ECONOMIC DEVELOPMENT WITH UNLIMITED SUPPLIES OF ENERGY: CAUSES AND CONSEQUENCES OF INDUSTRIAL REVOLUTIONS

by

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ABSTRACT

This dissertation contains two related chapters and an introduction. The common themes they explore are the unresolved questions surrounding the English Industrial Revolution (EIR). The questions include what happened, why did "it" happen first in England, why did it happen then in history, and what are the consequences? The story is a history of economic growth from a specific point of view—energy consumption for an economy; the framework can be used to illuminate our economic present and possible economic futures.

Economic and other historians have been grappling with these puzzles for a long time; their answers fall along a continuum from New Institutional Economics (some mix of institutions and perhaps culture) to almost pure chance. Institutional explanations are at least a plurality; this work makes the case that these explanations are not sufficient in the sense of not being primarily causal or sufficiently explanatory in the EIR's history. The work further explores that at least the major institutional changes are endogenous to the revolutionary economic changes.

The major claim is that the EIR was primarily an energy consumption revolution, the English having had the correct economic incentives and historical path to learn how to use steam power to replace muscle power. The contribution is the attempt to apply economic principles to the data and history and measure their explanatory power.

The work identifies two energy revolutions explaining the EIR. The first, converting from wood to coal for industrial and domestic heating purposes, probably happened several times in history at other places in addition to England. In addition to this first–phase energy revolution in England, Chapter 2 documents an added noteworthy instance, that of the iron and steel industry in Sung China (960–1126 CE). The second revolution, converting from muscle power to steam power, happened first in England before engulfing the world.

To support the claims the work employs several methods including empirical analyses, microeconomic theory, macroeconomic theory, and descriptive narratives from many sources. The general method is to apply basic economic principles to the available data and narratives.

Among the insights, the work proposes a hypothesis of industrial revolutions that can be tested beyond the cases included in this work. This work uses basic microeconomics, macroeconomics, and relevant empirical data (as the data permit) to test the cases of China and England.

To support the revolutionary growth on the supply side, the work makes the case that there was sufficient consumer demand to drive the efforts of the entrepreneurs and inventors.

Once the theoretical framework for industrial revolutions is explored, then the work turns to the question of how did these momentous economic events affect the growth of industrial capitalism since it is one of the more important institutions that is associated with the EIR.

For Dr. Stephen Reynolds

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I have been greatly influenced by the work of Peter Temin; his careful application of basic economic principles to any history with even a few scraps of available data has been an inspiration.

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CHAPTER 1

GENERAL INTRODUCTION

This introductory chapter outlines and connects the two primary chapters in this dissertation.

Chapter 2 covers the main hypotheses and evidence that are central to the dissertation's claims: the English Industrial Revolution, whatever else it was in terms of changed societies and institutions, was primarily an energy revolution in the strong sense that without the energy revolution, there could not be an industrial revolution leading to modern economic growth.

Further, this energy revolution was in fact two separate but related energy revolutions. The first—wood to coal—provided scale for domestic and industrial heating needs not provided by the prior main source—wood. Deforestation as populations grew depleted that source. The infrastructure required for this first revolution—capital investments—enabled the energy inputs required for the second revolution—muscle–power to steam–power. This second phase industrial revolution eventually led to the unprecedented continual rise in living standards, the era of modern economic growth.

And using basic economic principles can provide a clear picture of the incentives that inventors and entrepreneurs faced that pulled them into the revolutions.

Using Sung China as a natural experiment to test these hypotheses shows that the incentives and outcomes are more general than the English experiment, but that England had unique price differences that caused it to succeed.

Chapter 3 then explores the institutional implications of these revolutions. It focuses on what is, arguably, the most important institution arising from the English Industrial Revolution—industrial capitalism.

As in Chapter 2, Sung China is used to test the hypothesis that we can use basic economic principles to argue that the tendency toward industrial capitalism is more general than the English experience given the right economic conditions.

1.1 Chapter 2 – "Energy and institutions: What really happened in the English Industrial Revolution? What did not happen in China?"

This chapter is the core of the project to understand the link between economic growth and energy. By analysing two very long series—English gross domestic product and English energy consumption—with statistical tests, the chapter demonstrates that there is essentially no difference between these series. The original methodological strategy was to perform a cointegration analysis to test this hypothesis. However, presented with the graphical evidence and very high correlation coefficient, it was judged unnecessary to present those results in this chapter.

This evidence suggests that at least a plurality of economic and other historians who attribute the English Industrial Revolution (EIR) to one or more aspects of culture or institutions might additionally consider this very physical energy–growth channel as an important cause. The institutional and cultural changes were certainly large, but the chapter questions if they would have happened without the great surge in output, incomes, and wealth that can only be explained by learning to consume a virtually unconstrained amount of energy in the production process. So that is the chapter's major claim; the chapter then explores both macroeconomic and microeconomic theories to support the case.

After developing the English data and descriptive history, the chapter then suggests that after accounting for a background of increasing aggregate demand, it is useful to apply basic microeconomic principles to explain what would cause inventors, innovators, and entrepreneurs to invest in overcoming the great technical difficulties required to remove the supply–side constraint on growth in living standards before the EIR.

This same framework is then applied to the case of Sung China that experienced a period of economic growth, including living standards, that is remarkable in history. Some historians go so far as to call this episode an industrial revolution. The chapter develops partial support for that position.

Section 2.1 of Chapter 2 starting on page 6 is structured as a literature review and has several sections. The first section reviews the data and descriptive sources used to analyze English energy and macroeconomic performance over the period 1300 to 1873 common era (CE). Included are some who place the energy story very high in the list of possible explanations of the EIR. W. Fred Cottrell in particular takes a very thermodynamic–economic approach in his discussion of the transition to “high–intensity energy converters” from “low–intensity energy converters” as the primary mechanism causing the EIR. Kenneth Pomeranz believes it is English geographical luck that accounts for a large part of the causation of the EIR. Robert Allen takes a similar approach.

The second introductory section reviews the institutional literature. This is the major alternative explanation to the more physical explanations from the sources discussed in section one. The sources include Douglass North, David Landes, Jack Goldstone, Max Weber, and Daron Acemoglu.

The third introductory section reviews the literature on Chinese energy data focusing on the period of significant economic growth that occurred during the Sung dynasty. The sources include Robert Hartwell, William McNeil, Mark Elvin, and Robert Allen.

The fourth introductory section reviews Chinese institutions. This discussion is mainly about the Ming dynasty although Robert Hartwell discusses Sung dynasty institutions. The sources include Kenneth Pomeranz, R. Bin Wong, and Peer Vries.

The fifth introductory section reviews the literature of Chinese science and invention. This becomes important when attempting to understand some arguments that China had an insufficient tradition of invention and innovation to develop the technologies required to produce an industrial revolution. These sources claim China had a very rich tradition of innovation and invention probably sufficient to accomplish an industrial revolution. The authors include Joseph Needham and John Hobson.

The sixth introductory section reviews economic growth theory. The sources include Roy Harrod, Evsey Domar, Robert Solow, Trevor Swan, Paul Romer, and Robert Ayers.

Section 2.2 develops and analyzes English data, econometrics, and economics. The topics covered include discussions of the sources and methods for the data, an analysis of modern economic growth, a discussion of energy revolutions, formal econometric analyses, and the economic analyses.

In this section, the chapter applies structural change econometric methods to the data series and deduces four energy–gross domestic product (GDP) eras covering the historical period. Each has different aggregate demand and supply characteristics. Table 1.1 is a brief summary of each.

The important conclusion is that until 1750 with brief exceptions, economic growth for

Table 1.1: Energy/GDP eras

Era	AD/AS regime
1300 – 1500	European Marriage Pattern, Black Death, wages/family income increasing
1500 – 1600	Positive demand shock, high wages
1600 – 1750	Energy supply constraint
1750 – 1873	Positive supply shock, large income effect, “virtuous” macro feedback cycle

a growing population was largely constrained by a lack of energy supplies. The structural change analysis show that this constraint started lifting in about 1600 and then accelerated in the mid–eighteenth century. Using these data, the chapter claims that the energy revolution that became the EIR started 150 years earlier than the common starting point many historians claim. The story is consistent with a Malthusian story of temporary growth spurts in population that were eventually constrained by supply (in this story energy supply). Chapter 2 discusses the Malthusian constraint and its removal.

Section 2.3 on page 36 develops and analyzes Chinese data and institutions. The topics include discussions of the sources and methods for the data, a discussion of regional and global population and gross domestic product dynamics, and a discussion comparing Chinese and English institutions.

Section 2.4 on page 46 develops the beginnings of a theoretical framework of industrial revolutions.

Section 2.5 on page 54 concludes.

1.2 Chapter 3 — “The rise of industrial capitalism. What happens next?”

Chapter 3 analyzes the rise of industrial capitalism and its links with industrial revolutions. This is done both for England and China. England is normally thought of as the birthplace of industrial capitalism; the chapter attempts to identify traces of embryonic capitalism in the Chinese economic history starting with the Sung dynasty (960–1126 CE). If there are common institutional elements that can be linked to industrial revolutions, then it will improve our understanding of how both industrial revolutions and industrial capitalism happen.

The introduction for Chapter 3 is structured as a literature review. Topics include some definitions and then reviews of the sources for the English transition to industrial capitalism, and sources for discussion of a Chinese transition to industrial capitalism.

Section 3.3 on page 64 discusses the rise of English industrial capitalism. Topics include a discussion of the data including sources and methods, an analysis of global population trends, a discussion of Jan de Vries' survey of early modern capitalism to help understand common approaches to explaining the event, a review of industrial revolutions, and how they give rise to demand for the large capital investments of support the two English energy revolutions that were fundamental to the EIR. The section closes with a discussion of the two primary roles that capital played in the EIR.

Section 3.4 on page 79 discusses evidence for shoots of (embryonic) Chinese industrial capitalism including data and a discussion of the three eras for which we have evidence—the Sung, Ming, and Qing dynasties.

Section 3.5 on page 85 concludes.

CHAPTER 2

ENERGY AND INSTITUTIONS: WHAT *REALLY* HAPPENED IN THE ENGLISH INDUSTRIAL REVOLUTION? WHAT DID NOT HAPPEN IN CHINA?

2.1 Introduction

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. If validated, this will be applicable to current and future macroeconomies from a development standpoint.

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. This will also bear on the realistic chances of curbing ecologically damaging mineral (fossil) energy consumption for ecological economists and others interested in that critical topic.

2.1.1 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 [29] 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 [34] 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 [56] frets that England will lose its economic dominance when the coal supply runs out as perhaps an early version of today's "peak oil" concerns. Later, Edwin Eckel [32] 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 [102, 103, 104, 106, 105], presaging Herman Daly and Nicholas Georgescu-Roegen.

In John Nef's two-volume history of the coal industry in Britain [81], 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 [69] 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 [20] 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 [19, 16, 17, 18] 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 [77].

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" [27, 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 [124, 125] writes extensively about England's transformation from an "advanced organic" society mainly engaged in agriculture to an "industrial inorganic society" engaged primarily in nonagricultural 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 chapter calls an energy revolution, Italian economic historian Paolo Malanima [67] 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 chapter. 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 [74] focuses on explaining the "great divergence" between China and England starting around 1800 [90, 91]. 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 [100] that Pomeranz invokes along with armed mercantilism as instrumental to the England's successful industrialization. However, 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 [7] 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 chapter explores; he summarizes his view strikingly: "... there was only one route to the twentieth century – and it traversed northern Britain" [7, 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 [20], Robert Allen [7], E. A. Wrigley [124, 125], and Vaclav Smil [98, 99], 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 [41] 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 nonsubstitutable 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 [38, 39, 40] advances a modern treatment of this energy-based thermodynamic work, including its impact on long–range climate forecasts.

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

We first must include Max Weber [118, 119] 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 [84, 83] 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 [63, 64] 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 [72, 73] 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 historian who emphasizes 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 [43, 44, 45] on the West's cultural primacy allowing its comparative rise. In particular [44], 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 [3], growth theory [2], and institutions as causing growth [1]). 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 chapter, 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 [70] and Thorstein Veblen [113] 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 chapter.

2.1.3 Chinese energy data

Now we turn 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 [50, 51, 52, 53]. Mark Elvin [33], William McNeill [74], Fredrick Mote [78], and Eric Jones [57, 58] 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 [111] provides a survey that places the historical China work in context and empasizes the importance of Hartwell's contribution.

Robert Allen [7] provides comparative wage and energy cost data for China that enter prominently in my hypotheses. While Chinese data are 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.

2.1.4 Chinese institutions

Kenneth Pomeranz [90] 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 are: 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" [90, 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 meant 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" [90, 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 [88] for support and Peter Perdue [87] and Ricardo Duchesne [30, 31] 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 [122] provides a broad institutional comparison between China and England and comes to the same conclusion: functionally unremarkable institutional differences.

Peer Vries [114] 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 [92] 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 [7] 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 [5, 9, 6] 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.

2.1.5 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 [80] 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 [54] 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 [54, 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 [54, 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.

2.1.6 Growth theory

Concluding this introduction is a brief review of the major economic growth theories. While not the focus of this work, clearly there was no need for growth theory before 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 [49] 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—a higher level of capital stock produces more output.

The next significant growth model is Solow-Swan, named for Robert Solow [107] 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, meaning that changes to the state of model are caused by factors external to the model.

Paul Romer [95] 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 that actually wants units of energy as inputs. 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 specifically incorporate energy inputs. Perhaps the most provocative for mainstream models is the work of Robert Ayers [117, 12]. Ayers specifies a production function using solely an energy input and fits the model to U.S. GDP data between 1900 and 1998. The model residuals vary depending on the time frame from about zero to 12 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 chapter investigates using energy inputs as the primary way of modeling the English Industrial Revolution and for other comparisons.

2.2 English data, econometrics, and economics

2.2.1 A first look at the data

This section describes the three data series numerically and graphically.

2.2.1.1 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 chapter, that England's reign as the premier industrialized economy starts to decline.

Table 2.1 describes the sources for the data series.

Roger Fouquet provides an invaluable time series of English energy consumption and related data. Fouquet's book [35] and papers with Peter Pearson [37] 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.

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 [35] and they include formal modeling, interpolation, extrapolation, and assumptions. His energy sources include

Table 2.1: 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)

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 [101]. 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 [112] 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 [94].

For GDP estimates from 1700 through 1873, the study uses data from Lawrence Officer [85].

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 [101]. From 1541 to 1801, the series uses data from B. R. Mitchell [76]. After 1801, the series uses a Mitchell [76] 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 2.1 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

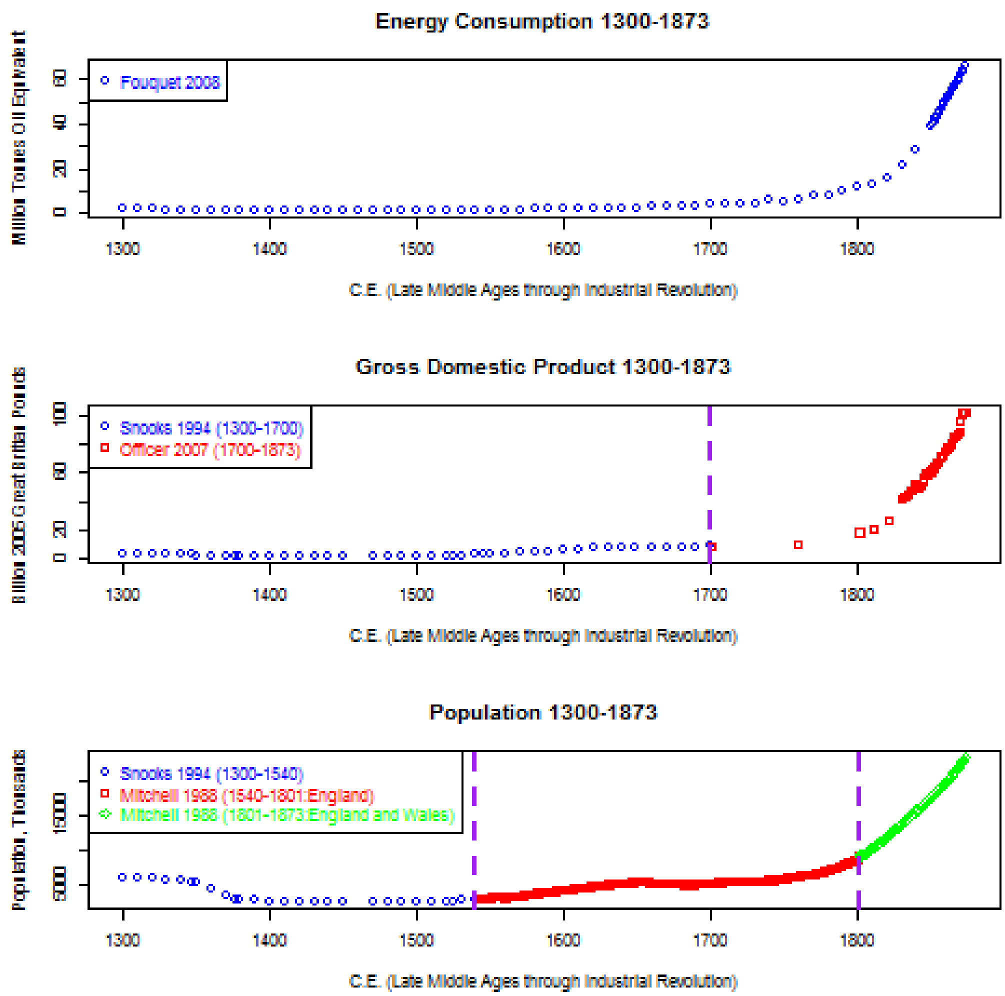


Figure 2.1: Author/time-span series of energy consumption, GDP, and population

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.

