Energy and institutions: What *really* happened in the English Industrial Revolution? What did not happen in China?

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Abstract

England during the period leading up to and spanning the first Industrial Revolution collectively learned how to consume a virtually unconstrained quantity of fossil (mainly coal) energy. Led by the period's effective aggregate demand growth this resulted directly in productivity growth that then led to modern economic growth in living standards for the first time in recorded history.

Studying the event empirically we can use recent long–period series estimates of levels of English energy consumption, gross domestic product, and population to test the hypothesis that this was primarily an *energy* revolution with important but mostly proximate institutional and cultural support.

Then a natural experiment is run using Ming and Qing China using limited data and important institutional comparisons that would not preclude China from completing an industrial revolution. In order to explain the English success and the Chinese failure a theoretical framework for industrial revolutions is explored.

The outcome should provide insights into economic development for growth economists by highlighting the importance of energy transitions for growth of economic systems. Additionally, the analytic framework developed can be applied across time and geography adding insights to ongoing development puzzles.

1 Introduction

1.1 English energy data

As early as 1734 observers of the economic panorama, later including economic and other historians, have commented on the role of energy inputs in economic activity and its social outcomes. These comments are not always explicitly related to energy but their implications often are. Jean Theophilus Desaguliers (Desaguliers, 1734) was a member of the Royal Society and "natural philosopher" (physicist and engineer) and observes that using human labor to pump water from coal mines was not profitable. He recommends "fire engines" (steam engines) to solve that problem. This is a clear call to substitute coal as a cheaper energy input for more expensive human and animal energy inputs to pump water from flooding coal mines.

Friedrich Engels (Engels, 1892) while writing of 1844 England asserts that the invention of the steam engine and machines for spinning and weaving cotton gives the impetus to the Industrial Revolution and changes the entire social structure of middle-class society. William Stanley Jevons (Jevons, 1965) frets that England will lose it's economic dominance when the coal supply runs out as perhaps an early version of today's "peak oil" concerns. Later, Edwin Eckel (Eckel, 1921) reports coal reserve estimates for several major economies and claims that World War I is significantly about resources including coal. Frederick Soddy who is a 1921 Nobel Laureate in chemistry writes widely on economics rooted in principles of physics and thermodynamics (Soddy, 1911, 1921, 1931; Soddy and others, 1933; Soddy, 1934), presaging Herman Daly and Nicholas Georgescu-

Roegen.

In John Nef's two-volume history of the coal industry in Britain (Nef, 1932) he demonstrates a strong sense of the importance of energy consumption primarily from coal in the growth of the British economy through an extended period from the sixteenth century on. He also describes in depth how the coal industry influences and encourages the rise of industrial capitalism.

French historian Paul Mantoux (Mantoux, 1961) writes in the early twentieth century of the machine industry transition in England during the eighteenth century with deep analyses of the key industries especially wool and cotton textiles.

Later in the twentieth century W. Fred Cottrell (Cottrell, 1955) writes about energy sources from the neolithic through nuclear energy. Cottrell uses an unusual syntax in describing this history: low-intensity energy converters for humans and animals and high-intensity energy converters for machines. Peculiarly he never as far as I could find uses the word "capital" just high-intensity energy converter. He thus focuses clearly on the distinction between low-capacity muscle-powered work and high-capacity machine-powered work an essential distinction made later in discussing industrial revolutions. He also discusses the impact each of the energy sources makes on society.

The Italian economic historian Carlo Cipolla (Cipolla, 1961, 1962, 1966, 1983) writes widely of energy revolutions including neolithic agriculture, the early modern European sea dominance, and the Industrial Revolution. Cipolla is an early chronicler of the roles various technologies played in these revolutions in a sense presaging Joel Mokyr (Mokyr, 1992).

Phyllis Deane in writing of the English Industrial Revolution notes "The most important achievement of the industrial revolution was that it [i.e. coal] converted the British economy from a wood-and-water basis to a coal-and-iron basis" (Deane, 1979, p. 129). Deane's comment is representative of energy-aware observers but misses the full significance of the energy source revolution that became the English Industrial Revolution. I plan to extend such thoughts into a more comprehensive story of this history.

E. A. Wrigley (Wrigley, 1988, 2010) writes extensively about England's transformation from an "advanced organic" society mainly engaged in agriculture to an "industrial inorganic society" engaged primarily in non-agricultural production in centralized factories. Wrigley interweaves the social impacts into this story very notably how it influenced the transition away from Malthusian demographic dynamics to a post-Malthusian dynamic. The Industrial Revolution eventually changed the sign of the correlation between increased living standards and fertility rates from positive to negative. This is a sign change that holds profound implications for our economic future.

What the paper calls an energy revolution Italian economic historian Paolo Malanima (Malanima, 2010) calls a transformation of the energy system. His time frame is the same as John Nef's and mine—from the sixteenth century through the nineteenth century. Malanima sketches out formally the essential features of this transition that become the focus for England and China in this paper. These include population growth, rising energy costs, and substitutions for heat and muscle power energy sources across Europe. He does this at a macroeconomic level. A focus on England allows us to explain in depth the energy foundations of the first Industrial Revolution, examine why they happened in endogenously in England, and describe both the microeconomic incentives behind the revolution hinted at by Desaguliers and its macroeconomic phases.

The twenty-first century has seen some very important work among historians relating energy inputs and growth. Kenneth Pomeranz is a Sinologist who like William McNeill is a "world" historian but unlike McNeill (McNeill, 1982) focuses on explaining the "great divergence" between China and England starting around 1800 (Pomeranz, 2001, 2002). Pomeranz explains why the English did the Industrial Revolution first compared to anyone else especially compared to China by invoking the English advantages in coal, colonies, and cotton. Coal removed the energy constraint faced by all growing economies from depending on wood for heat and steam. The English colonies provided both input resources such as cotton and (colonial) consumer markets for absorbing the increased capacity as production constraints dissolved in the face of steam-powered factories. This is a classic case of Adam Smith's vent-for-surplus theory (Smith and Stigler, 1977) that Pomeranz invokes along with armed mercantilism as instrumental to the England's successful industrialization. But very clearly he returns many times to the central fact: England was geographically and geologically lucky to have cheaply accessible coal supplies. The English Industrial Revolution was foremost an energy revolution.

Economic historian Robert Allen (Allen, 2009b) intensified the explanation of the English Industrial Revolution as an English energy revolution. Allen's approach is data-intensive; in particular he presents wage and energy cost series for England, China, and other important economies in the early and late modern eras. This allows him to construct a comparative wage-to-energy-price ratio for these areas in a critical proto-industrial era that not only answers the "why England and not China" question surrounding the Industrial Revolution but allows one to begin formalizing a theory of Industrial Revolutions or even more generally a new approach to growth theory as discussed below.

Allen's analysis bolsters the "energy revolution as primary" approach that the paper explores; he summarizes his view strikingly: "... there was only one route to the twentieth century – and it traversed northern Britain" (Allen, 2009b, p. 275). His view is that expensive English wages and cheap coal energy from Newcastle though a historical accident were the uniquely English causes for the Industrial Revolution and modern economic growth. As an essentialist Allen views the primary or ultimate cause of the English Industrial Revolution to be English labor and coal price differentials compared to other historians who might invoke several proximate causes.

While the scholars and observers cited above place energy consumption at the center of their explanations for the English Industrial Revolution and modern economic growth they seldom do so explicitly. The most explicit are W. Fred Cottrell (Cottrell, 1955), Robert Allen (Allen, 2009b), E. A. Wrigley (Wrigley, 1988, 2010), and Vaclav Smil (Smil, 1994, 2008) not mentioned above but a scientist and scholar with a very broad understanding of energy's role in society. The others cited represent a group of scholars who at least hint at the primary role energy plays in the *sui generis* English experience.

In a more general vein Nicholas Georgescu-Roegen (Georgescu-Roegen, 1971) focuses on the thermodynamic foundations of economic systems and helps found the field of ecological economics. This seemingly stark description of our normal daily activities holds an important truth: all economic activities indeed all activities require energy inputs. We can impute from this that limited energy inputs will limit economic outputs. Following his thinking I sometimes think that the only non-substitutable input is energy (as in Joules); energy sources can be substituted but you must have Joules for life and economic activity. Energy source substitution becomes fundamental to a story of industrial revolutions. Timothy Garrett (Garrett, 2009, 2012, 2015) advances a modern treatment of this energy-based thermodynamic work including its impact on long-range climate forecasts.

1.2 New institutionalists

Arrayed against this countably small group of major scholars is a large literature on the role of culture and institutions in explaining why England succeeded in its industrial revolution before anyone else was able to do so. I will review the very high points of this literature and then turn to a review of relevant Chinese literature as representing a "natural experiment" to compare with England.

This paper highlights the role of energy consumption and revolutions it its use as being at the center of the English Industrial Revolution and more generally on industrial revolutions and economic development and growth. While this necessarily displaces culture or institutions as prime causes of these events the purpose of this paper is to develop evidence and theory to make the different focus justifiable.

We first must include Max Weber (Weber, 1964, 2002) as representative of the institutional literature on the English Industrial Revolutions. Weber is clearly an early eurocentric scholar invoking

European Protestantism as a motivating force for capitalism and the events that flowed from it.

Douglass North is an economic historian instrumental in founding both New Economic History (Cliometrics) and New Institutional Economics and works on the broad issues of economic growth and development. He takes a very historical approach by describing market expansion from tribal local exchange dominated by informal rules to long-distance trade that require new institutions to deal with the problems of agency (not having physical control of the goods) and contract (providing transport protection and enforcement of contracts).

North (North and Thomas, 1973; North, 1990) focuses on the idea that economies require "efficient organization" to grow that is a self-admittedly neo-classical approach. Efficiency entails developing sufficient institutional arrangements to create individual incentives to inventors and producers. The most important institution is property rights. The West necessarily developed these institutions as conditions for its rise. He discusses both extensive growth defined as overall growth because of increases in the traditional factors of production (land, labor, capital) and intensive or per-capita growth that for him is true economic growth. Intensive growth is in turn caused by either per-capita increases in factor inputs or increased productivity through economies of scale, education, capital improvements via technology embedding, and by reducing market imperfections. He answers the puzzle of why given the straightforward prescription above every economy has not developed economically. And of course it is because they are not efficiently organized, lacking required institutions including most importantly property rights. North also comments on population growth as being important to economic growth; this important insight helps explain the basic motivation for inventors and entrepreneurs to invent and produce—population growth leads to increasing consumer demands that are the source of all production and input demands.

Contrasted with North, the major historian David Landes (Landes, 1969, 1999) writes widely on Western culture as primal in the Industrial Revolution. Landes like scholars discusses the role of energy and the technologies that enable its use but returns to culture as the reason for the rise of the

West. A more recent approach to this theme are books by Deirdre McCloskey (McCloskey, 2007, 2010) discussing the primacy of Western values, ethics, and culture in the comparative rise of the West; McCloskey does talk about the importance of coal but in a glancing discussion.

Another economic historians who emphasize cultural roots as the explanation for the rise of the West is Jack Goldstone. Goldstone is a member of the "California School" of economic history and writes widely (Goldstone, 1987, 2000, 2008) on the West's cultural primacy allowing its comparative rise. In particular (Goldstone, 2000) he develops the concept of "Efflorescence" or the asymmetric rise of economic activity among nations due to institutional differences. To illustrate he invokes the difference between North and South Korea since their partition and radical institutional divergence.

Daron Acemoglu's work represents a modern quantitative version of institutionally–driven growth; in particular he studies the role of the state (Acemoglu et al., 2005), growth theory (Acemoglu, 2012), and institutions as causing growth (Acemoglu, 2005)). Acemoglu often attributes growth differences to the presence or absence of Western–style property rights.

The defining point of view for this group is that certainly there was something that happened to the energy system yet the causes of the English Industrial Revolution and subsequent rise of the West were cultural and institutional. In this paper an there is an appeal to something even more fundamental and this is used to develop the view that while institutions are important they arise in response to underlying economic changes. Therefore we must study those to truly be able to answer North's puzzle of "why not everyone?"

The "culture and institutions *are* growth and development" group's view was not the first institutional approach to the question. Karl Marx (Marx, 1904) and Thorstein Veblen (Veblen, 2009) among other original institutionalists view institutional development as endogenous to the major economic developments. This is a point of view I have come to share and will develop in this paper.

1.3 Chinese energy data

Now turning attention to China as an important "natural experiment" comparison to England in order to test the hypotheses about growth and industrial revolutions. If in say 1400 a group of growth economists at a conference were sitting at the bar and speculating on what country was likely to accomplish the first industrial revolution China almost surely would have been in the lead. Large markets, one-quarter of global population, more than one-quarter of global GDP, and important inventions are among several important drivers legitimizing China as the leader in the gathering race toward industrialization. Some had never heard of England—it was a small even backwater and backwards economy somewhere near the Eurasian land mass. Yet three centuries later England was accelerating along its path of becoming the leading economy in the world. And by 1800 was clearly diverging from China and in the global economic lead.

The Chinese "energy" story is not nearly as well-developed as the English possibly because China did not experience a complete industrial revolution and thus did not generate all the questions related to that event that England did; nonetheless there are modern scholars who have important contributions. The cultural and institutional story surrounding China has ossified for many years attempting to explaining the puzzle the economists in 1400 were discussing of why China was not first. This Eurocentric attitude is best summarized by Marx as the "Asiatic mode of production" where Marx (and Engels) describe Asia as consumed by despotic rulers expropriating surplus from the economy, monopolizing land ownership, controlling irrigation systems, preventing trade and technological development, and in many other ways thus preventing modern economic development. This widely-held story may be too simplistic and is increasingly challenged by modern scholars.

Economic historian and Sinologist (and student of John Nef) Robert Hartwell lays the foundations for understanding the iron and coal revolution during the Northern Sung dynasty (A.D.

960-1126) ruling China from Kaifeng in northern China (Hartwell, 1962, 1966, 1967, 1982). Mark Elvin (Elvin, 1973), William McNeill (McNeill, 1982), Fredrick Mote (Mote, 1999), and Eric Jones (Jones, 1988, 1996) all make the key points: first, China during the Northern Sung blossomed economically including a significant period of intensive growth (growth in living standards); second, a significant part of the economic growth involved the rise of a large coal-fed iron and steel industry. Tim Wright (Tim Wright, 2007) provides a survey that places the historical China work in context and empasizes the importance of Hartwell's contribution.

Robert Allen (Allen, 2009b) provides comparative wage and energy cost data for China that plays prominently in my theses. While Chinese data is sparse compared to English data Allen publishes labor wage time series and energy price series that include China. Using this work a story is developed that Sung China had an energy revolution and a first–phase industrial revolution. These terms are defined later. China and England are very comparable in the theoretic structure developed below. However, China did not complete its industrial revolution and thus further theoretic structures are applied to describe the English success and test those against the Chinese failure.

Given that China failed at its industrial revolution attempt (though presumably no one except our conference–attending economists knew what an industrial revolution was) and that the preponderance of Western scholarship claims that the failure must be culturally or institutionally caused, a review is needed of the recent scholarship debunking this point-of-view.

