufacturer himself.[81]

Recruitment and maintenance of a labour-force were the defining problems of the factory colony. When a manufacturer came across a powerful stream passing through a valley or around a river peninsula, chances were slim that he also hit upon a local population predisposed to factory labour: the opportunity to come and work at machines for long, regular hours, herded together under one roof and strictly supervised by a manager, appeared repugnant to most, and particularly in rural areas. Colonisers following in the steps of Arkwright frequently encountered implacable aversion to factory discipline among whatever farmers or independent artisans they could find. Instead, the majority of the operatives had to be imported from towns such as London, Manchester, Liverpool and Nottingham, requiring steady advertisement in the press as well as attractive cottages behind leafy trees, allotment gardens, milk-cows, sick-clubs and other perks to persuade the workers to come, and to stay.[82]

While wages were generally lower in the countryside, the total costs for assembling and sustaining a labour force might well have been higher in the colonies. In 1826, an anonymous 'practical spinner' published a note 'on the comparative costs of power obtained by steam or water' in *Glasgow Mechanics' Magazine*, including in his calculation rent to the landlord, outlays on dam and sluices, expenses for transporting raw materials and a manager between mill and market and other costs associated with water. Even so, the steam engine's consumption of coal resulted in a balance in favour of water 'at the rate of £1.10s. per horse power: but this must be more than counterbalanced by the great advance of capital necessary to start such a work in the country, where

81. See, for example, Pollard 1964; Pollard 1968; Fitton and Wadsworth 1958; Chapman 1992; Ashworth 1951; Aspin 2003.

82. See, for example, Cohen 1981; Pollard 1968; Redford 1976; Cooke 2010.

a village must be built, loss of time in collecting a regular set of workers, with other innumerable inconveniences, which in many instances requires years to accomplish.'[83] The problem of labour was inherent in the centrifugal dynamic of water power: for every new colony constructed on a riverbank, there ensued the process of *ingathering of labour*, of concentrating workers from all possible directions on the spot. It was the constitutive feature of the colonies, their very structure intended to attract and keep operatives in place. When they failed – when workers left – the loss was of another magnitude than what an absent worker might cause in a town mill, since every employed piecer, spinner or mechanic was, almost literally, a living investment; their departure necessitated a new round of recruitment, posing the whole problem anew.

None of this was a fact of nature. Physical laws did not determine low concentrations of population in a water-rich area, the reluctance to enter the factories or the desire to escape once inside. These were socially determined factors, making labour difficult to capture and easy to lose, but they were played out and magnified in an immutable geography of riversides, from which the water wheels could never stray like the workers. The contradiction was generic to water power as a source of mechanical energy in capitalist commodity production, present from the very beginning. But in the late eighteenth and early nineteenth centuries, it was manageable and fully compatible with good business, for average profit rates were high, and the working class had yet to emerge as a force of organised power. By the 1830s, all of that had changed.

Crisis in the colonies

When the Combination Laws were repealed in 1824, the powder keg built up over half a century of industrialisation exploded in strikes and union activism across Britain. Cotton spinners were the most militant segment of the proletariat.[84] The epicentres of mobilisation were, of course, the towns, not the dells and brooks of the countryside, but rural colonies were always more vulnerable to the effects of disorder than urban factories. As strikes hit water mills with full force in the early 1830s – rioting workers rampaging through and partly trashing the colony of the Ashworths, operatives at the Catrine works blocking the gates and throwing dirt and stones on knobsticks, the Stanley colony turned into a bulwark of the Scottish spinners' union – that vulnerability was violently exposed.[85] Leading owners of water mills responded with unusually fanatical attacks on unions in general and those of

83. *Glasgow Mechanics' Magazine* 1826.
84. See, for example, Turner 1962; Kirby and Musson 1975.
85. *Manchester Guardian* 1830; *The Scottish Jurist* 1835; Cooke 2003, pp. 126–7.

their own workers in particular. The Ashworth brothers, major spinners of fine yarn near Bolton, referred to the legalisation of combinations as 'this indulgent Act' and sacked the entire vanguard of the strike-cum-riot in 1830. A perfectly viable tactic inside towns, the mass dismissal renewed the problem of labour supply: now the Ashworths had to advertise for spinners again, replacing the strike leaders with much difficulty and extra cost. The price of the strike was obliterated profits.[86]

By its very logic, the factory colony rendered layoffs, recruitment of strike-breakers, riots and repression risky and potentially ruinous; with the strike waves of the 1830s, the advantage of immediate access to a reserve army of labour came decisively to the fore. Adding to the pressure, profit rates in the cotton industry were falling, ever since the financial panic of 1825 set off a cycle of protracted stagnation and brief booms. In the mid-1830s, a bonanza of factory construction and expansion – the first in a decade – temporarily ended the depression. Manufacturers wishing to survive now had to keep up with the competition, introduce the latest machinery and enlarge their premises, but if they relied on water, they often faced a predicament: 'There is in this neighbourhood a greater scarcity of workpeople than I have ever known', Henry Ashworth lamented in 1835.[87]

For the Gregs, owners of Quarry Bank and two other water mills in Lancashire, the worries were similar: the scarcity of labour and the trade unions conspired to bring about 'a difficulty in obtaining labourers at extravagant wages in these northern counties.' If they would expand their water mills, there was an obvious risk that 'any further demand for labour would still further increase the unions, drunkenness, and high wages.'[88] Luckily for the Gregs, however, alternative options were available. In late 1826, the company acquired two factories inside the towns of Lancaster and Bury, both powered by steam. Most of the investment was redirected to these two mills; already in 1832, the one in Lancaster surpassed Quarry Bank mill as the largest establishment of the concern. The factories in Lancaster and Bury had one decisive advantage: they offered local supplies of labour power.[89] Throughout the 1830s, the Gregs continued to expand through their steam-powered assets – while the Ashworths, still based on water, lost their leadership position in fine spinning.[90]

Scarcity of labour was never absolute or evenly distributed. In Lancashire at large, the *Manchester Guardian* noted in 1835, there was in fact 'an abundance'

---

86. Boyson 1970, pp. 141–55.
87. Parliamentary Papers 1835, pp. 344–50.
88. Parliamentary Papers 1835, pp. 346–7.
89. Rose 1986, pp. 39, 43, 55; Owens 2011, p. 74.
90. See Boyson 1970.

of spinners.[91] McConnel & Kennedy never had reason to complain about a shortage of workers; 'unless they appear by Eight or Nine o'Clock on Monday Morning, we get fresh ones', they could boast.[92] It was an ever more powerful magnet. Throughout the strikes waves and business cycles of the 1830s, cotton capitalists sought to defend their positions against workers and each other by further mechanising production, introducing self-acting mules for spinning and power-looms for weaving; and with automation approaching, the premium on operatives amenable to the discipline of the machine rose. Inside the towns, a second generation of 'hands' had now grown up: 'There is always that superabundance of labour in the market that I can always attain a sufficiency of hands who have been accustomed to the work, and brought up in it, I suppose; which are always preferred', explained another Manchester manufacturer.[93] In the late eighteenth century, when factories were novel sights everywhere, the advantage of urban locations was muted. Three or four decades later, the towns of Lancashire and Scotland were brimming with the 'population trained to industrious habits' of which McCulloch spoke: young men but preferably women, born in a world of mills, resigned to bells and managers in a way country folk would rarely if ever be.[94]

A fascinating victim of the dynamics was Robert Thom. Having doubled the water supply of his cotton mill at Rothesay by excavating an ingenious system of aqueducts and reservoirs, he rose to become the foremost hydraulic engineer of Scotland and a zealous advocate of water as a superior source of energy. 'Get water if you can, and be quit of these smoky and expensive engines', ran his rallying cry to Britain's cotton manufacturers.[95] The pinnacle of his lifework was the Shaws' Water-Works at Greenock, by which water was collected and distributed to prospective mill sites, in quantities said to exceed the total power capacity of 'all the steam-engines in Glasgow and its vicinity.'[96] Deeply impressed, the *Manchester Guardian* proposed the construction of a similar system on the River Irwell, in the heart of Lancashire, to 'enable the mill-owners to dispense with the assistance of steam-engines'.[97] But in 1834, seven years after the inauguration of the Shaws' Water-Works, a dejected Thom had to concede that 'the waterfalls' he had made available to investors

91. *Manchester Guardian* 1835.
92. Quoted in Fitton 1989, p. 151. See further Lee 1972.
93. Parliamentary Papers 1834, p. D1.206 (James Fernley). On the self-acting mule, see Catling 1970; on the power-loom, see Bythell 1969.
94. Balderston 2010; Williamson 1988; Thompson 1966, p. 249; Redford 1976, p. 111; Gatrell 1977, p. 115.
95. *Mechanics' Magazine* 1832.
96. *Manchester Guardian* 1827.
97. *Manchester Guardian* 1831.

> go off very slowly – there being about thirty of them still unlet – while during the time these have been in the market, a great many Steam Factories have been erected at Glasgow, though steam power there costs about £20 per horse power, or nearly seven times the cost of water power at Greenock. And this preference is given to Glasgow, why? Because it is the principal seat of trade in Scotland with a trained population ready for such Factories.[98]

The Irwell reservoirs were planned and designed, but never built.[99]

What had happened by the 1830s was clearly not an exhaustion of the potentials of water power, in physical, technological or strictly economic terms. Instead, capitalist development had reached a point where the greatest advantage of steam power – its mobility in space – overrode all other concerns. The eruption of union struggles, the booms and busts of the post-1825 business cycle and the advancing mechanisation of cotton production enhanced the demand for workers that were substitutable, expendable and adapted to machinery. While the incentive to shift to urban steam was certainly already operative around the turn of the century, the underlying contradiction between the centrifugal dynamic of water-powered factories and the geographical concentration of suitable reservoirs of labour power became acute after the repeal of the Combination Laws and the financial crash of the mid-1820s. As profits fell, moreover, the cost of establishing a colony *de novo* became deterrent.

The boom of the 1823–5 period was the last to see a major expansion of water-powered factories. In the 1830s, colonies fell like dominoes, while mills survived and grew inside Manchester, Oldham, Stockport, Blackburn. The period marked a decisive shift from a centrifugal to a centripetal dynamic, as the cotton industry retracted into the urban core of Lancashire, in a process of urbanisation indistinguishable from the conversion to steam.[100]

The foundation of the industrial town, in other words, was fossil. Coal had the benefit of not being a part of the terrestrial landscape. Buried in its interior, it was reached through a hole in the ground – the pit-mouth – hauled up in bits and pieces and ferried off to circulate freely on the market. Unlike water, coal could be *transported* to mills and *stored* in warehouses, without the need for further attention, passively awaiting combustion. For the first time in history,

---

98. Thom archive: valuation report, 'On the Waterfall between Dalernie Mill and the Devils Bridge', 29 March 1834; emphasis in original.

