What *really* happened in the English Industrial Revolution?

Stephen C. Bannister

Department of Economics

University of Utah

Salt Lake City, Utah 84112

USA

steve.bannister@econ.utah.edu

Abstract

England, during the period leading up to and spanning the first Industrial Revolution, learned how to consume a virtually unconstrained quantity of fossil carbon energy. This led directly to modern economic growth for the first time in recorded history.

Studying the event empirically, I use recent long-period series estimates of the rate of English energy consumption, Gross Domestic Product, and population to test the hypothesis that this was primarily an *energy* revolution with important but very limited institutional/cultural support.

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

1 Introduction

Unravelling the history of the English Industrial Revolution remains in the center ring of economic history. Beyond its historical significance, it holds major lessons for development economists in modern eras.

In this paper, I propose a methodological return to data-informed economic principles to explain the miracle. And I conclude that it was primarily an energy revolution; the English learned how to consume virtually unconstrained amounts of fossil energy. This directly led to modern economic growth for the first time in history.

Many, but not all, historians look to primarily institutional or cultural explanations for the event often expressed as a form of English exceptionalism; I propose a taxonomy in table 1. But this is not a paper about institutions; it is about economics. I try to make a strong case that while (a very few) necessary institutions were proximate, they were not sufficient, and do so by telling a compelling economic story.

Table 1 about here

One must include Max Weber [1] among the canonical exceptionalists, although indirectly bearing on England. Rather than lengthening this paper with details of this taxonomy, those will be in a forthcoming project. So I will proceed with the economics, acknowledging the few potentially causal cultural/institutional events that are required.

The contributions I hope to make are to build a framework for analyzing the event which: coherently explains the event; can be extended to test the hypothesized importance of any institutional or cultural events; can accommodate new data series; proposes a structure of different energy/GDP regimes; re-dates the start of the event, moving it considerably earlier than many historians propose; uses statistical methods to understand the dynamics of the event; and applies macroeconomic and

[1] Weber (2002)

microeconomic theoretical principles to describe and explain the incentives embedded in this great *sui generis* event.

2 Research question

I seek to identify empirically, economically, and eventually institutionally, what facts constituted the English Industrial Revolution. What was it, why did it occur, why did it happen when it did, why did it happen in England and only England? This paper addresses a subset of this agenda, describing what happened empirically, and suggesting the economic events that caused this result.

3 Hypotheses

The English Industrial Revolution (henceforth EIR) was the first example of modern economic growth.[2] There were both macroeconomic and microeconomic forces that were causal. The primary driver of the EIR was an energy consumption revolution. There is limited statistical space for a very few causal institutional or cultural events.

4 Research approach

As this is a largely data-driven project, I will first describe the data sources and comment on their limitations.

4.1 Data

Table 2 enumerates the primary data sources in this paper. Figure 1 displays the three data series keyed to the sources.

[2] Kuznets 1996

Table 2 about here

The energy consumption data from Roger Fouquet covers England and Wales for the entire study period (1300 – 1873). A word about why I end analysis in 1873: that is the end date Robert Allen [3] places on the EIR. I can make a case from the data that it was a few years later, perhaps 1876, but there is little difference.

The gross domestic product data is composed from data series from Graeme Snooks and Lawrence Officer. The normalizing index is 2005 Great Britain Pounds. For this study period, those were the closest to England/Wales gross domestic product data that I have found.

The population data is composed from data series from Graham Snooks and Mitchell. For this study period, these were the closest to England/Wales population data I have found. Figure 1 summarizes the data series by author/time-span.

Figure 1 about here

All such historical series are clearly composed, modelled, estimated, and thus fraught; a common problem with macroeconomic data to the present day. That said, I reserve special admiration in general for the work of the English economics historians. And these series are generally bounded by their starting point, their ending point, and various benchmarks along the way. The historians use a variety of methods to validate their work. In general, they cannot be too far wrong with the worst case being shifts by several decades in the shape of the curve. And the later data is generally better.

