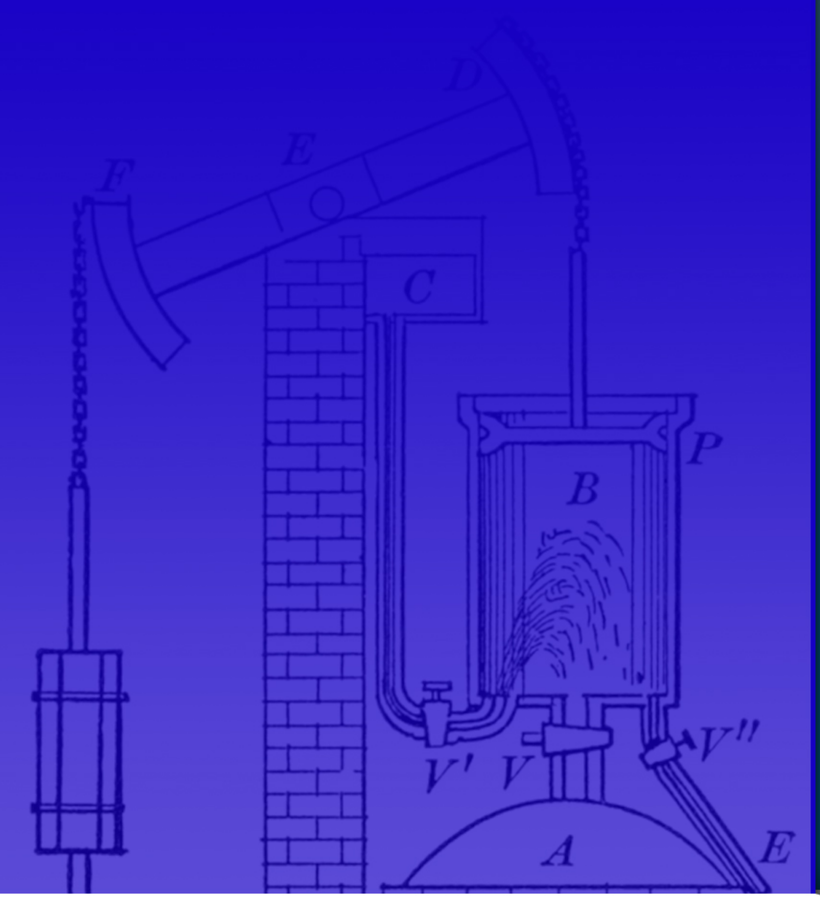

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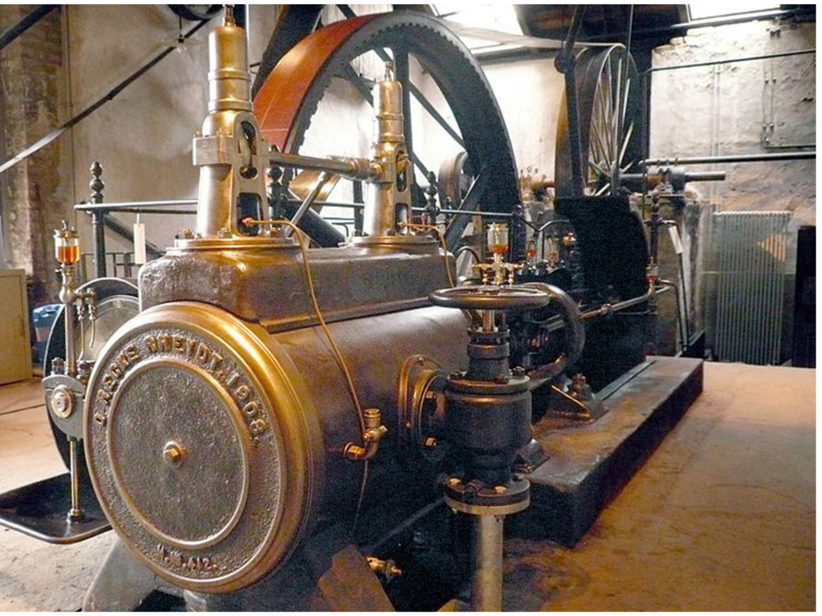

The History of Britain's Coal Exploitation

WATERLOO INSTITUTE for COMPLEXITY & INNOVATION

Clayton J. M. Dasilva

WICI Occasional Paper no. 6
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Cover Photos

Cover image by Imus Eus. A single-cylinder valve-drive piston steam engine with 80 hp at the LVR Industrial Museum - Mueller Cloth Mill (produced by Otto Recke, Rheydt, 1903). Photo via Wikimedia Commons.

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Author's Biography

Clayton J. M. Dasilva is a PhD student in Global Governance at the Balsillie School of International Affairs, University of Waterloo (Canada) where he also completed his Masters in 2012. He received his BA in Sociology and Cultural Anthropology at the University of Western Ontario in 2009, during which he completed a first-of-its-kind undergraduate field course in Madagascar on environmental anthropology, exploring charcoal usage and energy poverty for its independent research component. He has also worked for the Residential Energy Efficiency Project – or REEP House – in Kitchener, Ontario, a century home demonstration project operating with a nearly net-zero energy profile. His research currently focuses on the relationship between technological innovation, the natural environment, and energy issues in society.

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Disclaimer

This work is an elaboration of a University of Waterloo Master of Arts Major Research Paper in the program of Global Governance. The MRP in question is "Energetic Innovations: The History of Britain's Transition to Coal," Clayton Dasilva, University of Waterloo, 2012.