99. For an inquiry into the fate of these reservoirs, Thom's failures, and some other aspects of the political economy of the transition from water to steam, see Malm 2013.

100. Rodgers 1960; Taylor 1949; Atwood 1928; Ashworth 1951; Balderston 2010; Chapman 1972.

the converter and the source of mechanical energy – the engine and the mine – were disassociated in space.[101]

The mobility of capital, the freedom to seek out the 'populous towns, where labourers are easily procured', was constituted by fossil fuels. That freedom was only relative – the price of coal rose with the distance from mines – but Lancashire happened to lie on top of rich coal-fields, 'sufficient to supply the consumption of its steam-engines for uncounted generations', in the estimate of industrial traveller William Cooke Taylor.[102] Lancashire was likewise bathed in rivers, but whereas extended utilisation of water at one point or another required capitalists to move *away from the labour power*, the coal deposits merely demanded that collieries were sent into the ground. Space, however, was not the only dimension in which the transition unfolded. Time mattered as well.

Power to command labour

Nailed to the landscape, the flow of water was not only immovable, but exposed to shifts in the weather. A river might freeze, overflow, ebb and peter out. In 1833, Samuel Greg described the power source of the Quarry Bank mill:

> Water, ninety horse power; stream irregular, occasionally a day or day and a half lost by floods. In dry seasons, for some weeks, only three quarters of daily work done. In ordinary seasons, a few hours lost daily for two or three weeks.[103]

A book-keeper at a cotton mill near Bingley in the West Riding, named Edward Birkett, told the commissioners of the Factories Inquiry that work normally went on for 13 hours, but in dry summer months production might have to be discontinued after a mere six.[104] In the absence of massive reservoir structures of the kind Robert Thom championed, such weather-induced irregularities were an all but ineluctable feature of water power.

By its very nature, in other words, water was subject to the whims of the seasons – but the problem was constituted socially. As long as mills catered to a local market for corn, linen, silk or whatever produce they turned out, a day of too much or too little water in the river was 'a source of inconvenience

101. Adapted and developed from Smil 2008, p. 204; Sieferle 2001, pp. 124–5; Debeir, Deléage and Hémery 1991, p. 102.

102. Cooke Taylor 1843, p. 156.

103. Parliamentary Papers 1834, p. D1.301.

104. Parliamentary Papers 1833a, pp. C2.65–6.

but nothing more serious': people simply turned to other tasks for a while.[105] The cotton mills of the early nineteenth century operated on other principles. They were oriented towards global markets, tailored to maximise output, constructed with profit as sole *raison d'être* – and thus working days had to be long. If the norm had been, say, six or eight hours of production, the demand for uninterrupted water power would have been significantly easier to satisfy, but the norm in the early 1830s was 12 hours, at a minimum. Simple arithmetic tells us that such a long day of work – compared to a hypothetical, shorter day – was exacting for any given watercourse. Furthermore, if water had been the only source of energy available, its irregularity would have been a fact of life, to be handled with anything from insurance schemes or dams to slight variations in output: it was the challenge of the steam engine that defined it as a drawback.[106]

That drawback could be easily offset, up to the 1830s. If water was insufficient, the workers were simply sent home and ordered to make up for the shortfall when the flow returned *through even longer working days*, effectively cancelling out the power shortages over time. As Birkett explained: 'The hands are dismissed, and recalled by a bell; they have that time to themselves; they are always paid as working a full day, and expected to make up the time as opportunity may occur.' In its first summary of the Factories Inquiry, the Chadwick Commission submitted that 'it is the custom for the people to work sometimes half an hour, at other times an hour, and occasionally even as much as two hours daily, until the whole of the lost time be made up.'[107] The irregularity of water was thus translated into bouts of extreme working days; from the baseline of 12 hours, capitalists pushed their workers even further, to cushion themselves against intermittent flow. Within the parameters of early capitalist commodity production, as it intersected with the nature of water, the practice appears to have been a necessity.

But it was precisely from the unbearable extension of the working day that arose some of the most passionate popular fury in the early 1830s. The demand of the factory movement – a universally applicable Ten Hours Act – was dreaded by proprietors of water mills. The Chadwick Commission found them fearing for their commercial survival. One master of a water-powered factory at Burley, Yorkshire, believed that 'the contemplated Ten Hours Bill would be exceedingly injurious to the cotton-trade; the legislature no doubt wishes to encourage health and morals, but if this Bill becomes a law the effects would be *to destroy many water-mills entirely* in rural situations in the country, and

105. Shaw 1984, p. 481.
106. von Tunzelmann 1978, pp. 154, 170.
107. Parliamentary Papers 1833a, p. 10.

drive the trade into large populous towns.... Steam-power is mostly in large towns, and *can be set to work at any moment*; water-mills are subject to many interruptions for want of water.'[108] Edward Birkett the book-keeper testified that a Ten Hours Act would be 'ruinous' to water mills, telling his interviewer about three he knew first-hand, which 'the masters would be compelled to abandon, such would be the injury to their profits. It would be perfectly impossible for them to carry on their mills at all during the summer season, under such restrictions.'[109] Statements of the same tenor can be piled up from the Inquiry. Though some certainly exaggerated the threat – prophesies of doom were a constant in bourgeois polemics against the Bill – the fundamental concerns were real: water supplies did fluctuate, manufacturers did make up lost time, criminalisation of the practice would cause serious trouble. The special circumstances for water mills were widely recognised, including by adherents of the factory movement. And logically, resistance to factory legislation was led by proprietors of water mills: from the early 1830s to the early 1850s, the Ashworths and the Gregs commanded the forces of the manufacturing interests, headed the associations of the Lancashire cotton masters, negotiated with Parliament, lobbied commissioners, penned pamphlets, spoke at public meetings and did everything in their power to thwart any limitation on the working day.[110] Of all cotton capitalists, those dependent on water stood to lose most, and therefore came to articulate the common interests of their class with particular urgency and stridency. Due to the nature of their prime mover – and the social demands placed on it – they found themselves first in the line of fire.

Steam engines, meanwhile, were independent of weather. While their owners were, as a rule, equally opposed to the Ten Hours Bill, their motive force could be fully adapted to a shorter working day. As it became increasingly clear in the early 1830s that popular unrest was forcing the British state to place a cap on the working day lest the country descend into full revolutionary chaos, the incentive structure was altered, the mere threat of a Ten Hours Act reducing the expected profitability of water.

Despite the protestations of the Ashworths and their kind, Parliament made a first, meagre concession to popular pressure with the Factory Act of 1833. Employment of children below the age of nine was banned in textile factories, while the working day was limited to eight hours for children up to 13 and to 12 hours for 'young persons' up to 18; factory inspectors were charged with enforcing the regulations. After extensive deliberations, the Chadwick

108. Parliamentary Papers 1834, p. C1.19 (J. Whitaker); emphases added.
109. Parliamentary Papers 1833a, p. C2.66.
110. See Howe 1984; Ward 1962; Boyson 1970; Rose 1986.

Commission, on whose recommendations the Act was based, had concluded that water mills deserved exemptions, and so they were given the right to order their children and young persons half an hour extra per day to compensate for any shortfall in power.[111] Was that enough? Half an hour was at the low end of established custom. The special needs of water capitalists were enshrined in the Act, but their latitude was severely constrained; anything beyond half an hour overtime – previously *comme il faut* – was now a crime, at least on paper.

Proprietors of water mills immediately set about flouting the law. Soon responding in force, the factory inspectors endeavoured, under the leadership of Leonard Horner, to uncover their offences and bring them to court. In 1840, a parliamentary committee reviewing the workings of the Act asked Horner where he found the greatest number of violations: 'in the detached and outlying mills' situated 'on streams', he replied.[112] Water was less compatible with lawful behaviour than steam. Howard P. Marvel has demonstrated that reliance on water was closely correlated with court action already in the years 1834–6 in Lancashire and West Riding, heartland of the English cotton industry, in a pattern that would remain in force for the coming two decades: water capitalists committed more offences, were more likely to be prosecuted, and were subject to stiffer penalties than their steam-powered competitors.[113]

To this must be added another consequence of a capped working day. The grand strategy for counteracting any reduction of hours was *to produce more in the hours left.* The disposition of labour power curtailed, more must be squeezed out of the fewer hours of work by means of installing more productive machines, speeding up those already in place, and/or enjoining operatives to work more intensely. The Factories Inquiry and subsequent reports made it abundantly clear that this was the Plan B of the manufacturers. They had, Leonard Horner reasoned in 1845, all sorts of opportunities: 'The work turned off is produced by the combined effort of the steam-engine and the workman, and the amount contributed by each varies immensely in different factories, and in different departments of the same factory.' But the opportunities on the rivers were not as promising. 'In the case of water mills', Horner wrote, '*where the intensity of the power in some seasons is continually varying during the day*, the workman cannot bring increased vigilance or attention to bear.'[114]

111. See, for example, Horner 1834. For the history of factory legislation and the factory movement, see for example Gray 1996; Ward 1962.

112. Parliamentary Papers 1840, pt. 1, pp. 5, 9.

113. Marvel 1977. On the prosecution of the Act, see also Peacock 1984; Bartrip 1985; Nardinelli 1985; Peacock 1985.

114. 'Report', in Parliamentary Papers 1845, p. 22.

The prerequisite for neutralising the effects of factory legislation was a source of mechanical energy under the complete command of the master. In the autumn of 1848, when the Ten Hours Bill had finally been passed, Horner polled the opinions of mill owners, managers and labourers in Lancashire to see how they coped with ten hours only. One manager of a cotton mill explained: 'The weavers are now producing quite as much cloth as before in 12 hours. *The engine has been speeded*.' Two cotton spinners at another factory testified that 'they work harder now during the time, and turn off nearly as much work as they did in 12 hours, *the engine having been speeded*'.[115] Steam was an integral part of the capitalist solution to the reduction in the working day.

From the prelude to the Act of 1833 to the culminating Ten Hours Act of 1847, factory legislation gradually strangled water power: 'It is obvious', one Manchester cotton manufacturer noted, 'that the more you diminish the number of hours the more you decrease the value of a water-wheel, in proportion to that of a steam-engine.'[116] The Act of 1847 eventually sounded the death-knell of water power as a viable energy source in the British cotton industry.[117]

With this, we can suggest an answer to our main question. *Cotton capital turned to steam because it offered superior power over labour.* Needless to say, there were other factors at work as well; the shift from water to steam was, indeed, over-determined by a wide range of tendencies in early nineteenth-century British capitalism, others of which we cannot investigate here. But power over labour was an outstanding keynote of the transition.