I do not claim these series are definitive for all time, simply the best I know of at this point, and probably good enough. Their shapes clearly affect the analysis to follow. As better series appear, I will incorporate them into this analytic framework.

[3] Allen (2009)

4.2 Methodology

This paper uses largely descriptive statistics of the three data series to describe the EIR. Much of the discussion of results depends on the graphs. I do provide analytic statistics including correlations, sample tests, structural break analyses, bi-variate Granger causality tests, [4] and a scatterplot of energy consumption and gross domestic product. I also discuss the results in the context of microeconomic and macroeconomic theory.

I do not estimate a formal empirical model, such as a regression, as that seems redundant after examining the scatterplot. The correlation between energy consumption and gross domestic products is strikingly, and visibly, strong.

In an appendix, I do provide substantial time series analyses as a foundation for formal modelling when this work is extended to analysing how important key historical events are to explaining the outcome. I believe that will be the best use of formal modelling; the approach in this paper is sufficient to support my stated hypothesis.

5 Results and discussion

5.1 Modern economic growth

Simon Kuznets defined modern economic growth as high rates of growth of per capita product and population. Figures 2 and 3 indicate that England experienced high rates of growth of per capita product in (possibly) two eras, from 1500 to 1600 that was not sustained, and after 1750 that was mostly sustained. Clearly after about 1820 England had a high and sustained rate of growth in per-capita product here measured as gross domestic product. The annual rate after 1800 was 2.4 percent per-year total growth and 1.1 percent per-capita growth as seen in table 3. Figure 4 shows the log of population growth which, supporting the Kuznets definition, mirrors GDP growth with a

[4] Granger (1969)

lag.

Figures 2 and 3 about here

Figure 4 about here

Table 3 about here

5.2 An energy revolution

This paper's central assertion is that the EIR was, primarily, an energy revolution. Specifically an energy consumption revolution supported by an energy supply revolution. To support that hypothesis, first I present the data:

Figure 5 displays the log of energy consumption over the study period; the vertical lines are formally determined structural breaks. The log presentation enhances rate-of-change and potential structural differences in the series. I note four significantly different periods or regimes. The first is from 1300 to 1500, a period dominated by the Black Death epidemic; energy consumption clearly drops, then recovers. The second is from 1500 to roughly 1600 as determined by the structural break. 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 3. The final period is from 1750 through 1873; clearly the energy consumption rate-of-change accelerates as confirmed by the structural breaks in 5 and table 3.

Based on the structural changes, and based on the hypothesis that the EIR was an energy revolution, I propose that the revolution happened in two stages: one starting in the late sixteenth century, and one starting after 1750. The first, under this hypothesis, would have set the stage for the second.

Figure 5 about here

If we were to overlay the energy levels or logs charts with the GDP levels or logs charts the similarities would be striking; I think a more productive view is figure 6. This figure shows levels of energy consumption through the study period, and has a standardized series of GDP for the same period. By standardized I mean 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 period of 1500 to 1600 when growth in GDP clearly leads energy growth, and after 1750 (especially after 1800), when energy growth leads GDP growth.

Figure 6 about here

The dynamics of GDP growth and energy consumption growth can be seen more clearly by taking the differences of the last graph.

Figure 7 about here

The Black Death and its aftermath affected the relatively flat economic performance from 1300 to 1500, but set the stage for a growth boom in the period 1500 to 1600. In the period 1600 to 1750 growth in both relatively flattened, and then boomed during the period 1750 to 1873.

5.3 Correlations

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

Starting simply, a Pearson's correlation coefficient and a paired t-test of energy consumption and GDP yields the results in table 4:

Table 4 about here

These simple results suggest that the two series are statistically very similar; a more formal co-integration test could be expected to be positive and is presented in section 12. However, for the purposes of this paper, a scatterplot of the series is shown in figure 8. The solid green line is a linear fit; the solid red line is a *lowess* (non-parametric, non-linear) fit.

Figure 8 about here

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.

However, this overall view does hide important dynamics that the data contain. I examine these more subtle results next, and thereby set the stage for telling the story of the EIR.