2.2.1.2 Modern economic growth

Simon Kuznets defined modern economic growth as sustained and high rates of growth of per–capita product and population [60]. Figures 2.2 and 2.3 indicate that England experienced high rates of growth of per-capita product in (possibly) two eras from 1500

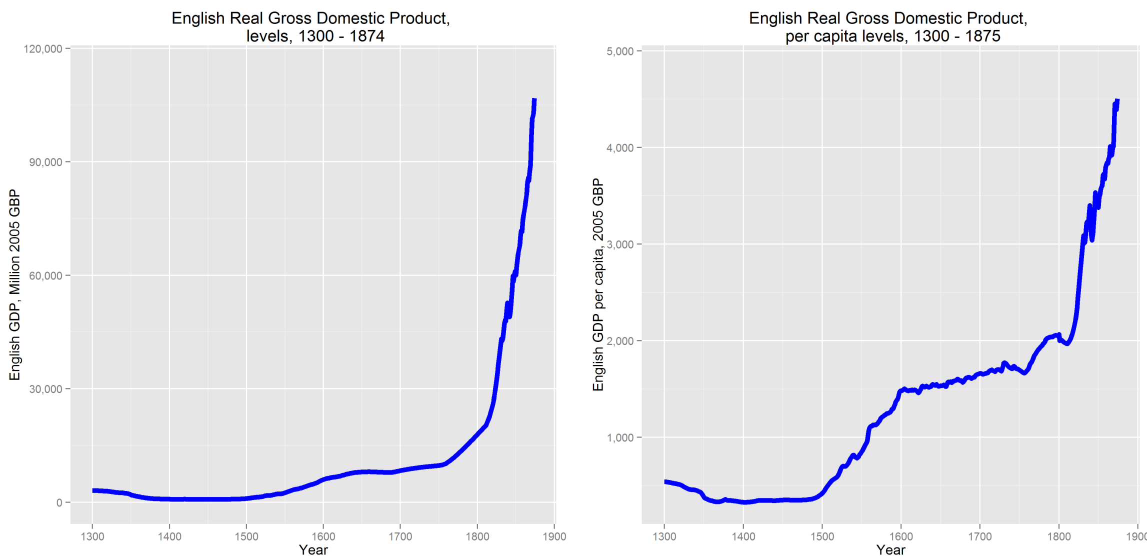


Figure 2.2: English real gross domestic product,
levels and per–capita, 1300–1875

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 2.2. Figure 2.4 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 2.3, note the interesting 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 30 percent due to higher mortality (famine) and lower fertility rates. See Jean Grove [47] and Geoffrey Parker [86] in a masterful historical account of the "long" seventeenth century.

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. Further comments on the population rise after 1500 are in the population discussion.

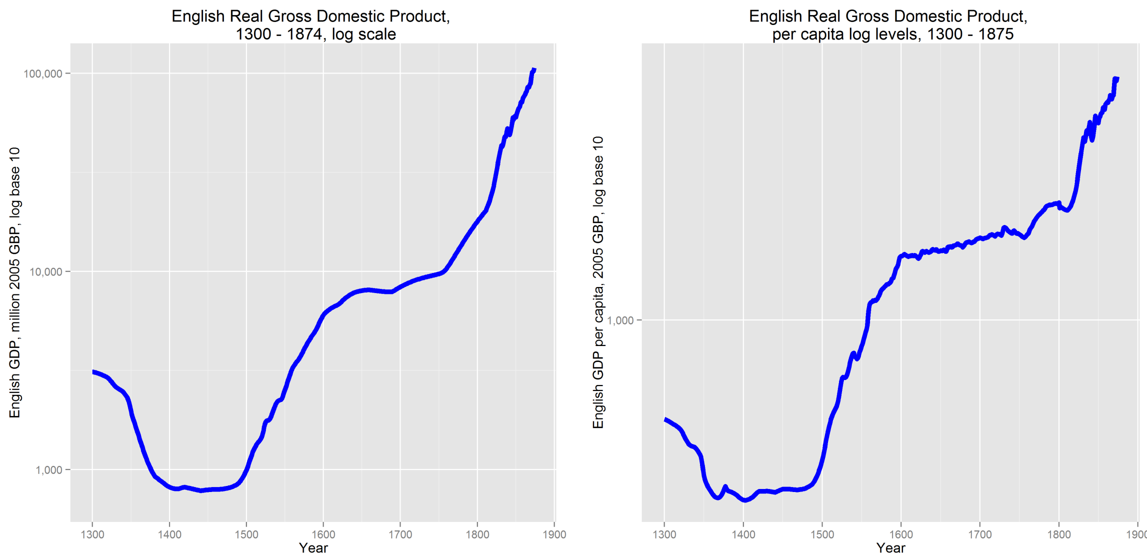


Figure 2.3: English real gross domestic product,
log levels and log per–capita, 1300–1875

To see the magnitude of the growth rates by century and compounded annually, refer to Table 2.2. 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. But we must not discount the importance of the dramatic increases in energy inputs as the fundamental part of this story.

Turning to the population data, Figure 2.4 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

Table 2.2: 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

interpretations described next.

2.2.1.3 An energy revolution

This chapter'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 understand the support for that hypothesis, first review the data:

Figure 2.5 presents the log transformation of energy consumption over the study period; the vertical lines are formally determined structural breaks.[1,2] 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

[1] The structural breaks use an F-test methodology on the time series as implemented in the *R* package strucchange [127].

[2] The structural break technique fits sliding window models and compares them using an F-test. It reports the breaks it finds in order of statistical significance. This chapter reports the three most significant breaks in structural analysis charts. For these reasons, in some cases, as in this figure, minimum points are not flagged as structural breaks.

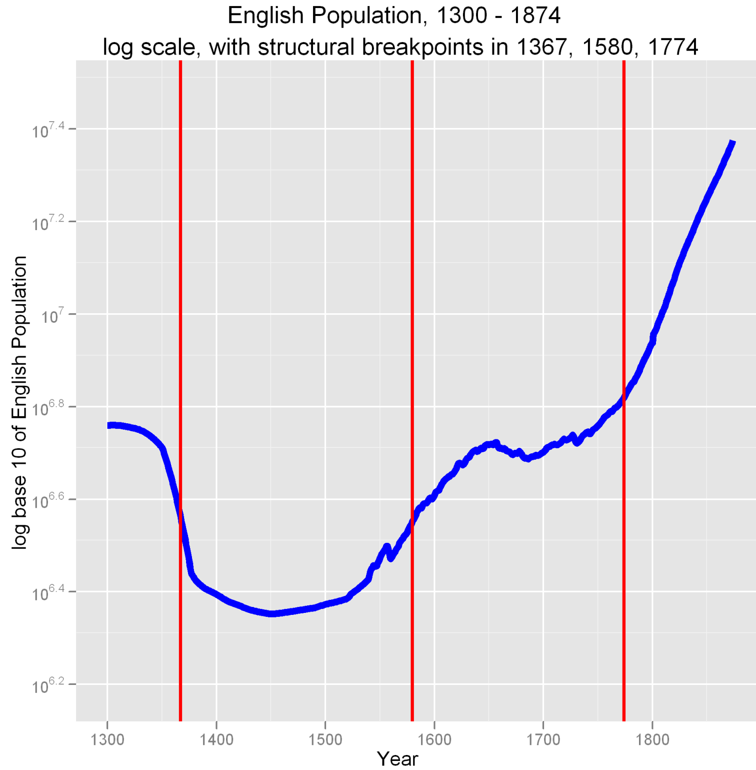


Figure 2.4: Log of population, with structural breaks

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; this rate of change similarity is confirmed by the presentation in Table 2.2. The final period is from 1750 through 1873; clearly the energy consumption rate-of-change accelerates as confirmed by the structural breaks in Figure 2.5 and Table 2.2.

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[3] and one starting after 1750. Under this hypothesis, the first revolution would have set the stage for the second. The second revolution required energy infrastructure built for the first.

[3]This validates John U. Nef's hypothesis of an early start to the British Industrial Revolution [81].

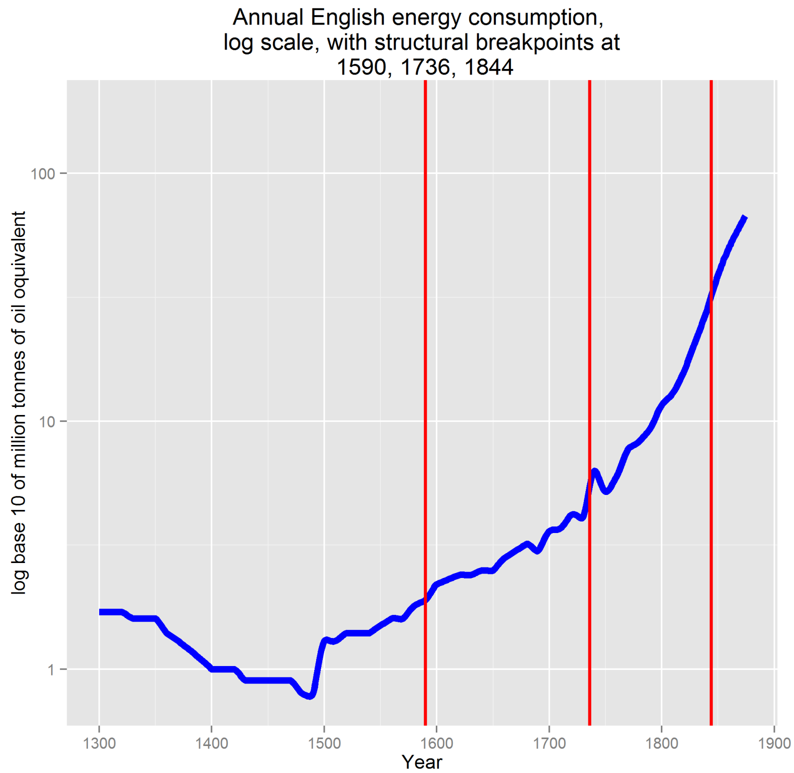


Figure 2.5: Log of energy consumption, with structural breaks

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 2.6. 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.

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

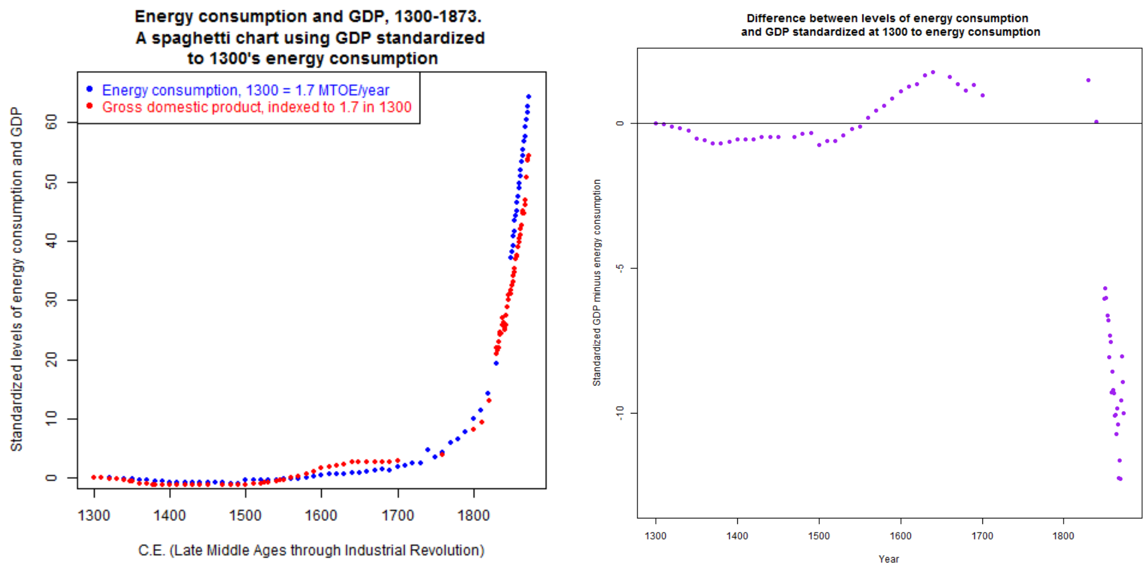


Figure 2.6: Energy consumption vs. standarized GDP,
levels and differences

looking at energy consumption graphs that show smaller growth rates than GDP but still very significant growth. Table 2.2 also clearly shows this comparison. In the period 1600 to 1750, growth in both GDP and energy consumption flattened and then boomed again during the period 1750 to 1873.

Observing the panels in Figure 2.6 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.

2.2.2 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 chapter. 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. They 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.

2.2.2.1 Econometric analysis

Starting simply a Pearson's correlation coefficient and a paired t-test of energy consumption and GDP yield the results in Table 2.3.

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 chapter, a scatterplot of the series is shown in Figure 2.7. The solid green line is a linear fit; the solid red line is a *lowess* (nonparametric and nonlinear) 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 Granger causality test to do so. [46].

Table 2.3: 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

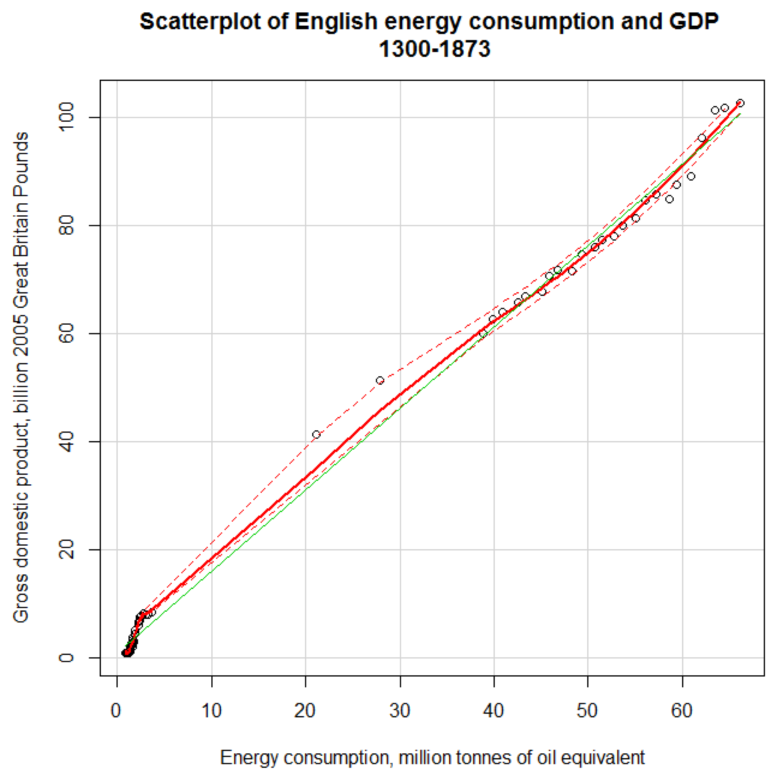


Figure 2.7: Scatterplot of energy consumption vs. GDP

Using the Granger bi–variate test to examine changing dynamics provides the results in Table 2.4; 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) [48] increased family incomes entering the early modern period.