The most tractable labourer we can employ

The character of steam power as a class project was written all over it. The very appeal of the steam engine – despite its strictly economic and technological inferiority, relative to the water wheel – was precisely its unique capacity to apply 'the industry of the working class' to the production of 'surplus wealth', in Farey's words. The formula of that capacity, and a recurring theme in the bourgeois visions of steam, was what we might call its *powerless power*. In the same breath, apologists would extol the great power of steam and its complete absence of any power of its own, outside that desired by its proprietors. 'What distinguishes it from all others', renowned bourgeois economist Nassau Senior alleged in his 1848 lectures,

115. 'Report', in Parliamentary Papers 1849, pp. 47–8; emphases added.
116. Parliamentary Papers 1833b, p. D2.49 (Charles Hindley).
117. Compare von Tunzelmann 1978, p. 225; Allen 2009, pp. 173, 177.

> is its manageability. Wind power must be taken as it is given by nature. It can neither be moderated nor augmented. Water power is rather more under control. It can always be diminished and a little may sometimes be done to increase it. *The power of steam is just what we choose to make it.*[118]

While noting the noxious effects of 'carbonic acid', Babbage admired steam for being 'obedient to the hand which called into action its *resistless powers*'.[119] M.A. Alderson, author of an acclaimed 1833 steam-engine manual, emphasised that it could 'be obtained on the spot', and '*its mighty services are always at our command*, whether in winter or in summer, by day or by night – it knows no intermission but what our wishes dictate.' [120] Fairbairn marvelled at 'powers so great and so energetic as to astonish us at their immensity, while they are at the same time *perfectly docile*', while another manual author lauded not only 'the prodigious powers of steam', but just as much 'the ease and precision and *ductility* with which they can be varied, distributed, and applied.'[121] But perhaps it was John Farey who offered the most pregnant formulation. James Watt and the other modern improvers of the steam engine had, he wrote, 'rendered it capable of very rapid movements, and put its powers so completely under control, that it is now *the most tractable, as well as the most active, labourer we can employ*.'[122] A perfectly docile, ductile, tractable labourer: the wettest dream of employers come true. Here were the reasons to glorify 'the creator of six or eight million labourers, among whom the law will never have to suppress either combination or rioting', in the words of François Arago, author of the first major biography of Watt.[123]

Steam was the consummate substitute for labour, ready to step into its shoes with an infantry of machines, because it was everything that labour was not. All its virtues were constituted as the negations of working-class vices. Just as much, however, they appeared in contrast to all other available prime movers, particularly water power, whose perceived deficiencies were uncannily analogous to those of labour. Unlike water, steam was appreciated for having no ways or places of its own, no external laws, no residual existence outside that brought forth by its proprietors; it was absolutely, indeed *ontologically* subservient to those who owned it. The purpose of machinery – to secure absolute power over labour – was understood to necessitate a prime mover *over which capital could exercise absolute power* while at the same time *offering*

118. Senior papers: B18, notes for 'Course II, Lecture 8', 1848.
119. Babbage 1835, p. 49; emphasis added.
120. Alderson 1834, p. 44; emphasis added.
121. Fairbairn 1861, p. 9; Stuart 1824, p. 192; emphases added.
122. Farey 1827, p. 13.
123. Arago 1839, p. 147. On this as the first biography of Watt, see Hills 2006, pp. 175–7.

capital all the power it needed. In the powerlessness of the great powers of steam, British capital found the ideal spring of its class power. The ultimate bedrock of all that power, however, was revealed in that one little detail: the engine had to be fed with coal.

The factor in everything we do

In the final years of the 1830s, the amount of motive power derived from water in the British textile industry began to fall. Cotton drove the decline, with an ever heavier weight in Lancashire; by 1838, steam had gained ascendancy in all parts of the county except for the outlying northern areas. The rise was particularly fast in the second half of the decade, at the time of the bonanza: between 1835 and 1838, horse-power from steam in the cotton mills of Lancashire and Cheshire jumped by 62 per cent.[124] With a lag, the transition was mirrored nationwide. In 1830, steam engines supplied as much power to the British economy as water wheels – adding wind to the side of water, steam provided slightly less – but 40 years later, steam gave almost ten times more than water and wind combined. In the meantime, after the initial triumph in the cotton industry, the engine swept the factories and workshops of Britain; 'it is only of late years', noted Fairbairn in 1864, 'that in this country the steam-engine has nearly superseded the use of air and water as a prime-mover.'[125]

Since steam engines had to be fed with coal, the shares of coal consumption were redistributed with their rise. In 1800, as we have seen, domestic heating was the pre-eminent sector, and 'in no sense could the coal industry be regarded as one of the fundamental basic industries' of Britain; little more than half a century later, the situation had been reversed.[126] Domestic heating fell below the 50% line in the 1820s, but remained the single largest end-use up to 1840. By 1855, general manufacturing had eclipsed it, taking up 31% of all coal consumption in the British Isles, as against 25% for domestic heating; by 1870, three times more coal was burnt in the sectors of general manufacturing, iron and steel than in the hearths and homes of Britain.[127] In this turning of tables,

124. Kanefsky 1979, pp. 254–5, 281–90, 301; *Journal of the Statistical Society of London* 1838; Gatrell 1977, p. 101.

125. Allen 2009, pp. 172–3, 177–9; Lloyd-Jones and Lewis 1998, p. 70; Fairbairn 1864, p. 67. There were, of course, a whole spectrum of branches that had yet to be mechanised. See, for example, Samuel 1977; Greenberg 1982.

126. Mitchell 1984, p. 1.

127. Mitchell 1984, p. 12.

'the major growth point was the consumption of coal for steam-powered production in factories and workshops.'[128]

Responding to the demand, output from British coalmines leapt ahead. Lancashire was the scene of the most dramatic advance, its mines expanding on the direct and indirect stimulus from the local cotton industry. Total output in Britain entered a phase of acceleration somewhere between 1815 and 1830, reaching an apex of growth in mid-century before falling back to previous levels; the span 1831–54 saw the highest growth rate in coal production ever experienced between 1700 and 1900.[129] The new deep roots of the British economy did not escape contemporary observers. 'Without an abundant supply of coal', Farey acknowledged, 'the use of steam-engines, and the practice of the modern system of manufactures, would be very limited.'[130] No longer was coal merely used for heating homes; these days, McCulloch pointed out – in the process defining the quintessence of the fossil economy – the British coal reserves 'are the principal source and foundation of our manufacturing and commercial prosperity.'[131] In 1866, when business-as-usual already appeared entrenched in Britain, Jevons famously summed up its logic: 'Coal in truth stands not beside but entirely above all other commodities. It is the material energy of the country – the universal aid – the factor in everything we do.'[132] The railway to global warming had been laid down.

Towards a theory of fossil capital

It should be clear by now that the transition to steam in the British cotton industry presents the Ricardian-Malthusian paradigm with a serious empirical anomaly. Not only was the vanquished contender not running on present photosynthesis, but the basic tenets of the paradigm run counter to perhaps the most remarkable aspects of the process: the abundance, the technological strength, and the cheapness of water *at the time* of the transition – and anything that happened subsequently cannot, of course, be used to explain it. The fact that the total consumption of mechanical energy in the British economy much later came to exceed the potential supply from the watercourses of the country could not possibly have been a factor in the actual transition.

128. Church 1986, p. 27.
129. Pollard 1980; Mitchell 1984, pp. 7, 23–31; Church 1986, pp. 28–9; Flinn 1984, p. 26; Church 1986, p. 3.
130. Farey 1827, p. 225; emphasis added.
131. McCulloch 1837, p. 2.
132. Jevons 1866, p. viii.

But Wrigley makes an attempt to apply the Ricardian law of diminishing returns to what we have here called the centrifugal dynamic. Water power, he claims, 'was subject to rising marginal cost of provision since the better sites were naturally developed first, leaving smaller or less conveniently situated falls for later exploitation.'[133] Though this might sound a good match for the law, in fact it diverges from it in crucial respects. There is no evidence that the waterfalls at the outer rims of the centrifugal dynamic were 'smaller' or worse in any other absolute sense, whereas the inferior soils of Ricardo's law were, as both he and Wrigley assert, *less fertile by the laws of nature* (thin soil, steep slopes, poor drainage, etcetera). The disadvantage of distant watercourses was not their deficient capacity to produce power – rather the opposite: waterfalls uphill tended to be *more* powerful than in the towns – but precisely their 'inconvenience'. And that was a socially determined factor. It arose not from the fixed supply of land, but from the contradiction between the locations of streams on the one hand and the need for cotton capitalists to access concentrated supplies of labour on the other.

As for the Malthusian component of the paradigm, it was hardly a desperate struggle to satisfy the needs for the clothing of a growing number of British denizens that made the Arkwrights, the Ashworths, the Gregs or any other manufacturers establish and enlarge their mills. If a causal connection can at all be stretched out from the acceleration of population growth in the late eighteenth century to the transition from water to steam in the second quarter of the nineteenth century, it looks set to be exceedingly tenuous. As it appears in the data, the transition was nothing like 'a valiant struggle of a society with its back to the ecological wall'.

Someone of neoclassical persuasion, finally, might object that if access to labour in space and time is counted as an *associated* cost of a prime mover, water was indeed more expensive than steam – but this is merely to displace the problem, to which neoclassical theory seems oblivious. In a capitalist economy, the relative cost-efficiency of prime movers cannot be understood outside of the relations of production. The obvious alternative is Marx. An exegesis of all that he and Engels wrote on steam remains an unfulfilled task, beyond the scope of this paper. Suffice it to say that the first volume of *Capital* contains a finely textured account of the rise of steam power, including an apt précis: 'The steam-engine was from the very first an antagonist of "human power", an antagonist that enabled the capitalists to tread underfoot the

133. Wrigley 1990, p. 75. Compare Wrigley 1972, p. 249.

growing demands of the workers, which threatened to drive the infant factory system into crisis.'[134]

As a starting-point for an analysis of the fossil economy – far more promising than anything derived from earlier classical economists – we may simply take the canonical Marxian view of the specificity of capitalist growth. The compulsion to expand the scale of material production is not an attribute of the human species, present – if only in latent, bottled-up form – from the beginning of history. It is an *emergent property* of capitalist property relations. Once the direct producers and the means of production have been separated, the compulsion is inscribed in the very structure of production, in a qualitatively novel, indeed historically unprecedented way.[135] Divorced and reconstituted as commodities, labour power and means of production can only be reunified – and reunified they must be, if society is to survive – 'in the hands of the capitalist'.[136] His function is to acquire both with money. When the new commodities begotten by the rendezvous are sold, the capitalist again receives money. But why exchange money for money? The point of the process can only be the difference between the original amount thrown into circulation and the amount withdrawn at the end. If the business forecast told the capitalist that he would get back 95 per cent of his money, he would be wise to keep it in his pocket or do something else with it; if it said that he would stand a good chance to get 100 per cent of the expenses covered but no more, he would still be prudent to abstain. The effort would be pointless. Given capitalist property relations, *only the reasonable expectation of an increment in exchange-value can set the process of production in motion.*

Another word for that increment is, of course, profit, obtained from the surplus-value produced by workers. Profit is the 'driving fire' of capitalist production.[137] It recognises no end: more money can only usher in attempts to make even more money, the profit from the first circuit igniting production anew on a larger scale. This is the process commonly known as 'growth', better understood as capital accumulation, encapsulated in Marx's general formula of capital as M – C – M′, or Money – Commodities – Money-with-an-increment. More precisely, the commodities purchased by the capitalist fall into the two categories of Labour Power and Means of Production, unified in the process of Production, giving the following extended formula:

134. Marx 1990, pp. 562–3.

135. For this analysis of the growth imperative, see for example Brenner 1986; Brenner 2007; Joffe 2011. For the specifically eco-Marxist analysis, see for example Burkett 2006; Foster, Clark and York 2010; Foster 2011; Blauwhof 2012.