1.4 Chinese institutions

Kenneth Pomeranz (Pomeranz, 2001) reviews China's institutional capabilities and comes to the conclusion that eighteenth-century England and regions of eighteenth–century China (as well as other global regions) were not significantly different from an institutional point-of-view. Among the areas Pomeranz investigates: dubious claims of English/Western European productivity advantages; a demographic-marital system that did not produce superior fertility control or life expectancy; a capital stock that was not larger and did not embody decisively superior technology; land and labor markets that were possibly less "Smithian" than elsewhere specifically including China; and China's pattern of family labor use that responded to shifting opportunities and price signals as well as Europe's input factors did.

His conclusion on institutional differences is striking: "Far from being unique the most developed parts of western Europe seem to have shared crucial economic features–commercialization, commodification of goods, land, and labor, market–driven growth, and adjustment by households of both fertility and labor allocation to economic trends–with other densely populated core areas in Eurasia" (Pomeranz, 2001, p. 107). Chinese and English institutions were, then, functionally similar enough that they should not prevent similar economic outcomes and indeed they did not. By functional similarity is mean supporting similar outcomes in important areas of economic performance.

Pomeranz makes a further striking observation: "Furthermore, there is no reason to think that these patterns of development were leading 'naturally' to an industrial breakthrough anywhere. Instead, all these core areas were experiencing modest per-capita growth, mostly through increased division of labor, within a context of basic technological and ecological constraints that markets alone could not solve" (Pomeranz, 2001, p. 107). Existing institutions anywhere were not sufficient to produce an industrial revolution. These observations help motivate the research question: what really happened in the English Industrial Revolution?

Pomeranz's radical claims have generated both academic support and refutation. See Philip Huang (**?**) for support and Peter Perdue (Peter C Perdue, 2009) and Ricardo Duchesne (Duchesne, 2004, 2011) for refutation. Duchesne further voices full–throated support for Western exceptionalism.

Pomeranz is not alone in observing the lack of functional institutional differences between China and England. R. Bin Wong (Wong, 1997) provides a broad institutional comparison between

China and England and comes to the same conclusion: functionally unremarkable institutional differences.

Peer Vries (Vries, 2003) attempts to straddle the arguments by claiming it was (must be?) culture but acknowledging that he cannot explain the fundamental reasons why people reacted differently; this puzzle further motivates the research. Kenneth Pomeranz replies to Vries' 2003 book in a most useful way since the book is written in Mandarin that Pomeranz reads.

Pomeranz (Pomeranz, 2004) notes the following as areas of agreement between Vries and the "California School" of Chinese historical (including the relevant eighteenth century) revisionists:

– The Qing state did not interfere with most economic transactions.

– Confucianism was no obstacle to economic development.

– Some (if not all) Chinese markets were remarkably well integrated.

– Even in the late eighteenth century Chinese agriculture had much higher land productivity than Britain.

– Differences in agricultural labor productivity were minimal.

– Differences in per–capita incomes (living standards?) were probably small.

What of Pomeranz's last point? He uses "per–capita income" and Robert Allen (Allen, 2009b) successfully demonstrates that incomes at least as represented by real silver wages were significantly different between eighteenth century China and England. Living standards could have been relatively the same if for example the Chinese cost-of-living was relatively lower than English cost-of-living; Allen (Allen, 2001; Allen et al., 2007; Allen, 2009a) provides support for this difference as well.

Pomeranz further notes areas of less agreement with Vries:

– That differences in English and Chinese technical ability cannot have been very great before Britain's technological take-off.

– Less proletarianism in China (fewer potential wage labor or factory workers).

– Less emphasis on the comparative inability of China to relieve resource shortages.

– The importance of British mercantilism and state activism.

Pomeranz views Vries' book as as representing a narrowing of the differences between the two great schools: culture versus geography. If true this current research could advance the role of geography and basic economic forces in a more hospitable climate.

1.5 Chinese science and invention

There is a literature claiming China was not able to invent necessary industrialization technologies for cultural/institutional reasons. Several scholars refute this. Joseph Needham (Needham, 1954) who started a still-ongoing project in eight volumes documenting the great Chinese scientific and technical achievements. Accepting this leads one to a useful question: why did they not commercialize their relevant technologies as the British did?

John Hobson provides more direct and recent refutation of the literature that for various reasons Chinese science and technology were sufficiently deficient that the Chinese could not have had an industrial revolution. Hobson (Hobson, 2004) makes two strong claims: first, each major developmental turning point of the "oriental West" was informed by assimilating Eastern inventions including ideas, technologies, and institutions that diffused from the more advanced East through oriental globalisation between 500 and 1800 CE; second, Europe after 1453 became imperialist and appropriated many Eastern resources including land, labor, and markets. This timing coincided with the Ottoman seizure of Constantinople and Pope Pius II resurrecting calls for a "great Crusade" to save Christendom from the Islamic threat.

Specifically Hobson recounts that as early as 31 CE Chinese water-mills propelled the bellows in iron blast furnaces; significantly the Chinese water bellows used a piston-rod and driving belt that bore a "remarkable" resemblance to the mechanics in John Wilkinsons's precursor to James Watts' steam engine. A device very similar to Wilkinson's was described in Chinese print form in 1313 CE and Hobson suggests it was one of the Chinese technologies assimilated by the Europeans in this case the defining technology of the English Industrial Revolution (Hobson, 2004, p. 225).

Hobson additionally claims the Chinese preceded the English in replacing charcoal with coal to produce iron in the eleventh century, originated the blast furnace in the second century BCE, and in the fifth century CE developed the process to produce steel by fusing wrought and cast iron.

Hobson claims these inventions made their way West and became the key technologies of the English Industrial Revolution (Hobson, 2004, 227).

It thus appears the Chinese were on the path to develop the technologies required to produce an industrial revolution; they did not and the question remains: why not? This research attempts to shed additional light on an answer.

1.6 Growth theory

Concluding this introduction there is a brief review the major economic growth theories. While not the focus of this work, clearly there was no need for growth theory before the the English Industrial Revolution because there was no persistent growth in living standards. Most countries had similar living standards—close to subsistence. After the event living standards diverged widely; the goal of growth theory is to explain this divergence in an attempt to provide policy prescriptions for economies that have not converged toward the living standards bar set by advanced economies. This work will suggest extensions for growth theory.

The first macroeconomic growth model many economists encounter is the Harrod–Domar model named for Roy F. Harrod (Harrod, 1939) and Evsey Domar who developed it independently. This model like most growth models is specified as a production function. For Harrod–Domar output is a function of (exogenous) capital stock—higher stock produces more output.

The next significant growth model is Solow-Swan named for Robert Solow (Solow, 1957) and Trevor Swan. Solow–Swan extended Harrod–Domar by adding labor and productivity to the aggregate production function; productivity is assumed to be labor-augmenting technology or knowledge. This is still an exogenously-driven model.

Paul Romer (Romer, 1994) developed a modern growth model that is the foundation for much subsequent work and contains the key feature of endogeneity—growth rates are determined by factors internal to the model and incorporates a constant marginal product of capital rather than a diminishing one as found in older theories.

The striking fact is that none of these models explicitly incorporate energy as an input. Given what the energy-aware observers cited above say that seems like a major oversight. These models may indeed pick up energy inputs indirectly because the mainstream models always have capital stock as an input. A, perhaps the primary, purpose of capital stock is to apply energy inputs to the production process. However capital, being a stock that is depleted—used up—at a much lower rate than direct inputs such as energy is therefore not in the correct units we need to specify a model. This needs to be kept in mind in thinking about modeling output using an aggregated production function.

There is a small but significant thread of research that does incorporate energy inputs. Perhaps the most provocative for mainstream models is the work of Robert Ayers (Warr and Ayres, 2006; Ayres et al., 2013). Ayers specifies a production function using solely an energy input and takes the model to U.S. GDP data between 1900 and 1998. The model residuals vary depending on the time frame from about zero to twelve percent. This is a striking result in the context of the empirical fit of other growth models. For example the canonical fit that Robert Solow did on his labor and capital input model resulted in a residual term of about 88 percent. Ayres' empirical results suggest we need a different approach to growth modeling. So this paper investigates using energy inputs as the primary way of modeling the English Industrial Revolution and for other comparisons.

2 English data, econometrics, and economics

2.1 A first look at the data

This section describes the three data series numerically and graphically.

2.1.1 Sources and methods

The primary data used to model the English Industrial Revolution are gross domestic product (GDP), population (for per-capita measures), and energy consumption. Since the estimated energy consumption series starts in 1300 CE and as it may be useful for both the model and theory to incorporate that entire series population and gross domestic product series were composed starting in the same year. The time series stop at 1873 CE because that is the date based on econometric structural change analyses developed later in this paper that England's reign as the premier industrialized economy starts to decline.

Table 1 describes the sources for the data series.

Roger Fouquet provides an invaluable time series of English energy consumption and related data. Fouquet's book (Fouquet, 2008) and papers with Peter Pearson (Fouquet and Pearson, 1998) are a remarkable accomplishment; these data are a major contribution to this work. Professor Fouquet gave me his data files and permission to use them.

Fouquet's methods for constructing the data series depend on the source of the energy and type of primary records. Overall he estimates energy consumption by energy services (essentially end use) in categories of domestic heating, industrial heating, industrial power, passenger transportation, freight transportation, and lighting.

Table 1: Data Sources

Data series	Year range	Geography	Source
Energy consumption	1300–1873	England/Wales	Roger Fouquet (2008)
Gross domestic product	1300–1700	England	Graeme Snooks (1994)
	1741–1873	England/Wales	Lawrence Officer (2009)
Population	1300–1540	England	Graeme Snooks (1994)
	1541–1800	England	B. R. Mitchell (1988)
	1801–1873	England/Wales	B. R. Mitchell (1988)

He uses actual data when possible and models data as necessary with a variety of techniques. He describes the methods in the data appendix to the book (Fouquet, 2008) and they include formal modeling, interpolation, extrapolation, and assumptions. His energy sources include wood, coal, food for horses (power and transport) and humans, wind and water power, and steam power (almost exclusively using coal). He does include electricity but its general use is beyond the study time frame so does not apply. Importantly for the work here there is no indication that any of his estimates use GDP and thus the energy consumption series and GDP are methodologically independent.

The GDP estimates are composed from two sources. The period from 1300 to 1700 uses data from Graeme Snooks (Snooks, 1994). Snooks is a sometimes–controversial English historian in the sense he estimates higher growth rates over a longer period than other estimates say from Angus Maddison as an example. His data are useful because they matches the studies' geographic coverage needs in its time frame. In any case the GDP sources going that far back are rare.

In general the GDP and population data are benchmarks often decadal and sometimes longer. For econometric purposes interpolation among the benchmarks is useful. The interpolation method is called Stineman as described and implemented by Bjornsson and Grothendieck (Bjornsson and

Grothendieck, 2012) in a R package named stinepack. All descriptive, modeling, and graphical work is done using the statistical analysis software R authored by the R Core Team (R Core Team, 2014).

For GDP estimates from 1700 through 1873 the study uses data from Lawrence Officer (Officer, 2009).

The population estimates are composed from three sources. Before 1801 the estimates are for England proper. After 1800 England became Great Britain and the population estimates are for a greater area.

From 1300 to 1540 the study uses data from Snooks (Snooks, 1994). From 1541 to 1801 the series uses data from B.R. Mitchell (1988). After 1801 the series uses a Mitchell (Mitchell, 1988) data series for England and Wales. This geographic discontinuity did not significantly affect the splicing of the data as far as the results are concerned.

Figure 1 presents the three historical series.

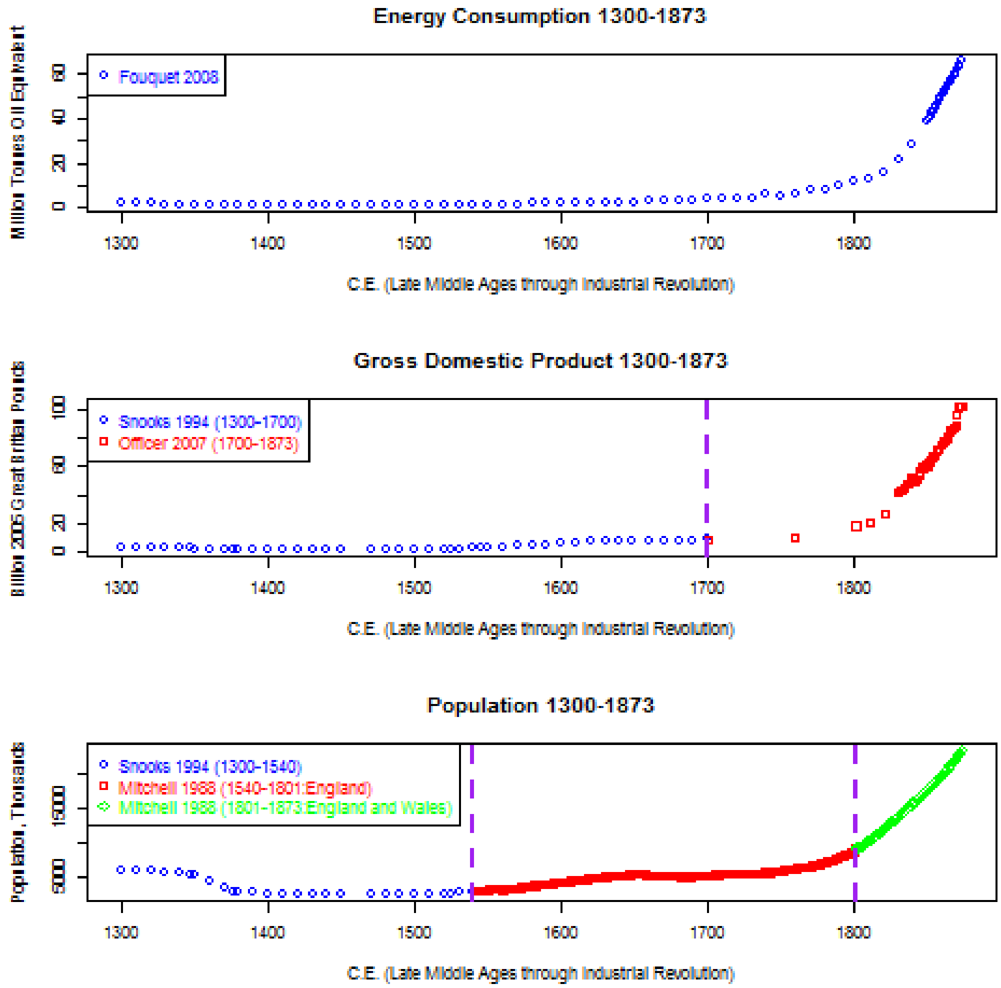
In this display we can see that both energy consumption and GDP have very similar shapes (the graphs are scaled to the same vertical distance so despite difference in units we can visually compare shapes) implying just at a visual level that they may be statistically cointegrated. this will be further discussed later. And we can see the levels increased most dramatically after 1700 and certainly after 1800.

The population graph's shape is less steep in the later periods implying the increase in living standards we already know happened based on many sources. The Black Death's (1348–1353) effect on the population level and its relatively long recovery period show nicely on this graph.

2.1.2 Modern economic growth

Simon Kuznets defined modern economic growth as sustained and high rates of growth of per–capita product and population (Kuznets, 1966). Figures 2 and 3 indicate that England experienced

Figure 1: Author/time-span series of energy consumption, GDP, and population



high rates of growth of per-capita product in (possibly) two eras from 1500 to 1600 that was not sustained and after 1750 that was mostly sustained. Clearly after about 1820 England had a high and sustained rate of growth in per–capita product here measured as gross domestic product. The annual rate after 1800 was 2.4 percent per-year total growth and 1.1 percent per–capita growth as seen in table 2. Figure 4 shows the log of population growth that supports the Kuznets definition and mirrors GDP growth with a lag.