Table 2.4: 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

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 [25]. There is further evidence that the English state supported an early version of Import Substitution Industrialization to replace imports and to increase exports [110]. 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 [22] 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 chapter 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 2.8 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.

2.2.2.2 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 2.4.

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 2.9.

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

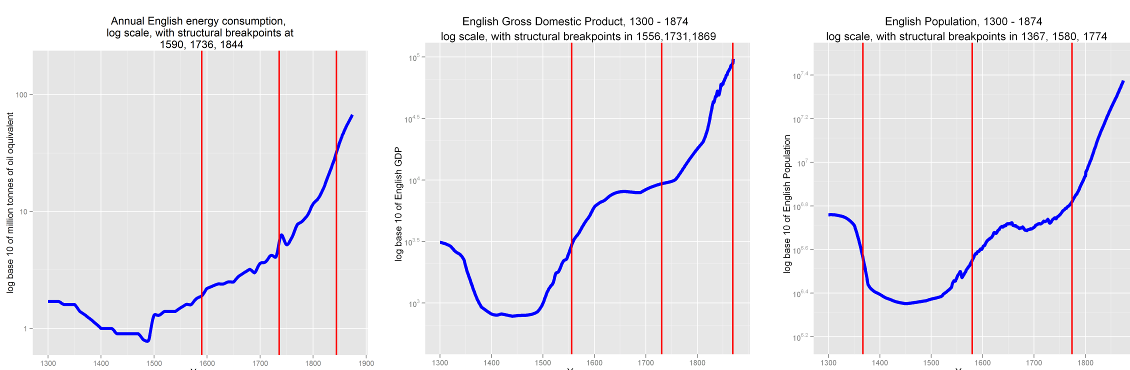


Figure 2.8: Structural break comparison

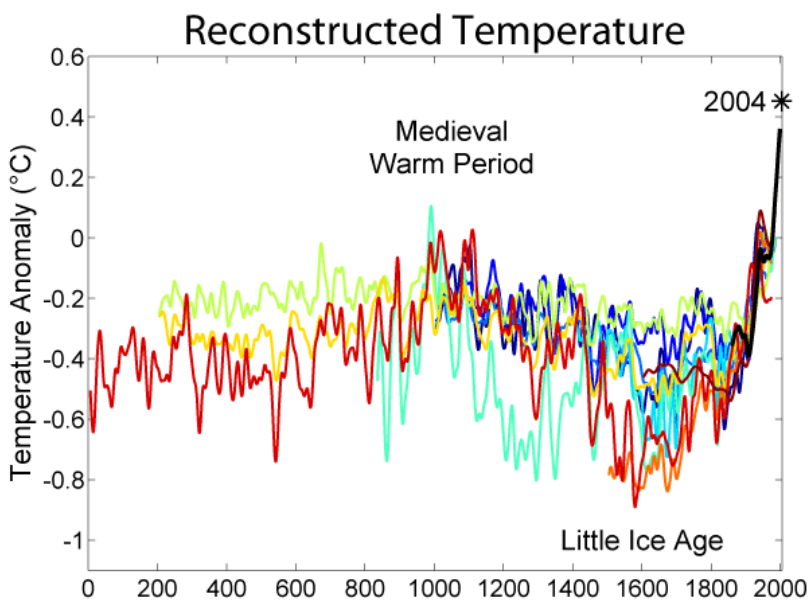


Figure 2.9: Late Holocene temperatures. *Source:* NASA and IPCC composite

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 [110]. Aggregate supply expanded, as can be seen by the stronger growth of energy consumption. Refer to Table 2.2 or Figure 2.5. 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 it was "... no less appropriate to call the sixteenth and seventeenth centuries an age of timber" [81, 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 so 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 2.9 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* [47]. Hubert Lamb is often cited as an early researcher.[4]

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 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 Figure 2.10.

Notably, this is also the era Nef calls the “first energy crisis” [82]. 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 [110].

As research for this chapter 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 [23]. de Vries also has an extensive empirical look at Dutch

[4]See for example [62]. 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.

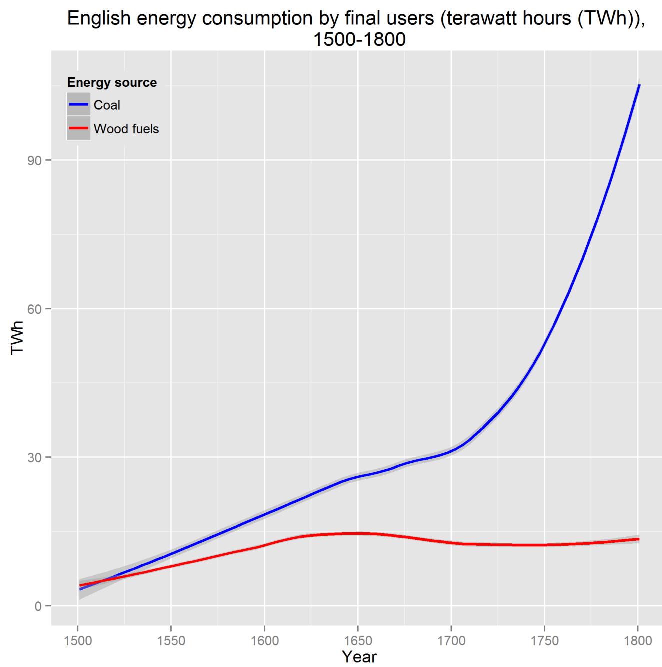


Figure 2.10: Coal and wood fuels energy sources.
Source: Data from Pearson and Fouquet [36, p. 103], graph by author

temperatures and various measures of agricultural output. In the end, he comes to few conclusions except that time–series data are essential [24].

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 more deeply, 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 2.5. Many though not all of these inventions are steam

Table 2.5: 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
	British inventor Henry Maudslay invents the first metal 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 Nicphore Nipce 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 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

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 [54] 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. The narrative will expose how close China came to having an early industrial revolution, but failed because they lacked important economic drivers. We can then begin work on a theory of industrial revolutions.

2.3 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 [13].

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, they 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.

2.3.1 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 [90], 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 [68], it should have dominated the world economy. And it did. From Angus Maddison's data [66], 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 someone 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 [80] 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 [54], 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 nonthreatening 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 Englis–style energy innovation. For English exceptionalism claims, see Max Weber [119], David Landes [63, 64], and Deirdre McCloskey [72, 73]. This is just the distinguished head of a very long list of scholars who invoke both English and European exceptionalism as the cause of the EIR and subsequent European growth.

This chapter explores the counter–question: what underlying *economic* reasons might account for this remarkable series of events and nonevents? 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?" This would be very useful for development economists.

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.

2.3.2 A first look at data and institutions

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

2.3.2.1 Sources and methods

The Chinese data are not nearly as rich as the English data; nonetheless, Angus Maddison [66], Vaclav Smil [98, 99], J. W. de Zeeuw [55], Robert Hartwell [50, 51, 52, 53], and the U. S. Energy Information Administration [4] 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 are from Maddison [66]. Maddison measures GDP in 1990 International Geary–Khamis Dollars that describe purchasing power parity (PPP) adjusted output. Maddison's dataset whatever its challenges is widely cited and is where many comparative scholars start. This study also starts with it.

2.3.2.2 Regional population and GDP dynamics

The two panels in Figure 2.11 show that both world population and GDP levels for years 1500 through 1900 CE underwent unprecedented growth; the two proportion panels in Figure 2.12 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 to Pomeranz among many scholars [90, p. 22], though on this chart, the English growth is hard to see.[5]

To abstract from that, next examine per–capita GDP growth. Figure 2.13 shows per–capita GDP by regional and national groupings of interest from 1 through 1900 CE, using the underlying Maddison [66]. Two facts stand out. First, China maintains a relatively constant level of per–capita GDP throughout the period. The Chinese did not become

[5]One theory (Alfred Crosby [22] 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.

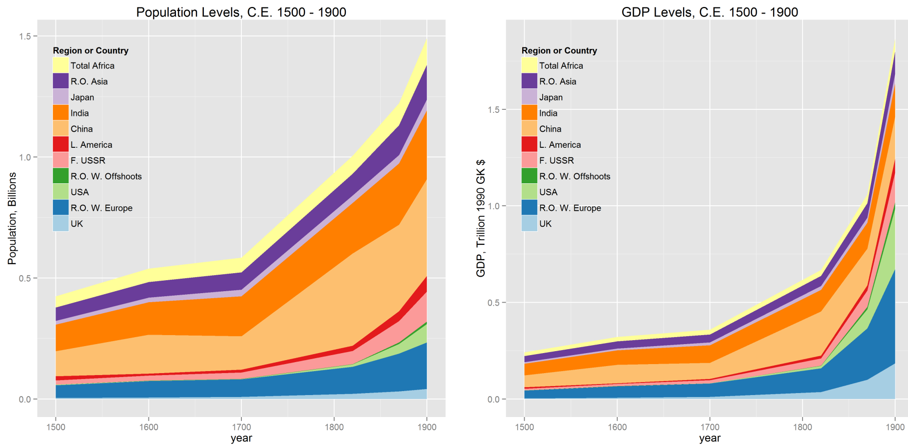


Figure 2.11: Population and GDP levels from 1500 to 1900.
Source: Data from Maddison [66], graphs by author

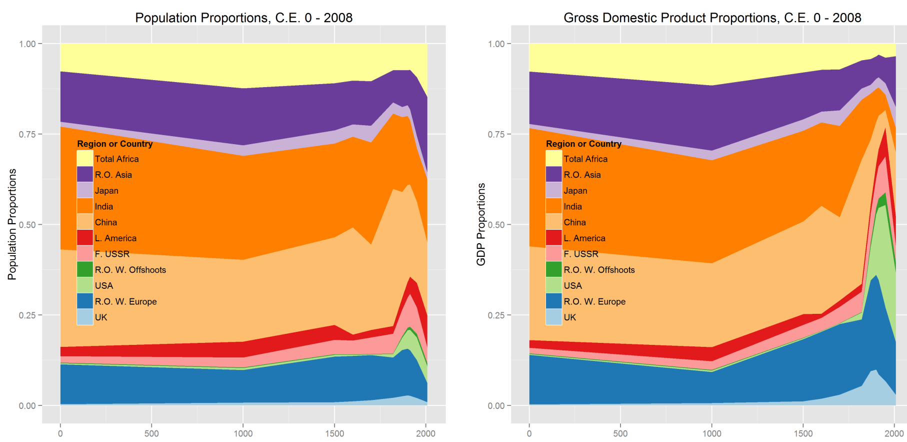


Figure 2.12: Population and GDP proportions from 0 to 2008.
Source: Data from Maddison [66], graphs by author

absolutely poorer; however, China did not share in the great average output growth of the Western nations. Second, the grouping denoted the EU–11,[6] 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

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

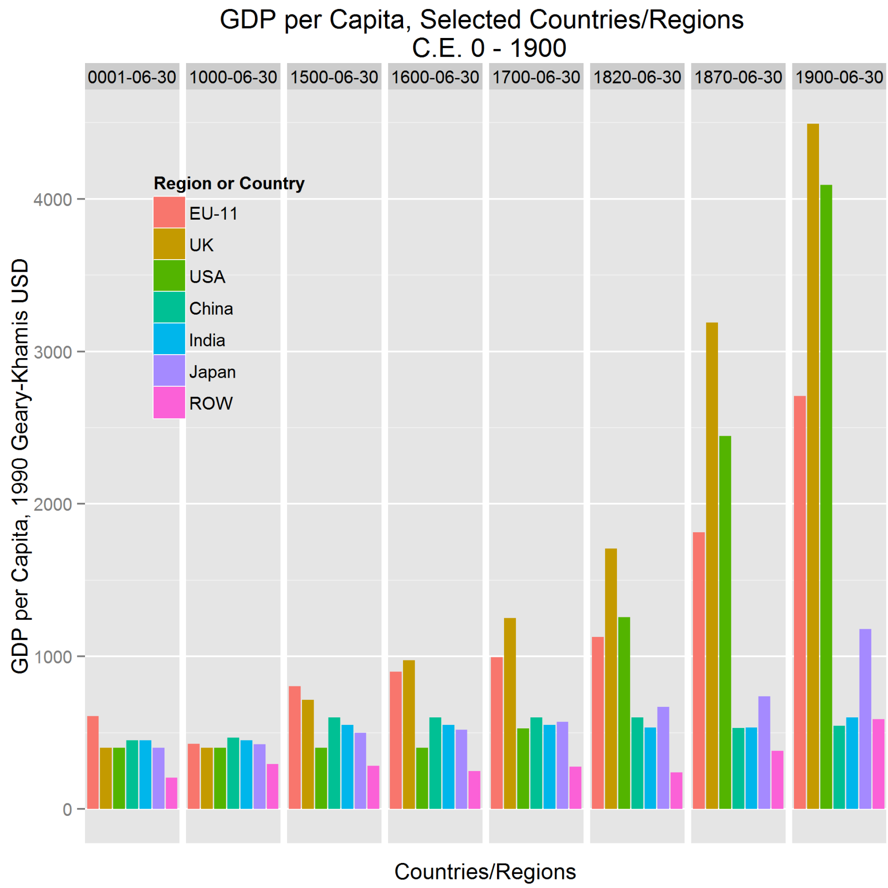


Figure 2.13: Comparative World Per–Capita GDP.
Source: Data from Maddison [66], graphs by author

of the world.[7]

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

[7] The western offshoots are statistically dominated by the United States but also include Canada, Australia, and New Zealand.

were for subsistence GDP, meaning essentially zero–growth per–capita levels forever. This informs our fascination with what actually happened and our dramatically different modern expectations.

The next several charts illuminate these dramatic changes. Figures 2.14, 2.15, and 2.16 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 percent 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 growth in both economies prior to 1820 and only England continues growth after that.

Figures 2.17, 2.18, and 2.19 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.

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 levels in the Lower Yangzi region in China were at English levels in 1800 [90, 107]. Decomposing the standard of living into wages and

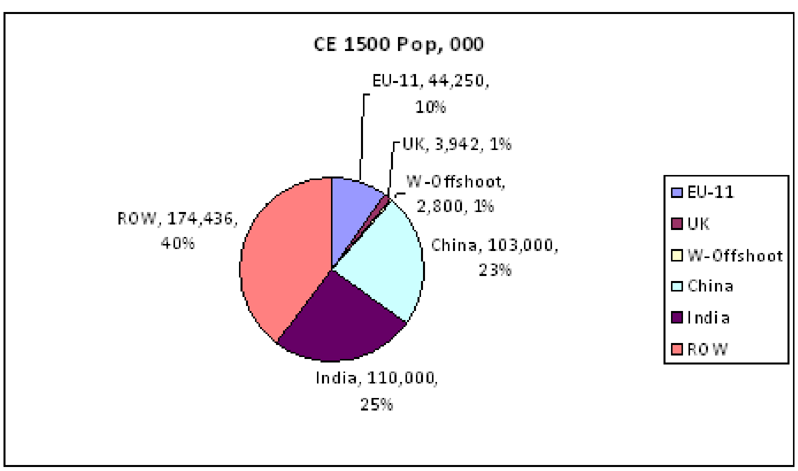


Figure 2.14: World population shares, 1500 CE

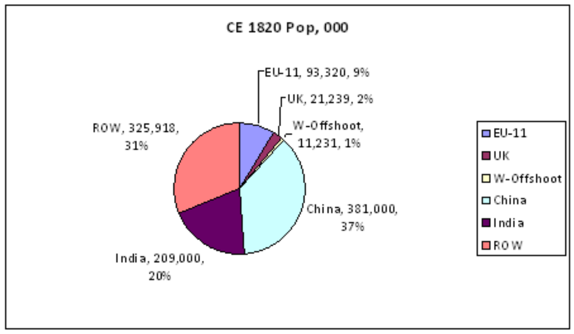


Figure 2.15: World population shares, 1820 CE

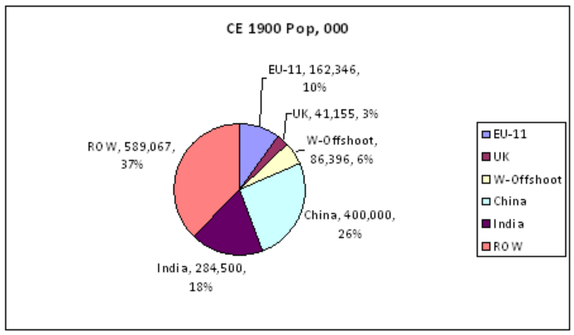


Figure 2.16: World population shares, 1900 CE

cost of subsistence softens those differences except in the Lower Yangzi, but in any case, we need to explain the post–1820 divergence.