136. Marx 1992, p. 120. Compare Marx 1992, pp. 114–15.

137. Mandel's translation of Marx. Mandel 1990, p. 60; compare Marx 1990, p. 254.

$$M - C\,(L + MP) \ldots P \ldots C' - M'.$$

Reigniting after every circuit, the driving fire never goes out, and the general formula can thus be extrapolated in perpetuity:

$$M - C \ldots P \ldots C' - M' \rightarrow M' - C' \ldots P \ldots C'' - M'' \rightarrow M'' - C'' \ldots P \ldots C''' - M''',$$

and so on. Capital is, by its very definition, this circulatory process of valorisation, or self-expanding value. But capital is also – by its very definition – the relation between capitalists and workers. The two moments are intrinsically connected: the relation unleashes the process, which in turn reproduces the relation.

Capital, thus defined, exists 'only by sucking in living labour as its soul, vampire-like'.[138] But if labour is its soul, nature is its body. No profit from commodity production is possible without the appropriation of nature as 'the material substratum of exchange-value'.[139] The deeper meaning of P in the formulae of capital is a closely regulated *Stoffwechsel*, or metabolism, between humans and the rest of nature: materials are withdrawn and, under the command of the capitalist, placed in the hands of workers as means of production.[140] Apart from machines and other instruments, they include raw materials, a subcategory of which is 'ancillary materials' or 'accessories', in Marx's terminology. These are the substances that do not enter into the product itself – in contradistinction to, say, cotton in a thread – but form a necessary part of the *process* of production. 'An accessory may be consumed by the instruments of labour, such as coal by a steam-engine, oil by a wheel, hay by draft-horses.'[141] Coal and oil are treated by Marx as the archetypal accessories.

All required means of production – 'machines, coal, oil, etc.' – have to be present in sufficient mass 'to absorb the mass of labour which is to be turned into products through them'.[142] In the right quantities, finely tuned to labour power, the means of production will then be productively *consumed*, for the production of commodities is also a 'consumption of the means of production, which become worn through use, and are partly (e.g. *in combustion*) dissolved into their elements again.'[143] As value expands, more of the body of nature thus has to be appropriated and consumed. The fire demands its fuel.

138. Marx 1993, p. 646.
139. Ibid.
140. For this analysis of the labour process, see Burkett 1999; Foster 2000.
141. Marx 1990, p. 288.
142. Marx 1992, pp. 177, 111.
143. Marx 1993, p. 90; emphasis added.

At a certain stage in the historical development of capital, fossil fuels become a necessary material substratum for the production of surplus-value. But they are not merely necessary in the sense that raw cotton is necessary for the production of cotton textiles, wood for that of tables, or iron ore for machines: they are utilised *across the spectrum of commodity production* as the accessory that sets it in physical motion. Other sources of rotary motion are pushed to tiny fringes, while capital expands in leaps and bounds, energised by fossil fuels. These have now become *the general lever for surplus-value production*.

With F for fossil fuels, we can thus derive the general formula of fossil capital:

$$M - C\,(L + MP\,(F)) \ldots P \ldots C' - M'$$

In the circuit of capital, fossil fuels are now a portion of the means of production. The more capital expands, the larger the volumes extracted and combusted. Integral parts of the *Stoffwechsel*, fossil fuels are subjected to productive consumption in ever growing quantities, with an inevitable chemical by-product, of which Marx and Engels were aware. In the second volume of *Capital*, Marx explains that the time expended by the capitalist on buying and selling his commodities, on prowling the market and securing transactions in meetings with other businessmen, is not value-creating time, but nonetheless 'a necessary moment of the capitalist production process in its totality'. Marx draws a parallel pregnant with meaning. The time spent on buying and selling

> is somewhat like the 'work of combustion' involved in setting light to a material that is used to produce heat. This work does not itself produce any heat, although it is a necessary moment of the combustion process. For example, in order to use coal as a fuel, I must combine it with oxygen, and for this purpose transform it from the solid into the gaseous state (for carbon dioxide, the result of the combustion, is coal in this state: F.E.), i.e. effect a change in its physical form of existence or physical state. The separation of the carbon molecules that were combined into a solid whole, and the breaking down of the carbon molecule itself into its individual atoms, must precede the new combination.[144]

When Engels edited the posthumous second volume of *Capital*, using his initials to mark insertions in Marx's manuscripts, the science of chemistry had made progress since the days of Babbage. Today, we may take Marx's analogy literally and conclude that constantly increasing quantities of CO_2, just as market transactions, are a necessary part of capital accumulation; the combustion of fossil fuels in their solid form and the consequent release of CO_2

144. Marx 1992, p. 208.

do not in themselves create any value for the capitalist, but they are materially indispensable for value creation. The extended formula of fossil capital thus reads:

$$M - C\,(L + MP\,(F)) \ldots P^{\,.\,.\,.CO_2} \quad \ldots C' - M'$$

Since fossil energy now fuels the *perpetuum mobile* of capital accumulation, igniting itself anew, as a driving fire that never goes out, the cycle continues indefinitely:

$$M - C\,(L + MP\,(F)) \ldots P^{\,.\,.\,.CO_2} \quad \ldots C' - M' \rightarrow M'\,(L' + MP'\,(F')) \ldots P^{\,.\,.\,.CO_2'} \quad \ldots C'' - M''$$

and so on. Valorisation proceeds through combustion. Fossil capital, in other words, is *self-expanding value passing through the metamorphosis of fossil fuels into* CO_2. It is a *relation*, a triangular relation between capital, labour and a certain segment of extra-human nature, in which the exploitation of labour by capital is impelled by the combustion of this particular accessory. But fossil capital is also a *process*, a flow of successive valorisations, at every stage claiming a larger body of fossil energy to burn. It recognises no end. One could think of this as the biophysical shadow of Marx's general formula of capital, coming to the forefront only in the times of unexpected biospheric dusk.

The general formula of fossil capital, in these simple, extended and extrapolated versions, does not, of course, capture the entire field of fossil fuel consumption even in a capitalist society. The most obvious omission is a form of consumption preceding fossil capital by at least six centuries: the purchase of use-values whose very usage emits CO_2. Heating cottages with coal falls into this category, as does, to take but two examples, driving to work in a car, or surfing the web with a computer (in so far as these run on fossil energy). The immediate cause of combustion in these cases is the satisfaction of some need or other in the sphere of private consumption. Here the formula would rather be:

$$C - M - C\,(F^{\,.\,.\,.CO_2})$$

But even though such individual consumption predates the productive consumption of fossil fuels as a source of rotary motion, it does not give rise to business-as-usual, for *individual consumption is not the ignition mechanism of capitalist growth.*

Only with the emergence of fossil capital was business-as-usual established. By placing coal right under the driving fire of capital accumulation, as the fuel transmitting physical motion to the labour process, a spiral of growing fossil fuel combustion was, for the first time, directly tied to the spiralling growth of capitalist commodity production. But why did capital strike root in fossil fuels? Why did capital in general become *fossil* capital? What tensions in the relationship between capital, labour and the rest of nature – or, what properties of the capitalist property relations – prompted this fateful step?

The abstract and fossil spatio-temporality of capitalism

The separation between direct producers and means of production means that peasants are pushed off their land. Capital hinges upon a popular exodus from the countryside. Released from their attachment to the soil, the 'free' workers congregate at particular points, where they reconnect with the means of production on someone else's property. The receptacle for this original spatial concentration of capitalist property relations is, of course, the factory, but it immediately points beyond itself: every factory 'bears in it the germ of a manufacturing town'.[145]

As the larger receptacle, the town amasses raw materials, instruments, means of subsistence and, above all, workers. The concentration of proletarians in the town is the flipside of the draining of the countryside. It is also a necessary condition for the production of surplus-value. If there are no unemployed workers knocking at the factory gates, labour will be in a perilously strong bargaining position; the 'dead weight of the industrial reserve army' has to be *in situ*, in the form a large, dense, overflowing market for labour power. In a small, thin, spatially dispersed labour-market, capitalists have to treat their workers as precious assets, circumscribing the power to extract surplus-value. Moreover, propertyless ex-peasants must become habituated to life as disciplined operatives, in a community where wage-labour has become the normal mode of existence for masses and generations of people. The town is the ideal if not the only feasible receptacle for all these mutually dependent processes.[146] Water stood in fundamental contradiction to it.

Capitalist property relations engendered concentration in space: capitalists sticking with water were obliged to expand *out from the centre.* In the colonies, they had to fuse the spaces of production and reproduction, providing for all the needs of their workers – accommodation, access to staple goods, religious institutions, schooling – rather than letting them get by on an infrastructure

145. Engels 2009, p. 34.
146. Storper and Walker 1989, pp. 140–5; Smith 2008, p. 116; Harvey 1999, pp. 381–4.

already in place.[147] It would have been different had the abundance of cheap water been located in a hole in the ground, in a trunk around which the town could bush out, or in some other vertical configuration – but then water would not have been water. As water, it flowed on the surface of the British landscape, fully available but incongruous with the emergent spatial dynamic.

The contradiction was present from the start, but it was long hidden under the super-profits of the first generations of cotton capitalists. Only after the mid-1820s was it brought to a head. Resolving the contradiction, the cotton capitalists then cut off the tether of water power, gained a fundamental mobility to seek out – and discard – workers, broke loose from what Henri Lefebvre called 'absolute space' and moved into its 'abstract' counter-dimension. Absolute space is 'made up of fragments of nature located at sites which were chosen for their intrinsic qualities (cave, mountaintop, spring, river). . . . Then the forces of history smashed naturalness forever and upon its ruins established the space of accumulation'.[148] There emerged *abstract space*. Instead of going reverently to the mountaintops and rivers and establishing its businesses there, capital produced a matrix of nodes and arteries through *its own* circuits. Absolute, natural space 'juxtaposes – and thus disperses'. Abstract, social space 'implies actual or potential assembly at a single point', and thereby also 'the possibility of accumulation'.[149]

But even abstract space ultimately has to rest on nature. Fossil fuels alone have the characteristics that allowed for its formation. They are not diffused on the surface of the natural landscape, not weaved into its qualitative properties but concentrated in deposits beneath the ground, outside the realm of human habitation and visible variety. Their most concrete property is their abstractness. While bound to specific, irreproducible places – seams, in this case – coal is buried at a remove from the space of humans, as the relic of a landscape long dead and gone.[150] It was the optimal raw material for the initial break-out into spatial abstraction. By virtue of being concentrated in subterranean sites of no other use or meaning, coal could be brought into the world of earthlings as loose fragments, passing from hand to hand, circulating freely inside the commodity circuits and releasing the forces of accumulation.

