Economic development with unlimited supplies of energy:

causes and consequences of industrial revolutions *

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1 General introduction

This dissertation contains two related papers and this 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

*In the spirit of Sir William Arthur Lewis

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, Paper one documents an added noteworthy instance, that of the iron and steel industry in Sung China (960–1148 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.

2 Paper one – "What really happened in the English Industrial Revolution?"

This paper is at the core of my project to understand the link between economic growth and energy. By analysing two very long series – English gross domestic product and English energy consumption – I fairly quickly conclude that there is essentially no difference between these series; this was a strong influence on the methods I used. Originally I had planned (and did) a cointegration analysis to test my hypothesis. But, presented with the graphical evidence and very high correlation, and the gentle input of my chair, I did not proceed with that. This is an important lesson – as Einstein makes clear: "Everything should be made as simple as possible, but not one bit simpler."

That is not to say that this is simple; the vast majority of economic and other historians attribute one or more aspects of culture or institutions as causing the EIR. These changes were certainly large, but my sense is they would not have happened, at least the way they did, without the great surge in output and wealth that can only be explained by learning to consume a virtually unconstrained amount of energy in the production process. So that is my claim. And I then use both macroeconomic and microeconomic theory to support the case.

After the introduction, sections two and three briefly discuss the research question and the hypothesis that the EIR was an energy revolution that created modern economic growth.

In section four, using the data series with some help from statistical structural change methods, I describe four energy/GDP eras covering the historical period. Each has different aggregate demand and supply characteristics. Here is a brief summary of each:

Table 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

The important conclusion is that until 1750, except for brief periods, economic growth for 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. Under this data, I claim 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). I discuss the Malthusian constraint and its lifting in paper three.

In section five I discuss the findings and present further supporting evidence.

Another interesting conclusion is the result of Granger tests of the four energy/GDP eras and the whole period. I find that for the entire period GDP Granger-causing energy consumption and

energy consumption Granger-causing GDP are both significant so there is a feedback between them as I would expect given both the very high correlation coefficient, discussed above, and the basic thermodynamic requirements of economic activity.

However, the GDP-to-energy Granger causality is a bit more significant than the other direction; this could be interpreted as supporting a demand-led regime throughout the period. And that is further support for my macro claim that population-growth-led demand was a primary cause of the EIR.

In section six, using the analytical results, I construct a narrative story of the EIR around the four identified energy/GDP eras.

Then, using these eras inductively, I construct a theory of the EIR and, perhaps, a generalizable theory of industrial revolutions. The theory is in two parts. Part one formalizes the substitution of coal for wood in industrial and domestic heating applications. The substitution mechanism is straightforward micro theory, with cheaper coal Joules substituting for increasingly expensive wood Joules. I present a series showing wood prices in the late middle ages-early modern periods to support this claim. The substitution was technically challenging and slow to realize given the more toxic emissions from coal-based heat. This stimulated inventions, including the claim by Robert Allen of the invention around London of the "coal-burning house."

This transition to coal for heating was the essential prerequisite for the second part of the EIR, and my theory, as it unleashed an essentially unconstrained supply of energy compared to prior sources. That enormous supply of energy began to be translated during the later seventeenth century and throughout the eighteenth century into the steam power that drove the later EIR. The theory is, again, a story straight from entrepreneurial business logic, and from principles of microeconomics.

This time cheap coal Joules were substituted for increasingly expensive animal muscle Joules. This includes, of course and somewhat uncomfortably for those with a Marxist bent, substitution of steam power for human power in the mechanical factories of the EIR and later periods. I believe this simple theory, supported by Robert Allen's data showing high wages and cheap energy in England, is especially useful in today's ongoing debate over automation of many production processes. In future work, I hope to contribute to clarifying and correcting some of the current arguments. There is contemporaneous written evidence of this substitution mechanism, clearly framed as profit maximization/cost minimization, and this I claim was sufficient to incentivize the inventors and entrepreneurs to develop this difficult and technically advanced technology.