England's GDP share has grown dramatically from the 1 percent proportional to its population share in 1500 to 2.5 times population share in 1820 to 3 times population share in 1900.

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

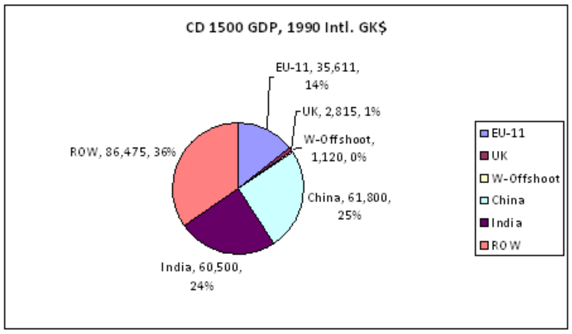


Figure 2.17: World GDP shares, 1500 CE

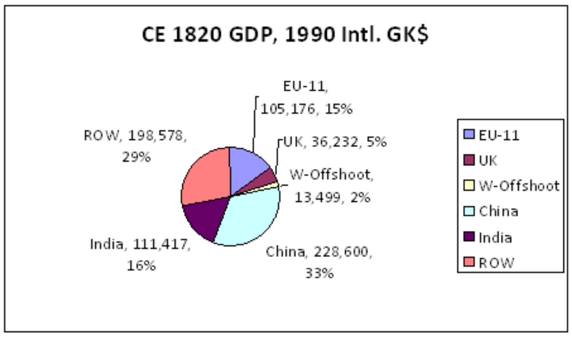


Figure 2.18: World GDP shares, 1820 CE

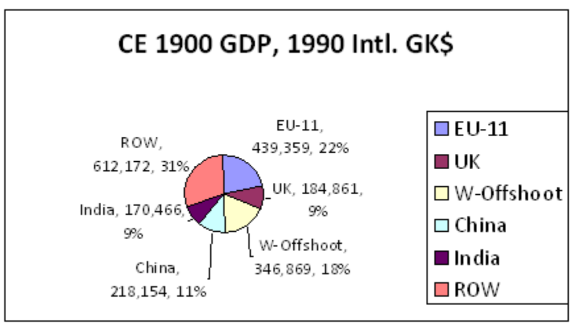


Figure 2.19: World GDP shares, 1900 CE

essential (functional) institutional sufficiency for growth in each country.

2.3.2.3 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 is 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 its 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. [122, 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. [122, 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.

We move 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.... [90, 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.

2.4 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.

Figure 2.20 displays 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 2.4), supply and

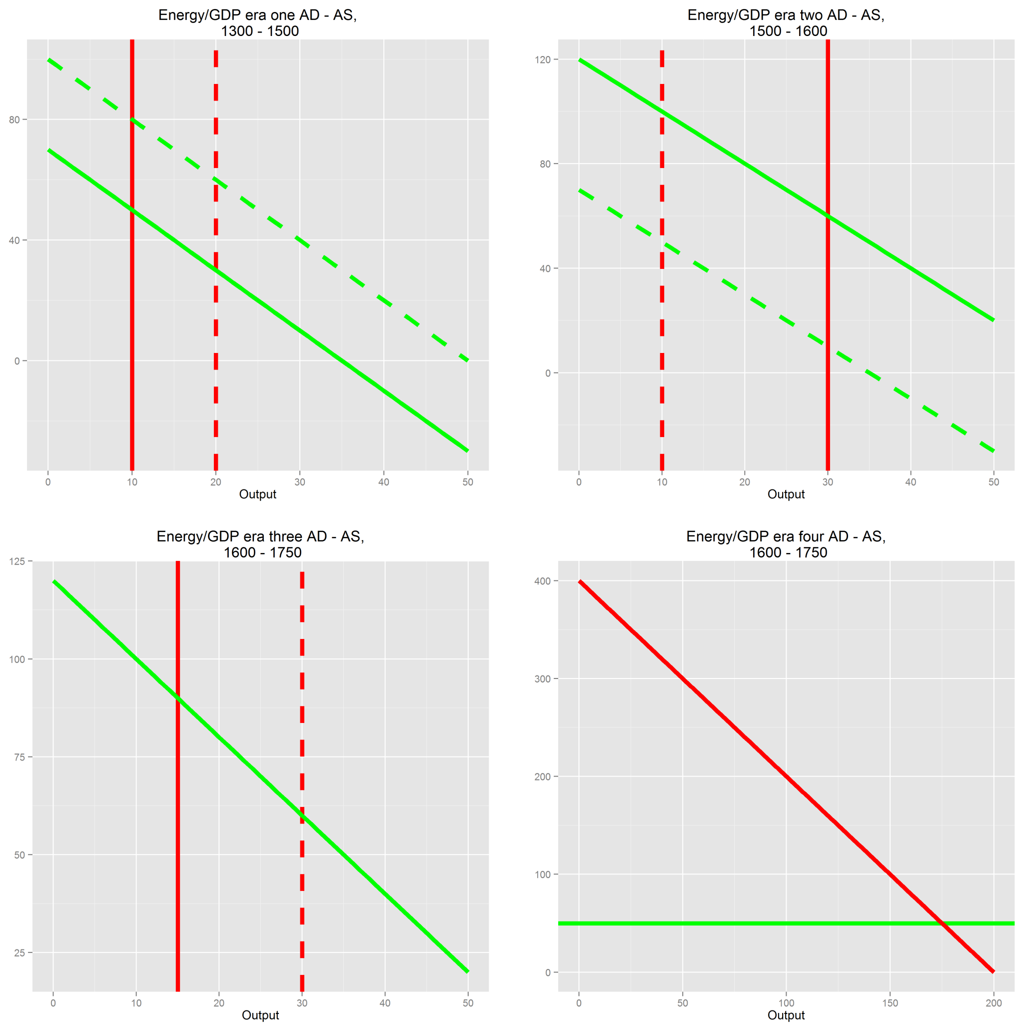


Figure 2.20: Aggregate Supply—Aggregate Demand
Four energy/GDP regimes

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 this question as at the end of the economic day, people require individual incentives to innovate and commercialize no matter what the macroeconomic pressures and/or institutional influences are. This chapter mainly discusses the supply–side of the story having already suggested a story of important demand–side factors in Section 2.2.2.2. 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. It is 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 is largely coal–fueled.

The phase–one revolution lasted through most of the first three AD—AS eras (see Table 2.4) until about 1700. To see this transition's time boundaries, refer to Figure 2.10 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 [81] and shown in Figure 2.21. 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.

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:

$$\frac{\text{Marginal Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Marginal Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}, \tag{2.1}$$

or if one prefers a nonneoclassical writing:

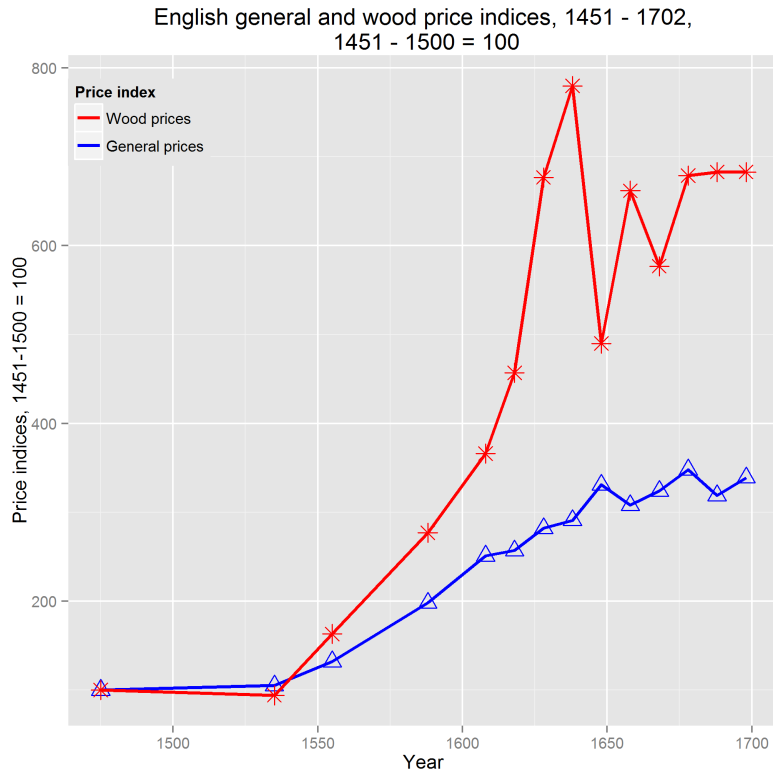


Figure 2.21: English wood and general price indices. *Source:* Data from Nef [81, pp. 158,221], graph by author

$$\frac{\text{Average Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Average Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}. \tag{2.2}$$

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 2.10).

This was not an easy transition. Coal was dirtier—perhaps even nastier—than charcoal 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 caused English coal demand and production to increase [7, p. 82]. This invention took more than a century to replace wood–burning stoves, but the economic incentives were eventually sufficient. See Figure 2.10.

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.

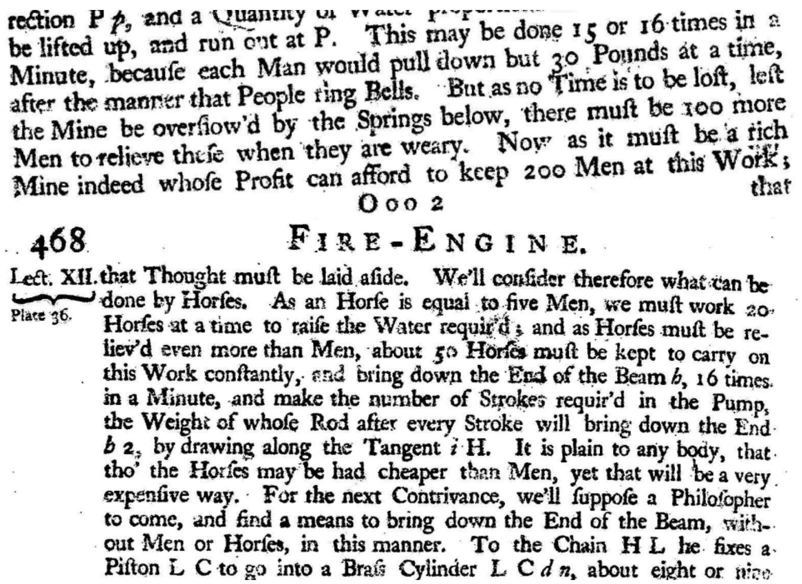
Jean (or John) Theophilus Desaguliers had a large influence on the EIR. He was an eighteenth–century English “natural philosopher” (physicist), a member of the Royal Society, colleague of Sir Isaac Newton, and author of *A Course of Experimental Philosophy*. This was an influential 1734 two–volume engineering 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 [29, Vol.II, pp. 467–468]. The age of the industrial capitalism fueled by fossil energy was dawning.

Figure 2.22 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.

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 2.5 for a list of the inventions that were converted to


rection P *p*, and a Quantity of Water ... 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

468 FIRE-ENGINE.

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 2.22: Desaguliers manuscript

steam–power, were originally developed for steam–power, or used steam–power to convert steam–power to a different transmission medium—electricity.

Figure 2.23 is from Robert Allen and shows the ratios of real wages to energy costs (the cheapest source by location) by benchmark city around 1700.

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 2.3 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.

$$\frac{\text{Average Product}_{\text{labor Joule}}}{\text{Price}_{\text{labor Joule}}} \ll \frac{\text{Average Product}_{\text{steam Joule}}}{\text{Price}_{\text{steam Joule}}} \tag{2.3}$$

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 nonsubstitutable input, as in you must have Joules from whatever source to do any economic transformation. If we take the numerators in Equation 2.3 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

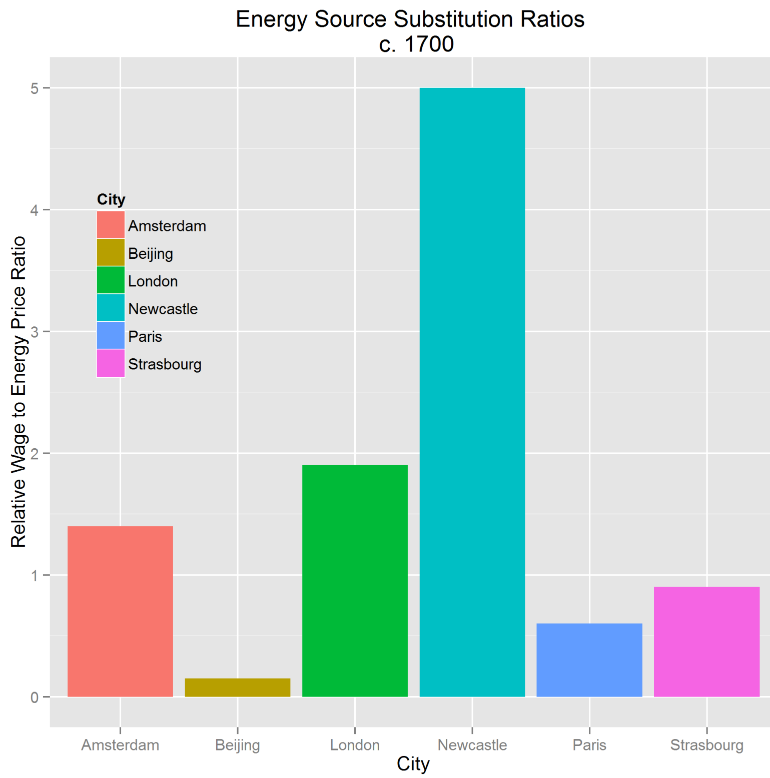


Figure 2.23: Real wage–to–energy price ratios.*Source:* Data from Allen [7], graph by author

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 chapter 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, 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 2.23. Essential to his argument is that England almost uniquely was a high–wage and low–energy–cost economy [7, p. 34].

We can use his supporting data to understand from microeconomic theory what did not happen in China. Refer to Figure 2.24 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 [7, p. 140]. The basis for this argument can be seen in Figure 2.25. Note that these prices reflect the cheapest energy source, usually either wood or coal.

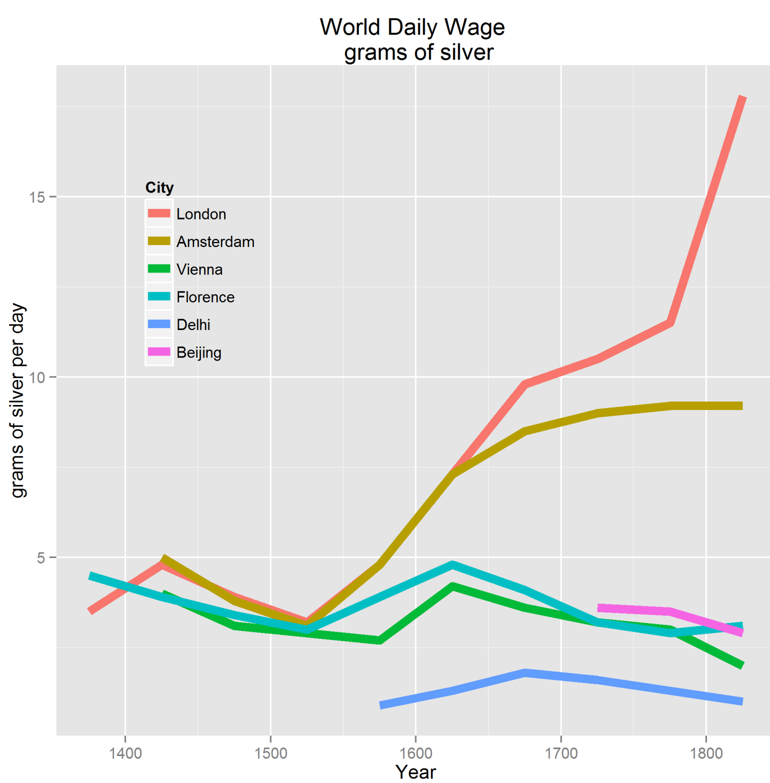


Figure 2.24: World wages, 1375–1825 CE. *Source:* Data from Allen [7], graph by author

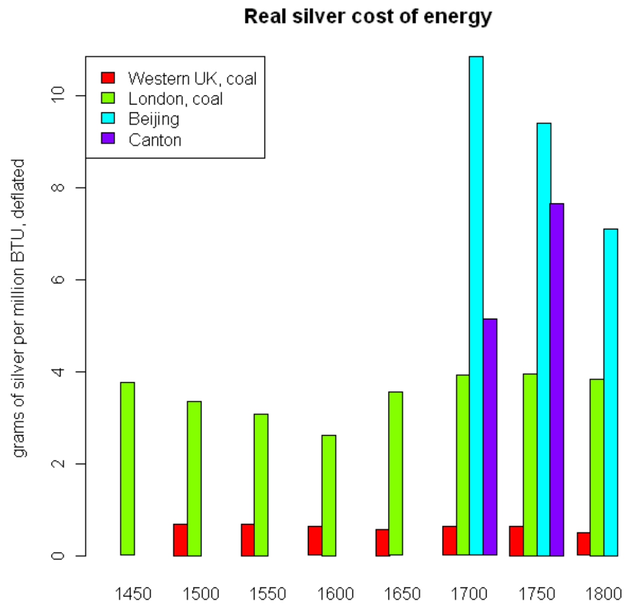


Figure 2.25: Comparative world energy prices, 1450–1800 CE. *Source:* Data from Allen [7], graph by author

Referring back to the Allen ratios in Figure 2.23 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 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.