The temporality of capitalist property relations is homologous. Pre-capitalist modes of production were structured by what Moishe Postone calls 'concrete time': time as dependent variable, the function of an occasion, process, or

147. Compare Lefebvre 1991, p. 319; Harvey 1999, pp. 398–405; Smith 2008, pp. 166, 182.
148. Lefebvre 1991, p. 49.
149. Lefebvre 1991, p. 101.
150. Compare the argument made in Mitchell 2011, especially Chapter 1.

sensuous rhythm. Above all, concrete time is *embedded in natural cycles*.[151] The pre-capitalist fisher attended to the tides, while the artisan downed his tools when darkness fell. In peasant households the grain must be harvested before the rains arrive, the cows must be milked in the morning, and the firewood must be at hand when autumn comes – in short, 'hours and task must fluctuate with the weather.'[152]

But capitalist property relations generate a radically different, indeed antithetical temporality: when a capitalist purchases the right to dispose of labour power, that right is restricted and specified in time (otherwise there would be slavery). His objective is to make sure that the worker *performs as much labour as possible within the given time-frame*, be it six or twelve hours, for one week or as long as the parties agree. The labour has to occur precisely within that time – not when the weather is right, or when the sun has risen, or when the worker happens to be in the mood for hard labour, for then the right to dispose of labour power might have already expired, and the purchase would come to nought. Moreover, the capitalist must see to it that his workers produce the commodities at least as fast as those of his competitors, and so he becomes intensely preoccupied with productivity: labour output as measured against a fixed time unit.[153] With the rise of capitalist property relations, there emerged, in Postone's terms, *abstract time*. This is time as independent variable, a mathematical vessel, an incorporeal repository of events which heeds no seasons, weather or other concrete appearances in nature. It serves as a measure *of* activity, beginning with labour.[154]

Water power was a legacy from the era of concrete time. It was eminently commensurate with modes of production attuned to the ups and downs of natural fluctuations, the ebbs and flows, the floods and dry spells, the freezing cold in wintertime. But abstract time inhered in capitalist property relations. A contradiction was inevitable, though it did not make itself felt until a certain juncture in the history of capitalist development: as long as absolute surplus-value was dominant – as long as manufacturers could extend the working day at will – water was still a perfectly viable energy source. It could be used to produce surplus-value, even as labour-time had to be adjusted to the power supply. But with the Factory Acts of 1833 and 1847, not only was the lengthening of the working day for the first time brought to a mandated halt, but the day was *shortened.* How did capital respond to this challenge? It 'threw itself with all its might, and in full awareness of the situation, into the production of

151. Postone 1993, pp. 201–2.
152. Thompson 1967, p. 78. Compare Ingold 1995.
153. Postone 1993, pp. 210–12; Thompson 1967, pp. 61, 90–1.
154. Postone 1993, pp. 202, 214–15.

relative surplus-value', by increasing the productivity and intensity of labour, so that more commodities were produced in the remaining given time units.[155]

The struggle for a shorter working day – *Urform* of working-class self-defence – provoked capital to counterattack with a further abstraction of time. 'The pores of time are so to speak shrunk through the compression of labour.'[156] Abstract time became ever more sovereign and supreme in its claims on labour – and consequently on nature. If labour was to proceed faster and more intensely, so must the prime mover; all bulging pores of interruption had to be banished. In the 1830s and 1840s, as absolute surplus-value was overtaken by its relative twin, the increased expenditure of labour had to be placed on the solid footing of the steam engine, utterly malleable to the temporal needs of capital – turned on, turned off, speeded up at will. Such virtues were mere corollaries of the essence of fossil fuels: *their ejection from perceptible natural rhythms through burial underground.* Frozen in time, coal was congenial to the abstract time of capitalist property relations, and, under the duress of factory legislation, it became a prerequisite for its continued abstraction.

Abstract space and abstract time together form what Noel Castree calls the 'distinctive *spatio-temporality*' of the capitalist mode of production.[157] Capital does not circulate *in* space and *through* time, as if the two were fixed axes along which it develops; rather, it produces its *own* abstract space-time. The one dimension is inseparable from the other. They constitute a single spatio-temporality, which emanates straight from the fundamentals of capitalist property relations. A primordial rift in the relation between humans and between them and the rest of nature – the separation between direct producers and means of production – is propagated in space and time, severing human beings from the qualitative properties of both dimensions. Labour is relocated to particular places and moments set aside strictly for the purpose.

The necessary material substratum for this spatio-temporality – long hidden from the view of most Marxists, however sharp their eyes have otherwise been – is fossil fuels.[158] They represent the geological compression of the time and space required for photosynthesis hundreds of millions of years ago, when no humans roamed the planet; *sui generis*, their dense energy permits capital to produce its own abstract spatio-temporality for the production of surplus-value. They are incorporated into capital *as its own motive force*.

---

155. Marx 1990, p. 534; emphasis added.
156. Marx 1991b, p. 335.
157. Castree 2009, p. 27; emphasis in original.
158. Some Marxists who have argued in this direction are Altvater 1994; Altvater 2006; Clark and York 2005; Huber 2009.

Marx comes close to capturing this logic in the third volume of *Capital*, at the beginning of his treatment of ground-rent, devoted to an extraordinary discussion of the relative benefits of water and steam. 'Assume', Marx opens his excursion, 'that the factories in a country are powered predominantly by steam-engines, but a certain minority by natural waterfalls instead.' Water is far cheaper, Marx further assumes – this is written in London in the mid-1860s – and provides the proprietors of water mills with 'exceptionally favourable conditions'. Labour applied in the water mill has greater productivity than in the steam mill, expressed 'in the way that it needs a smaller quantity of constant capital to produce the same amount of commodities, a smaller quantity of objectified labour than the others; and a smaller quantity of living labour as well, since the water-wheel does not need to be heated.'[159] However, water is

> a natural force that is not available to all capital in the same sphere of production, as is for example the elasticity of steam. . . . *It is in no way just up to the capital to call into being this natural condition* of greater labour productivity, in the way that any capital can transform water into steam. The condition is to be found in nature only at certain places, and where it is not found it cannot be produced by a particular capital outlay. *It is not bound up with products that labour can produce such as machines, coal, etc., but rather with particular natural conditions on particular pieces of land.*[160]

Water, Marx reiterates, 'cannot be produced by capital's own production process': capital 'cannot create a water-fall from its own resources'.[161] This is in stark contrast to fossil fuels. Their power is 'just what we choose to make it', in the words of Senior; their 'mighty services are always at our command', with Alderson. Needless to say, capital is unable to literally manufacture coal seams or any other fossil fuel reserves, but it can call them into being as energy deposits by mobilising its own resources: labour power and means of production. Indeed, fossil fuels are not a natural force like water, running through forests and meadows prior to capital's arrival, dispensing its energy merely by existing: fossil fuels *must be called into existence*. The appearance of fossil energy *qua* energy is not autonomous, but contingent upon capital itself. It assumes the guise of a power in motion internal to capital, lending it a physical life of its own.

Precisely because it is so abstract, and founded on the power of the capitalist class, the spatio-temporality of capitalism is *more* deeply rooted in a *particular*

159. Marx 1991a, pp. 779–81; emphasis added.
160. Marx 1991a, p. 784; emphases added.
161. Marx 1991a, pp. 784–5.

form of nature than other spatialities and temporalities in history. Arago neatly laid out the principles in his hagiography of Watt: 'The great mechanical powers which had formerly to be sought for in mountainous districts, at the foot of rapid cascades, will, thanks to Watt's invention, readily and easily arise, in the midst of towns, on any story of a house. The extent of these powers will vary at the will of the mechanician; it will no longer depend, as heretofore, on the most inconstant of natural causes, – on atmospheric influences.'[162] Instead, capitalist spatio-temporality came to influence the atmosphere. The depth of its dependency on nature is fully disclosed when carbon dioxide from the combustion of fossil fuels, with a transformative power unlike any other anthropogenic substance, rearranges the qualitative properties of space and jumbles historical and geological time in ways never previously seen. Abstracting itself from nature, capital ended up making it less and less liveable, in very concrete terms.

The persistence of business-as-usual

Fossil capital has proved fantastically profitable for almost two centuries. Up to this day, its rotation continues to propel business-as-usual, in complete disregard of the scientific knowledge of the noxious effects of increasing the atmosphere by large quantities of carbon dioxide. How do we approach this all-time social wreck? The favoured Ricardian-Malthusian explanation for the transition to a fossil economy – the liberation from land constraint – can only be a one-off driver, at the very best. This becomes obvious if we revisit the mathematical conversions from fossil fuels to acres of woodland so highly regarded as explanatory exercises by Wrigley and his followers. When Wrigley calculates that all coal in 1800 equalled 35% of the British land surface, rising to 150% in 1850, this is, of course, a hypothetical, counterfactual thought-experiment. Can it tell us anything about the causal forces operating in the expansion of coal consumption in the period? For that to be the case, Wrigley would have to present evidence that land scarcity pushed up prices for alternative fuels in the first half of the nineteenth century, that the rising costs of these other fuels impelled consumers to shift to coal, and that such cost-motivated consumption made up the bulk of all coal-burning. Wrigley does not, however, provide anything of the sort, and it would be difficult to do so. Then can the exercise tell us anything about the causal forces operating later in the history of business-as-usual?

162. Arago 1839, p. 150.

Consider Malanima's conclusion that a Europe bereft of fossil fuels would have needed 2.7 times its continental surface in 1900 and more than 20 times a century later: can it tell us anything about the driving force of this tremendous pyre? Logically it cannot, because if Europe was liberated from the land constraint – even before the onset of the twentieth century – it could no longer have operated as a causal factor. The supposed breaking of the Ricardian curse is a one-off event, evaporating as soon as it transpires. The same applies to the iron industry, the best case for the paradigm: the liberation from land provided by the conversion from charcoal to coke can explain the initial spike in coal consumption, but once that liberation had actually occurred, other drivers must have taken over. As for the Malthusian component, there is precious little evidence that population growth has been behind subsequent waves of expanding fossil fuel consumption.[163]

Adherents of the Ricardian-Malthusian paradigm are, of course, right in identifying fossil fuels as a necessary precondition for the kind of growth the world has seen in the past two centuries. But the only clue they can offer for an analysis of business-as-usual after the industrial revolution is a vague reference to growth as an innately human pursuit, common to all eras and modes of production, permanently throbbing if sometimes held back. It begs the question of *what is special with the fossil economy*. Nothing new has emerged; the old has merely been realised. The theory of fossil capital, on the other hand, appears to have explanatory power for the transition to a fossil economy *and for its continued development*. Consider only the case of China. The twenty-first century explosion in CO_2 emissions is centred on China, largely caused by the relocation of industrial production from advanced capitalist countries. This process obviously has nothing to do with land constraints or population growth in those same countries. But it has, as argued elsewhere, very much to do with the removal of factories to other situations, where labourers are easily procured and trained to industrious habits.[164]

This points towards a radical rethinking of the drivers of ecological destruction in our time. They should not be conceived as archaic yearnings of the human species, as a timeless growth pursuit bumping into walls of scarcity and transcending them by substituting abundant goods for scarce ones: a *universal* process unfolding through reaction upon *specific* constraints. The reverse appears more appropriate. Capital is a *specific* process that unfolds through a *universal* appropriation of biophysical resources, because capital itself possesses a unique, insatiable appetite for surplus-value extracted from

163. For a debunkning of the myth that population growth drives carbon emissions, see Satterthwaite 2009.

164. Malm 2012b.

human labour by means of material substrata. Capital, one could say, is super-ecological, a biophysical omnivore with its own peculiar social DNA.