Examining the log levels and log per–capita transformations in Figure 3 note the interesting

Figure 2: English real gross domestic product,
levels and per–capita

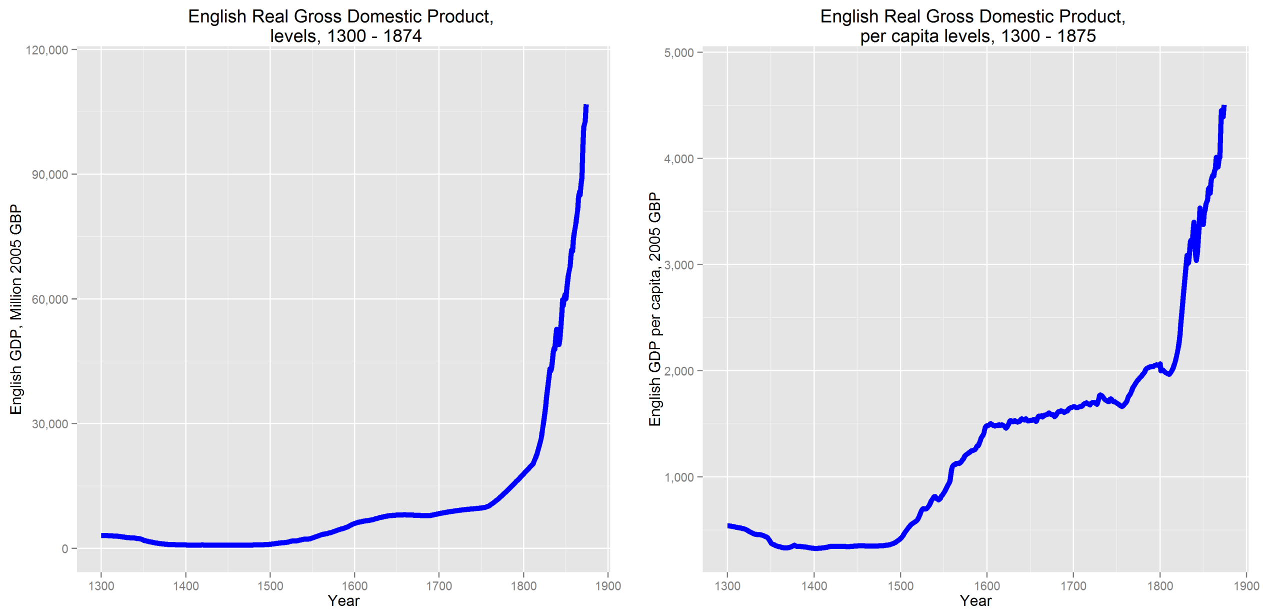
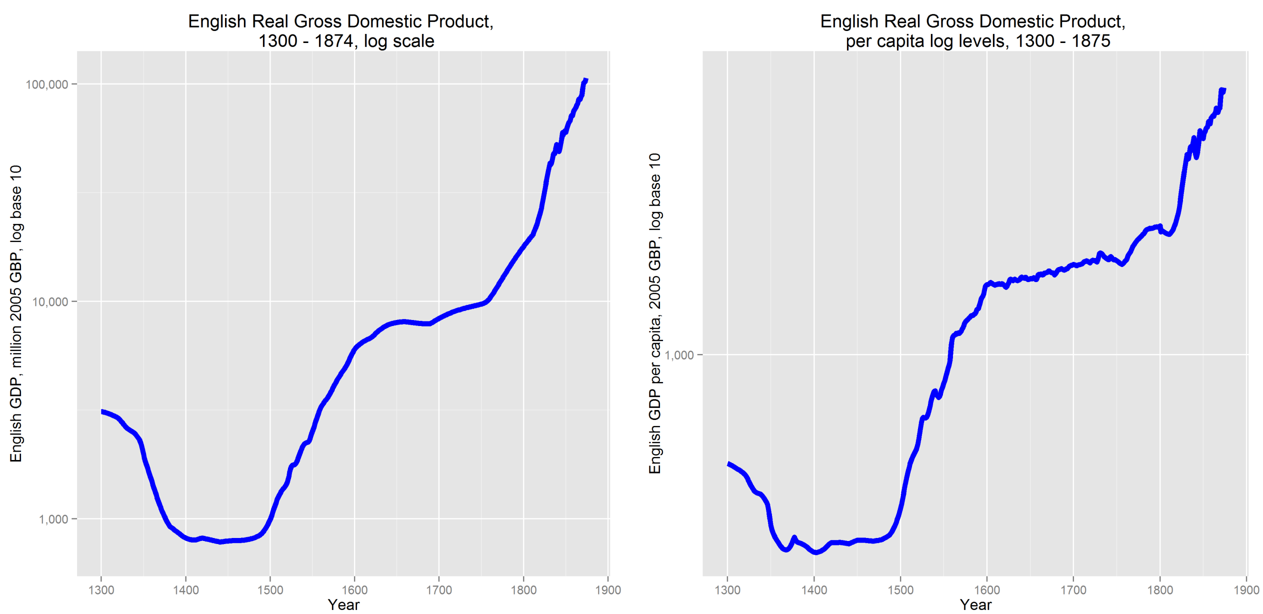


Figure 3: English real gross domestic product,
log levels and log per–capita



periods of growth rate changes. For example GDP growth rates plummet during the period of the Black Death, rise significantly after 1500, then go almost flat during the seventeenth century before recovering into high growth rates after about 1750. The flattening can be explained by what paleo-climatologists define as the "Little Ice Age." During this era average temperatures fell by about two or three degrees centigrade enough to shrink agricultural output and by some accounts caused population declines of about thirty percent due to higher mortality (famine) and lower fertility rates. See Jean Grove (Grove, 2003) and Geoffrey Parker (Parker, 2014) in a masterful historical account of the "long" seventeenth century.

Further comments appear below on the rise after 1500 in the population discussion although the significant per capita growth is somewhat of a surprise perhaps a continuation of the growth spurt in the middle ages and possibly some artifact in Snooks' GDP data.

To see the magnitude of the growth rates by century and compounded annually refer to Table 2. This table uses the same data as the graphs but does quantify the rates and the biggest surprise (certainly to our fifteenth-century economists) is the growth in living standards of over 100 percent between 1800 and 1873 and its annualized rate of 1.1 percent—a rate probably never attained or approached in prior eras. Of course this was possible because of the comparatively huge growth rate in total output (and its driver energy consumption) not completely matched by population growth. Note that we should discount the sixteenth century numbers due to possible artifacts in the Snooks data.

Turning to the population data Figure 4 provides a log levels picture. Note the similar patterns to the other series; a dip in growth rates due to the Black Death, the acceleration in the sixteenth century, a deceleration in the seventeenth century, probably a lagged reaction due to Little Ice Age fertility decreases, and the acceleration starting in the mid-eighteenth century. The vertical red lines indicate statistical structural breaks dating probable significant changes in the growth rates.

Examining these data patterns and the timing of their changes in growth rates along with the energy–consumption series discussed later suggests theoretical macroeconomic interpretations described next.

Table 2: Growth rates by century

Year range	1300	1300 - 1400	1400 - 1500	1500 - 1600	1600 - 1700	1700 - 1801	1801 - 1873	Total
GDP Million 2005 GBP	3115	815	994	6,031	8,361	18,110	102,811	
Century-over-century rate of growth		-0.738	0.220	5.066	0.386	1.166	4.677	32.008
Compounded annual rate of growth		-0.013	0.002	0.018	0.003	0.008	0.024	0.006
Energy consumption	1.7	1	1.3	2.2	3.6	11.6	66.1	
Century-over-century rate of growth		-0.412	0.300	0.692	0.636	2.222	4.698	37.882
Compounded annual rate of growth		-0.005	0.0026	0.005	0.005	0.012	0.024	0.006
Per–capita GDP 2005 GBP	542	329	421	1,484	1,663	1,999	4,392	
Century-over-century rate of growth		-0.393	0.282	2.521	0.121	0.202	1.198	7.108
Compounded annual rate of growth		-0.005	0.002	0.013	0.001	0.002	0.011	0.004

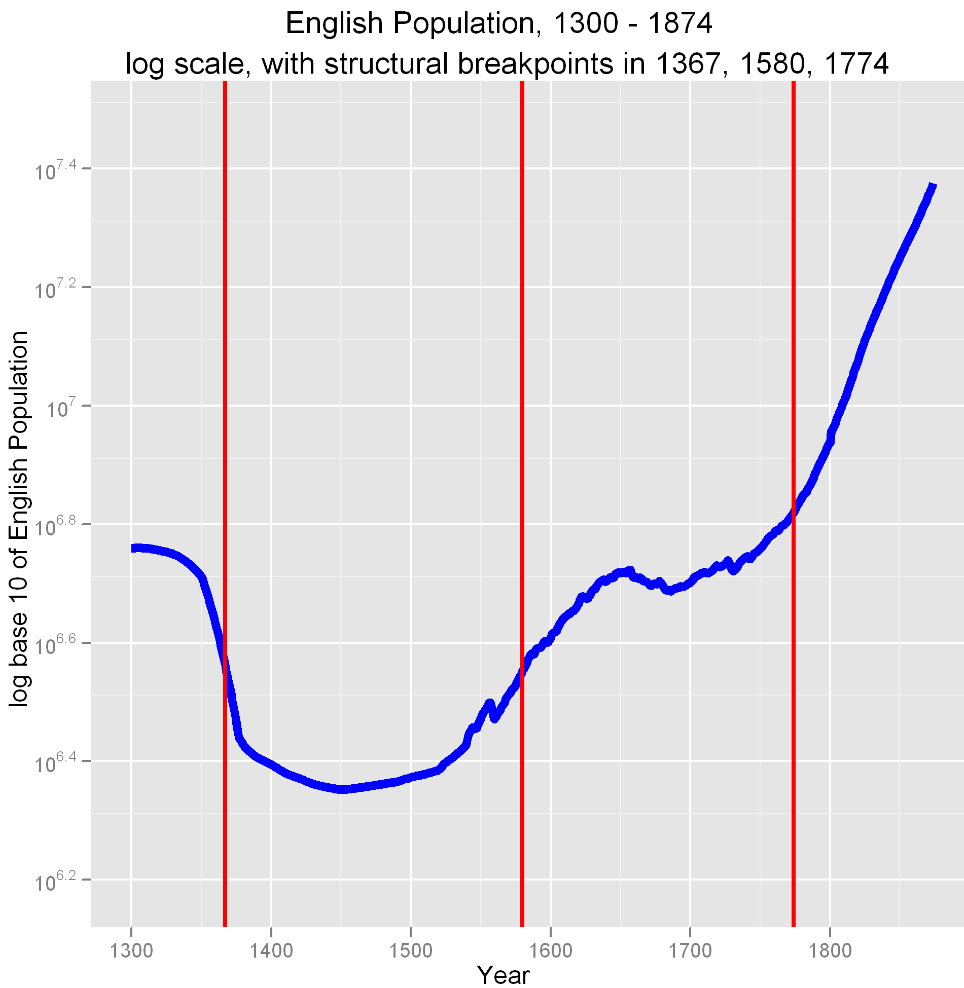
2.1.3 An energy revolution

This paper's central assertion is that the EIR was primarily an energy revolution on the supply–side. More generally, this was a demand–side consumer goods consumption revolution supported by a supply–side energy source revolution. To begin support for that hypothesis first review the data:

Figure 5 presents the log transformation of energy consumption over the study period; the vertical lines are formally determined structural breaks.[1] The log presentation enhances rate-of-change and potential structural differences in the series. We can observe four significantly different periods or regimes. The first is from 1300 to 1500 a period dominated by the Black Death epidemic; energy consumption clearly drops then recovers. The second is from 1500 to roughly 1600 as determined by the structural breaks. The third is the period from 1600 to roughly 1750; note that the rate-of-change of energy growth in this period is approximately the same as in the prior period;

[1]The structural breaks use an F-test methodology on the time series as implemented in the *R* package strucchange (Zeileis et al., 2003)

Figure 4: Log of population, with structural breaks



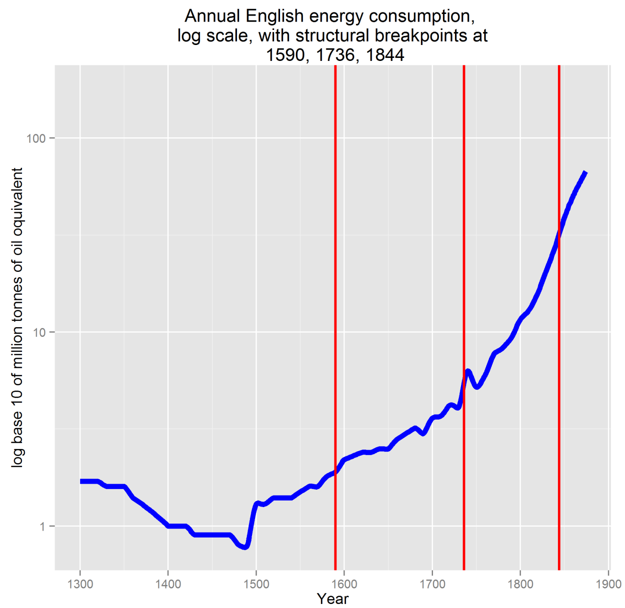
this rate of change similarity is confirmed by the presentation in Table 2. The final period is from 1750 through 1873; clearly the energy consumption rate-of-change accelerates as confirmed by the structural breaks in Figure 5 and table 2.

Based on the structural changes and based on the hypothesis that the EIR was an energy revolution one could propose that the revolution happened as two main eras: one starting in the mid-to-late sixteenth century [2] and one starting after 1750. Under this hypothesis the first revolution would have

[2]This validates John U. Nef's hypothesis of an early start to the British Industrial Revolution (Nef, 1932)

set the stage for the second. The second revolution required energy infrastructure built for the first.