I. Introduction

The critical importance of energy to our economies is well understood today; how distinct new forms of it are made available over time, however, is not. Technology is generally accepted as the primary mediating variable between the raw energy of nature and the physical-economic work requirements of human societies, and this is certainly true in some sense.[1] Yet the nature and kind of technological change that makes novel primary sources of energy available remains under-theorized.[2] Advanced hominids had found new ways to harness and make use of extra-somatic energy – that is, beyond the body – since before we were recognizably human. We have continued to do so from the Neolithic revolution to the Industrial revolution to the present.[3] But this was stochastic and not inevitable. If we are to avoid a teleological view of human development, we must accept that any 'modern' source of energy could theoretically have gone unnoticed and untapped by humanity, much as many individual societies failed to harness such resources before or after their discovery by other groups.

By the same token, though, we can easily admit the aggregate tendency, across the human species, of seeking to obtain more energy from the environment, or more economic outcomes for constant amounts of energy. Were this not the case it would be hard to explain the broadening of humanity's energy toolkit over the long-term, which now includes the direct conversion of photons into electrons (solar photovoltaic) and the manipulation of fissionable atoms (nuclear). With this in mind, the amount of research being done on extending this toolkit even further (nuclear fusion, deep geothermal, etc.) is explicable and unsurprising. Whether we will succeed or fail on these new fronts remains to be seen, however. It is therefore important to understand how past additions[4] to our energy toolkit have occurred.

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[1] This is a common view; For a discussion see *Global Energy Assessment: Toward a Sustainable Future* (Cambridge, 2012).

[2] Ibid, See also Vaclav Smil *Energy in World History* (Oxford, 1994) for a discussion of 'prime movers' throughout history. He deals less extensively with their creation and diffusion, however.

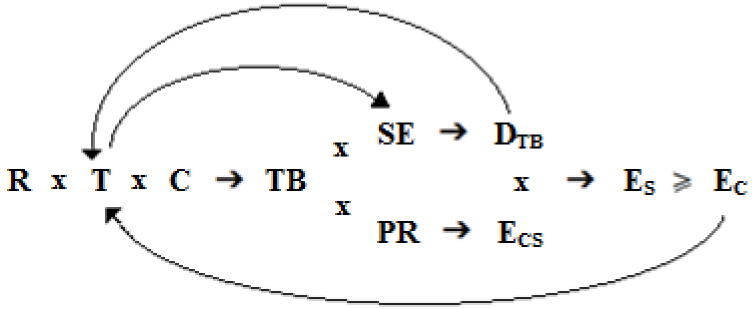
[3] Fire was the first form of extra-somatic energy that hominids harnessed. See Johan Goudsblom, *Fire and Civilization*, (Viking, 1992).

[4] I employ the term 'addition' rather than 'transition' because of the latter's connotation of leaving an older form of energy behind after the discovery of a new form; but this has never in fact occurred – biomass is still employed as an energy source in various settings, much as ancient hominids employed it several hundred thousand years ago.

Britain's exploitation of coal before and during the Industrial revolution will serve as a case study in this endeavor, outlining a causal framework of novel energy acquisition. In discussing the framework, this essay will elaborate on the relevant technological and socio-economic factors, as well as their relationships to one another through time, that describe not only how Britain accessed and harnessed coal for its economy, but how any technological breakthrough that adds to primary energy supply both occurs and diffuses. Three sets of causal factors are stressed: first, nature, or the existence of natural energy potentials in the environment (such as gushing rivers and coal deposits); second, technological innovation, in the form of discrete inventions or techniques that allow the exploitation of such potentials to accomplish physical work; and third, contextual, structural conditions that lead to the widespread diffusion/adoption of such inventions in the economy.

Figure 1 displays the causal framework that describes the process of natural energy acquisition.

Figure 1: A Causal Framework of Novel Primary Energy Acquisition



R: Research (or, broadly, tinkering, exploring, problem solving)
T: Technosphere (the stock of physical capital, technical capability, and engineering knowledge as they exist at a certain time in history)
C: Contingency
TB: Technological Breakthrough
PR: Physical Reality (physics, chemistry, biology, thermodynamics)
SE: Selection Environment
D_{TB}: Diffusion (of the TB through an industry or economy)
E_{CS}: Exergy* – convertible source (whether stock or flow)
E_S: Exergy – supply
E_C: Exergy – consumption
'x's refer to causal interactions, '→'s refer to the product of such interactions, and long arrows indicate causal feedback interactions

*Exergy is commonly defined as the 'work content' of an energy source. Energy is always conserved in any physical reaction, but exergy, because of the second law of thermodynamics, does diminish. Industry analysts often use the term energy to mean something that is consumed when they should say exergy (because energy can only be transformed, while exergy can be consumed and depleted). But to avoid confusion I follow the colloquial usage of the term energy as meaning its economically-useful work content, and use it interchangeably with the term exergy.

According to technology theorists, including W. Brian Arthur and Frank W. Geels for example, research *(R)* occurs in niches, and is highly specific and esoteric.[5] Any solution to a given niche problem, though, no matter how novel, springs from the stock of available knowledge, techniques and other extant technologies, what is here called the technosphere *(T)*.[6] Research is also a multifaceted aggregate variable: a product of the number of researchers and scientists devoted to an issue, the resources at their disposal, and their ability to do their work freely. These interact both with *T* – as a base from which to work – and a certain measure of randomness or contingency *(C)* to produce candidate solutions (*TB*s).