2.5 Conclusion

The main questions considered in this chapter are about how industrial revolutions come about. By considering the successful English attempt and the unsuccessful Chinese attempt, we find that England learns to consume unconstrained energy inputs while China does not. However, this story is more generally about economic growth. It is about the English economy spontaneously—no economy had achieved this before—learning to deliver modern economic growth. Simon Kuznets [60] defines this as persistent growth in living standards and population, a new economic regime overturning centuries, even millennia, of Malthusian growth constraints.

Why is learning to consume unconstrained energy inputs so fundamental to the growth story? Many economists agree that growth in living standards requires growth in labor productivity, measured most simply as output per labor hour input. Growth economists tell many stories about this, often observing comparative institutional and cultural differences in economies with significantly different living standards, and conclude logically that those must be the relevant differences. And many tell stories of capital accumulation as the key growth enabler delivered by whatever their important institutional mechanisms might be. These institutional changes and capital growth are indeed observables in the history.

However, if you are persuaded that it is energy inputs that fundamentally determine—in fact constrain—economic output and productivity growth, then we must fully understand the dynamics that deliver the important outcomes so we can tell policy makers that wish to pursue modern economic growth how to do so. To make growth prescriptions about proximate causes such as institutional changes and capital accumulation may miss the crucial ultimate cause requirements. Examining historical examples occurring before we "knew" how to create modern economic growth can help clarify our prescriptions. That is the hoped outcome of this chapter.

Briefly recalling the growth data presented above, refer to Table 2.2 and note that English annual per–capita growth rates by century, abstracting from the problematic Snooks–influenced early GDP data, only approach modern levels of 1.1 percent after 1820—after the English economy collectively learned to remove energy constraints on economic output. This learning is shown in the growth rates of energy consumption in the same table.

Now recall from Figure 2.13 how English living standards, with northwest Europe following closely, accelerated away from the rest of the world, including China, after 1700 and especially after 1820. With this in mind, review Table 2.6 showing per–capita energy consumption for some relevant economies across time.

For the current argument, note that Chinese per–capita energy consumption in 1973 is *significantly less than English per–capita energy consumption in 1820*. These data and the other country data in this table further support the essential claim that regardless of proximate causes, energy consumption appears to be the ultimate cause for modern

Table 2.6: Per–capita primary energy consumption, annual tonnes of oil equivalent. *Source:* Data from Angus Maddison, [a]de Zeeuw, [b]US DOE EIA

Year	England	China	Netherlands	India
1650[a]			0.63	
1820	0.61			
1840[a]			0.33	
1870	2.21			
1970[a]			8.07	0.33
1973		0.48		
1998[b]	6.56	1.18		
2008[b]	5.99	2.56	9.86	

economic growth.

Underweighting cultural, institutional, and social reasons for the great divergence in energy consumption and living standards between China and England raises the question then of how to explain it. We do so by appealing to basic economics. The aggregate demand—aggregate supply analysis in Section 2.2.2.2 sketches out the macroeconomic background in four eras. Importantly, this section covers the important demand–side story covered in additional detail in the next chapter, but that is not the current focus. The focus here is how to rid the economy of supply–side constraints—primarily energy inputs.

Hypothesizing two phases for the English Industrial Revolution allows a clear microeconomic explanation of the key input factor source substitutions founded on the most basic mechanism—relative price substitution. Phase one substitutes coal for wood in domestic and industrial heating applications, essentially removing that energy input constraint. For power applications such as producing commodities using muscle power, phase two substitutes steam–power for muscle–power and thus removes the nonscalable muscle–power constraint on output, thus increasing labor productivity and living standards.

Note that a crucial political–economy question—distribution—is not covered here. In fact, that story is likely where institutional explanations will dominate.

Finally, note that once the growth–genie is out of her bottle, certain institutions—sometimes autocratic states—are able to take the energy lesson described here and apply it directly to building economies delivering modern economic growth. Japan, the "Asian Tigers," and modern China come to mind. Studying their energy consumption history is a future project.

CHAPTER 3

THE RISE OF INDUSTRIAL CAPITALISM: WHAT HAPPENS NEXT?

3.1 Abstract

This chapter seeks to contribute to understanding the English Industrial Revolution and the rise of industrial capitalism by applying basic economic principles to the data and historical descriptions available over more than a millennium.

After using data and theory to characterize the rise of industrial capitalism in England starting in the early–modern period, the chapter examines the economically important Sung, Ming, and Qing eras in China to see if "sprouts of capitalism" existed. Finding evidence that they did then evokes an explanation of the failure of Chinese living standards to continue rising as England's did after the English Industrial Revolution. The evidence that explains the Chinese "failure" lies again in economic principles—China simply did not have strong enough incentives given relative prices to motivate the required invention, innovation, and entrepreneurial investments.

Finally, and briefly, the conclusions allow us to speculate on the future of industrial capitalism.

3.2 Introduction

This chapter attempts to contribute to answering the question of "why capitalism," primarily in the context of the Industrial Revolution, meaning the English Industrial Revolution (EIR). The specific form of capitalism the chapter investigates is industrial capitalism. The approach is that capitalism is an institution representing a mode of production, a social sytstem, or an economic system. The task then is to explain why and how that institution arose.

The chapter's primary motivation is to examine history to see if roots of capitalism are found in proto–industrial economies. English history is examined. However, the histories of Sung China and later dynasties are also mined for any evidence of embryonic capitalism. If found across comparative economies, the implication is that capitalism's roots may have been shared across those economies. Once more than one instance of proto–industrial capitalism is found, then finding what is common among those economies should yield clues about underlying roots of capitalism.

And if shared causes are found that can be explained in the context of the rise of industrial capitalism, then another interesting question can be asked: If the underlying roots are changing, then how will the institution itself be affected?

The intuition behind asking the main question is that applying basic economic principles may yield interesting outcomes. The most basic economic principles are those of the laws of supply and demand. Those principles will be tested in this chapter to see if they can add to the answer sought.

3.2.1 Definitions

Since the objects of study are in wide use, definitions are in order. Immanuel Wallerstein attempts the definition this way: "Historical capitalism, is, thus, that concrete, time–bounded, space–bounded integrated locus of productive activities within which the endless accumulation of capital has been the the objective or 'law' that has governed or prevailed in fundamental economic activity" [115, p. 18]. While not specifically defining industrial capitalism, Wallerstein's definition should encompass it.

A modern mainstream economics textbook would define capitalism in some manner close to this from Merriam–Webster: "an economic system characterized by private or corporate ownership of capital goods, by investments that are determined by private decision, and by prices, production, and the distribution of goods that are determined mainly by competition in a free market," with the essentials parts of the definition being private ownership and free market.

In his writings, Karl Marx seldom uses the word "capitalism" directly but often uses "capitalist mode of production." One interpretation of his term includes these attributes: private ownership of the means of production used to produce commodities for exchange, exploitation of wage labor, increasing value by appropriating surplus value beyond subsistence from wage labor, and class struggle between the bourgeoisie (owners of capital) and the proletariat (owners of labor power) over dividing value between wages and power [10, Definition of capital].

Marxists (meaning followers of Karl Marx's work in some sense) define capital as an accumulation of money that is then used in the circuit of capital (M–C–M') to purchase a commodity in order to sell it at a profit.

For this chapter's purpose, it will be useful to examine the idea of physical capital such as mines, roads, canals, transportation systems, and machines that are used in the circuit of capital; this definition of capital as physical is a characteristic important to the EIR. This contrasts with a purer Marxist definition such as merchant capital, which can be thought of as money invested in commodities purchased from someone else in order to pursue the circuit of capital.

3.2.2 English transition to industrial capitalism

Historians commonly discuss the rise of capitalism in terms of the transition from a feudal system to a capitalistic system and often describe it in terms of struggle and conflict among different classes of society. This can involve discussing an economy's structural change from primarily agrarian to primarily industrial.

Karl Marx's main written work was largely modeled on England [71] and thus the EIR. Other scholars have built on his great contribution to continue to describe the transition from feudalism to capitalism in western Europe. Maurice Dobb and Paul Sweezy in the 1950s engaged in a debate—the "transition debate"—that delineates the two main threads of Marxist thought [108]. Paul Sweezy attacks Dobb's theory that the decline of western European feudalism was due to the overexploitation of labor by the feudal ruling class. Feudalism is characterized by production for use through local markets rather than production for exchange, including long–distance markets. Sweezy identifies several sources of instability in the feudal society, including lords competing (warring) for land and vassals, and the growth of a population that is pushed from the manors and becomes brigands or mercenaries [108, p. 136]. Yet Sweezy does not explain how an otherwise such stable system as feudalism had proven to be could spark the kind of social revolution that causes a transition of social systems; this is the kind of change that is essentially Dobb's theory of the transition—an endogenous conflict between classes eventually causing the transition.

Rather, Sweezy sees the growth of long–distance trade in commodities produced explicitly for market or exchange value as the fundamental cause of the transition. His favored cause for this exogenous factor is Henri Pirenne's explanation—the eleventh–century re–opening of Mediterranean shipping between the western ports and the tenth–century development by Scandinavians of commercial routes from the North Sea and the Baltic via Russia to the Black Sea [89] [108, p. 143].

Many historians agree that European feudalism's demise was succeeded by an era of proto–industrialism (characterized by home production for market or exchange value) before industrial capitalism dominated. While in historical time these processes were likely arrayed along a continuum, focusing on the key elements of each era helps in understanding what the important changes were. Paul Sweezy describes the transition mechanism as composed of four elements.

First, the rise of long–distance trade causes an increase in production for exchange or market; this system that featured specialization and division of labor was more economically efficient than the manor–based production–for–use system it was competing with and eventually, this new exchange system dominated the older system. Second, the existence of exchange value as an ever more important economic fact changes the producer's attitude, allowing them to visualize accumulating riches in the form of money or claims to money and this change led to the desire for accumulating wealth as an end in itself. Third, the remaining feudal ruling class develops ever more of a taste for conspicuous—often luxury—consumption. Fourth, these changes were accompanied by the rise of the towns as centers of the exchange economy that attracted the former manorial vassals. Urbanization was underway as a major trend [108, p. 143–144].

Sweezy agrees with Dobb (and Marx) on the historical time frame of the transition events. This chronology has western European fedualism entering a period of acute crisis in the fourteenth century. The fifteenth and sixteenth centuries were characterized by "pre–capitalist commodity prodution" [108, p. 150] that laid the groundwork for the rise of capitalism in the second half of the sixteenth century. A non Marxist term might be proto–capitalism.

A different group of scholars writes about the transition period with a different point of view and one that is important as a prototype for the rise of industrial capitalism. E. M.

Carus–Wilson writes of a thirteenth–century industrial revolution centered on the important English wool textile industry [15]. Additional contributors to this literature include Lynn White [120], Jean Gimpel [42], and Debeir et al. [28], but Carus–Wilson tells the story in a most compelling manner.

Carus–Wilson relates the story of how fulling—one of the four key steps in the process of woolen–cloth making—was transformed in the thirteenth century from a manual (or importantly foot–based) process of beating the cloth in water to improve its finished characteristics. In a two–step invention, mechanical fulling evolves from the old method of fulling–by–foot. First, the two feet are replaced by two wooden hammers alternatively raised and dropped on the cloth in the fulling trough by the action of a revolving drum. Second, a series of these hammers was attached by their drums to a water–wheel spindle for power. Water power replaced human or muscle power and several—perhaps tens—of human fullers were replaced by one person managing the whole process and now called a fulling mill [15, p. 43].

Reviewing what happened in the thirteenth century, foot fulling gives way to mechanical fulling, human labor is displaced by water power, the industry is centralized at the mill rather than in homes, the new system depends "as never before" on capital equipment, and the system is passing out of guild system control. The investments are largely in the country around water sources on property owned by the church or landlords who are usually a member of royalty. The royal investments include those by King Henry III, who owned a fulling mill at Elcot [15, p. 50–51].

It is not difficult to visualize replacing water power with steam power when steam engine technology matures in the eighteenth century; the fundamental groundwork is already laid. Economists must ask what are the incentives to make this dramatic productivity–enhancing innovation? Two come to mind: one, a larger scale operation is required than is achievable by muscle power—an increase in aggregate demand could explain this; two, wages paid to fullers are sufficiently high that substitution of muscle power by water power promises sufficiently large economic returns (profit) that the large development effort and investment is worthwhile.

There is an extremely important related chain of events triggered by the great productivity gains in woolen manufacturing that were partly translated into lower costs and prices.

This encouraged converting land to enclosed sheep ranches—a momentous event that we call the "enclosure movement." Note that it implies economically an increase in demand for woolen cloth driven by increased population, lower prices, or both.

Later, this chapter explores the idea that an even more fundamental cause of the transition to industrial capitalism is the general rise in population levels driving increases in aggregate demand for many commodities including woolen cloth. This factor is woven throughout the transition debate and Sweezy explicitly refers to but does not develop the idea. Under this theory, the long–distance trading activities and trade route expansion that certainly happened are important proximate events but not the ultimate cause of the transition.

This demographic transition theory is sometimes referred to as demographic determinism and is explicitly rejected by Robert Brenner in a less–explicitly Marxist essay contained in *The Brenner Debate* [11]. Brenner favors the class–struggle explanation for the rise of capitalism; arrayed against his argument are contributions in the volume by M. M. Postan and John Hatcher [93], Emmanuel Le Roy Ladurie [61], and Guy Bois [14]. This group sees population changes as important in the transition away from feudalism.

John Nef's impressive two volume *The Rise of the British Coal Industry* (1932) discusses in depth the rise of industrial capitalism without explicitly invoking Marxist ideas. He however does not avoid discussing class–related conflicts, including the judicially–supported concentration of mineral rights in the hands of a few owners [81, v.1, p. 286] and the conflicts caused by the cleavage between capital and labor in the coal mines and coal trade [81, v.1, pp. 411–429].

Importantly for this chapter and discussed in more depth later, Nef explicitly attributes the rise of industrial capitalism to the rise of the British coal industry. This claim becomes an important piece of the argument in this chapter—that industrial capitalism likely arose primarily from fundamental economic changes no matter what other events were active at the same time.

The french historian Paul Mantoux writes extensively about the EIR and its connection to the rise of industrial capitalism in *The Industrial Revolution in the Eighteenth Century* [69]. Like Nef, Mantoux writes of the conflicts between capital and labor and the rise of industrial capitalism as an outcome of the EIR in a manner that is not explicitly Marxist yet is rich in the materialism that Marx exposes. Mantoux thus is also an important contributor to the ideas in this chapter.

3.2.3 Evidence of a Chinese transition to industrial capitalism

Is there evidence of an early Chinese transition to either proto–capitalism or industrial capitalism? This chapter investigates three Chinese historical periods—the Northern Sung dynasty (960–1126 CE), the Ming dynasty (1368–1644 CE), and the Qing dynasty (1644–1911 CE)—for such evidence.

What kinds of evidence would be interesting? Several come to mind—first, evidence of wage labor at least in some basic industries—Marx would look for alienated workers who primarily reproduced by selling their labor power to another; second, evidence of integrated labor and commodity markets, one sign being correlated wage rates for the same type of work across some logical geography; third, evidence of capital investment of a scale that is remarkably different than before, motivated by some identifiable economic incentive.