Such a theory might, furthermore, provide insights into the stalled shift to renewable energy sources. It has recently been demonstrated that *all* energy consumed in the world could be provided from wind, water and solar power, without any noticeable share of coal, oil or natural gas, within a few decades, at little or no extra total cost – if relevant actors only decided to harvest the abundance of energy surrounding us.[165] But there are hurdles in the way. In a major survey in 2010, *Science* noted that 'building solar or wind farms is a land-hungry process, and the energy they deliver is often intermittent and hard to store.' Quoting an ecological economist specialising in the field, it drew attention to the fact that ' "many of the windiest and sunniest regions in the world are virtually uninhabited" '.[166] Now these inherent properties of wind and sun – absolute space, concrete time – would perhaps not constitute such serious handicaps if it were not for the particular form of spatio-temporality that governs the world.

The problem is not new. One day in the late 1860s, as he sat preparing a lecture on the economics of coal, William Stanley Jevons's eyes fell upon a newspaper report about the Swedish-American inventor John Ericsson, who 'undertakes to supply a new fuel in the place of coal, and a new motive power instead of steam. For several years he has been experimenting with a view of collecting and concentrating the radiating heat of the sun' in a 'solar engine'.[167] Jevons saved the clip and scribbled down his excitement. It was the 'most sound' of all suggested solutions to what he perceived to be an impending coal shortage,

> and for my part I really do not look upon it as an unlikely notion to be carried out into practice some day. But if it be carried out, what will be the result for us – simply that we shall be replaced, and the seats of industry will be removed to the sunny parts of the earth. In Manchester at any rate we have little sun that we have to manipulate for light. . . . The tendency of things is such that we are likely to find coal a source of sunlight [rather] than sunlight a competitor of coal.[168]

This 'tendency of things', Jevons thus intimated, did not inhere in the sun or the earth themselves, but in the ongoing concentration of industrial commodity production to the galaxy gravitating around Manchester.

---

165. Jacobson and Delucchi 2011a; Jacobson and Delucchi 2011b; Leggett and Ball 2012.
166. Kerr 2010 (Cutler Cleveland). Compare the points raised by Trainer 2012.
167. Jevons archive: JA6/9/168, 'Fuel from the sun', undated clip from *Express*.
168. Jevons archive: JA6/9/168, note on the *Express* clip.

Today, the divergence between the potentials of renewable energy and the tendency of things – each advancing in their own direction – is, of course, far wider. Manchester and its twins in the advanced capitalist countries have lost their lustre, because capital has become *even more* bent on removing to locations where the supplies of labour power offer the highest rates of surplus-value, regardless of any intrinsic qualities of places. Here is a question rarely asked: is that tendency compatible with a complete cessation of fossil fuel use, the kind of change climate science tells us is our only chance to avoid a general breakdown of the ecological foundations of human existence? Even if a project such as Desertec – filling the Sahara with solar panels and sending the electricity to Europe – were to be implemented, it would still be impossible to export that solar energy to, say, the Yangzi Delta, or any other distant place capital currently might favour for commodity production.[169] But oil can be pumped out of the ground in Alaska or Angola and shipped to any site of accumulation, from Guangzhou to Ghent. A similar question pertains to the dimension of time. Are the principles of just-in-time and lean production at all reconcilable with renewable energy?

Globalisation may be conceived as a process in which the spatio-temporality of capital is extricated from and made to dominate all other aspects of human and natural life: a most unpropitious moment, it would seem, for embedding the world's energy system in the spatial and temporal matrix of wind, water and sun. It might well be the case that renewable energy can become as reliable and all-encompassing as fossil energy – if scaled up massively and assisted by super-grids, surplus capacity, intercontinental transmission, electricity storage systems and all the rest – but in the meantime, we may do well to wonder if the inaction on the most critical issue in the history of humanity is rooted in the compulsions of self-expanding value.[170] For two centuries, it has craved constantly increasing quantities of energy, whose qualities correspond to its own mode of existence, both of which moments seem to perpetuate business-as-usual and deflect alternatives. Will this fire have to be extinguished? What would that require, given that we have so precious little time to stave off the worst-case scenarios? Further research on fossil capital may throw light on the – literally – social nature of this challenge.

169. On Desertec, see for example Clery 2010.

170. Elaborate arguments for such potentials of renewable energy are made in Jacobson and Delucchi 2011a; Jacobson and Delucchi 2011b.

References

Alderson, M.A. 1834, *An Essay on the Nature and Application of Steam*, London: Sherwood, Gilbert, and Piper.

Allen, Robert C. 2009, *The British Industrial Revolution in Global Perspective*, Cambridge: Cambridge University Press.

Altvater, Elmar 1994, 'Ecological and Economic Modalities of Time and Space', in *Is Capitalism Sustainable?: Political Economy and the Politics of Ecology*, edited by Martin O'Connor, New York: Guilford Press.

—— 2006, 'The Social and Natural Environment of Fossil Capitalism', in *Socialist Register 2007*, edited by Leo Panitch and Colin Leys, London: Merlin Press.

Andrews, Thomas G. 2008, *Killing for Coal: America's Deadliest Labor War*, Cambridge, MA.: Harvard University Press.

Arago, François 1839, *Historical Eloge of James Watt*, London: John Murray.

Arrhenius, Svante 1896, 'On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground', *Philosophical Magazine and Journal of Science*, 5, 41: 237–76.

Ashmore, Owen 1969, *The Industrial Archaeology of Lancashire*, Newton Abbot: David and Charles.

Ashworth, W. 1951, 'British Industrial Villages in the Nineteenth Century', *The Economic History Review*, 3, 3: 378–87.

Aspin, Chris 2003, *The Water Spinners*, Helmshore: Helmshore Local History Society.

Aston, Trevor Henry and C.H.E. Philpin (eds.) 1987, *The Brenner Debate: Agrarian Class Structure and Economic Development in Pre-industrial Europe*, Cambridge: Cambridge University Press.

Atwood, Rollin S. 1928, 'Localization of the Cotton Industry in Lancashire, England', *Economic Geography*, 4, 2: 187–95.

Babbage, Charles 1835 [1833], *On the Economy of Manufactures*, London: Charles Knight.

Balderston, Theo 2010, 'The Economics of Abundance: Coal and Cotton in Lancashire and the World', *The Economic History Review*, 63, 3: 569–90.

Barca, Stefania 2011, 'Energy, Property, and the Industrial Revolution Narrative', *Ecological Economics*, 70, 7: 1309–15.

Bartrip, Peter 1985, 'Success or Failure? The Prosecution of the Early Factory Acts', *The Economic History Review*, 38, 3: 423–7.

Blauwhof, Frederik Berend 2012, 'Overcoming Accumulation: Is a Capitalist Steady-State Economy Possible?', *Ecological Economics*, online first, doi:10.1016/j.ecolecon.2012-03-012.

Boden, T.A., G. Marland and R.J. Andres 2011, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, Oak Ridge: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, available at: <http://cdiac.ornl.gov/>.

Boyson, Rhodes 1970, *The Ashworth Cotton Enterprise: The Rise and Fall of a Family Firm, 1818–1880*, Oxford: Clarendon Press.

Brenner, Robert 1986, 'The Social Basis of Economic Development', in *Analytical Marxism*, edited by John Roemer, Cambridge: Cambridge University Press.

—— 1987a [1976], 'Agrarian Class Structure and Economic Development in Pre-industrial Europe', in Aston and Philpin (eds.) 1987.

—— 1987b [1985], 'The Agrarian Roots of European Capitalism', in Aston and Philpin (eds.) 1987.

—— 2007, 'Property and Progress: Where Adam Smith Went Wrong', in *Marxist History-Writing for the Twenty-First Century*, edited by Chris Wickham, Oxford: Oxford University Press/British Academy.

Briggs, Asa 1982, *The Power of Steam: An Illustrated History of the World's Steam Age*, London: Bison Books.

Burkett, Paul 1999, *Marx and Nature: A Red and Green Perspective*, New York: St Martin's Press.