As is well known in engineering practice, however, incipient breakthroughs are not the end of the story of technological evolution. In order for the day-to-day macro-economy to be transformed by one, a *TB* must diffuse widely. Thus a *TB*, after being invented or discovered, must operate in a real economic environment with other competing technologies. Diffusion of the breakthrough (D_{TB}) – if it occurs – is therefore a product of its interaction with a Selection Environment *(SE),* itself composed of numerous factors. Geels lists seven: "technology, user practices and application domains (markets), symbolic meaning of technology, sectoral policies, infrastructure, industry structure, policy and techno-scientific knowledge."[7] To these we might add the production cost of the *TB*, the level of human capital or amount of skilled labour needed to make it and use it, the prices of other competing technologies, as well as other unknown or randomizing variables. If the factors in the *SE* are aligned in a way that is conducive to a niche breakthrough, diffusion will follow (D_{TB}).[8]

"In order for the day-to-day macro-economy to be transformed by one, a *TB* must diffuse widely. Thus a *TB*, after being invented or discovered, must operate in a real economic environment with other competing technologies."

Since energy is the prime focus we need not be concerned with the entire technosphere, or all types of breakthroughs. The discussion will focus on 'exergonic' technologies, those that store or convert the energy of nature to appropriate forms required by our economies. This is where physical reality *(PR)*, and our knowledge of it, becomes important to the framework and to any economic system, since the latter can only work with what nature at first

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[5] W. Brian Arthur, *The Nature of Technology: What it is and How it Evolves* (New York, 2009). Frank W. Geels, "Technological transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study," *Research Policy* 31 (2002).

[6] Ibid*;* much inspiration is also taken here from Stuart Kauffman, *Investigations* (Oxford, 2000) and Steven Johnson, *Where Good Ideas Come From: The Natural History of Innovation* (New York, 2010).

[7] Geels, "Technological Transitions," 1262.

[8] Rather, to avoid a priori reasoning where it is not appropriate, we should probably say that if there is adoption, then the selection environment must have been *ipso facto* conducive to it, and the question then turns to knowing what about that socio-economic context was conducive to the technology and why.

provides. *PR* is thus the physics, chemistry, biology and thermodynamics of the natural environment. The *TB* is the means by which humans reveal convertible energy flows or potentials from *PR*, thus forming the subset Exergy: convertible source (E_{CS}). This is the part of nature that is at least potentially capable of being "put to work," in the language of physicists, by a certain technological complex (based on a *TB*). To illustrate, a simple granite rock contains much energy within its nucleic bonds and is a part of *PR*; but unless a means is devised to productively liberate, so to speak, such trapped energy, granite does not form a part of E_{CS}.[9] If such a means ever was devised, then very suddenly all the granite on Earth would form – or be revealed as – a convertible source of usable energy (or exergy).

E_{CS} is thus the foundation upon which the physical work of economies can potentially be accomplished. To in fact accomplish such work, however, E_{CS} must first be converted to an actual supply of energy (E_S), to be stored or immediately consumed in the provision of an energy service. In order to produce real E_S, the *TB* must diffuse, both in an economic sense – among users, industries, etc. – as well as in a physical sense – through the environment where E_{CS} is located or distributed. It is thus the interaction between D_{TB} and E_{CS} that creates real E_S.

"…energy consumption (EC), like all the other main factors, is a product of many sub-factors: absolute population, per capita demand, industrial demand, and the efficiency of final energy provision technologies..."

Finally, energy consumption (E_C), like all the other main factors, is a product of many sub-factors: absolute population, per capita demand, industrial demand, and the efficiency of final energy provision technologies (light bulbs, fridges, cars, etc.) There are two salient points to note regarding consumption. First is that it cannot exceed supply in real terms (supply being the rate at which energy is being made available in appropriate forms for economic transformation and physical work).[10] Demand may exceed supply, leading to rising costs; but if supply diminishes, so will consumption.[11] Secondly, exergonic *TB*s themselves will likely consume energy (to operate or to make) and this has two effects. One, it allows for the model to include conceptions of EROEI (energy return on energy investment, or net energy payback) within it. And two, energy consumption will have its own feedback effects on the technosphere. For example, aspirations to improve the fuel-efficiency of engines (a consumption factor) may lead to new breakthroughs and in so doing

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[9] Bill Bryson, *A Short History of Nearly Everything* (Anchor Canada, 2003):122 for this conception of liberating the energy "bound up in every material thing."

[10] That is, with the state of technology constant.

[11] The efficiency of final energy service delivery technologies (illumination, heating, cooling, mobility) is important here, as gains in their efficiency can occasionally make up for absolute supply shortfalls (advanced LEDs provide the same luminosity for much less energy input over incandescent light bulbs, for example). This can be thought of as a 'quality of life' metric when applied to energy consumption.

change the technosphere. This latter effect is accounted for by the feedback between E_C and T.

Filling out the details of the framework, with Britain's exploitation of coal as a case study, will take place in three more sections. Section 2 will expand on the idea of *PR* as it is turned into E_{CS}, focusing on energy potentials in the environment (specifically Britain's forests and coal deposits). Section 3 will unpack the first part of the diagram, and explore the invention of the Newcomen steam engine as an example of a technological breakthrough *(TB)*. Section 4 will take up the idea of the selection environment *(SE)* and the factors that influence the diffusion of technology (D_{TB}). The conclusion will then draw these threads together and briefly apply them to potential breakthroughs currently on the horizon.

II. Energy in Nature

According to Einstein's $E = mc^2$, *all* mass is equivalent to energy. Every cell of every organism, every grain of sand and mote of dust, contains energy in the nuclei of the atoms that make them up, as well as in the electromagnetic bonds between atoms that form the basis of molecules. There is a reason we do not put sand in our gas tanks, however. Although its nuclei, electrons and the connections between them may contain a substantial amount of energy, it is not of a type or quality that we can "put to work" through any known conversion technology. Such qualities of matter (and radiation and other phenomena) vary quite widely, and technologies discordant with them will be unable to reveal from a given source – that is, from a localized part of *PR* – any work potential (E_{CS}).