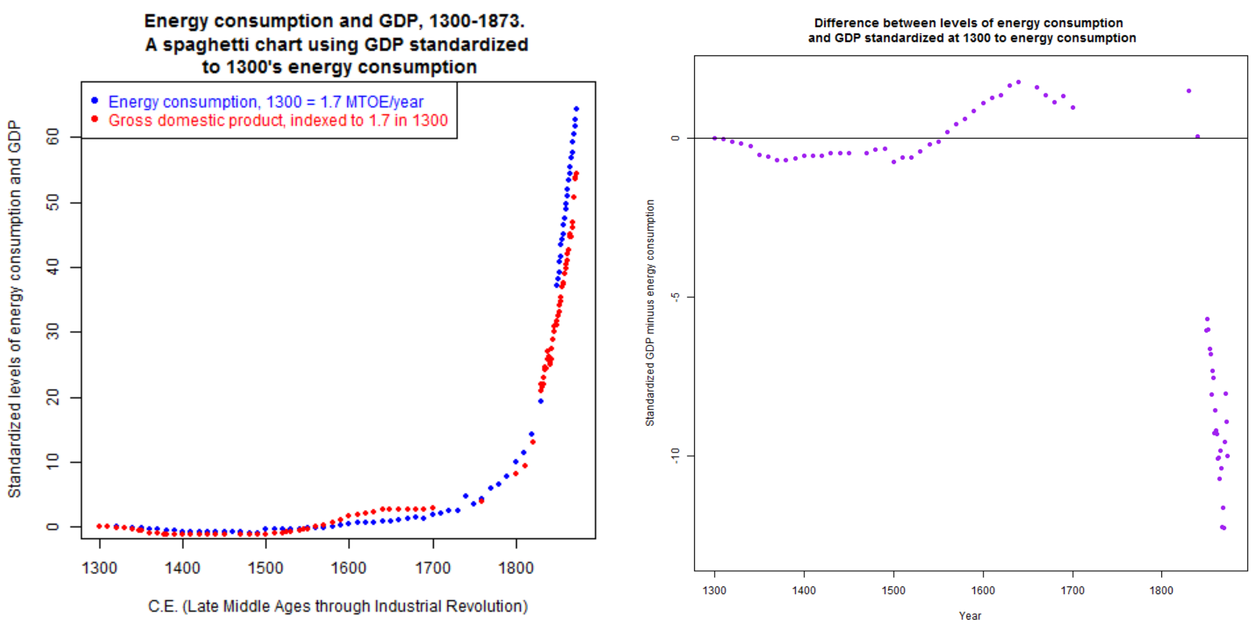
Figure 5: Log of energy consumption, with structural breaks



If we were to overlay the energy levels or logs charts with the GDP levels or logs charts the similarities would be informative; perhaps a more productive view is figure 6. This figure shows levels of energy consumption through the study period and has a standardized series of GDP for the same period. By standardized is meant matched in levels at the first period; the series' evolutions thus show differences in growth rates through continuous time. Again we see four distinct regimes. The most notable features are the periods from 1500 to 1600 when growth in GDP clearly leads energy growth and after 1750 (especially after 1800) when energy growth leads GDP growth.

Figure 6: Energy consumption vs. standarized GDP,

levels and differences



The dynamics of GDP growth and energy consumption growth can be seen more clearly by taking the differences shown in the right panel.

The Black Death and its aftermath affected the relatively flat net economic performance from 1300 to 1500 but set the stage for a growth boom in the period 1500 to 1600; this is subject to the caveat already mentioned regarding Snooks' GDP data but nonetheless there was a substantial pick up in growth rates during that period. We can see this by looking at energy consumption graphs that show smaller growth rates than GDP but still very significant growth. Table 2 also clearly shows this comparison. In the period 1600 to 1750 growth in both GDP and energy consumptions flattened and then boomed again during the period 1750 to 1873.

Observing the panels in Figure 6 suggests a very close correlation between energy consumption and GDP; the major divergence in these series is in the fourth period that has been identified after 1800 when data accuracy for GDP is probably the best in the sample. Even so this divergence is not large. More formal tests of the correlations will appear in the next section.

2.2 Econometric and economic analyses

To formalize the observations in the previous section correlations, paired t–tests, Granger–causality tests, and formal structural–break tests are used.

It is perhaps methodologically instructive to briefly discuss what is not covered in this paper. The original intent was to do a cointegrated vector error correction model (VECM) of energy and GDP. This methodology approaches equilibrium in a useful way for long-run macroeconomic models in the following sense: the only equilibrium a VECM assumes is a statistical one; this is sharply different than normal economic modeling that presumes some mean–reversion—a long run dynamic of stationarity. When one looks at any of the long–run macroeconomic series they clearly are not stationary. The are either exponential or super–exponential.

The results of cointegration tests on energy consumption and GDP series are that they are cointegrated of order about 2.5–clearly in the super-exponential range. Why then not model with this specification? Simply any of the graphs displaying energy consumption and GDP indicate a very high degree of correlation. And a very wise statistician teaches that you only need to do what is econometrically sufficient to make your point. So we proceed with that thought in mind.

Next some simple analytic statistics are presented to support the hypothesis that the EIR was at its root an energy revolution responding to a positive aggregate demand shock.

2.2.1 Econometric analysis

Starting simply a Pearson's correlation coefficient and a paired t-test of energy consumption and GDP yield the results in table 3:

Table 3: Energy and GDP fit tests

Test	Statistic	p-value
Pearson's correlation	0.998	
Paired t-test	5.592	4.991e-07
Chi-square	2864	0.0004998

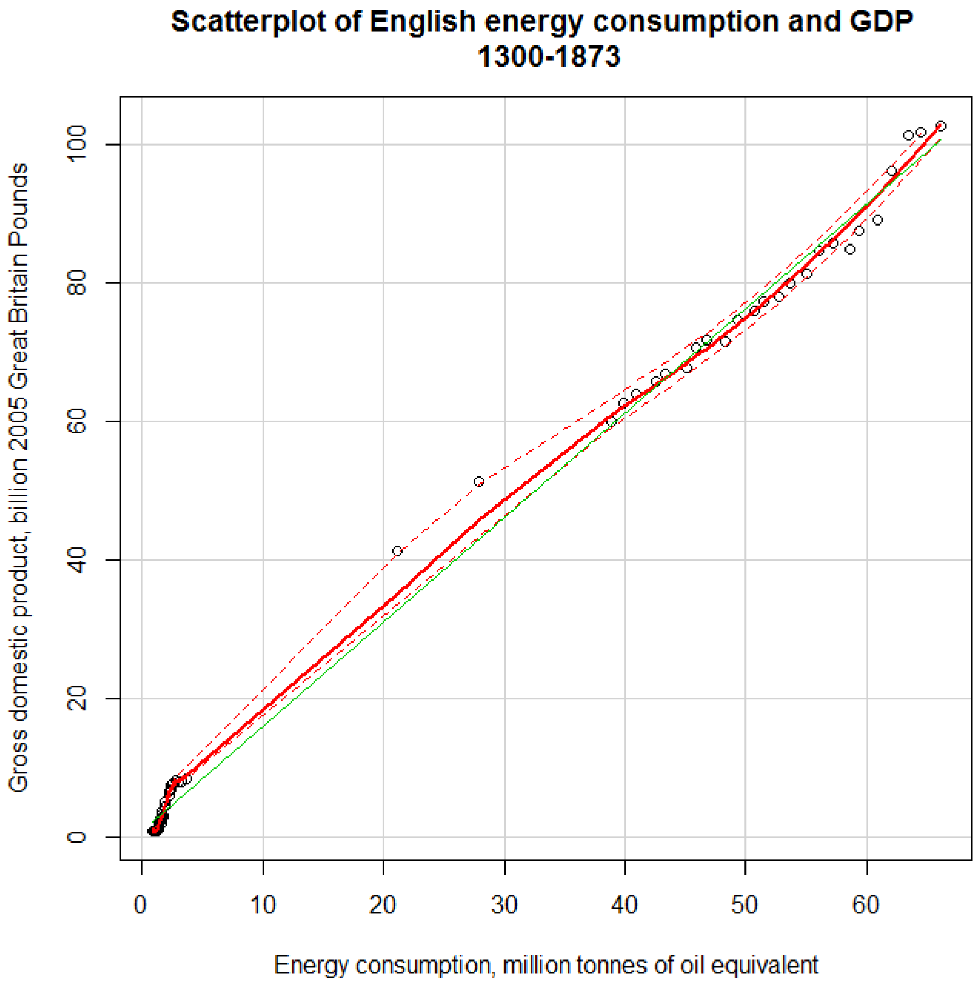
These simple results suggest that the two series are statistically very similar; in fact at that level of correlation one could think about claiming that these two series are the same—the result of a common data–generating process. A more formal co–integration test could be expected to be positive and will be presented in a future version. For the purposes of this paper a scatterplot of the series is shown in figure 7. The solid green line is a linear fit; the solid red line is a *lowess* (non-parametric and non-linear) fit.

Clearly there is a very high correlation between the two series. For current purposes more formal modelling is not needed. Overall statistically these two series are very close to being the same that is they share a common data generating process. In a strong sense this is a validation of the thermodynamic view of economic production and growth at least in the long run.

From an economic point of view this graph suggests a Leontief fixed-factors production function that would also be consistent with a Sraffian production interpretation.

However this overall view does hide important dynamics that the data contain. By examining these more subtle results next the stage is set for telling a history of the EIR. The study uses a

Figure 7: Scatterplot of energy consumption vs. GDP



Granger causality test to do so. (Granger, 1969).

Using the Granger bi–variate test to examine changing dynamics provides the results in Table 4; the eras tested were suggested by the statistics above and in total.

During the first energy/GDP era Granger causality between energy and GDP runs both ways at significant levels; while not ignoring these results we should not over–interpret what was happening given the huge aggregate demand and aggregate supply shocks of the Black Death. It is significant for later eras that the Black Death caused wages to rise and the European Marriage Pattern (EMP)

Table 4: Granger tests of energy-GDP dynamics

Era	Energy ~ GDP Pr(>F)	GDP ~ Energy Pr(>F)	AD/AS regime
1300–1500	0.0106	0.0003	EMP, Black Death, wages/family income increasing
1500–1600	0.1939	0.6126	Positive demand shock
1600–1750	0.3529	0.5185	Energy supply constraint
1750–1873	0.0024	0.1100	Positive supply shock, "virtuous" macro feedback cycle
1300–1873	0.0002	0.0361	Total study period

(Hajnal, 1965) increased family incomes entering the early modern period.

During the second energy/GDP era of 1500 to 1600 causality from GDP growth to energy consumption is weakly significant; energy Granger–causing GDP growth is not at all significant. However there is narrative evidence that this was an important proto-industrial period when home manufacture for markets became important; this is the "Industrious Revolution" of Jan de Vries (1994). There is further evidence that the English state supported an early version of Import Substitution Industrialization to replace imports and to increase exports (Thirsk, 1978). These events support the idea that demand must have been growing in domestic consumption markets, for military goods demand from the government, and eventually for exports.

These events occur in a backdrop of global population growth during a century of benign agricultural climate; croplands expanded, food was plentiful, real wages likely grew, nuptiality and fertility increased, and England participated in this bounty. The positive effect on agricultural productivity of the Columbian Exchange from transplanting highly efficient new–world potato and maize crops to Europe was in play. Alfred Crosby (Crosby, 1972) provides the seminal account of this important event. The transfer increased productivity both extensively (the new crops could be grown on previously unproductive land) and intensively (more output both per hectare and per labor hour). Population growth is positive even though the era continues to be dominated by Malthusian population dynamics.

In the third energy/GDP era of 1600 to 1750 neither direction of causality is significant. This will turn out to have important implications as the paper builds the history for the EIR.

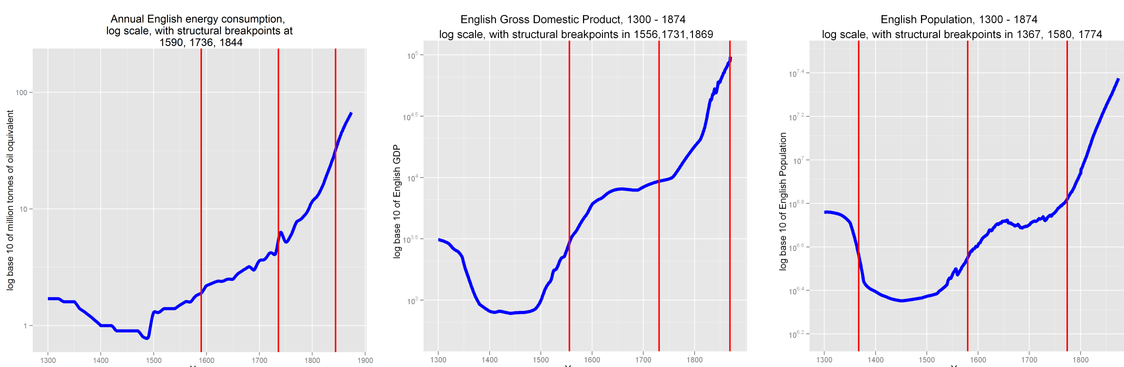
In the fourth energy/GDP era of 1750 to 1873 we again see both directions of causality significant with GDP Granger–causing energy consumption being the stronger.

Notably over the entire study period GDP Granger-causes energy consumption more significantly than energy Granger–causes GDP but causality is significant in both directions.

Finally, structural breaks in the series are examined; these are usually correlated with significant changes in underlying economic dynamics and will figure into the story of the EIR.

Figure 8 juxtaposes frames with logs of energy consumption, gross domestic product, and population, each with formal structural break lines noted. The point here is to note the correspondence of the structural breaks again suggesting the same underlying data generating process but with causality–implying lags in the population dynamics.

Figure 8: Structural break comparison

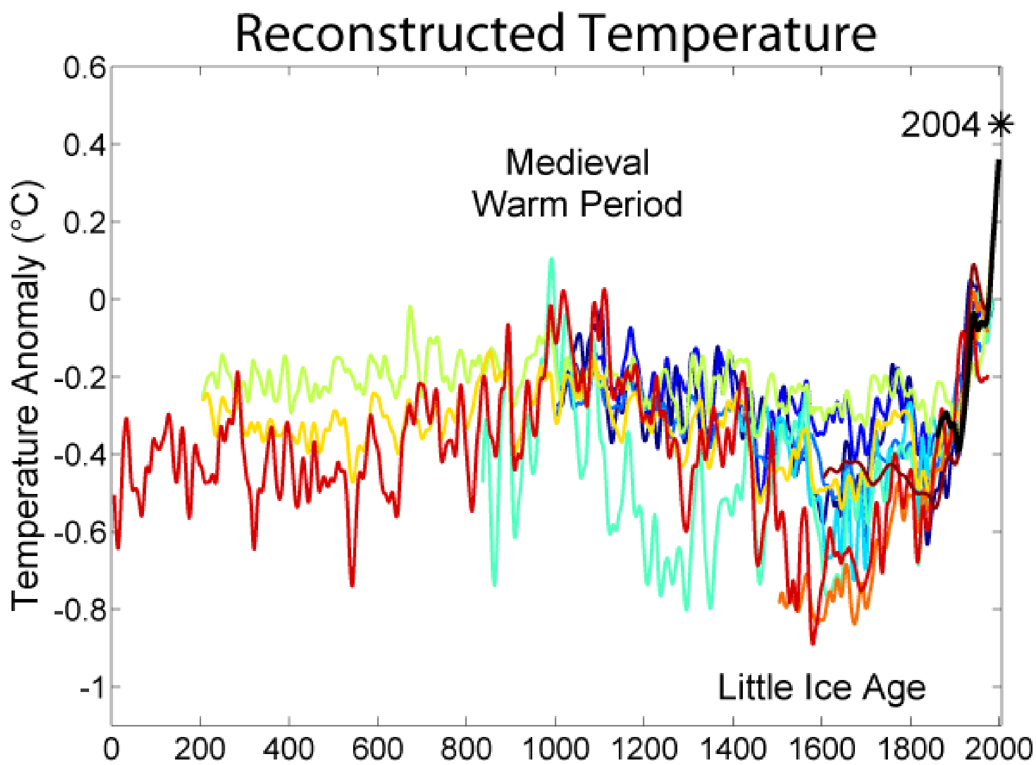


2.2.2 Economic analysis

Now it is possible to compose a story of the EIR as supported by the data presented above. The eras refer to Table 4.

Energy/GDP era one because of the Black Death disaster saw both negative demand and supply shocks but set the stage for the subsequent EIR eras through long–term effects on wages, incomes, and effective aggregate demand. More broadly the five centuries prior to era one comprise the Medieval Warming Epoch (or Period) supporting higher agricultural output and population levels with both supporting increased effective aggregate demand through expanded incomes. See Figure 9.