—— 2006, *Marxism and Ecological Economics: Toward a Red and Green Political Economy*, *Historical Materialism* Book Series, Leiden: Brill.
Buxton, Neil K. 1978, *The Economic Development of the British Coal Industry: From Industrial Revolution to the Present Day*, Newton Abbot: Batsford Academic.
Bythell, Duncan 1969, *The Handloom Weavers: A Study in the English Cotton Industry during the Industrial Revolution*, Cambridge: Cambridge University Press.
Cameron, Rondo 1985, 'A New View of European Industrialization', *The Economic History Review*, 38, 1: 1–23.
Castree, Noel 2009, 'The Spatio-temporality of Capitalism', *Time and Society*, 18, 1: 26–61.
Catling, Harold 1970, *The Spinning Mule*, Newton Abbot: David and Charles.
Chaloner, W.H. 1954–5, 'Robert Owen, Peter Drinkwater and the Early Factory System in Manchester, 1788–1800', *Bulletin of the John Rylands Library*, 37: 87–92.
Chapman, Stanley D. 1969, 'The Peels in the Early English Cotton Industry', *Business History*, 11, 2: 235–66.
—— 1971, 'The Cost of Power in the Industrial Revolution in Britain: The Case of the Textile Industry', *Midlands History*, 1, 2: 1–24.
—— 1972, *The Cotton Industry in the Industrial Revolution*, Basingstoke: Macmillan.
—— 1992 [1967], *The Early Factory Masters: The Transition to the Factory System in the Midland Textile Industry*, Aldershot: Gregg Revivals.
Church, Roy 1986, *The History of the British Coal Industry. Volume 3: 1830–1913: Victorian Pre-eminence*, Oxford: Clarendon Press.
Clark, Brett and Richard York 2005, 'Carbon Metabolism: Global Capitalism, Climate Change, and the Biospheric Rift', *Theory and Society*, 34, 4: 391–428.
Clery, Daniel 2010, 'Sending African Sunlight to Europe, Special Delivery', *Science*, 329, 5993: 782–3.
Cohen, John S. 1981, 'Managers and Machinery: An Analysis of the Rise of Factory Production', *Australian Economic Papers*, 20, 36: 24–41.
Cooke, Anthony 2003, *Stanley: From Arkwright Village to Commuter Suburb: 1784–2003*, Perth: Perth & Kinross Libraries.
—— 2010, *The Rise and Fall of the Scottish Cotton Industry, 1778–1914: 'The Secret Spring'*, Manchester: Manchester University Press.
Cooke Taylor, William 1843, *The Hand Book of Silk, Cotton, and Woollen Manufactures*, London: Richard Bentley.
Crafts, Nicholas 2004, 'Steam as a General Purpose Technology: A Growth Accounting Perspective', *The Economic Journal*, 114, 495: 338–51.
Crutzen, Paul J. 2002, 'Geology of Mankind', *Nature*, 415: 23.
Crutzen, Paul J. and Will Steffen 2003, 'How Long Have We Been in the Anthropocene Era?', *Climatic Change*, 61, 3: 251–7.
Dearne, Martin J. and Keith Branigan 1995, 'The Use of Coal in Roman Britain', *The Antiquaries Journal*, 75: 71–105.
Debeir, Claude, Jean-Paul Deléage and Daniel Hémery 1991 [1986], *In the Servitude of Power: Energy and Civilisation through the Ages*, London: Zed Books.
Engels, Friedrich 2009 [1845], *The Condition of the Working Class in England*, edited by David McLellan, Oxford: Oxford University Press.
Fairbairn, William 1861, 'Speech at the British Association for the Advancement of Science Meeting in Manchester', *Proceedings of the Thirty-First Meeting of the British Association for the Advancement of Science*, Manchester: Guardian Steam-Printing.
—— 1864 [1863], *Treatise on Mills and Millwork, Part I., On the Principles of Mechanism and on Prime Movers*, London: Longman, Green, Longman, Roberts, and Green.

Farey, John 1827, *A Treatise on the Steam Engine, Historical, Practical, and Descriptive*, London: Longman, Rees, Orme, Brown, and Green.
Fitton, Robert S. 1989, *The Arkwrights: Spinners of Fortune*, Manchester: Manchester University Press.
Fitton, Robert S. and A.P. Wadsworth 1958, *The Strutts and the Arkwrights, 1758–1830*, Manchester: Manchester University Press.
Flinn, Michael W. 1984, *The History of the British Coal Industry, Volume 2, 1700–1830: The Industrial Revolution*, Oxford: Clarendon Press.
Foster, John Bellamy 2000, *Marx's Ecology: Materialism and Nature*, New York: Monthly Review Press.
—— 2011, 'Capitalism and Degrowth: An Impossibility Theorem', *Monthly Review*, 62, 8: 26–33.
Foster, John Bellamy, Brett Clark and Richard York 2010, *The Ecological Rift: Capitalism's War on the Earth*, New York: Monthly Review Press.
Foulkes, Edward J. 1964, 'The Cotton Spinning Factories of Flintshire, 1777–1866', *The Journal of the Flintshire Historical Society*, 21: 91–7.
Gatrell, Victor A.C. 1977, 'Labour, Power, and the Size of Firms in Lancashire Cotton in the Second Quarter of the Nineteenth Century', *The Economic History Review*, 30, 1: 95–139.
Glasgow Mechanics' Magazine 1826, 'On the Comparative Costs of Power Obtained by Steam or Water', 7 January.
Gordon, Robert B. 1983, 'Cost and Use of Water Power during Industrialization in New England and Great Britain: A Geological Interpretation', *The Economic History Review*, 36, 2: 240–59.
Gray, Robert 1996, *The Factory Question and Industrial England, 1830–1860*, Cambridge: Cambridge University Press.
Greenberg, Dolores 1982, 'Reassessing the Power Patterns of the Industrial Revolution: An Anglo-American Comparison', *The American Historical Review*, 87, 5: 1237–61.
Greg archive, Manchester Archives and Local Studies: R. Greg and Co. Ltd. of Quarry Bank Mill, Styal.
Harvey, David 1999 [1982], *The Limits to Capital*, First Edition, London: Verso.
Hatcher, John 1993, *The History of the British Coal Industry, Volume 1: Before 1700*, Oxford: Clarendon Press.
Hills, Richard L. 1970, *Power in the Industrial Revolution*, New York: Augustus M. Kelley.
—— 1989, *Power from Steam: A History of the Stationary Steam Engine*, Cambridge: Cambridge University Press.
—— 2006, 'The Importance of Steam Power during the Nineteenth Century', *Transactions of the Newcomen Society*, 76, 2: 175–92.
Horner, Leonard 1834, *The Factories Regulation Act Explained, With Some Remarks on Its Origin, Nature, and Tendency*, Glasgow: David Robertson.
Howe, Anthony 1984, *The Cotton Masters, 1830–1860*, Oxford: Clarendon Press.
Huber, Matthew T. 2009, 'Energizing Historical Materialism: Fossil Fuels, Space and the Capitalist Mode of Production', *Geoforum*, 40, 1: 105–15.
Humphrey, William S. and Joe Stanislaw 1979, 'Economic Growth and Energy Consumption in the UK, 1700–1975', *Energy Policy*, 7, 1: 29–42.
Hyde, Charles K. 1977, *Technological Change and the Development of the British Iron Industry, 1700–1870*, Princeton: Princeton University Press.
Ingle, George 1997, *Yorkshire Cotton: The Yorkshire Cotton Industry, 1780–1835*, Lancaster: Carnegie Publishing Ltd.
Ingold, Tom 1995, 'Work, Time and Industry', *Time and Society*, 4, 1: 5–28.
Jacobson, Mark Z. and Mark A. Delucchi 2011a, 'Providing All Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials', *Energy Policy*, 39, 3: 1154–69.

—— 2011b, 'Providing All Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies', *Energy Policy*, 39, 3: 1170–90.
Jevons archive, John Rylands Library, Manchester: William Stanley Jevons.
Jevons, William Stanley 1866, *The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines*, London: Macmillan and Co.
Joffe, Michael 2011, 'The Root Cause of Economic Growth under Capitalism', *Cambridge Journal of Economics*, online first, doi:10.1093/cje/beq054.
Jones, Christopher F. 2010, 'A Landscape of Energy Abundance: Anthracite Coal Canals and the Roots of American Fossil Fuel Dependence, 1820–1860', *Environmental History*, 15, 3: 449–84.
Journal of the Statistical Society of London 1838, 'Increase of Steam-Power in Lancashire and Its Immediate Vicinity', 1, 5: 315–16.
Kanefsky, John William 1979, *The Diffusion of Power Technology in British Industry, 1760–1870*, unpublished PhD thesis, University of Exeter.
Kennedy, John 1818, *Observations on the Rise and Progress of the Cotton Trade in Great Britain*, Manchester: The Executors of the Late S. Russell.
Kerr, Richard A. 2010, 'Do We Have the Energy for the Next Transition?', *Science*, 329, 5993: 780–1.
Kirby, Raymond George and Albert Edward Musson 1975, *The Voice of the People: John Doherty, 1798–1854. Trade Unionist, Radical and Factory Reformer*, Manchester: Manchester University Press.
Lee, Clive Howard 1972, *A Cotton Enterprise, 1795–1840: A History of the M'Connel & Kennedy Fine Cotton Spinners*, Manchester: Manchester University Press.
Lefebvre, Henri 1991 [1974], *The Production of Space*, translated by Donald Nicholson-Smith, Oxford: Blackwell.
Leggett, L. Mark W. and David A. Ball 2012, 'The Implication for Climate Change and Peak Fossil Fuel of the Continuation of the Current Trend in Wind and Solar Energy Production', *Energy Policy*, 41, 610–17.
Lloyd-Jones, Roger and Myrddin John Lewis 1998, *British Industrial Capitalism since the Industrial Revolution*, London: Routledge.
Lord, John 1965 [1923], *Capital and Steam Power, 1750–1800*, New York: Frank Cass.
Malanima, Paolo 2001, 'The Energy Basis for Early Modern Growth, 1650–1820', in *Early Modern Capitalism: Economic and Social Change in Europe, 1400–1800*, edited by Maarten Prak, London: Routledge.
—— 2006, 'Energy Crisis and Growth 1650–1850: The European Deviation in a Comparative Perspective', *Journal of Global History*, 1, 1: 101–21.
Malm, Andreas 2012a, 'Steam: Nineteenth-Century Mechanization and the Power of Capital', in *Ecology and Power: Struggles over Land and Material Resources in the Past, Present and Future*, edited by Alf Hornborg, Brett Clark and Kenneth Hermele, Abingdon: Routledge.
—— 2012b, 'China as Chimney of the World: The Fossil Capital Hypothesis', *Organization & Environment*, 25, 2: 146–77.
—— 2013, 'Fleeing the Flowing Commons: Robert Thom, Water Reservoir Schemes, and the Shift to Steam-Power in Early Nineteenth Century Britain', *Environmental History*, forthcoming.
Manchester Guardian 1827, 'Great Hydraulic Improvements in Scotland', 3 February.
—— 1830, 'Serious Riot', 17 April.
—— 1831, 'Proposed Reservoir Near Bolton for Supplying the Mills on the Irwell', 30 June.
—— 1835, 'Emigration of Labourers – Poor Law Commissioners', 21 March.
Mandel, Ernest 1990 [1976], 'Introduction', in Marx 1990.
Marshall, J.D. 1957, 'Early Applications of Steam Power: The Cotton Mills of the Upper Leen', *Transactions of the Thoroton Society*, 60: 34–43.
Marvel, Howard P. 1977, 'Factory Regulation: A Reinterpretation of Early English Experience', *Journal of Law and Economics*, 20, 2: 379–402.