The control of fire can be considered the first exergonic technological breakthrough. After a long passive exposure and some level of active perpetuation, the discovery or invention of deliberate and controllable techniques of combustion was transformative.[12] For this immediately turned a previously non-energy related aspect of physical reality (whole forests of wood and other organic matter) into a massive stock of potential thermal energy (E_{CS}). Organic biomass then remained the foundation of our thermal energy requirements for potentially millions of years, depending on the disputed origin of fire sometime between 0.5 and 1.5 million years before present.[13]

Several thousand years ago coal was also discovered, along with its amenability to known combustion techniques. Of course it had always been present in physical reality during the long dominance of organic biomass, but was unknown. It has a higher energy density than dried wood (26-32 MJ/kg vs. 12-15 MJ/kg)[14] and a much higher spatial power density (~100-1000W/m^2 vs. >1W/m^2)[15] because wood's energy-kilograms are incredibly dispersed in forests. And to the extent that forests are renewable while coal is not, it is only so long as the former are not cut down faster than they are allowed to re-grow. The point is that while both wood and coal are combustible, there are important structural, ecological and chemical differences between them. One cannot be substituted perfectly for the other.

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[12] Goudsblom, *Fire and Civilization*.

[13] Steven R. James et al., "Hominid Use of Fire in the Lower and Middle Pleistocene: A Review of the Evidence," *Current Anthropology* 30, No.1 (Feb, 1989): 1-26.

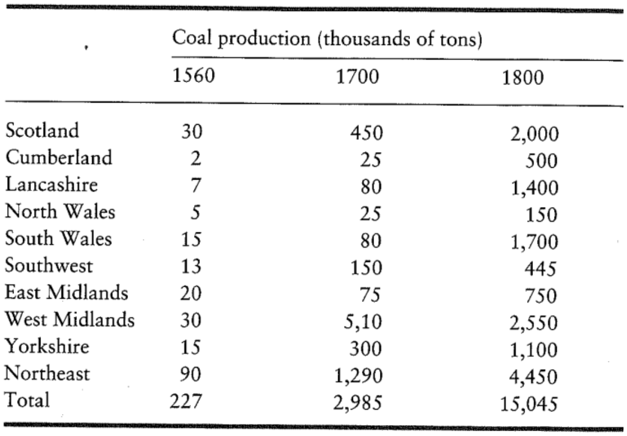
[14] Vaclav Smil, *Energy in Nature and Society*, 206.

[15] Ibid, 311.

Although the historical and archeological records are incomplete and uncertain, the evidence suggests that even after the initial discovery of coal it was rarely employed, and certainly never contested wood as the foundation of our thermal energy requirements.[16] It must also be stated that the foundation of all our mechanical energy requirements (for providing force) were also organic – or, more precisely, animate – in the form of human or animal muscle power. These of course require food, and it can therefore be unambiguously stated that all our early energy demands were supplied by land: agriculture for muscle power and forestry for heat.[17] Yet no matter how productive the land might be made, it would not compare with the physical reality of a massive stock of energy that could, if made accessible, be drawn down at a much higher rate than any sustainable conversion of biomass derived from photosynthesis.[18]

Could such a stock be made available though? The historical record is clear. In the late 16th century Britain's coal output was already hovering under three-hundred thousand tons. By the turn of the 18th century it reached close to three million tons. By the turn of the 19th it had surpassed fifteen million (see figure 2).[19]

Figure 2: Britain's coal production 1560 – 1800



	Coal production (thousands of tons)		
	1560	1700	1800
Scotland	30	450	2,000
Cumberland	2	25	500
Lancashire	7	80	1,400
North Wales	5	25	150
South Wales	15	80	1,700
Southwest	13	150	445
East Midlands	20	75	750
West Midlands	30	5,10	2,550
Yorkshire	15	300	1,100
Northeast	90	1,290	4,450
Total	227	2,985	15,045

Source: Allen, 2009.

This supply growth also occurred at relatively constant real prices (especially in and around London; see figure 3).[20]

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[16] Michael Flinn, *The History of the British Coal Industry, 1700-1830*, (Oxford, 1984).

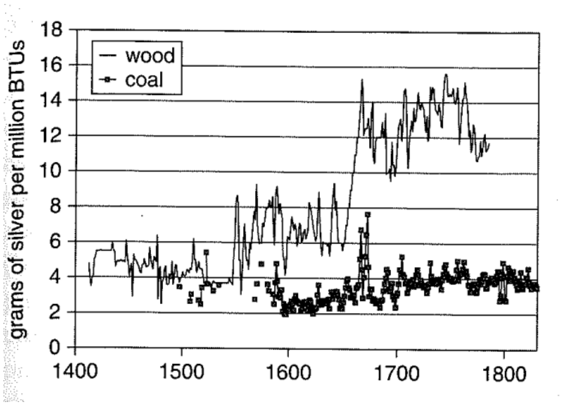
[17] E.A. Wrigley, *Continuity, Chance and Change: The Character of the Industrial Revolution in England* (Cambridge, 1988).

[18] Ibid.

[19] Robert C. Allen, *The British Industrial Revolution in Global Perspective*, (Cambridge, 2009): 82.

[20] Ibid.

Figure 3: The Price of wood and coal in and around London 1400 – 1800



Source: Allen, 2009.

The increase in Britain’s thermal energy consumption would not have been possible with organic biomass as its primary source – not, at least, in its circumscribed land area. Whether or not trade for timber might have fulfilled the same function is an interesting question, but not the important one here. A dramatic and unprecedented growth in coal output is what historically occurred, and we must therefore ask, how was it achieved? Having known of coal’s existence for millennia, and been fairly familiar with it since the 12th century, how did Britain only begin to take advantage of its coal stock (its known E_{CS}) in the 18th and 19th centuries?