5.4 Causality tests

I continue by using basic statistical causality tests, specifically the Granger bi-variate test. [5] Table 5 reports this result for the four main eras already identified.

Table 5 about here

During the first energy/GDP era Granger causality between energy and GDP runs both ways at significant levels; while not ignoring these results, I do not want to over-interpret what was happening given the huge shocks of the Black Death. However, it is significant for later eras that the Black Death caused wages to rise, and the European Marriage Pattern (EMP) [6] increased family incomes entering the early modern period.

During the second energy/GDP era of 1500 to 1600 causality from GDP growth to energy consumption is weakly significant; energy Granger-causing GDP growth is not at all significant.

[5] Granger (1969)

[6] Hajnal (1965)

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 we build the narrative shortly 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, through the entire study period GDP Granger-causes energy consumption more significantly than energy Granger-causes GDP, but causality is significant in both directions.

5.5 Structural breaks

Figure 9 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.

Figure 9 about here

6 Discussion of results

I can now present a story of the EIR as supported by the data presented above.

6.1 Narrative discussion

Energy/GDP era one, due to the Black Death, saw both negative demand and supply shocks, but set the stage for the following EIR eras.

In energy/GDP era two, wages rose due to the negative labor supply shock of era one. Demand had positive shocks, as a result both of wages and of incomes rising due to later marriages and women working – the EMP outcomes. Supply expanded as can be seen by the stronger growth of energy consumption. Refer to table 3 or figure 5.

In energy/GDP era three, rates of growth for both GDP and energy consumptions stagnated. A story that fits the data, and the history, is that this era was one of a negative energy supply shock, and the whole economic system growth slows down. This era was the transition between primarily wood-supplied energy to primarily coal-supplied energy. As London grew because of world trade domination, wood became scarcer and more expensive, driving demand for coal for heating from the north east. You can see this pattern during the 1600 to 1750 era three in the following figure 10.

Figure 10 about here

This demand for heating coal and the fortuitous geology of the English coal mines created the path necessary to support energy/GDP era four, in which the EIR accelerated into modern economic growth via the 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 dug deeper, more water had to be pumped out. This provided an economically feasible site for the seminal but very inefficient Newcomen steam engines to pump the water. The coal was essentially free to power the engines. Human or horse power were too expensive. And as the steam engines gained efficiency, they began to be applied to industrial capitalism. That is the story of energy/GDP era four, the age of steam. I turn next to telling that story; again it is an economic story, supported by data.

6.2 Theory discussion

We have already examined the GDP and energy consumption data for the fourth era. To finish the story, I will retreat to economic theory. First, I summarize the eras in aggregate supply/aggregate demand charts; second, I address the question of what were the incentives for the English inventor/entrepreneur to spend the time and money to make the inventions of the EIR, particularly the steam engine. To do this, I appeal to microeconomic theory.

Figure 11 displays the four eras in an aggregate demand/aggregate supply (AS/AD) framework.

The dotted lines indicate prior locations of AS/AD; solid lines indicate the ending locations. Lines colored red indicate the constraint in each era. These are obviously abstract depictions of the history I have told above. I do this for two reasons; first to solidify and emphasize the history so that the debate can commence; second to provide a framework for later projects incorporating the institutional and cultural events into the history. If we can agree on the AS/AD 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.

Figure 11 about here

A notable observations is that energy/GDP era four is the first in which supply was not the constraint; according to the Granger causality tests, supply and demand were jointly constraining in that era, but the lack of relative barriers in consuming energy was surely the defining event of the era.

Second for the theoretical discussion of the EIR, it is important to consider at the microeconomic level what can explain the event. At this level I will discuss only the supply side having already suggested the demand side factors. So the question becomes what were the incentives or motivations of the English inventors and entrepreneurs during energy/GDP eras two and three, so from 1500 through 1750.

For this analysis I rely on three sources; first the contemporaneous comments of a key participant in the EIR; second the excellent work of Robert Allen; and third an appeal to microeconomic theory.