Figure 9: Late Holocene temperatures. *source:* NASA and IPCC composite



In energy/GDP era two wages rose due to the negative labor supply shock of era one. Aggregate demand had positive shocks as a result both of rising wages and of rising family incomes due to delayed marriages and women in the labor force—the EMP outcomes—and favorable agricultural conditions. Expanded household production (Jan de Vries 1994) and explicit import substitution policies starting with Henry VIII and continuing through Edward VI and Elizabeth I, supported increased aggregate demand (Thirsk, 1978). See table 6 for reigns. Aggregate supply expanded as can be seen by the stronger growth of energy consumption. Refer to table 2 or figure 5. This era provided the positive demand shocks and increasing supply constraints that caused the EIR. It started here.

John Nef amplifies this view. He tells the story of era two as the “age of timber.” While his time frames are a bit offset he says “. . . no less appropriate to call the sixteenth and seventeenth centuries an age of timber” (Nef, 1932, p. 191). Nef tells a very rich story of rising use of timber for industrial and home heating use, for construction, and the beginnings of a timber crisis. Dates for era two are 1500–1600 that Nef’s dates overlap by going into era three.

Rates of growth in energy/GDP era three for both GDP and energy consumptions stagnated. This still puzzles scholars including Braudel and Hobsbawm, but there are several potential stories that can be sketched here. Return to figure 9 and notice that a decline in mean temperatures occurred in the early modern era. This era is called the Little Ice Age and is believed to have been a global phenomenon. This would have opposite effects from the Medieval Warming Epoch such that the climate conditions should reduce agricultural output and population levels and cause a negative aggregate demand shock due to reduced income levels. In a sense this is also a negative energy supply shock featuring shrinking growing space and time due to less effective insolation.

Scholarly discussion of both the Medieval Warming Epoch and the Little Ice Age seems concentrated among paleoclimatologists; yet they often refer to the effects on the economy sometimes citing contemporaneous accounts. Jean Grove provides a survey in The Little Ice Age (Grove, 2003). Hubert Lamb is often cited as an early researcher.[3]

A related story that fits the data and the history is that this era was one of a negative energy supply shock due to deforestation and growth in the whole economic system thus slowed. This

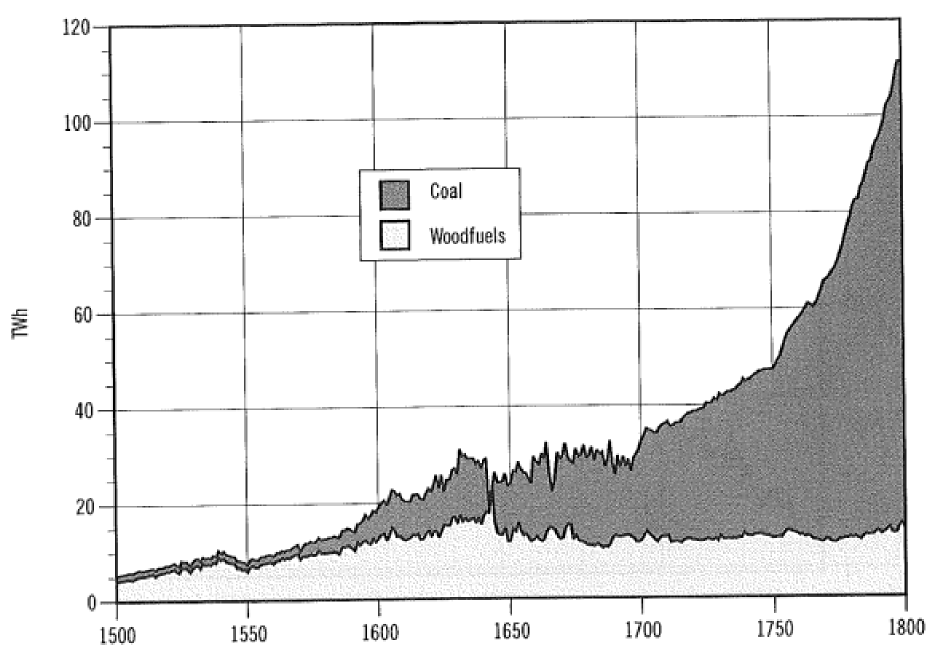
[3]See for example (Lamb, 1980). Lamb describes failed grain harvests in Scotland and the disappearance of the cod schools in the Atlantic. These examples are typical though not the focus in the climatology literature. They do provide a plausible economic explanation for the stagnation in GDP and the lagged stagnation in population growth.

era was the transition between primarily wood–supplied energy to primarily coal–supplied energy for both industrial and home heating needs. As London grew because of internal growth, exports, and world trade domination wood became scarcer and more expensive driving demand for coal for heating from the north east. You can see this pattern during the 1600 to 1750 era three in the following figure 10.

Figure 10: Coal and wood energy sources

Source: Pearson & Fouquet

Figure 4: Energy consumption by final users (terawatt hours (TWh)), 1500–1800



Note: The consumption of candles is not visible in this graph: even by 1800, it was only equivalent to 0.5TWh, while in 1500 it was only 0.1TWh. As a percentage share, it is just visible between 1500 and 1700, with its maximum value being around 4% of energy used (see Figure 10).

Notably this is also the era Nef calls the "first energy crisis" (Nef, 1977). According to Nef during the period 1550 to 1700 increased heating and building demand for wood and reduced woodlands due to agricultural demands caused wood prices to rise dramatically.

We can hypothesize that this series of events provided the economic pressure to cause the first phase of the energy revolution—the transition from wood to coal for heating needs.

A further potential explanation appeals to political events mainly the large number of wars during the period. The contemporary anecdotes were that war was economically stimulative (Thirsk, 1978).

As research for this paper progressed reviews of further work by Jan de Vries showed he refuted any climatic explanation. In discussing the 1600 to 1750 era de Vries indeed says the climate evidence is not consistent with population evidence; the current work shows that population lags GDP and GDP was plausibly affected by climate change suggesting a more consistent data set. Separately note that energy/GDP era three has the same year boundaries as de Vries (de Vries, 1976). De Vries also has an extensive empirical look at Dutch temperatures and various measures of agricultural output. In the end he comes to few conclusions except that time–series data are essential (de Vries, 1980).

This demand for heating coal arising from the first energy crisis and the fortuitous geology of the English coal mines created the path necessary to support energy/GDP era four when the second phase of EIR accelerated into modern economic growth via a virtuous mutually reinforcing growth cycle between GDP and energy consumption.

The geology story is that the coal mines were water–infused and as they were mined deeper more water had to be pumped out. This provided an economically feasible site for the seminal but very inefficient Newcomen steam engines to pump the water. The coal was essentially free to power the engines. Human or horse power were too expensive. And as the steam engines gained efficiency they began to be applied to the products of industrial capitalism. That is the story of energy/GDP era four that becomes the age of steam.

A list of inventions that depended on and drove demand for steam power is impressive. Here is a broad list of Industrial Revolution–era inventions from many sources including Joel Mokyr (1992). See Table 5. Many though not all of these inventions are steam–driven. Some such as Arkwright's water spinning frame were originally water-powered; these inventions switched to steam power as that technology matured. Others such as the sewing machine were eventually converted to electricity a dominant power source of what some call the second industrial revolution. Electricity is still largely produced by steam "engines" (generators).

Of course John Hobson (Hobson, 2004) would claim Asiatic origins for many of these inventions; thus the puzzle of "why not China?" remains or perhaps the question arises why did the Chinese not commercialize the labor-saving inventions they were at least on the path to develop? To answer this it is useful to compose a narrative of China's failed industrial revolution next then begin work on a theory of industrial revolutions.

Table 5: Industrial Revolution inventions (partial list)

Year	Inventor/invention
1712	Thomas Newcomen patents the atmospheric steam engine
1733	John Kay invents the flying shuttle
1764	James Hargreaves invents the spinning jenny
1768	Richard Arkwright patents the spinning frame
1769	James Watt invents an improved steam engine
1775	Jacques Perrier invents a steamship
1779	Samuel Crompton invents the spinning mule
1783	Benjamin Hanks patents the self-winding clock
	Englishmen, Henry Cort invents the steel roller for steel production
1784	Andrew Meikle invents the threshing machine
1785	Edmund Cartwright invents the power loom
1786	John Fitch invents a steamboat
1794	Eli Whitney patents the cotton gin
	Welshmen, Philip Vaughan invents ball bearings
1797	Wittemore patents a carding machine
	A British inventor, Henry Maudslay invents the first metal or precision lathe
1799	Alessandro Volta invents the battery
	Louis Robert invents the Fourdrinier Machine for sheet paper making
1800	Frenchmen, J.M. Jacquard invents the Jacquard Loom
	Count Alessandro Volta invents the battery
1804	Richard Trevithick, an English mining engineer, developed the first steam-powered locomotive
1809	Humphry Davy invents the first electric light – the first arc lamp
1814	George Stephenson designs the first steam locomotive
	Joseph Nicéphore Niépce was the first person to take a photograph
1825	William Sturgeon invented the electromagnet
1829	American, W.A. Burt invents a typewriter
1830	Frenchmen, Barthelemy Thimonnier invents a sewing machine
1831	American, Cyrus McCormick invents the first commercially successful reaper
	Michael Faraday invents a electric dynamo
1834	Henry Blair patents a corn planter, he is the second black person to receive a U.S. patent
	Jacob Perkins invents an early refrigerator type device – an ether ice machine
1835	Englishmen, Henry Talbot invents calotype photography
	Englishmen, Francis Pettit Smith invents the propeller
	Charles Babbage invents a mechanical calculator
1836	Francis Pettit Smith and John Ericcson co-invent the propeller
	Samuel Colt invented the first revolver
1837	Samuel Morse invents the telegraph

Table 6: Early modern English monarchs

Monarch	Reign	House
Henry VIII	1509-1547	Tudor
Edward VI	1547-1553	Tudor
Mary I	1553-1558	Tudor
Elizabeth I	1558-1603	Tudor
James I	1603-1625	Stuart
Charles I	1625-1649	Stuart
Oliver Cromwell	1653-1658	Commonwealth
Richard Cromwell	1658-1659	Commonwealth
Charles II	1660-1685	Stuart
James II	1685-1688	Stuart
Mary II	1689-1694	Stuart
William III	1689-1702	Stuart
Anne	1702-1707	Stuart

3 Chinese comparative data and institutions

It is time to focus on those key facts about China and its paradoxical failure to participate in the growth miracle emerging from the English Industrial Revolution. Recalling our group of fifteenth century conference–goers we remember the claim that they would have bet the ranch on China having the first industrial revolution while most had never heard of England. In this sense this story could be tagged as “The empire that did not bark” in the spirit of Arthur Conan Doyle (Bentley, 1941).

As it turns out the cleverest among them knew that China had already had an industrial revolution; more precisely they knew that they had a partial industrial revolution—identified as a first phase revolution—and being good growth economists knew that it positioned China for the second phase. These terms are defined later. For now note first that the data for China are not nearly as rich as for England but after a preamble to set the comparative context between China and England let us examine the Chinese data.

3.1 Preamble to Chinese growth

Given that recent scholarship suggests that eighteenth–century per–capita incomes in England and similar parts of China were roughly comparable and had both grown somewhat since the sixteenth century (Pomeranz, 2001) why did English output then accelerate into the first continually sustained period of per–capita growth ever experienced—modern economic growth—and Chinese output relatively stagnate?

Since China is a highly integrated society sharing world population dominance with India by all the known rules explaining economic dynamics up to that time as summarized by the Reverend Thomas Malthus (1973) it should have dominated the world economy. And it did. From Angus Maddison’s data (Angus Maddison 2007) China and India had roughly 50 percent of both world population and gross domestic product (GDP) at the beginning of the sixteenth century while England accounted for 1 percent of population and 1 percent of GDP. Yet England's growth so dominated the eighteenth and nineteenth century that in 1900 England's share of world GDP was 9 percent while her population was only 3 percent of the world total. China and India's combined share of GDP in 1900 had fallen to 20 percent while their combined population was still 44 percent of the world total.

Many scholars search for and discern some combination of social, cultural, and institutional factors to explain the phenomenon of the Industrial Revolution. Yet the magnitude of the post eighteenth-century growth trajectory differences imply a level of English exceptionalism in those factors that begins to strain credulity. Are we to believe that over a very few generations English "growth enabling" institutions somehow grew sufficiently superior to Chinese institutions to account for the growth differences? This class of explanation is even more problematic in that it at least implicitly assumes that some one or some group understood what institutions were needed for this sui generis event and had the powers to form them.

A further mystery is the "Needham question" that arises from the fact, as Joseph Needham (Needham, 1954) documented in the eight volumes of Science and Civilisation in China, that China had great scientific and technological discoveries but lost the "race" to both the Scientific and Industrial Revolutions. Needham seems to support the idea of functionally sufficient Chinese institutions of the very kind needed to supply the inventions required to participate in the revolutions. A later scholar John Hobson (Hobson, 2004) explicitly makes this claim.

In the long sweep of history England had a relatively brief period of per–capita growth dominance. By no later than 1875 the growth revolution was quickly spreading to North Western Europe, North America, and Meiji Japan. If England's lead in growth was uniquely determined by a specific set of exceptional institutions is there evidence that such usually long–gestation changes in culture, institutions, and society itself were so quickly transmitted to other cultures?

And if transmitted institutional exceptionalism accounts for the rapid spread of growth why was it transmitted relatively narrowly until the second–half of the twentieth century? Why didn't China immediately converge? Is the relevant effect in fact that societies and their institutions oppose fundamental economic changes that in turn cause societal changes until the economic forces becoming overwhelming? Was China "not barking" because there was nothing to bark at because the dog saw nothing but the long familiar non–threatening agrarian empire? This explanation is certainly consistent with a story of China not enjoying English–style exceptionalism. Or is it rather a story that there were no Chinese economic forces that at the macroeconomic level would have driven Chinese entrepreneurs to English style energy innovation. For English exceptionalism claims see Max Weber (Weber, 2002), David Landes (Landes, 1969, 1999), and Deirdre McCloskey (McCloskey, 2007, 2010).

This paper explores the counter–question: what underlying *economic* reasons might account for this remarkable series of events and non-events? Above it is argued that what England discovered and transmitted to the world was an energy revolution in economic activity. Why did China fail to follow that revolutionary path until the twentieth century? Do basic *economic* explanations provide a more satisfactory story for this "great divergence?"

A related question is one of primary or ultimate causality rather than monocausality. Institutionalists claim that superior institutions were the primary cause of the Industrial Revolution. One can show evidence and claim that superior economic dynamics were the primary cause while fully acknowledging the proximate supporting and surrounding institutional and cultural fabric as a necessary condition.

3.2 A first look at data and institutions

In this section the Chinese data in a global context and the institutional background is reviewed.

3.2.1 Sources and methods

The Chinese data is not nearly as rich as the English data; nonetheless Angus Maddison (Maddison, 2007), Vaclav Smil (Smil, 1994, 2008), J. W. de Zeeuw (J. W. de Zeeuw, 1978), Robert Hartwell (Hartwell, 1962, 1966, 1967, 1982), and the U. S. Energy Information Administration (Administration) provide interesting clues.