Sinologist Robert Hartwell provides significant evidence of wage labor in one important Sung Chinese industry—the iron and steel industry. Sung iron production is remarkable in its industrial scale—producing more iron than Europe up until the late eighteenth century in centralized industrial areas with large capital investments—and marked by its use of wage labor [50, 51, 52, 53].

Japanese Sinologist Yoshinobu Shiba prodvides a detailed look at the structure of several key industries during the Sung dynasty [97].

Robert Allen provides data on Chinese labor markets during the Qing dynasty [8]. This will provide the basis for finding whether China had developed integrated labor markets. Kenneth Pomeranz provides additional evidence of wage labor and market integration [90].

Xu Dixin and Wu Chengming provide a very detailed Marxist–structured analysis of Chinese capitalism during the Ming and Qing dynasties. They provide evidence of wage labor and other capitalist signature attributes as they evolved through these more than 300 years [126].

John Hobson provides evidence of Chinese water wheel powered production requiring substantial capital investment [54]. This is one of capitalism's signatures—significant investment in mechanical devices to either scale up or replace labor inputs.

3.3 English industrial capitalism

Karl Marx used the EIR and the related rise of industrial capitalism as a primary source for his monumental work *Capital: A Critique of Political Economy*. England was the first economic system to widely industrialize with masses of wage laborers confined in centralized mechanized factories tending machines that produced commodities at greater scale and lower cost than ever in history. The momentous changes in living standards, culture, institutions, and entire social systems put the world on a course that it still travels.

Understanding the rise of industrial capitalism—the underlying reasons for its existence and dominance of economic systems—may lead us to an understanding of its possible futures. Economists are first trained to think about markets—a fundamental component of economic systems—as a way of explaining how economic systems work. They learn that demand and supply are the rules—even laws—that govern how markets function. And they learn that demand for inputs to the production process is a *derived* demand depending on the demand for the commodity it helps produce and its own cost and productivity. While much of the history written about the EIR talks mainly of the supply side—the inventions, innovations, and the capital needed to build and commercialize them—it may be fruitful to first examine the demand side for capital.

This chapter explores how using the idea of the derived demand for capital helps explain the rise of industrial capitalism. Many analyses of capitalism focus on the idea that capitalists simply want to accumulate capital for personal gain. There is almost surely some truth in this, but this cannot on its own explain why capital and capitalism have come to dominate the world's economies. First, we will investigate how the demand for capital arises. For the most part, this will be an investigation of productive—physical—capital.

3.3.1 A first look at data

It is possible to think about aggregate demand for produced commodities and services as having two components—a subsistence component and a living–standards component. The subsistence component is essentially a function of population levels. The living-standards component is demand above subsistence. Total aggregate demand is the sum of both.

For most of economic history, population levels have been the sole determinant of levels of aggregate demand; most of the world lived at subsistence most of the time. That began to change around the time frame of the EIR when living standards began their long march upward. That trend still continues to this day. But in order to understand where the basic aggregate demand comes from that the Industrial Revolution met and therefore where demand for capital comes from, we should first examine population levels through time.

3.3.1.1 Sources and methods

The primary source for population data is the database started by Angus Maddison [66] as supplemented by United Nations data [79]. The main analytic tools are graphs of population levels and transformations of that data to clarify trends.

3.3.1.2 Global population trends

The left panel of Figure 3.1 displays the log of population levels since year one. This is smoothly increasing super–exponential growth with some barely visible wiggles. This population growth dynamic and its ever–increasing aggregate demand drove the supply side of the global economy into creating the EIR and thus created industrial capitalism due to the self–accumulating nature of the investments that were required.

The right panel is in log differences of annual population levels since the year 1 CE and thus shows approximate annual growth rates. Note that the growth rate peaked in 1971 at 2.2 percent, has declined to about 1 percent now, and appears poised to head lower. If population growth was the underlying cause of industrial capitalism, then we must question the implications of its plummeting growth rate. A later section will address that possibility.

One can clearly see the gobal population liftoff in the late middle ages followed by accelerating growth during the early modern period and "going exponential" during the EIR. England's population growth follows this pattern providing expanding aggregate demand in its domestic market. Population growth globally accounts for aggregate–demand expansion that caused a commercial and trading expansion. This was first exploited in the Dutch Republic, then England as that country began to dominate world trade. Most of this growth can be characterized as subsistence with the great gains in living standards awaiting the second–phase EIR in the nineteenth century. As aggregate demand grows, the supply side must respond, but in the still Malthusian pre–EIR world, living standards increased slowly at best until the late eighteenth century. Nevertheless, there is significant and increasing total aggregate demand growth.

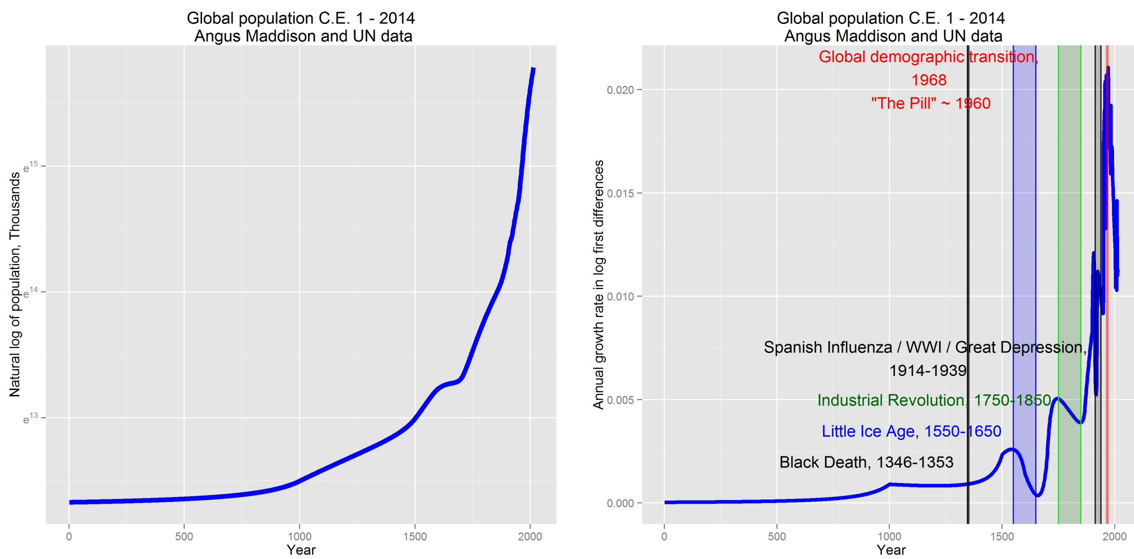


Figure 3.1: Angus Maddison and UN: log and log differences of global population

There are many approaches to understanding the great event that is the EIR from purely institutional to purely economics driven. The next sections relate several stories of the The English Industrial Revolution and the rise of industrial capitalism.

3.3.2 Jan de Vries from Early Modern Capitalism—a survey

Jan de Vries writing in a chapter in Maarten Prak's edited volume *Early Modern Capitalism—Economic and social change in Europe, 1400–1800* clearly defines the great debates among the various disciplines and schools who continue to attempt to explain the English Industrial Revolution.

de Vries' chapter "Economic growth before and after the Industrial Revolution—a modest proposal" explains the contours of the debates and in the end argues for a broad historical approach rather than one dominated by a particular school of thought [26].

3.3.2.1 Different schools produce an ahistorical approach

de Vries opens by analyzing the problems in past and current approaches: "Coherent accounts of historical economic growth are difficult to achieve only in part because of the venerable jurisdictional boundaries that have for so long governed the training of professional historians" [26, p. 177]. This allows for potentially different stories among eighteenth–century (early modern) and nineteenth–century (late modern) histories.

"One might suppose that what historians tear asunder with their conventions of periodization, economists would stitch together with the healing balm of theory" [26, p. 177]. However, before the neo–classical era, economists applied classical models with some binding constraint, usually land, whether the modeler followed Smith, Malthus, or Ricardo in details. Later neo–classical modelers assumed constant returns to scale, substitutability at all margins, and technologies freely available to all, and thus told a story abstracting from time and space—no history and no geography. Thus, he introduces his case for a more integrative approach to fix the rifts in both historical and economic story telling.

de Vries reviews the commonly–held neoclassical model's "bookends" of the EIR, meaning the neo–Malthusian model that precedes it, and the Kuznetsian model of modern economic growth that follows it as a unitary growth model with a single long–term trend; de Vries accepts the revisionist criticisms from many, including Mokyr [77], Jones [57, p. 26], and Crafts [21]. The revisionists claim the EIR covered a longer period and had a slower rate of growth than Kuznets' version. de Vries does not fully dismiss the bookends but instead appeals to the complexity of the event and says that we must revise those models. de Vries dismisses as un–historical and un–empirical the neoclassical "Solow" convergence models.

de Vries sketches the post–Industrial Revolution contours of modern economic growth using the empirical work of Simon Kuznets, Phyllis Deane and W. A. Cole, and Angus Maddison. He supports and explains the empirics with the neoclassical growth theory represented by Robert Solow's work that highlights the role of technology. These works describe a higher growth structural break from the prior rate of economic growth and is supported by a growth theory that demands technological change for its growth engine.

3.3.2.2 The neo–Malthusian model: Pre–industrial growth

Next, de Vries outlines the pre–Industrial Revolution neo–Malthusian models. He cites a large number of contributors, including François Simiand, Wilhelm Abel, Ferdnand Braudel, Michael Postan, E. H. Phelps Brown and Sheila Hopkins, B. H. Slicher van Bath, Emmanuel Le Roy Ladurie, and the team of E. A. Wrigley and R. S. Schofield. The consistent essence of this model is that movement in populations, fuelled by sexual relations, is the dominant economic relationship and is always constrained by a more–or–less fixed supply of land to feed the population and an agricultural technology at its frontier [26, p. 181].

Surveying the extended era of pre–industrial growth, de Vries summarizes that given the "revised view of British macroeconomic performance during the Industrial Revolution…" (less than earlier estimates) "…would appear to require that significant pre–industrial growth took place in the long run" [26, pp. 188–189]. He cites contributing factors to this secular growth as including institutional development, urbanization, demographic control mechanisms, market expansion, agriculture, industrial organization, and technology. These are all important proximate events; this chapter investigates if one can be identified as a primary or ultimate cause.

3.3.2.3 Wrigley's neo–Malthusian world

E. A. Wrigley models the Malthusian world, which he describes in *People, Cities and Wealth*. The main components of the Wrigley model include living standards (most often represented as gross domestic product per capita), nuptiality (marriage) rates and ages, and fertility rates. In the neo–Malthusian world before about 1880 in England, there is a strong positive correlation between living standards and nuptiality rates and also a very strong positive correlation between nuptiality rates (and age at first marriage) and fertility rates. In this world, as living standards fluctuate upward, due typically to exogenous factors such as better weather and crops, more women marry at a younger age and therefore, increasing fertility rates drive up population levels.

Wrigley's (and Scofield's) Wrigley [123, p. 237] major correlations for his neo–Malthusian model for England are summarized in Table 3.1.

Thus rising population caused lower living standards and retarded fertility through the nuptiality mechanism. Wrigley claims a different mechanism for China's version of a neo–Malthusian model as shown in Table 3.2.

Wrigley summarizes the "Chinese" version of his model this way: "Here to balance the books nature audits with a red pencil" [123, p. 236]. This neo–Malthusian variant was not the most pleasant of existences.

The fundamental importance of Wrigley's theories is that they fit the historical data

Table 3.1: English Malthusian model

Factor 1	Factor 2	Sign of correlation
Population increase	Food prices increase	Positive
Food price increase	Real income decrease	Negative
Real income decrease	Nuptiality decrease	Positive
Nuptiality decrease	Fertility decrease	Positive
Fertility decrease	Population decrease	Positive

Table 3.2: Chinese Malthusian model

Factor 1	Factor 2	Sign of correlation
Population increase	Food prices increase	Positive
Food price increase	Real income decrease	Negative
Real income decrease	Mortality increase	Negative
Mortality increase	Population decrease	Negative

that we know describes the millennia preceding the EIR in terms of population and living standards and suggest how radically these changed post–Revolution. The history is of increasing total final demand because of gradually rising population and occasionally rising living standards. However, the rising final demand eventually ran into some constraint or set of constraints that caused living standards to fall.

Only in the late eighteenth century was this perpetual cycle interrupted, allowing persistent and simultaneous increases in both population and living standards. Total final demand started marching inexorably upward and the supply revolution that was the EIR was able to continually match the population's rising desires and incomes for the first time in history.

3.3.2.4 From two models to one

de Vries approaches the great question of how to explain the miracle of the EIR by quoting from David Landes:

> In a polemic directed against revisionists of the Industrial Revolution, David Landes excoriates economists in general and Cliometricians in particular for being 'passionate seekers after the One Cause, the prime mover.' He (Landes) observes that these methodologically sophisticated economists forget that everything is substitutable and hence nothing is indispensable,. . . and

praises the approach of 'multiple causation'. [26, p. 189]

de Vries further comments that "Landes fails to acknowledge that the search of the One Cause of the Industrial Revolution arises from the need to explain the lifting of the great constraint that defines the neo–Malthusian model" and then invokes Wrigley as a champion of the 'essentialist' (primary cause) approach [26, p. 189].

He concludes by describing a gradualist time line and then makes the case for a centrist approach, basically ignoring Wrigley's core essentialist message in *Continuity, Chance and Change* [124]. This chapter investigates the Wrigley approach.

3.3.3 Nicholas Kaldor

Kaldor attempts to explain the large regional differences in development rates and comments on the essentialist version of history. He verges on declaring economics as the primary or ultimate cause.

> ... industrial production requires a great deal of capital—both in terms of plant and machinery, and of human skills, resulting from education—but in explaining such differences in 'capital endowment' it is difficult to separate cause from effect. It is as sensible—or perhaps more sensible—to say that capital accumulation results from economic development as that it is a cause of development. ... Accumulation is largely financed out of business profits; the growth in demand in turn is largely responsible for providing both the inducements to invest capital in industry and also the means of financing it. [59, p. 339]

The rest of this chapter explores strengthening the essentialist message of the cause of the EIR, which then leads directly to explaining the rise of industrial capitalism. It develops a very basic theory of the EIR, which applies also to China and perhaps to other premodern industrialization attempts such as the Dutch Republic during the sixteenth and seventeenth centuries.

3.3.4 Industrial revolutions

The first chapter in this dissertation moves toward a theory of industrial revolutions centered on the EIR. It claims and demonstrates empirically that the EIR was essentially an energy revolution in the strong sense that without the energy revolution, there would not have been an event which has come to be called the EIR. The core elements of this theory are in AppendixB.

There was an up welling of populations and thus total incomes during the Middle Ages; this is temporally related to the Medieval Warming Epoch, which increased (likely globally) agricultural yields and influenced institutions and culture. Increased goods and services demand led to increased production in heat–consuming industries such as smelting, metal working, salt making, dyeing, and brewing. Heat–consuming industries used mainly wood (sometimes as charcoal) as their energy source. The rising wood demand deforested neighborhoods, regions, and countries. Wood prices rose dramatically for example in sixteenth–century England. This also affected household uses of wood for heating and cooking.

Producers and households naturally sought alternative energy sources. In England and China, that source was coal. Using coal for heating was not an easy technological transition for many reasons; the full transition was on the order of centuries. In the Dutch Republic, the energy source was peat. The Dutch ran out of peat supplies and their industrialization attempt stalled.

In premodern eras, the path to an industrial revolution was the transition from an inherently limited heat energy source—trees—to an essentially unlimited source—coal. Both England and China did this and further research should show that other areas in addition to the Dutch Republic did as well. However, this is only the first step on the path.

The main leap to a complete industrial revolution was learning to apply the new highly–scalable energy source to steam–powered devices to replace human and animal power. This invention unleashed the enormous productivity gains and scale that are the hallmarks and legacy of the EIR.

High wages in England provided sufficient incentive for inventors and entrepreneurs to invent and commercialize steam–power and this added momentum to the rise of industrial capitalism.

3.3.5 The demand for capital and its supply—the path to industrial capitalism

This section develops the derived–demand–for–capital story that causes the rise of industrial capitalism in England.

3.3.5.1 Transition from wood to coal for heating in England

In the "real economy" story of the previous section, there are clues that explain how the demand for capital arose that when paired with the capital supply story will present a picture of the economic foundations of industrial capitalism.