Jean Theophilus Desagulier had a large influence on the EIR. He was an eighteenth century English "natural philosophe (physicist), member of the Royal Society, colleague of Sir Isaac Newton, and author of "A Course of Experimental Philosophy." This was an influential 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. The age of the industrial capitalism, fueled by fossil energy, was dawning. [7]

Figure 12 shows a page of this manuscript.

Figure 12 about here

Beyond the quaintness of the 1734 English prose, this man demonstrated the soul of a profit-maximizing capitalist. In that context, let's examine some data that drove Desagulier.

Figure 13 is from Robert Allen and shows the ratios of real wages to energy costs (the cheapest source) by benchmark city around 1700.

Figure 13 about here [8]

Clearly, Newcastle in 1700 had high wages and very low energy costs, by far the largest ratio in the sample. Those were the economic fundamentals that faced Desagulier and motivated his profit comment. London had the second largest ratio, and thus the economic incentives existed there as well. Beijing had the lowest ratio, a topic I investigate in another research project.

While the economics of these ratios may be intuitive, why not appeal to microeconomic theory to help us understand what motivated Desagulier, Newcomen, Watt and all the other founding fathers of the EIR.

Equation 1 is a variation on production theory that will be familiar to those who remember their Econ 101. A major topic of production theory is how entrepreneurs maximize profits given the derived demand curves of the various input choices. This equation is a variation on that theme: [9]

[7] Desaguliers 1734, vols. II, 467-468

[8] Allen 2009

[9] We can proceed either with a neo-classical factor substitution argument, or a more general classical view of normal prices of production. Either approach will react to the enormous productivity-enhancing energy supply shock that was

Equation 1 about here

Instead of using different substitutable inputs such as labor and capital, I apply the theory to the different sources of energy, energy being essentially the only non-substitutable input as in you must have joules from whatever source to do an economic transformation. This equation is written as the profit-maximizing equilibrium that will substitute between human-input joules and coal-input joules. Clearly, the equation needs additional terms to cover the amortization of whatever equipment is necessary to apply either kind of joule, but also clearly from just what is written we see that when wage-to-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 London, later spreading to the world.

7 Conclusion

The English Industrial Revolution, whatever else it was, was an *energy consumption* revolution. This stands out as its primary feature, a feature that caused, for the first time in history, modern economic growth. Mankind learned to consume energy in the economic process at a rate that was essentially unbounded, such that there was no longer an energy supply constraint on output.

This happened in England because England had a set of critical conditions that were rare: high wages, high family incomes, sufficient knowledge to construct "Fire-Engines", and very low relative energy costs with essentially unlimited supply. Of these critical factors, only England had very low relative energy costs; this last factor then must be deemed the necessary condition for the EIR.

The EIR happened in distinct stages, each of which can be defined as specific energy/GDP (aggregate supply - aggregate demand) regimes which frame further research on what institutions may

---

the Industrial Revolution. A more challenging story to tell is one which identifies the sources of aggregate demand that supported expansion of English production. Here, I simply stipulate that aggregate demand existed.

have been important. We can use simple macroeconomic principles and data to usefully investigate the EIR. England collectively "learned" how to create a positive virtuous macroeconomic growth feedback cycle

Further, the behavior of the EIR inventors and entrepreneurs can be explained using simple microeconomic principles.

Given all this, extant hypotheses of English cultural and/or institutional exceptionalism seem redundant to the outcome. England was a very lucky country, geographically advantaged, at the right place and time for this miracle to occur.