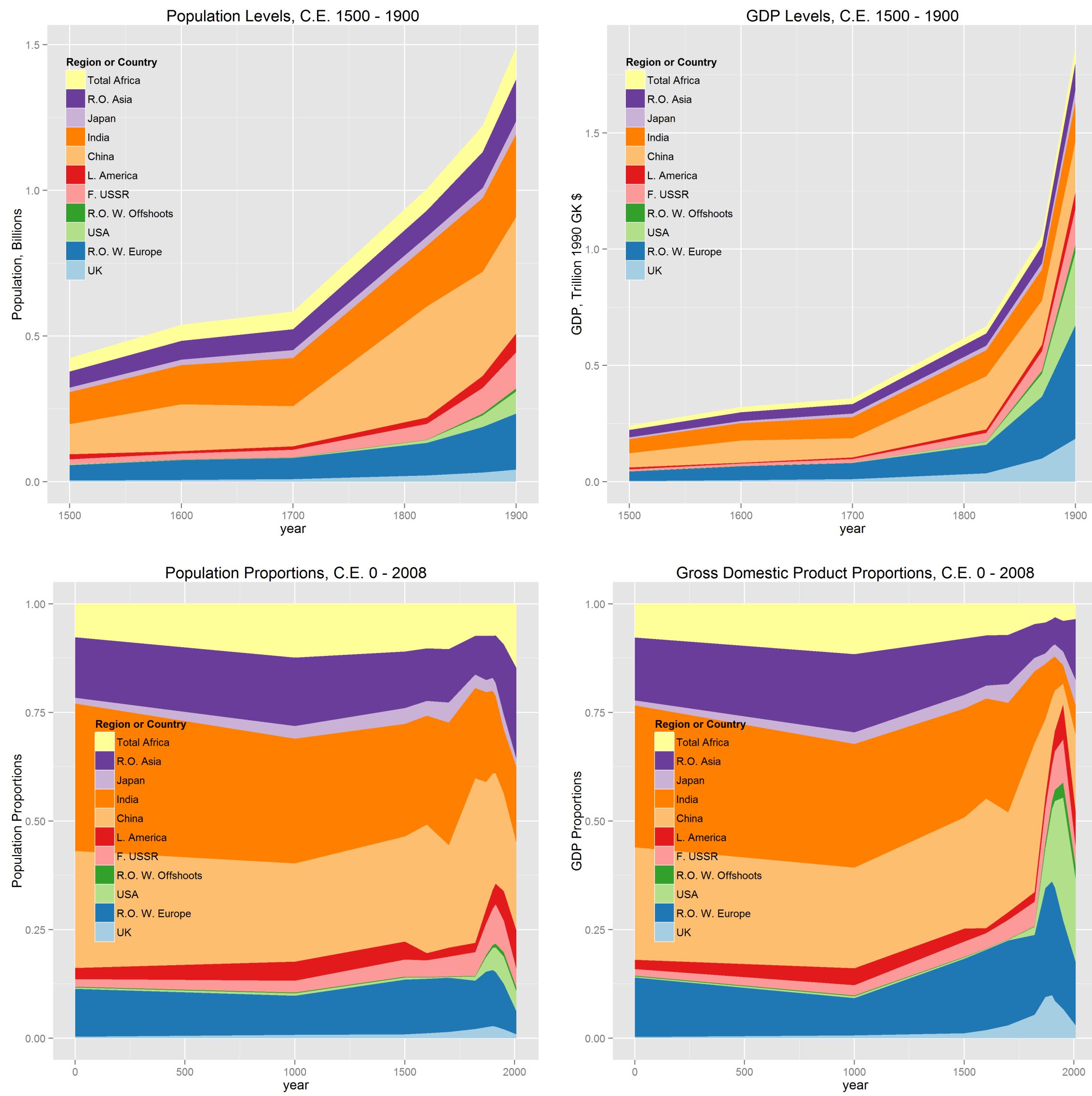
Again for context, to support the thinking of our fifteenth century conference attendees, and to understand the scale of the divergence we can begin by examining world population, gross domestic product, and the resultant per–capita GDP through the current historical period covering the crucial pre–industrial and Industrial Revolution periods while showing the current levels for context. The initial data is from (Maddison, 2007). Maddison measures GDP in 1990 International Geary-Khamis Dollars that describe purchasing power parity (PPP) adjusted output. Maddison's data set whatever its challenges is widely cited and is where many comparative scholars start. This study also starts with it.

3.2.2 Regional population and GDP dynamics

The top two panels in Figure 11 show that both world population and GDP levels for years 1500 through 1900 CE underwent unprecedented growth; the bottom two proportion panels demonstrate that much of the growth was in Europe and the western offshoots. It is clear that China and India dominated both world population and GDP until about 1700. These are the data that our conference group would have been relying on. However when world GDP started a period of super–exponential growth the proportion charts show that Western Europe and the United States dominated GDP growth and had population growth above the world rate.

The pattern of faster population growth rate in both Chinese and English proto-industrial periods remains an open demographic question (Pomeranz, 2001, p. 22) though on this chart the English

Figure 11: Population and GDP levels from 1500 to 1900; population and GDP proportions from 0 to 2008. *Source:* Data from (Maddison, 2007), graphs by author.



growth is hard to see. [4]

To abstract from that next examine per–capita GDP growth. Figure 12 shows per–capita GDP by regional and national groupings of interest from 1 through 1900 CE, using the underlying Maddison

[4] One theory (Alfred Crosby (Crosby, 1972) and others) asserts that the post–"Columbian Exchange" arrival in Europe and China of American crops like maize and potatoes increase agricultural productivity per land unit by 3 or 4 times, enabling a rise in otherwise Malthusian constrained subsistence population levels.

(Maddison, 2007). Two facts stand out. First, China maintains a relatively constant level of per–capita GDP throughout the period. The Chinese did not become absolutely poorer; however China did not share in the great average output growth of the Western nations. Second, the grouping denoted the EU-11, [5] led by England is increasing in per–capita GDP starting in 1500 with rapid increases after 1800. The Western Offshoots show a similar growth pattern of per–capita GDP. The sustained productivity growth arising during the Industrial Revolution led to sustained standard-of-living increases. This sui generis episode of modern economic growth stands in stark contrast to China and the rest of the world. [6]

The lack of a growth pattern in Chinese per–capita GDP leads to a fascinating question: How much is our perception of this fact coloured by our twenty-first century point-of-view? More formally what would our expectations for the rate of growth of per–capita GDP have been as an astute economic observer in eighteenth–century China? Or, for that matter in England?

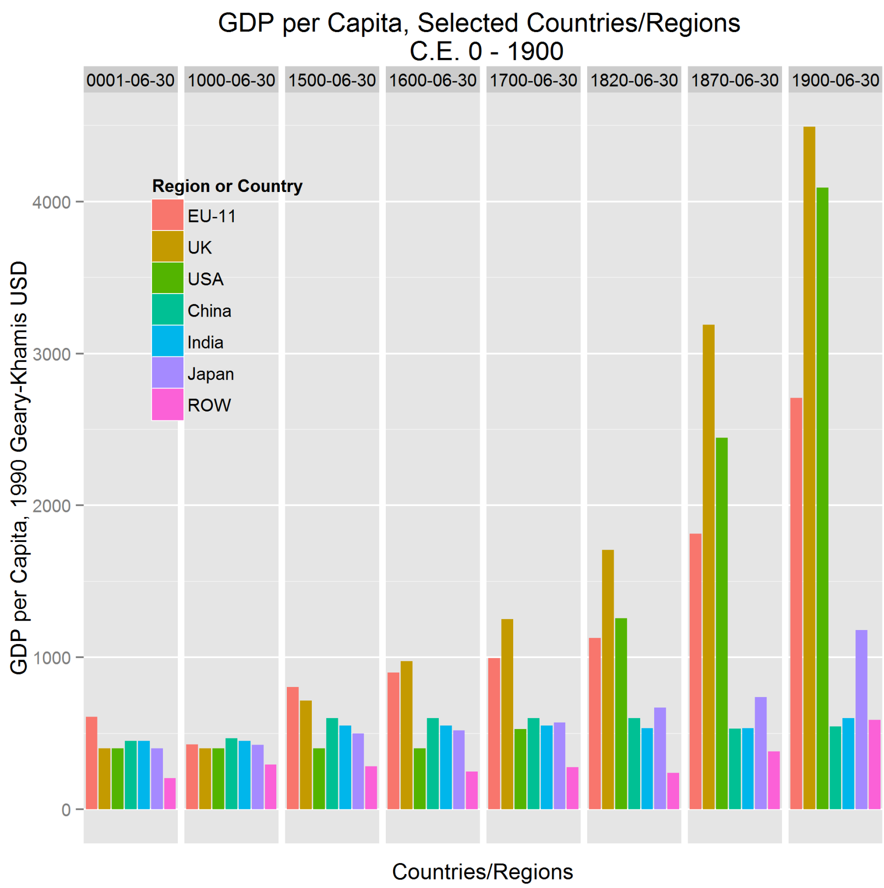
The evidence is that the classical economists had no expectations for any prolonged positive growth in GDP per–capita because they had never observed that phenomenon. Thomas Malthus clearly represents the then widespread point-of-view that expectations were for subsistence GDP meaning essentially zero–growth per–capita levels forever. Thus our fascination with what actually happened and our dramatically different modern expectations.

The next several charts illuminate these dramatic changes. Figures 13, 14, and 15 trace the evolution of global population shares from CE 1500 through 1900 grouped by major regions. We see China undergoing a population explosion and collapse between 1500 and 1900 CE with a peak share of 37% of world population in 1820. England is on a steady growth march starting at 1 percent share in 1500 and ending at 3 percent in 1900. We can discern the proto–industrial population

[5] The EU-11 grouping includes Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Sweden, and Switzerland.

[6] The Western Offshoots are statistically dominated by the United States but also include Canada, Australia, and New Zealand.

Figure 12: Comparative World Per–Capita GDP. *Source:* Data from (Maddison, 2007), graphs by author.



growth in both economies prior to 1820 and only England continues growth after that that.

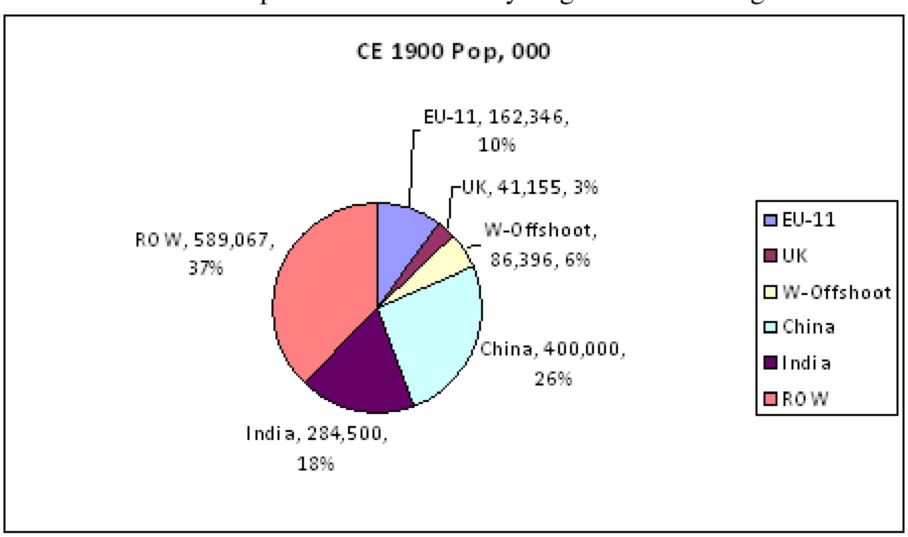


Figure 13: World population shares, 1500 CE

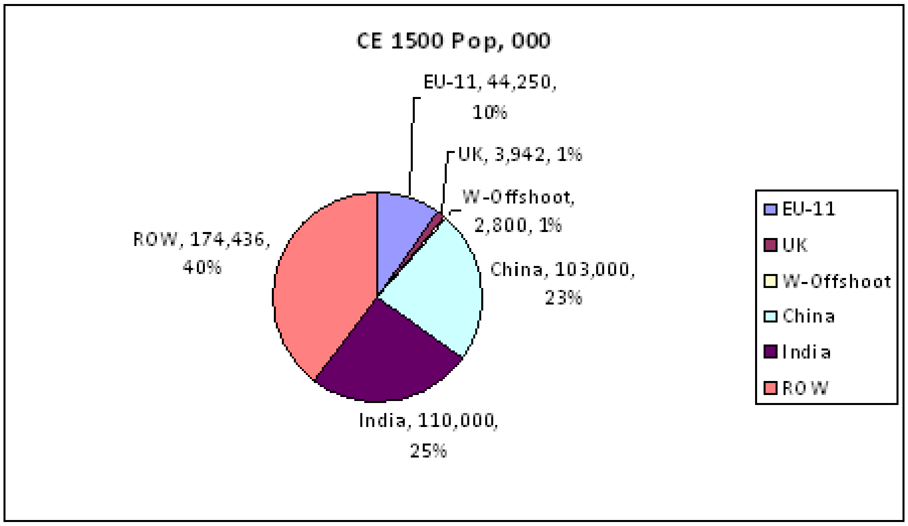


Figure 14: World population shares, 1820 CE

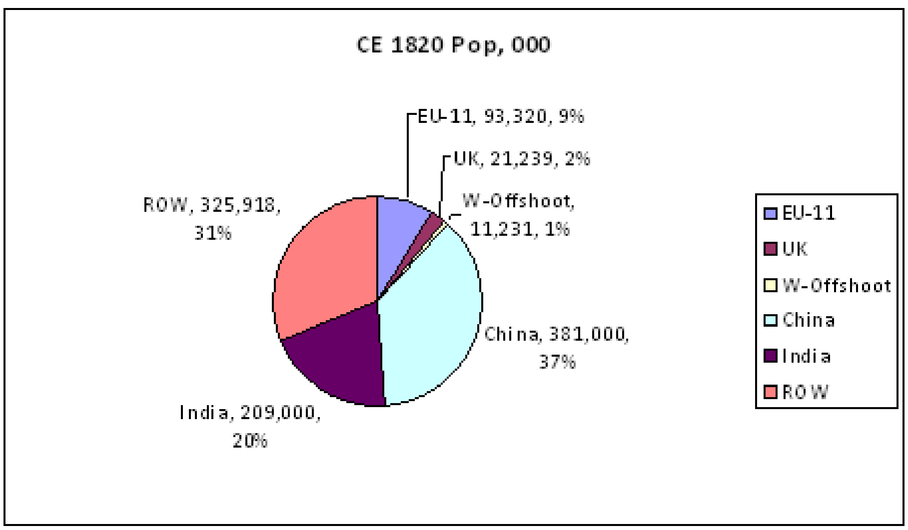


Figure 15: World population shares, 1900 CE

Figures 16, 17, and 18 trace the path of global GDP shares from 1500 through 1900 CE grouped by major regions. We see China's gobal GDP share staying roughly in line with its populations share so peaking in 1820 at the end of the world proto–industrial era.