Marx, Karl 1990 [1867], *Capital: A Critique of Political Economy. Volume I*, translated by Ben Fowkes, Harmondsworth: Penguin.
—— 1991a [1894], *Capital: A Critique of Political Economy. Volume III*, translated by David Fernbach, Harmondsworth: Penguin.
—— 1991b, 'Marx's Economic Manuscripts of 1861–63', in *Marx and Engels Collected Works*, Volume 33, London: Lawrence and Wishart.
—— 1992 [1885], *Capital: A Critique of Political Economy. Volume II*, translated by David Fernbach, Harmondsworth: Penguin.
—— 1993 [1939/41], *Grundrisse: Foundations of the Critique of Political Economy*, Harmondsworth: Penguin.
Mayumi, Kozo 1991, 'Temporary Emancipation from Land: From the Industrial Revolution to the Present Time', *Ecological Economics*, 4, 1: 35–56.
McCulloch, J.R. [unsigned] 1833, 'Babbage on *Machinery and Manufactures*', *Edinburgh Review*, Volume LVI, January: 313–32.
—— [unsigned] 1835, 'Philosophy of Manufactures', *Edinburgh Review*, Volume LXI, July: 453–72.
—— 1837, *A Statistical Account of the British Empire: Exhibiting Its Extent, Physical Capacities, Population, Industry, Civil and Religious Institutions*, London: Charles Knight.
Mechanics' Magazine 1832, 'The Shaws' Waterworks, Greenock', 11 August: 306–13.
Meiksins Wood, Ellen 1995, *Democracy against Capitalism: Renewing Historical Materialism*, Cambridge: Cambridge University Press.
—— 2002, *The Origin of Capitalism: A Longer View*, Second Edition, London: Verso.
Mitchell, Brian R. 1984, *Economic Development of the British Coal Industry, 1800–1914*, Cambridge: Cambridge University Press.
Mitchell, Timothy 2002, *Rule of Experts: Egypt, Techno-Politics, Modernity*, Berkeley: University of California Press.
—— 2011, *Carbon Democracy: Political Power in the Age of Oil*, London: Verso.
Musson, Albert Edward 1976, 'Industrial Motive Power in the United Kingdom, 1800–70', *The Economic History Review*, 29, 3: 415–39.
Musson, Albert Edward and E. Robinson 1959, 'The Early Growth of Steam Power', *The Economic History Review*, 11, 3: 418–39.
Nardinelli, Clark 1985, 'The Successful Prosecution of the Factory Acts: A Suggested Explanation', *The Economic History Review*, 38, 3: 428–30.
Nef, John U. 1966 [1932], *The Rise of the British Coal Industry*, Volumes I–II, Abingdon: Frank Cass.
Nuvolari, Alessandro 2004, *The Making of Steam Power Technology: A Study of Technical Change during the British Industrial Revolution*, Eindhoven: Eindhoven University Press.
Owens, Jessica 2011, *Quarry Bank Mill and Styal Estate*, National Trust, GCSE Resources, available at <http://www.nationaltrust.org.uk/>.
Parliamentary Papers 1833a, Volume XX, *Reports from Commissioners: Factories, First Report.*
—— 1833b, Volume XXI, *Factories Inquiry Commission, Second Report.*
—— 1834, Volume XX, *Reports from Commissioners: Factories Inquiry, Part II.*
—— 1835, Volume XXXV, *First Annual Report of the Poor Law Commissioners.*
—— 1840, Volume X, *Reports from Committees: Factories.*
—— 1845, Volume XXV, Factory Inspectors: 'Report for the Quarter Ending 30th September, 1844; and from 1st October, 1844, to 30th April, 1845'.
—— 1849, Volume XXII, Factory Inspectors: 'Report for the Half-Year Ending 31st October 1848'.
Peacock, A.E. 1984, 'The Successful Prosecution of the Factory Acts, 1833–55', *The Economic History Review*, 37, 2: 197–210.
—— 1985, 'Factory Act Prosecutions: A Hidden Consensus?', *The Economic History Review*, 38, 3: 431–6.

Pollard, Sidney 1964, 'The Factory Village in the Industrial Revolution', *The English Historical Review*, 79, 312: 513–31.
—— 1968 [1965], *The Genesis of Modern Management: A Study of the Industrial Revolution in Great Britain*, Harmondsworth: Penguin.
—— 1980, 'A New Estimate of British Coal Production, 1750–1850', *The Economic History Review*, 33, 2: 212–35.
Pomeranz, Kenneth 2000, *The Great Divergence: China, Europe, and the Making of the Modern World Economy*, Princeton: Princeton University Press.
Postone, Moishe 1993, *Time, Labor, and Social Domination: A Reinterpretation of Marx's Critical Theory*, Cambridge: Cambridge University Press.
Redford, Arthur 1976 [1926], *Labour Migration in England, 1800–1850*, revised and edited by W.H. Chaloner, Manchester: Manchester University Press.
Reynolds, Terry S. 1983, *Stronger than a Hundred Men: A History of the Vertical Water Wheel*, Baltimore: Johns Hopkins University Press.
Rodgers, H.B. 1960, 'The Lancashire Cotton Industry in 1840', *Transactions and Papers of the Institute of British Geographers*, 28: 135–53.
Rose, Mary B. 1986, *The Gregs of Quarry Bank Mill: The Rise and Decline of a Family Firm, 1750–1914*, Cambridge: Cambridge University Press.
Rosenberg, Nathan 1994, *Exploring the Black Box: Technology, Economics, and History*, Cambridge: Cambridge University Press.
Samuel, Raphael 1977, 'Workshop of the World: Steam Power and Hand Technology in Mid-Victorian Britain', *History Workshop Journal*, 3, 1: 6–72.
Satterthwaite, David 2009, 'The Implications of Population Growth and Urbanization for Climate Change', *Environment and Urbanization*, 21, 2: 545–67.
Schaffer, Simon 1994, 'Babbage's Intelligence: Calculating Engines and the Factory System', *Critical Inquiry*, 21, 1: 203–27.
Senior papers, National Library of Wales, Aberystwyth: Nassau William Senior.
Shaw, John 1984, *Water Power in Scotland, 1550–1870*, Edinburgh: John Donald.
Sieferle, Rolf Peter 2001 [1982], *The Subterranean Forest: Energy Systems and the Industrial Revolution*, Cambridge: The White Horse Press.
Smil, Vaclav 2008, *Energy in Nature and Society: General Energetics of Complex Systems*, Cambridge, MA.: The MIT Press.
Smith, Neil 2008 [1984], *Uneven Development: Nature, Capital, and the Production of Space*, Athens, GA.: Georgia University Press.
Steffen, Will, Paul J. Crutzen and John R. McNeill 2007, 'The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?', *AMBIO*, 36, 8: 614–21.
Storper, Michael and Richard Walker 1989, *The Capitalist Imperative: Territory, Technology, and Industrial Growth*, Oxford: Basil Blackwell.
Stuart, Robert 1824, *A Descriptive History of the Steam Engine*, London: John Knight and Henry Lacey.
Tann, Jennifer 1970, *The Development of the Factory*, London: Cornmarket Press.
—— 1973a, 'Richard Arkwright and Technology', *History*, 58, 192: 29–44.
—— 1973b, 'The Employment of Power in the West of England Wool Textile Industry, 1790–1840', in *Textile History and Economic History: Essays in Honour of Miss Julia de Lacy Mann*, edited by Negley B. Harte and Kenneth George Ponting, Manchester: Manchester University Press.
Taylor, A.J. 1949, 'Concentration and Specialization in the Lancashire Cotton Industry, 1825–1850', *The Economic History Review*, 1, 2/3: 114–22.
The Circulator of Useful Knowledge, Literature, Amusement, and General Information 1825, 'Mr. M'Culloch's Lectures on Political Economy, at the London Tavern', 9 April: 228–32.
The Civil Engineer and Architects' Journal 1840, 'Comparative Power of Steam Engines', 3: 7–8.

The Scottish Jurist 1835, 'M'Leod v. Buchanan and Rose', 24 January.
Thom archive, Bute Museum, Rothesay: Robert Thom.
Thomas, Brinley 1985, 'Escaping from Constraints: The Industrial Revolution in a Malthusian Context', *Journal of Interdisciplinary History*, 15, 4: 729–53.
Thompson, Edward Palmer 1966 [1963], *The Making of the English Working Class*, New York: Vintage.
—— 1967, 'Time, Work-Discipline, and Industrial Capitalism', *Past and Present*, 38: 56–97.
Trainer, Ted 2012, 'A Critique of Jacobson and Delucchi's Proposals for a World Renewable Energy Supply', *Energy Policy*, 44: 476–81.
Turner, Herbert Arthur 1962, *Trade Union Growth, Structure and Policy*, London: Allen and Unwin.
Turner, W.H.K. 1958, 'The Significance of Water Power in Industrial Location: Some Perthshire Examples', *Scottish Geographical Magazine*, 74, 2: 98–115.
Ure, Andrew 1835, *The Philosophy of Manufactures: Or, An Exposition of the Scientific, Moral and Commercial Economy of the Factory System*, London: Charles Knight.
—— 1836, *The Cotton Manufacture of Great Britain*, London: Charles Knight.
von Tunzelmann, G.N. 1978, *Steam Power and British Industrialization to 1860*, Oxford: Clarendon Press.
Ward, J.T. 1962, *The Factory Movement, 1830–1855*, London: Macmillan and Co.
Weart, Spencer 2003, *The Discovery of Global Warming*, Cambridge, MA.: Harvard University Press.
Wilkinson, Richard G. 1973, *Poverty and Progress: An Ecological Model of Economic Development*, London: Methuen.
Williamson, Jeffrey G. 1988, 'Migrant Selectivity, Urbanization, and Industrial Revolutions', *Population and Development Review*, 14, 2: 287–314.
Woolrich, A.P. 1997, 'John Farey, Jr. (1791–1851), Engineer and Polymath', *History of Technology*, 19: 112–42.
—— 1998, 'John Farey, Jr., Technical Author and Draughtsman: His Contribution to Rees's *Cyclopedia*', *Industrial Archaeology Review*, 20, 1: 49–67.
—— 2000, 'John Farey and His *Treatise on the Steam Engine* of 1827', *History of Technology*, 22: 63–106.
Wrigley, Edward Anthony 1962, 'The Supply of Raw Materials in the Industrial Revolution', *The Economic History Review*, 15, 1: 1–16.
—— 1972, 'The Process of Modernization and the Industrial Revolution in England', *Journal of Interdisciplinary History*, 3, 2: 225–59.
—— 1988, 'The Limits to Growth: Malthus and the Classical Economists', *Population and Development Review*, 14, Supplement: Population and Resources in Western Intellectual Traditions, 30–48.
—— 1990 [1988], *Continuity, Chance and Change: The Character of the Industrial Revolution in England*, Cambridge: Cambridge University Press.
—— 2000, 'The Divergence of England: The Growth of the English Economy in the Seventeenth and Eighteenth Centuries', *Transactions of the Royal Historical Society*, 6, 10: 117–41.
—— 2004, *Poverty, Progress, and Population*, Cambridge: Cambridge University Press.
—— 2010, *Energy and the English Industrial Revolution*, Cambridge: Cambridge University Press.
Zalasiewicz, Jan, Mark Williams, Alan Smith, Tiffany L. Barry, Angela L. Coe, Paul R. Bown, Patrick Brenchley, David Cantrill, Andrew Gale, Philip Gibbard, F. John Gregory, Mark W. Hounslow, Andrew C. Kerr, Paul Pearson, Robert Knox, John Powell, Colin Waters, John Marshall, Michael Oates, Peter Rawson and Philip Stone 2008, 'Are We Now Living in the Anthropocene?', *GSA Today*, 18, 2: 4–8.