Section seven sketches many unresolved questions. Section eight concludes.

Summarizing the claims in paper one,

> The EIR was, primarily, two energy revolutions driven by demand from rising population levels.
>
> Rising population drove rising aggregate demand sufficiently to attract inventors and entrepreneurs to eliminate supply side constraints. We now call this the Kaldor-Verdoorn law.
>
> The primary supply-side constraint was energy; the transition from wood to coal, first for heating then for power, eliminated the constraint.
>
> We can apply the economic theory of input substitution due to changing price ratios to energy inputs to understand the motivation inventors and entrepreneurs faced to develop and commercialize difficult technical advances. While large institutional changes happened during and because of this process, they were not a primary cause. This becomes an evolv-

ing theory of industrial revolutions.

The energy revolution claim is supported by empirical analyses; the EIR, using the data, started in the late sixteenth century rather than 150 years later as in many accounts.

3 Paper two – "China – The empire that did not bark"

In this essay I explore the question of why China did not have an industrial revolution like England did. China had very large coal reserves, twenty-five percent of world population thus large and growing internal markets, a rich tradition of invention and innovation, and sufficient capital sources. Kenneth Pomeranz documents that the Yangzte Delta region, at least, was comparable to eighteenth century England in resources, living standards, and institutions. If final demand and functionally comparable institutions are sufficient for an industrial revolution, China in many ways was the logical choice. But it did not happen, and I give an explanation of why not.

After introduction, hypothesis and contribution sections, section four examines comparative data for England and China, and summarizes the important comparisons of institutions and their political economies. The conclusion is that, following Pomeranz and others, the institutions were functionally similar, and thus should not have *per se* obstructed China from having an industrial revolution if institutions were a primary cause for these events. Then I apply the "Allen" principle of high wages/low energy costs facilitating the EIR and find it did not hold in Yangtze China. This points to an economic explanation for the Chinese failure, supporting my main hypothesis.

Section five presents added empirical data, and section six concludes.

As part of my study, I analyze institutional similarities and differences for England and the richest part of China (the Yangtze Delta as extensively described by Kenneth Pomeranz) in the

late seventeenth and early eighteenth centuries. I attempt to discern if there were sufficient institutional differences to account for China's "failure?" My answer was no, the countries were not that functionally different – they both had markets, financial services, merchant trading and so forth. If that is correct, what could account for the difference in economic performance?

We know the following. First, China did complete a "phase-one" industrial revolution culminating during the Sung dynasty (approximately CE 960 – 1279), meaning they did make a transition from wood to coal for domestic and industrial heating. This was driven by, anecdotally, deforestation causing wood and charcoal prices to rise in the face of rising population and therefore rising aggregate demand. Thus they had no energy supply constraint to prevent the transition to steam power. I elaborate on the story of Sung China's early-second-millennium large iron industry in paper three.

Second, however, we know from the Robert Allen data that in 1700 the ratio of wages to energy costs in China was very low compared to England at the same time. Thus, applying the theory of industrial revolutions from paper one, the incentives and motivation to invent and commercialize energy sources and technologies to substitute for labour and other muscle power were missing compared to England, and therefore they did not complete their industrial revolution. While wage and price data is currently scarce for Sung China, I am prepared to speculate that if China then had the wage/energy price ratio that England had in 1700 they may well have had the second phase-industrial revolution of steam power replacing muscle power.

Summarizing the claims in paper two,

> I provide evidence for an early Chinese industrial revolution consisting of a "first-phase" energy revolution transitioning from wood to coal for industrial and domestic heating. This supports my theory of first-phase industrial revolutions as energy revolutions caused by

price-substitution mechanisms.