III. Technological Breakthroughs

The answer to the former question will require exploring the development of the 18th century's paramount exergonic innovation: the Newcomen atmospheric steam engine (the world's first true heat engine, demonstrating that thermal energy could be converted into mechanical energy). The steam engine enabled coal production to continue rising with growing demand throughout the 18th century, keeping its price low and thus creating an incentive for many fuel-intensive industries to substitute coal as their primary thermal input (the most important of which were iron and steel production). What, then, are the conditions and causal factors that allowed the steam engine to be invented?

In this endeavor we might focus on the originator, and the place and time of origin; i.e. why Newcomen, why Britain, and why the 18th century? For why not instead, the ancient Roman Empire, where Hero (sometimes Heron) of Alexandria built the first steam-based mechanical apparatuses around 60 CE: a rotating sphere called the Aeolipile, and temple doors which opened as a result of water, displaced by the expansive force of steam.[21]? Or why not 5th century China, where the creation there of a unique box bellows was one or two steps removed from Newcomen's reciprocal single-acting engine?[22] Why not mid-17th century Britain, when the basic principles underlying even Newcomen's version were understood, but not pieced together?

Trying to explain such non-starter counterfactuals is an intractable intellectual challenge. The primary three questions require a more direct approach. Firstly, as for why Newcomen, the argument could potentially be made against his additionality (the claim that he was essential, and without him the steam engine would never have been invented) based on the history of 'multiples.' Multiples are instances of inventions that have various independent originators.[23] Many individuals were working on the exact same problem as Newcomen, and many ideas had been tried before them, perhaps the most famous of which was Christian Huygen's in the 1670s, which used gunpowder explosions to drive a piston pump. Thomas Savery's was the next closest that was actually constructed, but Denis Papin's blueprint in

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[21] Ibid.

[22] Ibid, 261. See also Pomeranz, *The Great Divergence*, 61-61; and Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York, 1990).

[23] Steven Johnson, *Where Good Ideas Come From: The Natural History of Innovation* (New York, 2010); Mokyr, *The Lever of Riches*; William Ogburn and Dorothy Thomas, "Are Inventions Inevitable? A Note on Social Evolution," *Political Science Quarterly* 37, No. 1 (1922): 83-98.

1690 was evidently the next closest in design.[24] Although it is difficult to make the strong claim that 'someone else would have invented the same type of engine eventually,' such a claim is not improbable considering the context. Of course, considering how close the Chinese were with their box bellows in the 5th century, it is certainly possible to come so close and yet not succeed, supporting the conjecture that perhaps Newcomen was essential. The best that can be said is that, for technical problems, where potential solutions are very likely finite – based on the materials and tools at hand – their successful solution, at least ahead of time, must be considered probabilistic.[25] That is, depending on the nature of the problem, and the number of individuals dedicating their effort to solve it in some fashion, there is no way of knowing ahead of time what solution will work, and who will come up with it.

"By the turn of the 17th century, Britain was a relatively wealthy nation, with high wages (expensive labour) cheap coal, a long history of mining, and an economic system already somewhat conducive to capital-based problem solving."

As for why Britain, Joel Mokyr has described the advanced character of British inventiveness. By the turn of the 17th century, Britain was a relatively wealthy nation, with high wages (expensive labour) cheap coal, a long history of mining, and an economic system already somewhat conducive to capital-based problem solving.[26] The latter is an important feature, and is apparent in the decline of guilds (that is, monopolies) while maintaining a robust apprenticeship system, all within the broader culture of what he has labeled the 'Industrial Enlightenment' and 'Baconian program' – the latter named for Francis Bacon's explicit call to material betterment through technological progress.[27] Beginning with universities, scientific societies and other like-minded organizations, eventually even the industrial cultures of Britain's engineers, millwrights, instrument makers, and skilled craftsmen were affected by this new ethos.

It produced a veritable "army of mostly anonymous artisans and mechanics, the unsung foot soldiers of the Industrial Revolution whose names do not normally appear in biographical dictionaries but who supplied that indispensible workmanship on which technological progress depended."[28] Mokyr continues:

> These were craftsmen blessed by a natural dexterity, who possessed a technical *savoir-faire* taught in no school, but whose experience, skills, and practical knowledge of energy and materials constituted the difference between an *idea* and a *product*.

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[24] William Rosen, *The Most Powerful Idea in the World*, (New York, 2010): 29.
[25] Arthur, *Increasing Returns*.
[26] Robert C. Allen, "Why the Industrial Revolution was British: Commerce, Induced Invention, and the Scientific Revolution," in *Economic History Review* 64, 2 (2011).
[27] Mokyr, *The Enlightened Economy*.
[28] Ibid, 110.

> They were mechanics, highly skilled clock and instrument makers, metalworkers, woodworkers, toymakers, glasscutters, and similar specialists, who could accurately produce parts of the precisely correct dimensions and materials, who could read blueprints and compute velocities, and who understood tolerance, resistance, friction, lubrication, and the interdependence of mechanical parts."[29]

The line of cumulative, if minor, adaptations and micro-inventions that this mechanically-inclined section of the labour force was able to perpetuate has led to the distinction in the literature between *savants* and *fabricants*, or inventors and tweakers, according to Mokyr's own usage.[30] The disproportionately large and mobile population of tweakers is partly why Britain could become the so-called 'workshop of the world' in the late 18th and 19th centuries.[31]

As for why the 18th century, the answer may effectively come down to the cumulative nature of science, or knowledge-acquisition generally. An intriguing idea for understanding the path-dependent nature of scientific discovery and invention, as they actually occur over time and place, is Stuart Kauffman's concept of the 'adjacent possible'.[32] Although Kauffman exemplified his original formulation of the concept within the universe of chemical structures, he did not restrict it to them, and Steven Johnson has indeed extended it to the macro-phenomena of (mechanical) inventions. For example, "[i]n the case of prebiotic chemistry, the adjacent possible defines all those molecular reactions that were directly achievable in the primordial soup. Sunflowers and mosquitoes and brains exist outside that circle of possibility."[33] To elaborate, the chemical elements of the primordial soup would constitute what Kauffman calls the 'actual' – things as they are – and the adjacent possible represents the range of chemical structures that could be achieved by one chemical reaction between the elements in the primordial soup. The adjacent possible therefore represents the space of things that can be made out of presently existing elements, but have not yet been made.