England's GDP share has grown dramatically from the 1 percent proportional to its population

Figure 16: World GDP shares, 1500 CE

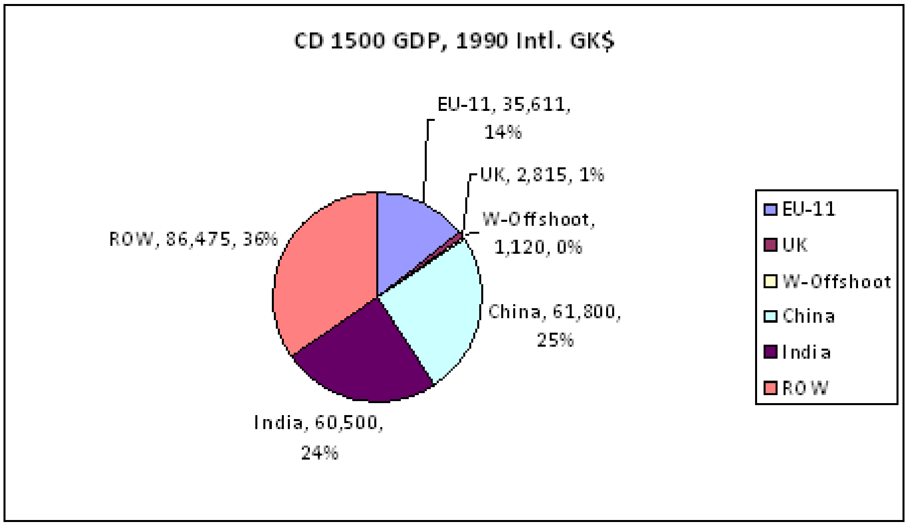
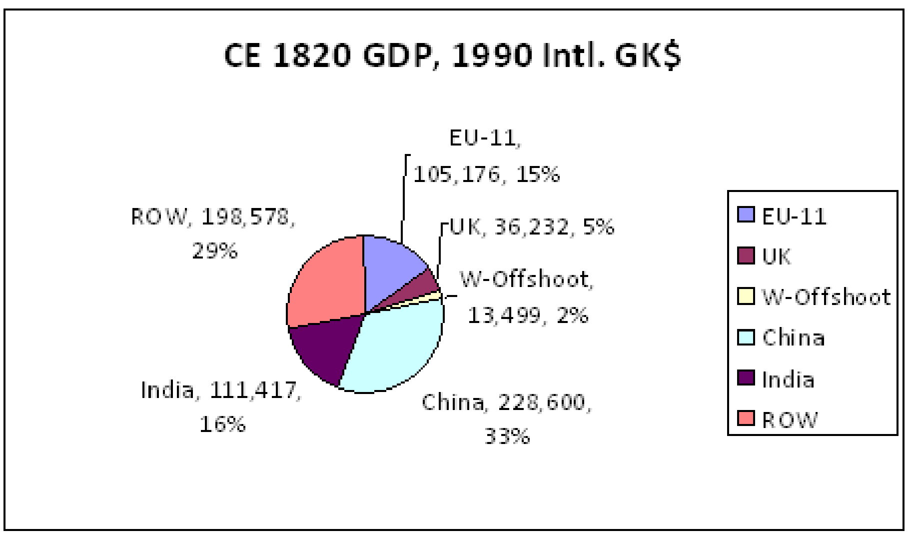


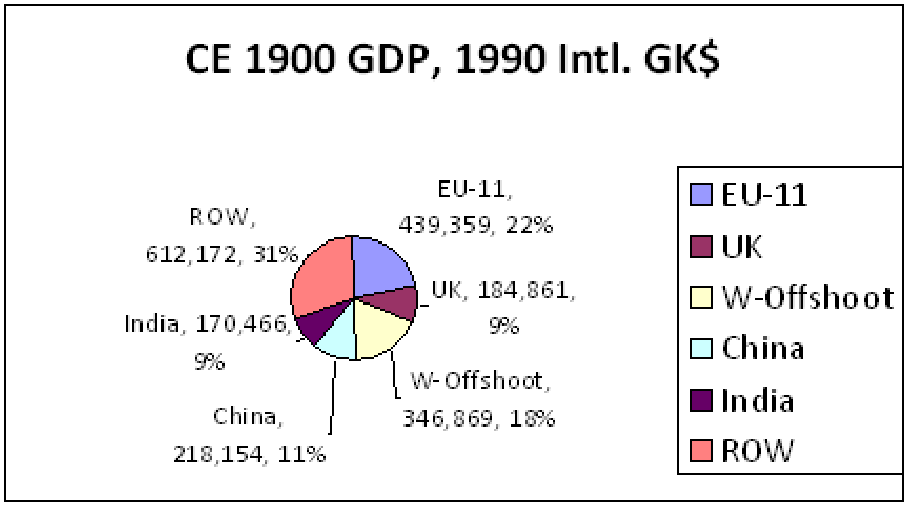
Figure 17: World GDP shares, 1820 CE



share in 1500 to 2.5 times population share in 1820 to 3 times population share in 1900.

These charts represent highly aggregated data and thus potentially mask important underlying structural and regional differences especially in China. Kenneth Pomeranz for example asserts that the standard of living in regions of China was equivalent to Western Europe in 1800 (differently than the Maddison data that however is for all of China) and that the standard–of–living adjusted wage

Figure 18: World GDP shares, 1900 CE



levels in the Lower Yangzi region in China were at English levels in 1800 (Pomeranz, 2001, 107). Decomposing the standard of living into wages and cost-of-subsistence softens those differences except in the Lower Yangzi but in any case we need to explain the post–1820 divergence.

Two main explanatory threads wrestle or perhaps dance with each other: One thread appeals to institutional differences the other to economic and geographic differences exploited by inventor/entrepreneurs. The essential factor to decode is the *prime* mover recognizing that there are interaction effects over time that are surely important.

The study proceeds by questioning the institutional argument that the prime mover in the Industrial Revolution was English institutional exceptionalism and sets up the economic/geographical prime mover hypothesis; this suggests analyzing the growth divergence between China and England as an exercise in comparative micro– and macroeconomics. But first we should examine the political economies to establish that there exists essential (functional) institutional sufficiency for growth in each country.

3.2.3 Comparative institutions

The logic for underweighting English institutional exceptionalism as the primary factor explaining the EIR is that whatever the institutional differences between China and England there were sufficient functional similarities to yield similar economic results up until 1800 at least in the most comparable Chinese region the Lower Yangzi. It is thus difficult to imagine sufficient institutional differences to cause such a dramatic divergence over the next century. This logic uses the work of R. Bin Wong and Kenneth Pomeranz.

First a comparison of political economies in post–1500 late Imperial China and early modern Europe from R. Bin Wong:

> "The Chinese state maintained an active interest in the agrarian economy, promoting is expansion over large stretches of territory and its stability through uneven harvest seasons. . . Despite considerable variation in techniques, there was basic agreement through the eighteenth century about the type of economy officials sought to stabilize and expand. They supported an agrarian economy in which commerce had an important role" (Wong, 1997, p.115–116).

> "Mercantilism, the dominant philosophy of political economy in Europe between the late sixteenth and the early eighteenth century, posed a close relationship between power and wealth. For a state to become powerful, society had to become wealthier. This was achieved by expanding economic production in rich core areas and by extending trade across the country and especially beyond it. . . competition for wealth on a global scale became a component of European state making. European states promoted the production and commerce of their private entrepreneurs, whose successes contributed to the consolidation and prosperity of competing states" (Wong, 1997, p.140).

Wong thus contrasts a Chinese imperial agrarian state interested in social stability with a group of European power elites competing over a zero-sum economic game with military Mercantilism. Yet until the eighteenth–century divergence roughly the same level of subsistence was the norm.

Moving to Kenneth Pomeranz who evaluates Chinese and English and wider Asian and Western European economic levels at more granular scales involving agriculture, transport, and livestock capital, longevity, health and nutrition, birthrates, accumulation, and technology.

> "...as late as the mid-eighteenth century, western Europe was not uniquely productive or economically efficient...many other parts of the Old World were just as prosperous and "proto-industrial" or "proto-capitalist" as western Europe...What seems likely is that no part of the world was necessarily headed for such a [industrial] breakthrough."
>
> "...the production of food, fiber, fuel, and building supplies all competed for increasingly scarce land...western Europe...became a fortunate freak only when unexpected and significant discontinuities in the late eighteenth and especially nineteenth centuries enabled it to break through the fundamental constraints of energy use and resource availability that had previously limited *everyone's* horizons...the new energy itself came largely from a surge in the extraction and use of English coal..." (Pomeranz, 2001, p. 206–207).

Pomeranz's detailed comparative evaluation thus somewhat contradicts Maddison's data and highlights both institutional differences and similarities but the differences are irrelevant in the end simply because England uniquely led the organic–to–fossil energy transition that was the revolutionary foundation for and the prime–mover at the center of the Industrial Revolution. Next turn to the economic incentives that England had and China did not to make that transition.

4 Toward a theory of industrial revolutions

We have already examined the GDP and energy consumption data for the fourth era. To complete the story we can now appeal to economic theory. First, we summarize the eras using macroeconomic theory illustrated in aggregate demand—aggregate supply charts; second, we examine the transition for industrial and domestic heating from wood–to–coal that unleashed a highly scalable source of heat energy; third, we address the question of what caused the English inventor/entrepreneur to spend the time and money to create the inventions of the first and second phases of the EIR particularly the steam engine that enabled the transition from muscle–power to steam–power using coal as the energy input. To do this we can appeal to standard microeconomic theory.

Figures 19 and 20 display the four eras in an aggregate demand—aggregate supply (AD—AS) framework. The dotted lines indicate prior locations of AD—AS; solid lines indicate the ending locations. Lines colored red indicate the constraint in each era. These are obviously abstract depictions of the history told above. This is done for two reasons; first to solidify and emphasize the history so that the debate can proceed; second to provide a framework for later projects incorporating the institutional and cultural events into the history. If we can agree on the AD—AS by era then we can hypothesize about those events that might have caused the location or shape to change and then test those ideas in an econometric framework.

A notable observation is that energy/GDP era four is the first when aggregate supply was not the constraint; according to the Granger causality tests (see Table 4) supply and demand were jointly constraining in that era. Statistically only GDP Granger–causing energy consumption is significant at normal levels but the removal of barriers for consuming energy was likely the uniquely defining event of the era.

Secondly for the theoretical discussion of the EIR it is important to consider at the microeconomic level what can explain the event. Microeconomics is relevant and important to help answer

Figure 19: Aggregate Supply—Aggregate Demand
Four energy/GDP regimes

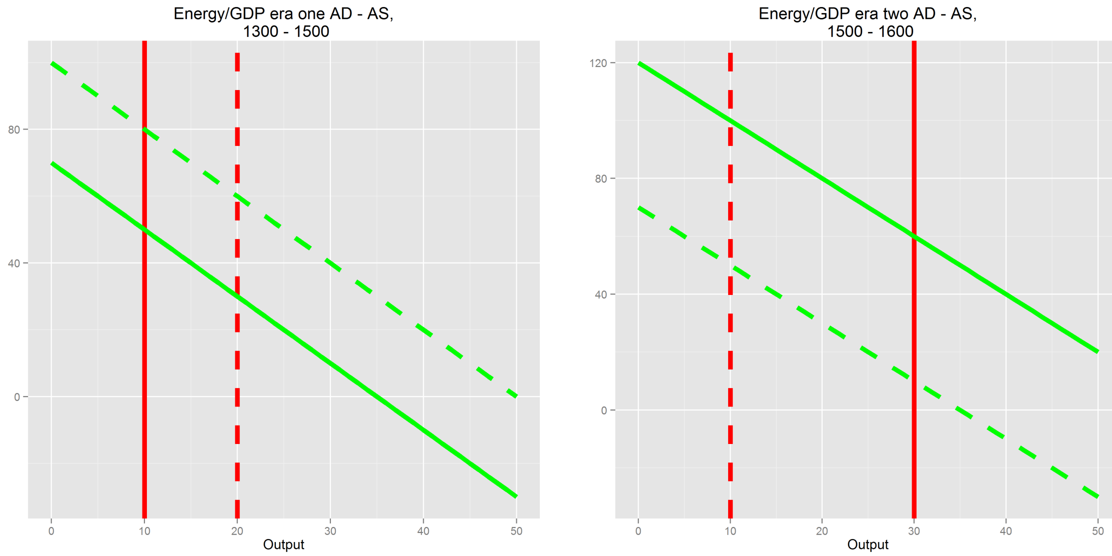
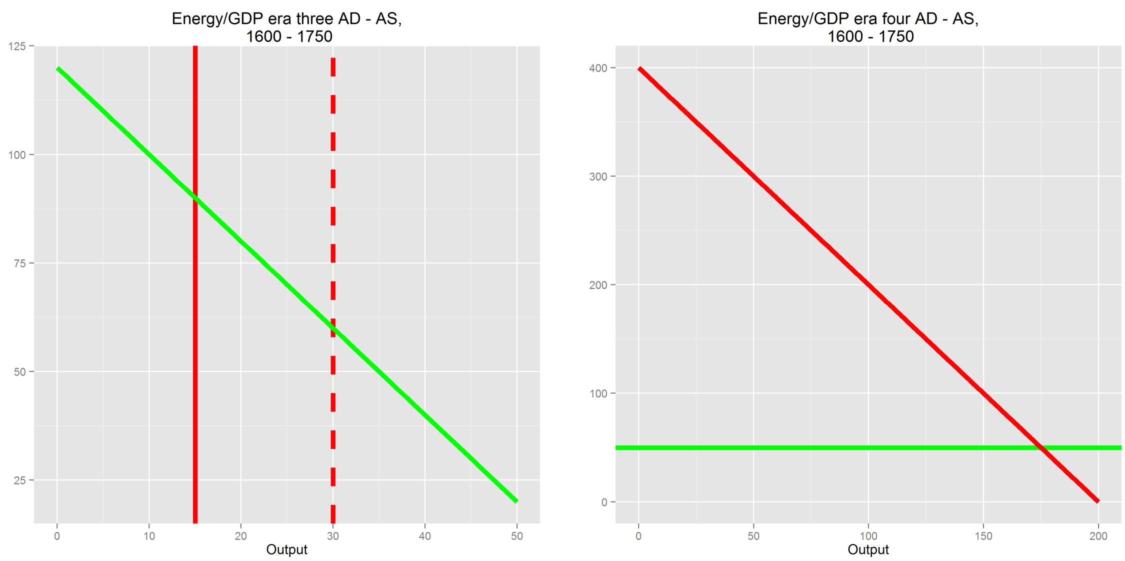


Figure 20: Aggregate Supply—Aggregate Demand
continued



this question as at the end of the economic day people have to have individual incentives to innovate and commercialize no matter what the macroeconomic pressures and/or institutional influences are. This paper mainly discusses the supply–side of the story having already suggested a story of important demand–side factors in Section 2.2.2. So the question becomes what were the incentives or motivations of the English inventors and entrepreneurs during energy/GDP eras two and three that is from 1500 through 1750.