I provide evidence, following Kenneth Pomeranz and others, for functionally equivalent institutions in the relevant locations and periods in China and England, meaning the Yangtze Delta and early modern England. This, I argue, moves toward eliminating culture and institutions as primary causes for the "great divergence" in economic performance starting in the eighteenth century.

This is, then, a "natural experiment" of my Allen-price-ratio-based theory of phase-two industrial revolutions; China failed at this phase as their wages were too low to drive the essential substitution.

4 Paper three – "The rise and fall of industrial capitalism"

In this essay I examine the intertwining of population dynamics, global effective aggregate demand, and energy and industrial revolutions as they conspire to create the institution of industrial capitalism. In my story, the whole supply system, including its endogenous institutions, is driven by population dynamics. Until 1971 population growth rates steadily increased. I argue this created ever expanding demand, and this led directly through industrial capitalism to ever increasing capital accumulation.

Surprisingly to me, global population growth rates peaked at 2.2 percent per year in 1971; since then growth rates have fallen, perhaps even plummeted, to close to 1.0 percent per year in 2014, and almost surely are headed to zero growth. The first time in history that population grew at 1.0 percent or greater rates was around 1900. Given the dynamics of the supply system, I conjecture on the fate of capitalism with shrinking demand growth rates, eventually shrinking

demand levels, and thus shrinking demand for (productive) capital.

In order to underline population's importance for my arguments, I include graphs here from paper three, and briefly discuss them.