The same line of reasoning can apply to the technosphere. Simple engines employing pistons and pumps could not exist before pistons and pumps were each created on their own. But upon their creation, they become part of the technosphere (or the 'actual' in Kauffman's conception) and a new space of adjacent possible states therefore opens up that

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[29] Ibid, 110, italics mine.

[30] Ralf Meisenzahk and Joel Mokyr, "The Rate and Direction of Invention in the British Industrial Revolution: Incentives and Institutions," *National Bureau of Economic Research*, Working Paper 16993 (Cambridge, 2011).

[31] Mokyr, *The Enlightened Economy*.

[32] Stuart A. Kauffman, *Investigations* (Oxford, 2000).

[33] Johnson, *Where Good Ideas*, 31, italics mine.

can use pistons or pumps as building blocks or basic elements.[34] It is like a cumulative conditionality, where a "relentless probing of the adjacent possible" tends to lead to innovations, each one "opening up new paths to explore."[35]

Newcomen's engine depended on several principles and natural phenomena that all needed to be understood, at least in an applied sense, before they could be purposefully harnessed in a mechanical apparatus.[36] These include: the nature of vacuum; the nature (and especially weight) of atmosphere, or air; the nature of water vaporization and steam condensation; the nature of combustion (for a heat source to produce steam); and the physics of pistons and pumps. Some of these were known for millennia (combustion) but others were only beginning to be understood in mid-17th century Britain, which would include the nature of vacuum, atmospheric air pressure, and steam condensation that could produce a vacuum. Other nations may have known about some of these phenomena at earlier points in time – China in the 13th century had well developed knowledge of vacuum and adiabatic air pressure, as demonstrated by Joseph Needham[37] – but in Europe this would not be the case until well into the scientific revolution, after Galileo took up work on water pumping on behalf of the Grand Duke of Tuscany.[38] Based on this line of reasoning, and the dates at which British science became well versed in the phenomena and principles that underlay the operation of Newcomen's engine, the claim that it could not have been built before the early- to mid-17th century – in Britain – is perhaps warranted.

The long history of mining in Britain, mostly but not exclusively for coal, therefore turned out to be a 'focusing agent' for a problem that required a specific solution: some sort of very low-depth pumping or water-drainage system.[39] The timing of Newcomen's efforts quickly followed or at best coincided with progress in the natural sciences of pumping, based on the dynamics of vacuum-and-air-based piston work. His breakthrough was one of several attempts at a solution – recall Huygens and Savery – but Newcomen's version diffused the

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[34] This line of reasoning is very consonant with the recent work of W. Brian Arthur. In *The Nature of Technology: What it is and How it Evolves* (New York, 2009) he argues that technology is recursive – every technological apparatus is made up of building blocks which are themselves technologies – and this allows technology to feed on itself to continually become more complex over time.

[35] Johnson, *Where Good Ideas*, 33.

[36] Arthur, *The Nature of Technology*, see especially Ch.3 "Phenomena."

[37] Joseph Needham, "The Pre-Natal History of the Steam Engine," *Newcomen Society Transactions*, 35, no.49, 1962-63.

[38] Rosen, *The Most Powerful Idea*, 8. Others had started work on water pumps earlier: Giambattista della Porta, a Neapolitan engineer, experimented with steam-pumping in 1606. Salomon de Caus, a French fountain designer, "built a number of steam driven toys at one of the residences of the Prince of Wales" in 1609.

[39] Mokyr, *The Enlightened Economy*.

most broadly among British collieries, with over 300 operating by 1772.[40] This diffusion then allowed British coal miners to keep accessing seams at lower depths, and thus enabled British coal production to continue on its path of exponential growth.

There is a fine distinction to be made, however, between the inception of an invention and its diffusion, leading to the transformation of a macroeconomic environment and its production function. The factors conducive to diffusion are often different, though, from those conducive to invention proper.

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[40] Griffin, *A Short History*, 117. According to Allen there were 100 Newcomen engines by the year 1733 (a marginal difference from the 78 that Griffin mentions were operating in the year 1732) but perhaps more than 1,500 atmospheric engines by the year 1800 – a massive increase from the few hundred that Griffin says were operating in the year 1772, though perhaps such an increase was possible. See Allen, *The British*, 162.

IV. Selection Environments and Diffusion

Simply inferring that, because the Newcomen engine successfully diffused, it therefore must have been the "best" solution does not explain much. If it was the best, in some real sense, what made it so?

It goes without saying that once an invention has been made it must operate in a real socio-economic context, potentially with many other competing technologies. And no individual version of one can be determined as 'objectively better' than any other for its inherent attributes. One or more variations of an invention may only diffuse throughout an economy because of the features of that economy – what Geels calls a 'selection environment' *(SE)*.[41]

In all likelihood there is no certain set of features or qualities that a socio-economic system can have that will make it predictably receptive to a new invention, even one with specific characteristics. But this has not prevented many from exploring this topic, the research of which falls along two main avenues.