John Nef plays an important role in telling this story. Nef's 1932 two–volume work titled *The Rise of the British Coal Industry* is a little–cited work in recent scholarship, but is as definitive a work as one could hope for on a most important event of the EIR [81].

In Volume I, Nef lays out the case for the development of capitalism as a result of the level of investment needed in the nascent coal industry. Nef dates the start to the mid–sixteenth century along with the rise of using coal as a heating fuel. He discusses that the division of labor in the mining and transportation of coal was great, calling a mine or colliery "a Jack of all Trades shop" [81, p. 348]. Most of this labor was wage–labor from workers who depended entirely on these wages for their living and that is a signature feature of capitalism. Quoting Nef as he captures the state of capitalism across the continent as well as in England:

> There was no other British industry of equal importance which had advanced so far on the road to modern capitalism. This observations leads naturally to the question: How far does the expansion of the coal industry in Great Britain at an earlier period than in any other part of the western world account for the fact that the new capitalistic order, which, before the reign of Elizabeth, had found more fruitful soil in Italy, Flanders, and southern Germany than in England, should have obtained, during the seventeenth and early eighteenth centuries, a tighter hold on the economic life of England than on that of any continental country? How far, in other words, is the growth of modern capitalism as the dominant form of economic organization related to the rise of the coal industry? [81, p. 349]

He then develops the case for the large demand for capital in the first phase of the EIR—the transition from wood to coal for industrial and domestic heating. He relates the large costs of exploratory drilling, deep structural requirements (up to 36 fathoms), and drainage requirements, sums far beyond the resources of a few workers to supply on their own. He relates many cases of individual investments (capital supply), and concludes the section on the capital requirements of coal mining by saying "For the first time in western Europe, in connection with an industry employing a considerable portion of a country's population, large capitals had become the rule" [81, p. 380].

These events begin in the sixteenth century and grow dramatically in the seventeenth and eighteenth centuries, and thus precede the dating many other estimates claim for such a beginning for the EIR. Nef further elaborates on the even higher capital requirements for transporting mined coal; the early mines were in north east England, far from London and other consumption centers. This required capital investment in boats, wharves, warehouses, wagons, and roadways.

Are we yet at what we might recognize as industrial capitalism? No, but we have in the investment required for coal mining an engine of demand for capital that leads inexorably to nineteenth–century institutions.

The capital supply required came mainly from wealthy merchants and nobility. Thus, the story of the rise of merchant capitalism, an activity that had relatively low capital demand and high capital accumulation (supply) is important. Eric Mielants in his *The Origins of Capitalism and the 'Rise of the West'* makes the strong case for a rise in merchant capitalism among the western European city–states between 1000 and 1500 CE [75]. This becomes an important capital accumulation source to supply the capital investment required by the EIR.

This first phase of the EIR has given us two critical pieces of infrastructure: the technologies and physical infrastructure for the mining, transportation, and consumption of coal for industrial and domestic heating applications; and a financial institution—merchant capitalism—capable of supplying the comparatively large capital needs of the physical infrastructure.

3.3.5.2 Transition from muscle to steam power in England

The second phase of an industrial revolution is the transition from muscle power of both human and other animals to mineral (coal) power. This is exemplified during the EIR by the increasing substitution of steam–power for muscle–power for both commodity production and transportation. This promotes a great increase in labor productivity and—given distribution—living standards. A key invention is of course the steam engine. By contrast, China knew of steam engines by at least the seventeenth century, but they did not apply them to practical applications until the nineteenth century [116, pp. 31–54].

However, in England, this was not the case. After making the wood–to–coal heating transition, England made the muscle–to–machine power transition by increasingly taking advantage of the enormous energy and power supply scalability of coal–fired steam engines.

The English had strong economic incentives to apply machine technology as a substitute for high–wage English labor throughout much of the early–modern era. This argument extends the work of Robert Allen *The British Industrial Revolution in Global Perspective* [7] who covers this transition as well. The Chinese had little such incentive—wages are thought to be low during the relevant historical periods.

This application of economic incentives is sufficient to explain why England completed their industrial revolution and China did not. Section 3.4 discusses Chinese economic transitions in greater detail.

As England proceeds on the path toward the EIR, the demand for capital increases. Capital is now required for building the new steam engines, steam–powered factories, and the steam–powered land– and water–transportation systems. So we have an energy source revolution causing the derived demand for capital to increase dramatically. By this stage in English history (eighteenth century and later), more formal financial systems were increasingly participating in creating credit to supply the inventors and entrepreneurs with needed capital.

The muscle–power–to–steam–power transition story is masterfully told by French historian Paul Mantoux in *The Industrial Revolution in the Eighteenth Century* [69]. Mantoux published this in the original French in 1907; the first English translation was 1928. Mantoux is another great historian who is under–cited by contemporary economic historians, to their detriment. T. S. Ashton in the preface to the 1961 edition says:

> . . . in both its architecture and detail this volume is by far the best introduction to the subject in any language. It is, moreover, a permanent work of reference. . . . It is astonishingly fresh. And not a few of the findings of modern writers that one had thought of as new are now seen to have been anticipated by M. Mantoux. His book is one of a few works on economic history that can justly be spoken of as classics. [69, p. 23]

Mantoux draws a clear distinction between “manufacture” and the “factory system.” Manufacture is to him the centralization and division of labor; the factory system expands upon that by using machine power instead of labor power. Woven throughout is the role of first the merchant capitalists and then the great landowners in this centralization of labor and its mechanization, including the transportation infrastructure required for the associated expansion of exchange (trade). Mantoux covers in great detail the ways this evolution of production affected the "whole economic system and consequently the whole social system, which is controlled by the growth and distribution of wealth." [69, p. 25]

Among the industries Mantoux cites is the woollen industry during the Renaissance, starting in the the fourteenth century and the seventeenth and eighteenth centuries. Specifically, he relates "the existence of capitalist undertakings, particularly in the woollen industry, and the beginning of the sixteenth century and even in the fifteenth and fourteenth" [69, p. 33]. He also describes these capitalist roots: "Instead of being mere merchants, buying cloth from the weavers and selling it in markets or at fairs, they [rich cloth merchants in the north and west of England] set up workshops which they supervised themselves. They were manufacturers in the modern sense." [69, p. 33]

This story seems to be clear evidence of early roots of English industrial capitalism. One must next ask why would these merchants travel this path and what were the expectations of the future of their business that motivated them? While Mantoux does not directly address the growth of demand that surely must be behind the merchants activities, he talks about a proxy for that.

That proxy is commercial expansion starting before and continuing during the early modern period. One can ask why would such a commercial expansion arise? Was it *sui generis*? Almost certainly, the cause here was the increase in populations in at least the countries comprising the trading world, including England and its export targets. As an illustration of continually–rising population levels, refer again to Figure 3.1.

Mantoux further analyzes land redistribution in England and focuses on the enclosure movement. This episode is fascinating and important in that it freed agricultural labor to urbanize and provide the labor source for the EIR and, as a by–product, raised agricultural productivity. The story of the thirteenth–century water–powered mechanization of the woolen–industries' fulling process is reviewed in the introduction. See this description in Section 3.2.2.

Mantoux traces the beginnings of replacing labor with machinery in the textile industry and the role of capitalist undertakings resulting in the rise of the factory system. He discusses the technologies such as the knitting frame and the silk throwing mill and their inventors in detail. This includes a fascinating narrative on the transition from tools to machines that changed the nature of labor described as essentially a skill transfer from man to machine; this initially uses wind and water power but enables the application of steam–power when that becomes technically and cost feasible [69, pp. 189–191].

Not all important inventions were developed in England. Mantoux relates the story of John Lombe pirating Italian silk–throwing technology and using it to build a very large (five hundred feet long and five or six stories high) Derwent factory that was centrally powered by a water wheel. This was in about 1718 and illustrates his three key points: the skill transfer from men to machine, the power transfer from men or animals to something much more scalable, and the demand for capital to realize this achievement. John's brother Thomas supplied that capital; the capital source is likely from Thomas' merchant activities. The factory employed about three hundred workers [69, p. 191].

This clearly was the prototype for the future of the factory system in cotton and woollen textiles and thus heralded the course of the EIR over the following 150 years. The more famous inventors and entrepreneurs such as John Kay (fly shuttle), John Wyatt (cotton spinning machine), William Hargreave (spinning jenny), and Richard Arkwright (water frame) built on this successful factory template, created the EIR, and greatly increased the demand for capital.

The factory system was a fertile ground for the application of steam–power; this loosed the constraints of finding a suitable water–power location or unreliable wind power source and thus began the essentially uninterrupted productivity rise, leading to ever–increasing per–capita living standards. This also led to the revolution in land transportation represented by the railroads and the maritime transport revolution of the steam ship. And all of these events led to a great increase in the demand for capital.

While actual aggregate capital stock data are sparse for the era, a simple illustration will show the growth–rate leverage capital had as growing population demands drove aggregate output.

An article by Jeffrey G. Williamson, "Why Was British Growth So Slow During the Industrial Revolution?," provides a survey of capital growth rates and, importantly, estimates through time of the Capital/Output ratio. Williamson draws on work by Phyllis Deane, Floud and McCloskey, and Simon Kuznets. The data are partially reproduced [121] as Table 3.3.

Table 3.3: British capital productivity. *Source:* Data from Jeffrey Williamson [121, p. 702]

Period	Capital's productivity Y/K	Calculated K/Y
1761–1820	0.36	2.78
1791–1820	0.38	2.63
1821–1860	0.53	1.89

Before 1820, for every additional British pound of aggregate output, more than 2.6 British pounds worth of capital stock was required. During this period, gross domestic product estimates went exponential in Britain. Note that while growth rates of GDP and capital will be the same, the capital growth rate adds to an ever larger base such that capital accumulation is increased at the multiplied rate.

It does not appear from either Nef or Mantoux that capital supply was a real constraint with investment flowing from wealthy merchant capitalists, wealthy landowners (often nobility), and eventually a banking system. Instead capital appears to have been called forth by capital demanded to keep up with aggregate demand growth and the technical productivity factors summarized by the K/Y ratios in the table.

Thus, we have a straightforward supply and demand economic story for the rise of industrial capitalism. This was facilitated by the fact that capital stock is consumed only over many units of output, and thus the relative mathematical ease of building large capital accumulations during the nineteenth century.

3.3.6 The primary roles of capital in the EIR

Tangible capital has two primary roles in the EIR:

The first is the infrastructure investment required to extract and transport coal as a scalable energy source used initially to substitute for ever more expensive wood–supplied Joules in heat–using applications. Increasing demand caused deforestation causing rising wood prices. Compared to using wood as the primary heat source, English coal supplies were distant, deep, wet, but ultimately cheaper than wood. As John Nef documents [81], the investment required for successful coal extraction and distribution was large and historically unprecedented.

The second is to replace muscle–supplied power inputs to the production process with steam–powered mechanical devices. The energy input is largely from coal during this revolution so the tangible capital assets use coal energy inputs to provide power in the form of rotating or reciprocating motion through the mechanical application of steam—the steam engine.

There is an important class of mechanical devices—gears and levers—that amplify muscle power by allowing increased muscle power input for a given output, thus allowing low-intensity muscle power to leverage up their power inputs to accomplish higher–intensity tasks. Note that this requires added muscle Joule inputs for a given amount of output, recognizing the energy input constraint that humans have fixed potential power output per unit of time; the important EIR capital devices allow essentially unconstrained energy inputs per unit of time. The purely mechanical muscle assists are not the important technologies in the second phase industrial revolution.

There were noncoal nonmuscle power inputs to manufacturing through much of recent history. These were either water– or wind–powered rotary and reciprocating machines and were precursors to steam–powered machines. In recent scholarship Örjan Wikander claims "Today, we may state with confidence that the breakthrough of the water–powered mill did not take place ... in the early middle ages, but rather ... in the first century A.D., or perhaps even slightly earlier." The water wheel was known and used during the late Roman republic or the early empire (as cited in [109, p. 224]). The Arkwright water frame was an EIR water–powered mechanical cotton spinning device, but the true energy revolution was fulfilled when the essentially unconstrained scale of steam power was applied through such devices to manufacturing processes.

Note that in the theory of industrial revolutions (formalized here in Equation 2.3), capital is always labor substituting since the Joules of energy that are production inputs are either muscle or fossil inputs but not both. Tangible capital applies additional fossil Joules to industrial processes. Rather than the normal economic analysis of labor substitution, this frameworks suggests that the economic analysis of capital inputs may be better understood as how much energy input can be added to any process. Of course both organic and inorganic energy input sources for a production process can be mixed and it is this frequent case that causes the "complements" versus "substitutes" economic conversation.

To crystallize the increase in scale the energy revolution represented in choosing among energy input sources, Fred Cottrell wrote *Energy and Society* in the mid–twentieth century: Cottrell sharply contrasts low–intensity and high–intensity energy regimes and societies. Low–intensity "converters" include human and animal power using plant–based input sources, and water– and wind–mills [20].

The first high–intensity converter in Cottrell's history is the sailing ship that provides at least an order of magnitude increase in energy surplus over low–intensity converters, and dramatically changed the economics and institutions of the world's economies.

Cottrell recognizes that the most disruptive high–intensity converter was the steam engine—the signal technology of the EIR. The steam engine disrupted the economic systems and their social systems and institutions, a legacy of turmoil that continues to this day.

3.4 Evidence of Chinese industrial capitalism

With the case made above that industrial capitalism is a more–or–less expected outcome of an energy–driven industrial revolution, a series of interesting questions regarding historical China can be asked. The questions are designed first, to detect if there were enough economic incentives in historical China to foment at least the beginnings of industrial capitalism, and second are there other markers of capitalism and industrial capitalism that would support a positive answer to the question. If there is sufficient evidence, then we can think about possible generalizations of the rise of industrial capitalism across otherwise disparate economies.

The main questions we would like to answer about China during the three eras we have some data on are:

- What is the aggregate demand posture of China during the Sung, Ming, and Qing dynasties? This is primarily an investigation of population level changes.
- What are the price levels and dynamics of energy inputs?
- What are the price levels and dynamics of labor inputs?
- What is the evidence of nonmuscle power energy sources?
- Is there evidence of large–scale centralized commodity production in any industry?

– What is the invention evidence relevant to a possible industrial revolution?

– Is there evidence of the building of a factory system?

– What is the evidence about wage labor?

– What is the evidence about integrated markets including labor?

3.4.1 A look at the data sources and interpretation

This section will investigate available evidence organized by the three eras—Sung, Ming, and Qing.

3.4.1.1 Sung dynasty: 760–1279 CE

Determining what is happening to aggregate demand is important to help understand the economic incentives inventors and entrepreneurs might face to overcome supply–side constraints if demand is increasing. In the three eras under investigation, much of aggregate demand is population–growth driven as the evidence indicates mean living–standards are at low levels and likely close to subsistence—except in the Sung era as explained below.

Robert Hartwell presents population estimates for China for the years 742, 1014, and 1064 CE. This span covers the period leading up to the start of the Sung dynasty in 960 CE and the first hundred years or so of that dynasty. This gives at least some idea of population dynamics [51]. The data are summarized in Table 3.4.

These population growth rates are very low and probably could not have by themselves provided much aggregate–demand–based economic incentives to entrepreneurs; if they

Table 3.4: Chinese population dynamics 742–1064 CE *Source:* data from Robert Hartwell [51, p. 34 Table 1 footnote *b*]

Year	Population–million	Period growth rate–midpoint	Compound annual growth
742	52.5		
1014	55.0	0.047	0.0002
1064	62.5	0.128	0.0025
Total		0.175	0.0004

are accurate, was there another dynamic in play? Hartwell claims that there was a large increase in living standards during the era:

> From about 750 to 1100, China experienced a series of economic changes roughly comparable to the subsequent patterns of European growth from the Crusades to the eve of the French Revolution. The spread in the use of money, development of new credit and fiscal institutions, increase in interregional and international trade, and colonization of hitherto marginal land which took place in the Occident during the half millennium preceding the Reformation was paralleled by an earlier era of progress in East Asia during the two–hundred–fifty years from the rebellion of An Lu–shan (755) to the treaty of Shan–yüan 1004). [51, p. 29]

Hartwell further presents evidence of significant increases in the real money supply and in the output of several industrial enterprises, including alum making, salt processing, quicksilver and cinnebar production, shipbuilding, making, and printing. He concludes that the best explanation is an increase in real per–capita income (and consumption).