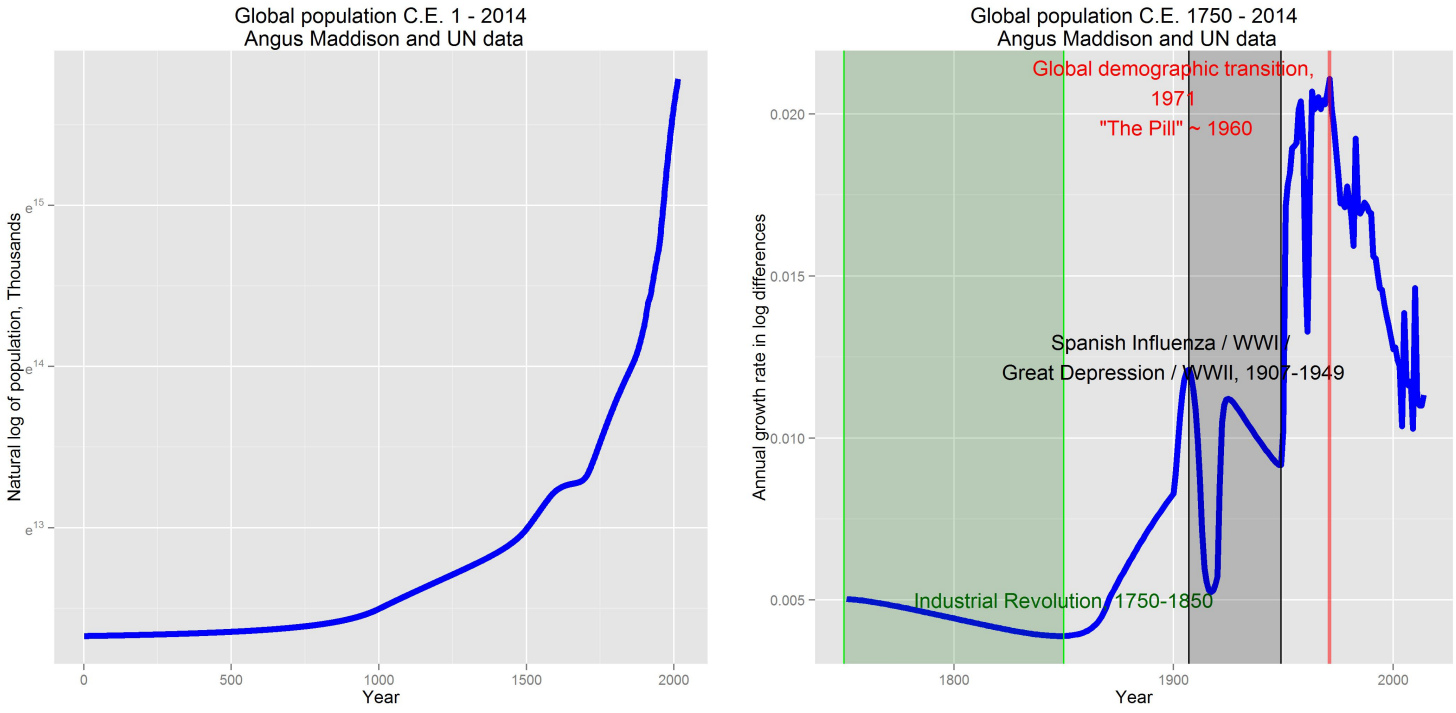

Figure 1: Angus Maddison and UN: log and log differences of global population

The left panel of figure 1 displays the log of population levels since year one. This is super-exponential growth, with barely visible wiggles. This population, and thus aggregate demand, growth dynamic drove the supply side into the EIR and created industrial capitalism. The right panel is in log differences of annual population levels since 1750 (a common starting date for the EIR), so shows 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, perhaps much, lower. If population growth was the underlying cause of industrial capitalism, then we must question the implications of its plummeting growth rate. I do so in a conjectural section in paper three.

After introductory comments, the essay's second section covers the important literature on this key intertwining of population dynamics-driven demand, supply-side economic responses, and the endogenous institutional growth arising from these powerful forces. The topics and authors covered in some depth are Karl Marx on Historical Materialism, Ruttan and Hayami on institutional endogeneity, a passing reference to Max Weber representing the vast institutionalist literature of all stripes, an in-depth review of Jan de Vries' excellent survey of (historically) recent thought on the industrial revolution and population dynamics, E.A. "Tony" Wrigley's significant contribution on both population dynamics and energy revolutions, and Nicholas Kaldor's contribution on essentialist causation.

Section three is a brief summary of the course of the EIR (generalized by my theoretical work); I have developed this story in other work included in this dissertation and I will not comment further here.

Section four develops the primary support for my claim that industrial capitalism was an outgrowth of the supply-side response to population dynamics during the relevant periods. Here I rely heavily on the work of three authors – John Nef and Paul Mantoux on England, and John Hartwell on Sung China. None are commonly cited, an unfortunate oversight. Nef recounts the rise of the English coal industry, and directly comments in multiple passages that this economically-driven event caused industrial capitalism. Mantoux has very similar comments on the transition to machine industry using English textiles as an important frame. Hartwell covers the wood-to-coal revolution in the Sung Chinese iron industry including recounting the several rich Chinese families that financed the significant investments.

Given my theoretical framework, I organize this section according to the wood-to-coal transition (Nef and Hartwell) and the muscle-to-steam transition (Mantoux). These authors provide

my main support for the primary claim of the essay.

Section five discusses capital's role in the EIR. This becomes a straightforward application of basic demand and supply laws. The primary story is the rise of demand for capital because of the energy revolutions; supply seemed never to be a true constraint.

Section six summarizes. Section seven contains my conjectures on industrial capitalism's future given my data on current population dynamics and the analysis in this essay.

Summarizing the claims in paper three,

> I claim an economically essentialist cause for the EIR and industrial capitalism; this contradicts most historians, economic and other, who rely on cultural and institutional causes; these are of course important, but not, in my reading of the evidence, causal.
>
> Summarizing and connecting the work of under-cited authors, the rise of the institution of industrial capitalism was caused first by rising aggregate demand due to population dynamics, second by the the supply-side response to this (several energy revolutions), and third by the need to finance the largest investments in economic history to meet the demand.
>
> If rising consumer demand caused the the rise of industrial capitalism, then it may be logical and important to argue that falling consumer demand due to the reversal of the population dynamics that caused the rise will reverse the rise of industrial capitalism, a major, albeit speculative, claim.