"It goes without saying that once an invention has been made it must operate in a real socio-economic context, potentially with many other competing technologies."

The first has its origin in economic theorizing on factor proportions and prices, where novel macro-inventions create 'biased technical change.' This is technical change that "save[s] one input disproportionally and reduce[s] costs the most where that input [i]s most expensive."[42] Allen has made this argument with regard to the steam engine, which was a biased technical change towards capital- and energy-intensive work, and was thus also, by implication, labour-saving. Since labour was expensive in Britain relative to the Continent and energy was relatively inexpensive, Allen argues that the usefulness and widespread diffusion of an invention like Newcomen's steam engine should have been predictable, had anyone imagined its characteristics ahead of time.[43]

The second avenue of research on diffusion has separate origins in both the sociology of technology and evolutionary economics, but each discipline has converged and come to think in terms of Darwinian mechanisms (variation and selection) as they apply to novel

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[41] Geels, "Technology Transitions."
[42] Allen, *The British*, 151.
[43] Ibid, 162.

inventions within an economy.[44] From the former group, Geels' work on technology transitions as "evolutionary reconfiguration processes" offers an illuminating starting point. According to this line of reasoning, variation happens as a matter of course in technological 'niches,' but selection (or diffusion) only occurs when there is consonance between a new technology at the niche level with sociological and technological elements at the higher level, that of 'socio-technical (ST) regimes.'

> A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts [*sic*] and persons, ways of defining problems; all of them embedded in institutions and infrastructures.[45]

The ST-regime-level of an economy is composed of multiple regimes, and "in evolutionary terms, ST-regimes thus function as selection and retention mechanism..."[46]Above the regime-level there is also the 'socio-technical landscape,' which consists "of a set of deep structural trends… heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems."[47] The ST-landscape provides broad trajectories for work at the regime level. Geels then specifies a candidate mechanism by which regimes select from among niche-level breakthroughs: technological "add-on" and/or "hybridization," where "new technologies in their early phase physically link up with established technologies, often to solve particular bottlenecks… Steam engines, for example, entered sailing ships as an auxiliary device. The first oceanic steamships were actually sailing ships with additional steam engines."[48]

The identification of such a mechanism is an important step forward, but as such does not specify how one from among multiple niche breakthroughs might succeed in diffusing widely where another might fail to do so; that is, by what criteria a novelty might be judged as having more 'add-on' potential than another. Working within evolutionary economics, Eric Beinhocker has productively added the concept of a *fitness function* to explain this aspect of diffusion.

> For any design [of a technology] there are variants of that design that may be better or worse at fulfilling the design's purpose or solving the problem. What constitutes

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[44] Beinhocker, "Evolution as computation." Geels, "Technology transitions." The concept of 'retention' is also occasionally added after 'variation' & 'selection'.

[45] Arie Rip and Rene Kemp, "Technological Change" in Rayner, S. Malone, E.L. *Human Choice and Climate Change*, Batelle Press, Columbus, OH, Vol. 2 (1998): 327-399.

[46] Geels, "Technological transitions, 1260.

[47] Ibid, 1260.

[48] Ibid, 1271.

> ‘better or worse’ is referred to as the fitness function and may contain any number of dimensions. For example, the fitness function for the design of a chair might include dimensions of comfort, attractiveness, cost, durability and so on... The source of the fitness function is the environment into which the design is physically rendered. ...Fitness functions are dynamic and *change over time* as the environment changes, and there is dynamic feedback between or co-evolution between designs and the fitness function generated by their environment.[49]

In this sense, ‘factor-savings potential’ might be considered a primary dimension of any given technology’s fitness function, as will Geels’ ‘add-on’ capability (or the ‘closeness’ of a technical breakthrough with more established, regime-level technologies). No doubt cost of production and thermodynamic efficiency (for exergonic technologies) will feature prominently in their fitness functions as well. These various features of a selection environment – by which means an innovation is determined as having a degree, if not of fitness per se, but simply a degree of fit inside an ST-regime – are central to the diffusion of any breakthrough.

Needless to say, the Newcomen engine displayed clear thermodynamic and economic advantages over any other mine-pumping technology. It did not have any inherent depth limit like the Savery pump (only 25 feet in the latter case). It did not depend on buckets, chains or horses, which cannot lift hundreds of feet of heavy chain, or would tire quickly if they could. It did not require nearly as much water to operate as a water wheel, which needs a full stream. And the steam engine could use the product of the collieries that it was helping to drain of water – the refuse coals – to power itself. Indeed, with a very low thermodynamic efficiency (about 1% in absolute terms, which was likely still more energy efficient than the other options) it was only really economical, at first, in this precise fashion.[50]

Such selective factors – which depend on both the inherent attributes of any new technology as well as the desires and goals of its likely users (collieries in this case) – are what imparted a higher fitness to the Newcomen engine in the end, leading to its widespread adoption (potentially in the low thousands in the first decades of the 19th century).[51] Widespread usage then led to more research into ways to improve the engine itself, or to adapt it to new circumstances, improving its fitness function still further and helping it to have a selective advantage over other animate sources of mechanical power.

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[49] Beinhocker, “Evolution as computation,” 9, italics mine.

[50] John Desaguliers, *A Course of Experimental Philosophy*, Vol.II, p.464-65, 1734-44.

[51] Allen, *The British,* 162

V. Conclusion

We can now return to the central questions of this essay and the diagrammatic framework. How did Britain accomplish its feat of being the first to truly tap its massive energy potential (that coal, among other substances and flows, represented) before anyone else?