His most "astonishing" estimate was the scale of production in the extraction and refining of metallic ores, including iron, copper, lead, and tin. In all these cases, he claims the scale of operation and absolute level of output were greater than any other national economy until the late eighteenth century. The iron output in the northern Sung increased six fold between 806 and 1078 CE. In 1078, that meant per–capita iron consumption of 3.1 pounds, roughly comparable to Europe's 3.5–4.3 pounds per–capita in 1700. Some northern Sung market areas had per–capita consumption of at least 7.0 pounds. These estimates suggest strong and growing industrial scale and output and support the idea that living standards must have been increasing [51, p. 31–33].

Iron relative price dynamics indicate that there must have been significant innovations and investment in those innovations between 997 and 1080 CE since the price ratio of iron to rice dropped from 632:100 to 177:100 [51, p. 33]. Examples of Chinese productivity–enhancing innovation include the use of water–wheel powered bellows in smelting operations as early as 31 CE, and the eleventh–century substitution of coke for charcoal as wood became scarce in Sung China. This prefigures the same dynamics starting in sixteenth–century England, although Alexander Darby did not discover coke use in England until the early eighteenth century. Sung China also prefigured England with major technical advances in silk production [54, p. 53].

The uses for iron output included armaments produced in government–owned armories and private Kaifeng manufacturers producing for market. The iron demand market appears well integrated based on records of transportation costs for iron that vary by distance from the production site as one would expect in an integrated market [51, p. 37].

There is an increasing contrast in the scale of the large iron works surrounding Kaifeng and the many traditional small smelting operations that co–existed and were likely spread throughout China. Mining and smelting in the large operations are "full–time occupations of wage laborers employed by ironmasters who owned the ore deposits and smelting plant and who provided the requisite operation capital. . . . By the last quarter of the eleventh century , over 3,600 full–time, free, wage–earning workers were engaged . . . at the thirty–six complex and costly mining and metallurgical establishments." [51, p. 45]. Wealthy families funded these large operations; at some point, they likely made the transition from wealthy landed gentry to industrialists—industrial capitalists—to meet the swelling demand for iron output.

Yoshinoba Shiba writes of many wage–paying occupations in the Sung dynasty that arose along with the growth of urban areas. His examples beyond agriculture include smithies, water mills, threshing yards, rice–cake shops, oil shops, tea plantations, orchards, fish–rearing pools, building, transport and communications, and the handling of cargo [97, p. 209].

These stories expose two hallmarks of capitalism—wage labor and capital–intensive profit–oriented production for exchange. Hartwell draws many comparisons between the Sung and eighteenth–century England in these respects—capitalism seems to have common seeds across space and time.

The controversy of whether the economic successes of the Sung era spread across China in later eras continues. One group claims a decline in living standards after the Sung period of intensive growth. Another claims that the Sung successes did indeed spread but modern economic growth stalled [111, p. 406]. Mark Elvin's "high level equilibrium trap" describes this second view [33, p. 285]. Are there possible economic hints about what happened?

Recall that Hartwell's data show very low population growth during the Sung era. Refer to Table 3.4. If output is growing ahead of population growth rates, it is likely that wages must be increasing. Using the theory of industrial revolutions logic, this would account for productivity–enhancing investments during the Sung—substituting cheap nonmuscle power for expensive labor power. Refer to Appendix B. In the next section, we will see that population growth exploded in later eras but productivity and wages likely stagnated and even decreased. This is a clue then as to why Sung China's incipient industrial revolution stalled—not enough expensive labor pressure to drive productivity innovation and investment.

3.4.1.2 Ming dynasty and Qing dynasty capitalism

Xu Dixin and Wu Chengming edited a major work of Chinese history: *Chinese Capitalism, 1522–1840*; this was translated to English in 2000. Notably the work was commissioned by Premier Zhou Enlai to produce a history of Chinese capitalism as China was exiting the Mao era of experimentation. The translation of its original title is "The Sprouts of Chinese Capitalism" [126, p. ix]. Its methodology is rigorously Marxist—seeking evidence of capitalist relations of production in various sectors. Evidence includes commercial capital investing for profit; integration of markets across regions, the nation, and internationally; industrial capitalism with large producers emerging either from small producers or investments by commercial capital; and a propertyless full–time wage labor force employed by capitalists [126, p. xv].

The analysis is meticulous. Within the boundaries of the scholarly debate over the course of the early–modern Chinese economy, this work is "situated at the cautious end of this spectrum" but mostly rejects the idea of a major decline in overall living standards. This contrasts with the conclusion of Chris Bramall and Peter Nolan in the introduction that surveys recent scholarship.

Their view is that "It is now abundantly clear that there was a long sustained phase of economic development interrupted only in the mid–seventeenth century" [126, p. xxiii]. In coming to this conclusion, they cite Mark Elvin [33], W. T. Rowe [96], and Li Bozhong [65]. Li in particular takes a more positive view on the advance of embryonic capitalism in the early modern period. In fact, his approach focuses on the most advanced economic areas including the lower Yangzi region—the same comparison that Kenneth Pomeranz and other "California School" historians make [126, p. xxvii].

In his conclusion, Fang Xing summarizes the findings on embryonic capitalism. First, there clearly was embryonic capitalism that paved the way for the modern capitalism since the new industries are founded on old industries that incorporated elements of capitalism. Among these elements are creating social conditions for employment of labor by capitalists—there is a ready supply of skilled workers available for hire for example in the tea and textile industries suggesting elements of a market for labor; long–distance trade exists in the products of Ming and Qing industries where capitalist relations appear; and early capitalist elements in several industries provide a physcial and capital base for modern industry—these include calendering, tobacco processing, printing and book production, and shipping [126, pp. 424–427].

These are markers of capitalism—labor markets populated by wage laborers, integrated long–distance markets, and innovation and investment in physical capital that also, because of the durable nature of physical capital, implies capital accumulation. But for more evidence that can provide hints about why pre–modern China did not participate in the level of growth after 1800 that England did, we can turn to Robert Allen.

First, Allen provides data indicating that integrated Chinese labor markets existed at the beginning of the nineteenth century. This is presented as a table of daily nominal wages for the same occupations and skill levels across many prefectures [9, p. 46]. One can see essentially the same level wages, an indicator of an integrated labor market, even though at a much lower level than contemporary European wages.

Kenneth Poemeranz comes to similar conclusions finding that the use of labor in China around the eighteenth century conformed to principles of a market economy (wage labor and market integration) at least as well as in Europe [90, p. 70]. While these are revisionist scholars, they do provide convincing evidence of wage–labor markets in China.

However, it is the level of the wages that provides a major clue on the apparent very slow upward trend in early modern Chinese growth. Figure 3.2 shows that real wages in Beijing were low by world standards and declining.

When combined with relatively high energy costs in China and presented in Figure 3.3, note that the ratio of real wages–to–energy costs was very low in China, especially compared to England.

In the terms of the theory presented in Appendix B, Chinese inventors had very low economic incentives to invent, innovate, and commercialize productivity–increasing investments as long as wages were so low compared to the energy costs that were needed to

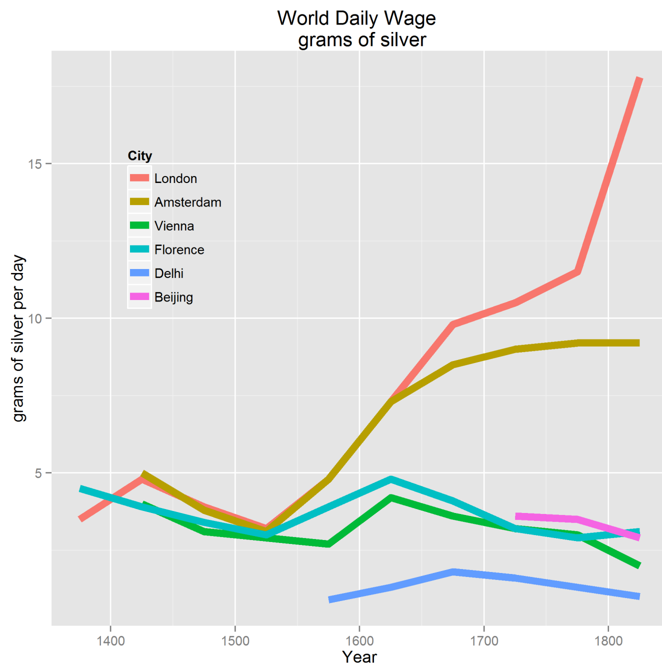


Figure 3.2: World wages, 1375–1825 CE
Source: data from Allen [7].

power them.

3.5 Conclusion

This chapter presents evidence that the rise of industrial capitalism can be explained by basic economic principles: demand and supply; profit–seeking by entrepreneurs; and input substitution in production based on relative input prices.

Demand as an economic principle dominates the story. The seldom interrupted rise in global population since 1 CE is mirrored in national population growth rates in England and China. Even in millennia characterized by subsistence–level–living standards, this provides increasing potential market size that often pushes against perpetual supply constraints—the Malthusian story. One of this chapter's claims is that the supply constraints are often energy inputs—either too expensive or simply not enough to supply the required scale.

Secondly, demand enters the story in another important way. As inventors and profit–seeking entrepreneurs invest to remove the supply constraints, they naturally accumulate capital. Since capital is essentially nonrival, meaning it is not consumed in the production process, it will—even with a strict assumption of constant capital–to–output ratios—

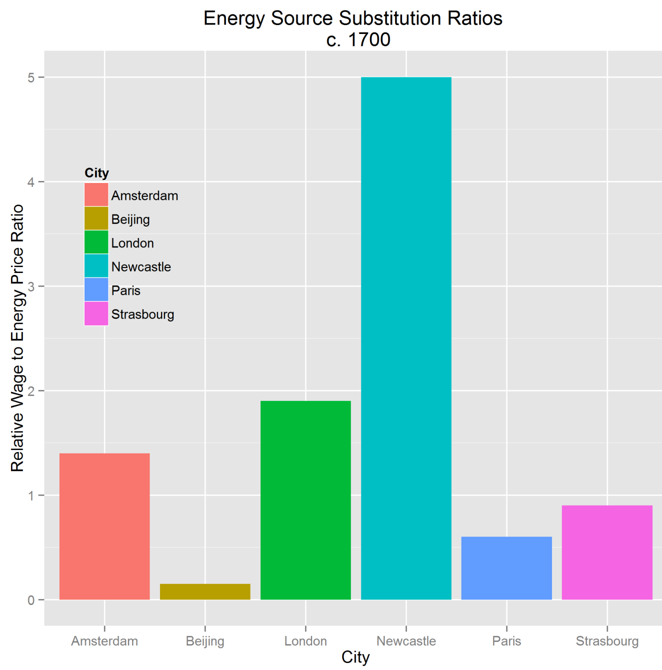


Figure 3.3: Real wage–to–energy price ratios
Source: data from Robert Allen [7].

accumulate rapidly in the face of population–growth–driven demand increases. Viewing economic history through this lens suggests that—given population increases and supply constraints—the rise of capitalism in its most productively–efficient form of industrial capitalism is inevitable.

Breaking supply constraints is not a trivial exercise—it took the English several centuries of invention and innovation. To explain the willingness and persistence of inventors, innovators, and entrepreneurs to make the necessary time and treasure investments requires an explanation of incentives. When the price of nonmuscle–energy inputs drops sufficiently relative to the price of muscle–energy inputs, economic incentives come into play to justify the difficult work of inventing and commercializing the labor–substituting technologies of the English Industrial Revolution. And a probably inevitable outcome given the levels of physical capital required is industrial capitalism.

China over many centuries longer than England and Europe displayed "sprouts of capitalism." As in England, these were driven partly by the investments required for China to overcome deforestation–driven–energy–supply constraints in the first millennium in the face of increasing population and aggregate demand. In a strong contrast with

England, equally–capable Chinese inventors, innovators, and profit–seeking entrepreneurs face relatively high energy costs and low wages. And while China likely continues to slowly grow in living standards through the second millennium, once cumulative English advances began to pay off in the early nineteenth century, China simply does not have enough gathering momentum to prevent the “Great Divergence” that we call the English Industrial Revolution and the rise of industrial capitalism.

Given an understanding of the rise of industrial capitalism as an institutional phenomenon primarily caused by a centuries–long population–driven increase in aggregate demand, what happens next? Referring to Figure 3.4, we note that since about 1970, the growth rate of global population has been moderating and it appears possible it will approach zero sometime in the middle of the twenty–first century. When that happens, the aggregate–demand engine that drove industrial capitalism will start grinding to a halt. It is unknown if that will be enough to damage the institution, but for the first time since the dawning of the age of industrial capitalism, its fundamental driver will start to disappear.

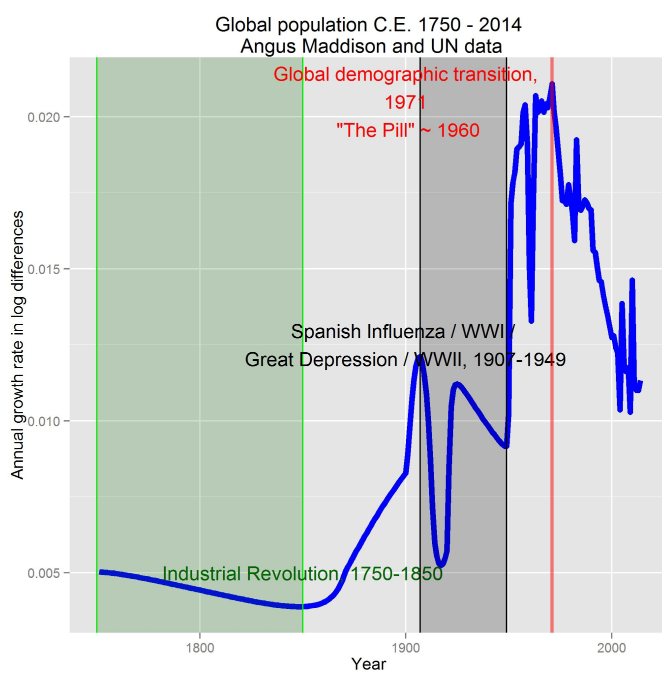


Figure 3.4: Log differences of global population
Data from Angus Maddison and UN, chart by author.

APPENDIX A

CHINESE IMPERIAL DYNASTIES

Table A.1: Chinese imperial dynasties

Empire	Historical Era
Qin Dynasty	221–206 BC
Han Dynasty	202 BC–AD 220
Wei and Jin Period	AD 265–420
Wu Hu Period	AD 304–439
Southern and Northern Dynasties	AD 420–589
Sui Dynasty	AD 589–618
Tang Dynasty	AD 618–907
Five Dynasties and Ten Kingdoms	AD 907–960
Sung, Liao, Jin, and Western Xia Dynasties	AD 960–1234
Yuan Dynasty	AD 1271–1368
Ming Dynasty	AD 1368–1644
Qing Dynasty	AD 1644–1911

APPENDIX B

TECHNICAL APPENDIX

B.1 Importance of energy for growth and development

Table B.1: Energy/GDP correlations – the case for energy revolutions

Period	Pearson Correlation Coefficient: energy and GDP
England 1300-1873	0.998
World 1980-2008	0.993

B.2 Cross-country history of energy consumption

Table B.2: Per–capita primary energy consumption, annual tonnes of oil equivalent. *Source:* Data from Angus Maddison, [a]de Zeeuw, [b]US DOE EIA

Year	England	China	Netherlands	India
1650[a]			0.63	
1820	0.61			
1840[a]			0.33	
1870	2.21			
1970[a]			8.07	0.33
1973		0.48		
1998[b]	6.56	1.18		
2008[b]	5.99	2.56	9.86	

B.3 Theory of industrial revolutions

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:

$$\frac{\text{Marginal Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Marginal Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}, \tag{B.1}$$

or if one prefers a non-neoclassical writing:

$$\frac{\text{Average Product}_{\text{wood Joule}}}{\text{Price}_{\text{wood Joule}}} \ll \frac{\text{Average Product}_{\text{coal Joule}}}{\text{Price}_{\text{coal Joule}}}. \tag{B.2}$$

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. This is the first phase of an industrial revolution.

Equation B.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.

$$\frac{\text{Average Product}_{\text{labor Joule}}}{\text{Price}_{\text{labor Joule}}} \ll \frac{\text{Average Product}_{\text{steam Joule}}}{\text{Price}_{\text{steam Joule}}} \tag{B.3}$$

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 B.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.

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