5 Postscripts to the general discussion – insights for future work – interesting questions:

PS1 In evolving to an understanding of the EIR, one of my earliest explorations was the relationship between historical English Gross Domestic Product (GDP) and energy consumption. Having the good fortune of finding a new data series on English energy consumption starting in 1300, I found a very high correlation coefficient between that and GDP; this correlation is 0.998. Statistically, there is no difference between these two data series. This leads me to surmise that this is perhaps the most important fundamental relationship on the supply side. Reflecting on this, it is not that surprising since energy input, no matter the source, is required for all economic, indeed all, activity. And these thoughts contrast fairly dramatically with Robert Solows's famous model in which his capital and labor inputs explained about fifteen percent of the output. Economic output seems tightly tied to thermodynamics, perhaps the truly important connection between economics and physics.

PS2 Related to PS1, energy, again from any source, is non-substitutable. That is, you can change energy sources, and here economic theory describing input substitution works well, but you can not substitute away from energy however measured – Joules, watt-hours, Million Tonnes of Oil Equivalents (MTOE), horsepower, human power, and so forth. Energy is perhaps the only essential input.

PS3 Related to PS2, the theory of value comes to the fore, at least for me. What I claimed above is that it is the energy input that is fundamental to the production process. The source does not matter; a Joule is a Joule whether from a coal lump or a person, purely from the energy input perspective. Given this, what becomes of our theories of value? In particular the labor

theory of value, via Smith, Ricardo, and most famously Marx, poses some issues given my claim. And I think these are real, but in order to really understand the implications, we need to categorize the types of labor, then redo the theory of value. Brad deLong offers an interesting taxonomy of the way humans add value:

1. Using their strong (often testosterone-boosted) thigh, back, and shoulder muscles to move things around.
2. Using their nimble fingers to finely-manipulate things.
3. Using their brains as cybernetic-feedback control loops to make sure that the muscles, fingers, and machines do what they are supposed to do.
4. Using their voices, smiles, and frowns to keep us as a group (roughly) on the same page and (roughly) pulling in the same direction.
5. Fully using our brains to think of better ways and more useful ways to do things.

Clearly one, two, and, with increasing automation, three are becoming less efficient for humans to do, so will be substituted away. Four could be jeopardized depending on artificial intelligence development. Five seems secure at the moment as it involves creativity, but is perhaps also susceptible. So most humans do, and have done, work that can be increasingly easily substituted to various machines. What does that do to the traditional theory of value? I do not have a clear answer; I do know the distribution implications are probably very large.

PS4 In the third paper I explore a simple theory of a very important institution – Industrial Capitalism. I use the basic economic principles of demand and supply. Demand for output has been increasing for a very long time as a function of growing population and living

standards, driving the derived demand for productive capital stock upward. There appeared to be no big constraint on supply from the histories. Thus the rise of industrial capitalism in my telling was demand driven, and became sufficiently large that it caused the institution we call Industrial Capitalism. Fundamental economic change caused institutional change.

Beyond this example, I have thought considerably about institutions, and suspect that many are similarly endogenous to economic change. Further, institutions are inherently conservative, reactionary, or even repressive as they represent the powerful vested interests in societies. Conservative institutions, paraphrasing William Buckley, try to halt the progress of history. Reactionary ones try to turn history back.

PS5 Since production is a derived demand from final demand, we must make a statement about from where the demand driving the EIR came. I find it useful to think about two kinds of demand in this context: primary demand which is subsistence demand, enough to survive. Now I believe we should measure this in a cultural context; I recall that Brad deLong brought forward an idea of "bio-cultural subsistence" in a paper. This is close to what I want to think about. Because then, using that measure, I can measure secondary demand, which one can think of as living standards above bio-cultural subsistence.

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