The analysis here has explicitly noted that energy, in various forms, truly permeates our environments. It often goes unnoticed as such, however, because we have no technologies that match it as exergy to the needs of our physical economic systems: before combustion timber was a tool-making material rather than a fuel; before the airfoil wind was just a cool breeze; before fission uranium ore was just another rock-like material in nature. Technological breakthroughs (such as combustion, the airfoil, or fission) do then occasionally occur that reveal a portion of *PR* as convertible into an energy form that we can use. The revelation of a resource (that is, of E_{CS}) in this way does not make it immediately available though, and other breakthroughs (or policy interventions) may be required to enable diffusion, then permitting the production of real supply (E_S).

Long before human settlement, Britain's massive stocks of coal were formed. The first known uses of it go back about two millennia before present, and the first mines to the middle ages. In the early modern period these mines were beset by flooding at regular depths (100-150 feet), well short of Britain's true reserves. The steam engine was crucial to both accessing this stock and providing a means by which it could be used across many industries (textile factories, railway locomotives, steamships, etc.) thus decoupling both thermal and mechanical energy needs from the land and solar insolation.

The salient point to note regarding the evolution of technology per se is that it is path-dependent. Technologies are purposive, and based on principles of application, of phenomena in action.[52] Newcomen's steam engine had to orchestrate combustion, water vaporization, steam condensation, vacuum generation, atmospheric pressure, pistons, a balance beam and pump into a coherent device. None of this would have been possible without practical or useful knowledge of those phenomena themselves, as well as mechanical principles by which they could be actively coordinated to the purpose of pumping. And, as was demonstrated above, practical knowledge of those phenomena did not arrive or occur in Britain until at least the mid- to late-17th century.

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[52] Arthur, *The Nature of Technology.*

Lastly, and just as importantly, the steam engine could not successfully diffuse across Britain unless the socio-economic context was conducive to it. In this regard factor prices and technical expertise (or human capital) were likely the deciding factors. Britain's geographically-fortuitous deposits of coal and its long history of mining provided the right price structure for the former (and, incidentally, the long history of mining leading to the steam engine itself). Its disproportionately large skilled labour-force during the Industrial Enlightenment provided the foundation for the latter.

Relating this all once more to the causal model, we can say the following of the British case: research *(R)* by a number of individuals into the nature of certain phenomena (vacuum, atmospheric pressure) based on the technosphere *(T)* of the late 17th century (using pistons, pumps, boilers, etc., in the niches of water pumping and mine drainage) culminated in two technological breakthroughs *(TBs)* – the Savery pump and the Newcomen engine. Each had been designed to solve a very specific niche problem, for which other technologies had previously been applied (bucket gins and waterwheels) but that were also beginning to hit certain limits. The selection environment of the day (collieries at first) could easily judge that the Newcomen engine was more 'fit' than the Savery pump for the purpose they required, most likely based on thermodynamic efficiency (essentially a measure of cost). A serendipitously long history of mining coal – which kept it inexpensive – meant that Newcomen engines also had a selection/retention advantage in Britain that they had nowhere else; whence their relatively rapid diffusion (D_{TB}) throughout British coal mines, and later throughout other British industries.

"With each new steam engine built – that is, with each step of its diffusion – Britain's technosphere was changing, and a new actual state of affairs was emerging."

With each new steam engine built – that is, with each step of its diffusion – Britain's technosphere was changing, and a new actual state of affairs was emerging. This is why D_{TB} feeds back into T. This feedback is always epistemologically expansive, always opening up new paths to explore, based on the creation of new building blocks to use in yet newer technologies. This also means that the process of research can begin again, even if only to improve on what is already known. Take, for instance, James Watt's separate condenser, double-acting cylinder and rotary motion, three technological breakthroughs in their own right that deeply augmented the power and applicability of the Newcomen engine.

Diffusion of the Newcomen engine throughout Britain's collieries also meant that the deep coal deposits that existed (E_{CS}) could now be accessed in order to greatly expand the annual supply of fuel (E_S), one capable of being drawn down in a way that woodlands simply could not. This meant that a new and much larger 'consumption horizon' (E_C) was now possible – a potential that was soon reached, both for the population's "sustenance" (space heating and cooking requirements) as well as for industry.

Also, having reconfigured the technosphere for the mid-18th century, the widespread diffusion of Newcomen engines across Britain also affected the selection environment for other technological breakthroughs: for iron-smelting (by creating a demand for innovation that would allow substitution of coal over charcoal) as well as high pressure engines; for textile factories run by steam engines; and of course for locomotives, steamships, and later other types of combustion engines. This process is illustrated by the arrow leading from *T* to *SE* (although strictly speaking, the ever-changing technosphere, occurring as the result of the diffusion of many contemporaneous breakthroughs, will likely impact the fitness factors within a selection environment differently, such as costs of production, factor-savings, infrastructure, user competence/preferences, etc., which is an important avenue for future research).

With this basis we can briefly examine several other natural energy potentials and hypothetical breakthroughs that could have a powerful economic impact in the future. The widespread geothermal heat energy in the earth's crust, or magnetosphere-level solar radiation, for example, both constitute massive energy potentials without either (1) technologies to permit exploitation, as for the latter case; or (2) an appropriate socio-economic context for the current level of technology to sufficiently diffuse (in the case of geothermal energy we do have technologies to capture the heat in the crust, but only in 'hot-zone' locations, as it is otherwise still expensive relative to other sources of energy). In the case of photovoltaic solar cells, as another example, the costs per kilowatt-hour are continually dropping through technical innovations, and this will certainly allow for more widespread adoption. But it has been a long process, just like the diffusion of the steam engine. Although it may not arrive when and where we might like it, technological innovation will therefore be critical in the ongoing history of energy acquisition by human groups.

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