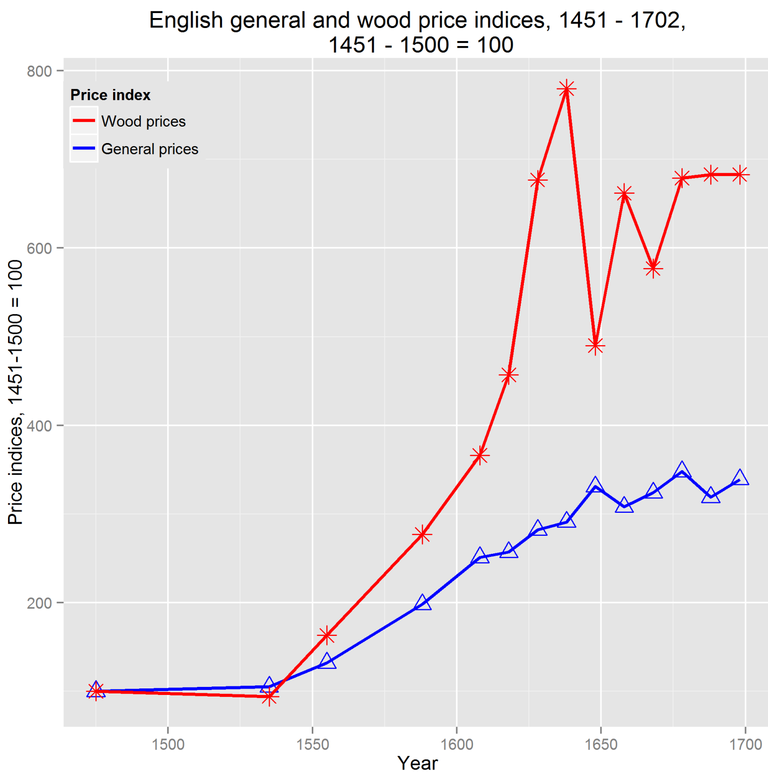
For this analysis we rely on several sources: John Nef's monumental work documenting the rise of the English coal industry; the contemporaneous comments of a key participant in the EIR; the excellent work of Robert Allen; and an appeal to microeconomic theory.

The microeconomic story of the EIR turns out to be two stories so in effect two energy revolutions. The first revolution or better for comparative work a first–phase industrial revolution tells the story of the essential transition from wood–to–coal for domestic and industrial heating applications. Essential because as important in its own right as it is to continue to scale heat production in the face of rising population and therefore rising aggregate demand the first transition lays the foundation of building a coal extraction, transportation, and distribution infrastructure that is essential for supporting the ever more energy–hungry second–phase industrial revolution. The second–phase's signature development replaces muscle–power with steam–power that largely coal–fueled.

The phase–one revolution lasted through most of the first three AD—AS eras (see Table 4) until about 1700. To see this transition's time boundaries refer to Figure 10 and note the take–off in coal consumption levels after 1700.

Can we appeal to basic microeconomics to help understand this revolution? This is possible with John Nef's help. Examine the data taken from Nef (Nef, 1932) and shown in Figure 21. Note that starting about 1540 English wood prices rose by almost a factor of eight by 1700. This results both from rising aggregate demand and deforestation. Importantly even compared to general price inflation wood prices increased by twice the change in the general price level. During the same period, coal prices were declining at least until 1600 and in northern England remained much lower still. See Figure 25.

Figure 21: English wood and general price indices *Source:* (Nef, 1932, pp. 158,221)



With the price spread between coal and wood used for such an essential economic input as energy-for-heating moving dramatically in coal's favor the basic economic mechanism of input–price substitution should work. It does explain the transition. To formalize this we can write:

$$\frac{\text{Marginal Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Marginal Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}, \tag{4.1}$$

or if one prefers a non-neoclassical writing:

$$\frac{\text{Average Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Average Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}. \tag{4.2}$$

Either writing leads to the same theoretical conclusion: assuming no qualitative difference in the two inputs in terms of work being done (a Joule is a Joule) with the data showing the right–hand–side coal ratio being significantly greater than the wood ratio we would expect entrepreneurs to substitute away from wood to coal. And this is exactly what happened (see Figure 10).

This was not an easy transition. Coal was dirtier—perhaps even nastier—than coal and this required new technologies both industrially (for example in iron making) and domestically. But it was a powerful enough economic incentive that the inventors did what they do best—invent.

Some sense of the difficulties that the inventors eventually overcame is related by Robert Allen. Allen argues the following logic chain: Coal was plentiful and cheap in both northwest and northeast England. As London grew rapidly due to English success in international trade London experienced high wages that spread throughout England and faced increasing heating prices due to local deforestation. Thus beginning in the sixteenth century the "coal–burning house" (new room and chimney designs were required as well as new stove designs) that was invented in London led English coal demand and production to increase (Allen, 2009b, p. 82). This invention took more than a century to replace wood–burning stoves but the economic incentives were eventually sufficient. See Figure 10.

Moving to the phase–two industrial revolution of replacing muscle–power with steam–power can basic microeconomics help explain this revolution as well? Again the claim is yes. Here we ask Desaguliers, Robert Allen, and theory for assistance.

Jean (or John) Theophilus Desaguliers had a large influence on the EIR. He was an eighteenth century English "natural philosopher" (physicist), a member of the Royal Society, colleague of Sir Isaac Newton, and author of A Course of Experimental Philosophy. This was an influential 1734 two–volume engineering text that contained a chapter on "Fire-Engines" (steam engines). In this chapter Jean Theophilus describes the economic and scalability motives of replacing men and horses with coal-fired steam engines to pump water out of Newcastle mines. Profit was on his mind (Desaguliers, 1734, Vol.II, pp. 467–468). The age of the industrial capitalism fueled by fossil energy was dawning.

Figure 22 shows a page of his manuscript.

Beyond the quaintness of the 1734 English prose this man demonstrated the soul of a profit–maximizing capitalist. In that context let us examine some data that drove Desaguliers.

Figure 23 is from Robert Allen and shows the ratios of real wages to energy costs (the cheapest source by location) by benchmark city around 1700.

Figure 22: Desaguliers manuscript

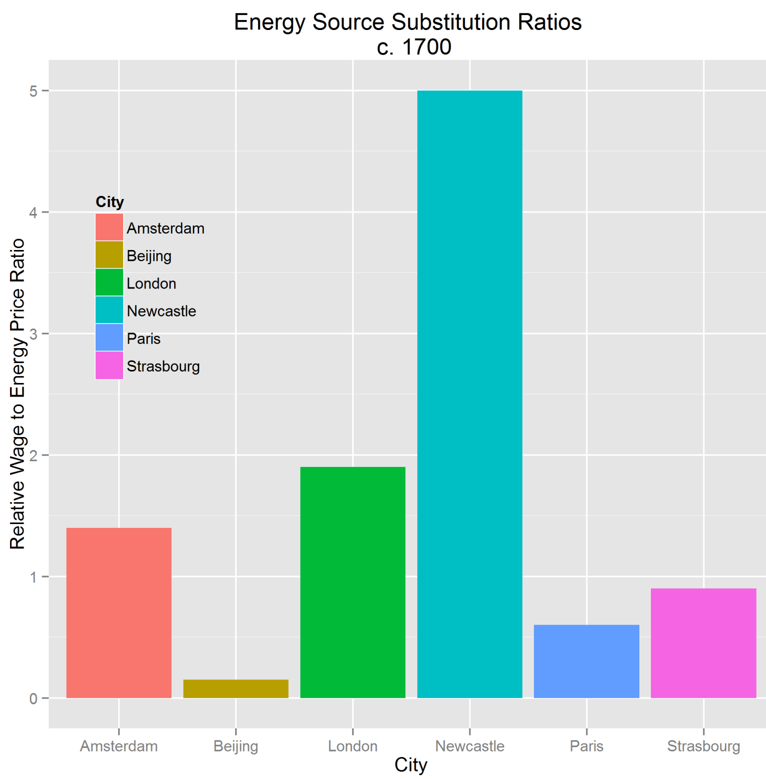
rection P *p*, and a Quantity of Water propor-
be lifted up, and run out at P. This may be done 15 or 16 times in a Minute, becauſe each Man would pull down but 30 Pounds at a time, after the manner that People ring Bells. But as no Time is to be loſt, leſt the Mine be overflow'd by the Springs below, there muſt be 100 more Men to relieve theſe when they are weary. Now as it muſt be a rich Mine indeed whoſe Profit can afford to keep 200 Men at this Work; that

Ooo 2

Lect. XII. Plate 36.

that Thought muſt be laid aſide. We'll conſider therefore what can be done by Horſes. As an Horſe is equal to five Men, we muſt work 20 Horſes at a time to raiſe the Water requir'd; and as Horſes muſt be reliev'd even more than Men, about 50 Horſes muſt be kept to carry on this Work conſtantly, and bring down the End of the Beam *b*, 16 times in a Minute, and make the number of Strokes requir'd in the Pump, the Weight of whoſe Rod after every Stroke will bring down the End *b* 2, by drawing along the Tangent *i* H. It is plain to any body, that tho' the Horſes may be had cheaper than Men, yet that will be a very expenſive way. For the next Contrivance, we'll ſuppoſe a Philoſopher to come, and find a means to bring down the End of the Beam, without Men or Horſes, in this manner. To the Chain H L he fixes a Piſton L C to go into a Braſs Cylinder L C *d n*, about eight or nine

Figure 23: Real wage–to–energy price ratios
Source: Robert Allen (Allen, 2009b)



Clearly Newcastle in 1700 had high wages and very low energy costs exhibiting by far the largest ratio in the sample. Those are the economic fundamentals that faced Desaguliers and motivated his profit comment. London had the second largest ratio and thus the strong economic incentives existed there as well. Beijing had the lowest ratio and that is a topic investigated later.

Intuitively if this wage–to–energy cost ratio is high enough as it was in England entrepreneurs and inventors will have a large incentive to develop the steam technologies to enable the revolution. Refer to Table 5 for a list of the inventions that were converted to steam–power, were originally developed for steam–power, or used steam–power to convert steam–power to a different transmission medium—electricity.

While the economics of these ratios may be intuitive why not appeal to microeconomic theory to help us understand what motivated Desaguliers, Newcomen, Watt and other founding fathers of the EIR. Equation 4.3 is a variation on production theory that will be familiar to those who remember their Econ 101. A major topic of mainstream production theory is how entrepreneurs maximize profits given the derived demand curves of the various input choices.

$$\frac{\text{Average Product}_{\text{labor Joule}}}{\text{Price}_{\text{labor Joule}}} \ll \frac{\text{Average Product}_{\text{steam Joule}}}{\text{Price}_{\text{steam Joule}}} \tag{4.3}$$

Instead of using different substitutable inputs such as labor and capital we apply the theory to the different sources of energy since that is essentially the only non–substitutable input as in you must have Joules from whatever source to do any economic transformation. If we take the numerators in Equation 4.3 to be equal abstracting again from the difficulties in invention that were eventually solved then because of the much lower price of English coal–Joules than wages for labor–Joules the relentless (in the face of rising wages) pressure will be for the inventors to invent and the entrepreneurs to commercialize steam–power thus creating the machine age and completing the EIR.

These equations need additional terms to cover the amortization of whatever research and development and capital equipment is necessary to apply either kind of Joule but clearly from just what is written we see that when wage–to–coal–energy cost ratios are sufficiently high entrepreneur/inventors will be motivated to substitute coal–Joules for human–Joules. And that is what happened at the micro level to drive the EIR first in Newcastle atop the mines, then in the English textile mills, then in other English industries, then in transportation, and later spreading to the world.

What of China? China is our natural experiment; as it turns out China experienced a phase–one industrial revolution—from wood to coal—in the tenth and eleventh century Sung dynasty. We will complete that story in the next paper of this dissertation. For now we can look to later dynasties—the Ming and the Qing— to see why assuming the Chinese had completed phase–one of a revolution they did not complete phase–two and thus confounding our conference attendees.

As we have seen Robert Allen proposes a relatively simple factor substitution argument that relies on differences in relative labor and energy prices between China and England most dramatically between Newcastle and the rest of the world. Refer to Figure 23. Essential to his argument is that England almost uniquely was a high–wage and low–energy–cost economy (Allen, 2009b, p. 34).

We can use his supporting data to understand from microeconomic theory what did not happen in China. Refer to figure 24 and note how low Chinese wages were compared to England in the pivotal 1700 time frame.

He also examines world energy prices; we have already noted England had the lowest energy prices in the world. This led to a high English wages–to–energy prices ratio that fuelled the energy transition so notably compared to China (Allen, 2009b, p. 140). The basis for this argument can be seen in the Figure 25. Note that these prices reflect the cheapest energy source usually either wood or coal.

Referring back to the Allen ratios in Figure 23 note that the relative price ratio of wages–to–energy prices was highest in Newcastle and lowest in Beijing. Thus there was a strong economic

Figure 24: World wages, 1375–1825 CE. *Source:* Allen (2009)

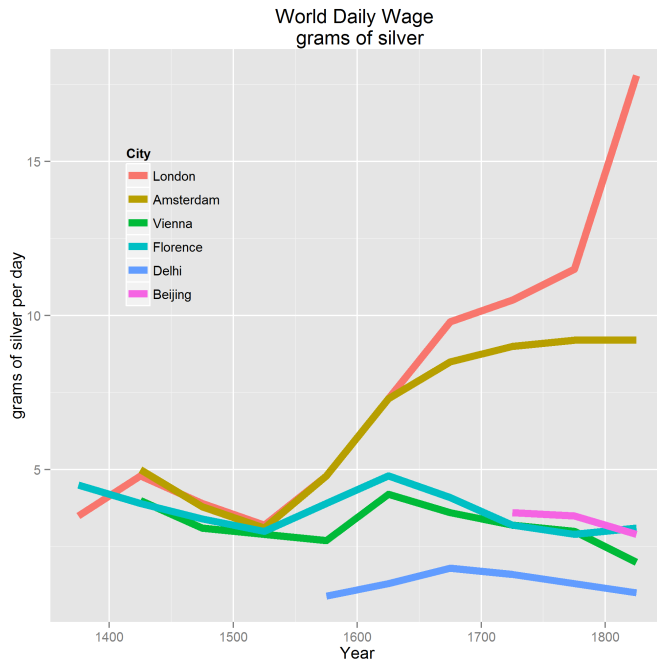
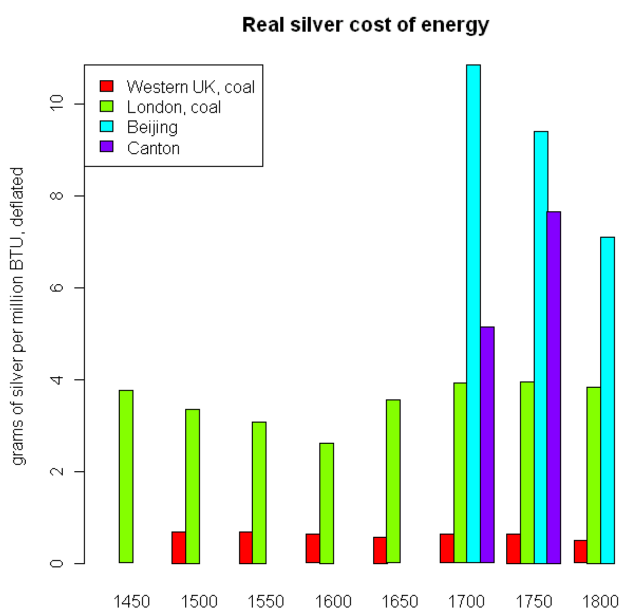


Figure 25: Comparative world energy prices, 1450–1800 CE. *Source:* (Allen, 2009b)



incentive among inventors and entrepreneurs to substitute coal–power for muscle–power in Newcastle and almost none in Beijing. With little economic incentive for Chinese inventors to invent (though we have seen they were capable of doing so) the technologies needed for an industrial revolution and certainly no wage–energy cost ratio pressure to commercialize the relevant inventions the Chinese did not complete a phase–two industrial revolution. Muscle–power was simply too cheap.

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