List of Tables

List of Figures

List of Equations

8 Tables

Table 1: Taxonomy of EIR explanations

Label	Examples
English exceptionalists	Landes (1969), McCloskey (2010), Mokyr (1992,2010)
Partial culturalists	Cipolla (1966), Pomeranz (2001), Allen (2009)
Primarily energetic	Cottrell (1955), Wrigley (1988,2010), Malanima (2010)
Thermodynamicists	Georgescu-Roegen (1975), Ayres (2003), Garrett (2009)

Table 2: 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)

Table 3: growth rates by century

Year	1300	1400	1500	1600	1700	1801	1873	Total
GDP Million								
2005 GBP	3114.7541	815.1288	994.4571	6031.953	8361.5911	18110	102811	
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

Table 4: 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

Table 5: granger tests of energy/gdp

Era	Energy ~ GDP Pr(>F)	GDP ~ Energy Pr(>F)	AS/AD 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

9 Figures

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

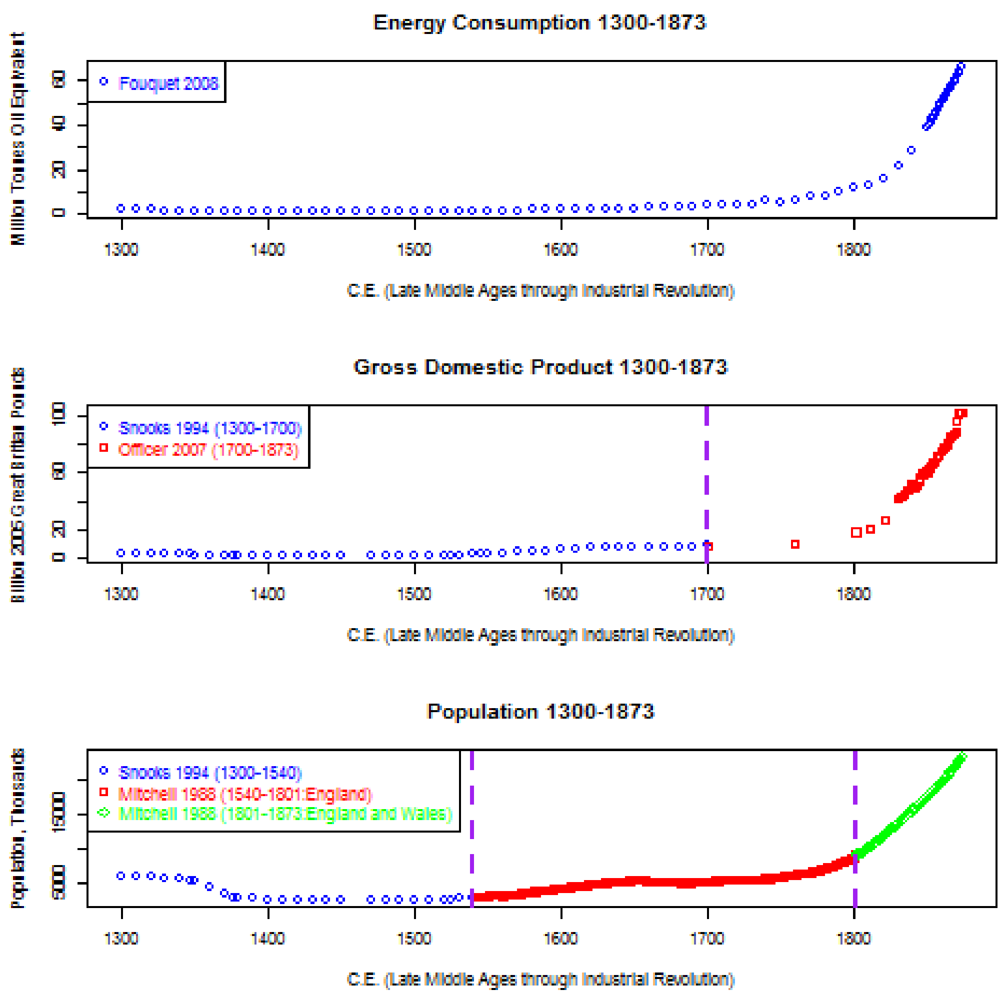


Figure 2: English real gross domestic product,

levels and per–capita

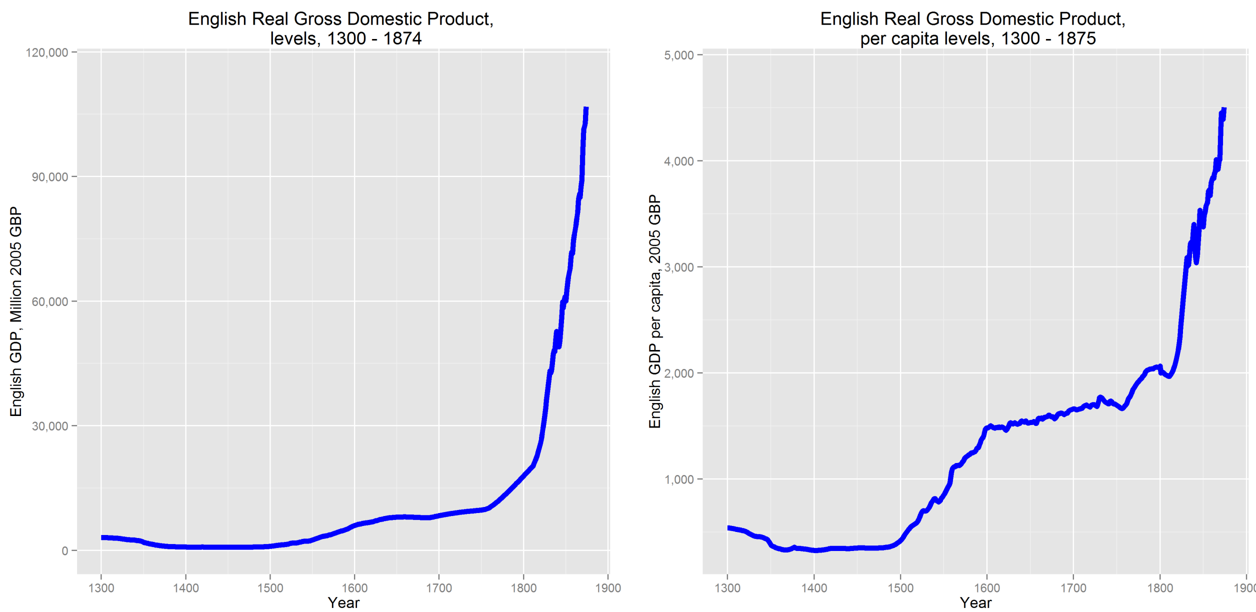


Figure 3: English real gross domestic product,

log levels and log per–capita

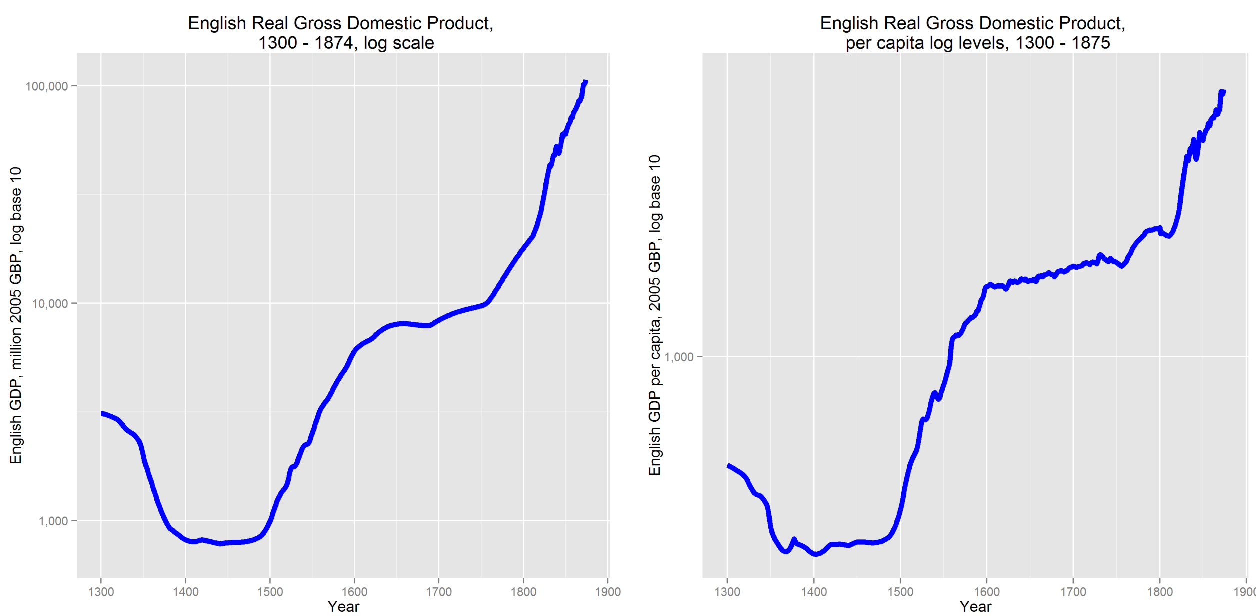


Figure 4: Log of population, with structural breaks

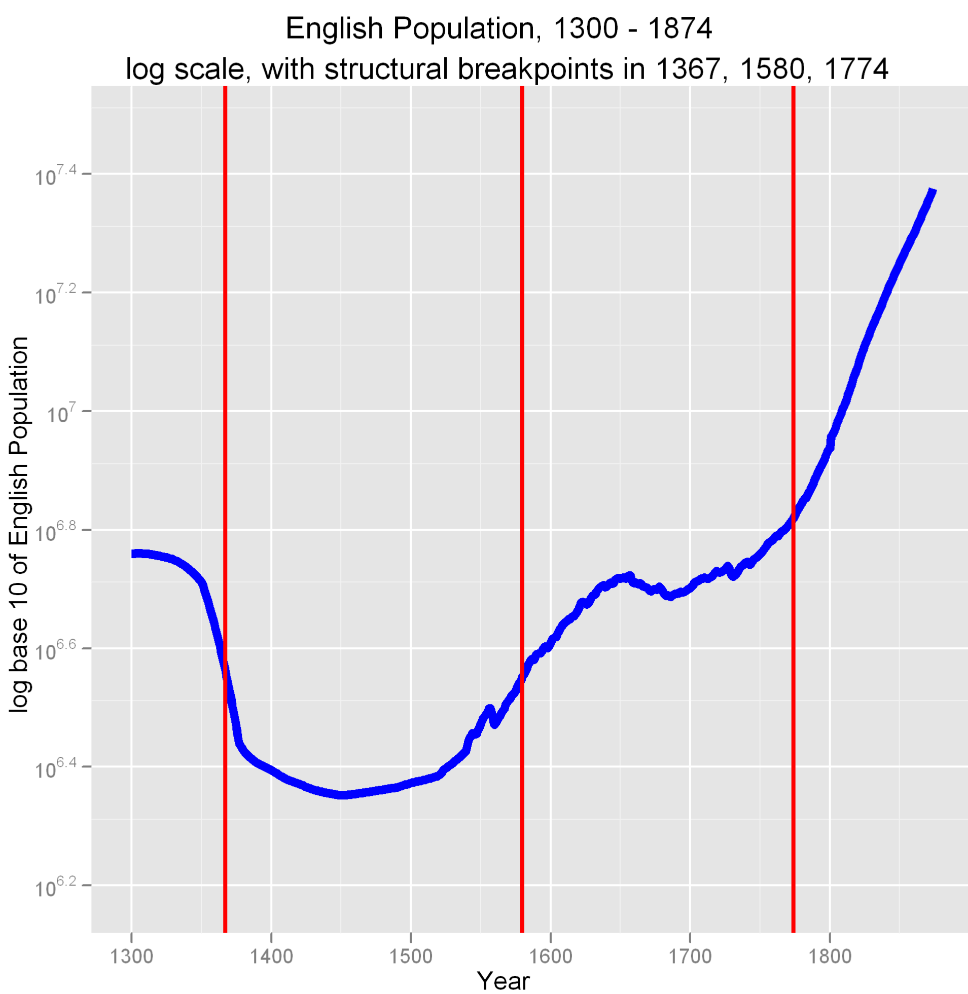


Figure 5: Log of energy consumption, with structural breaks

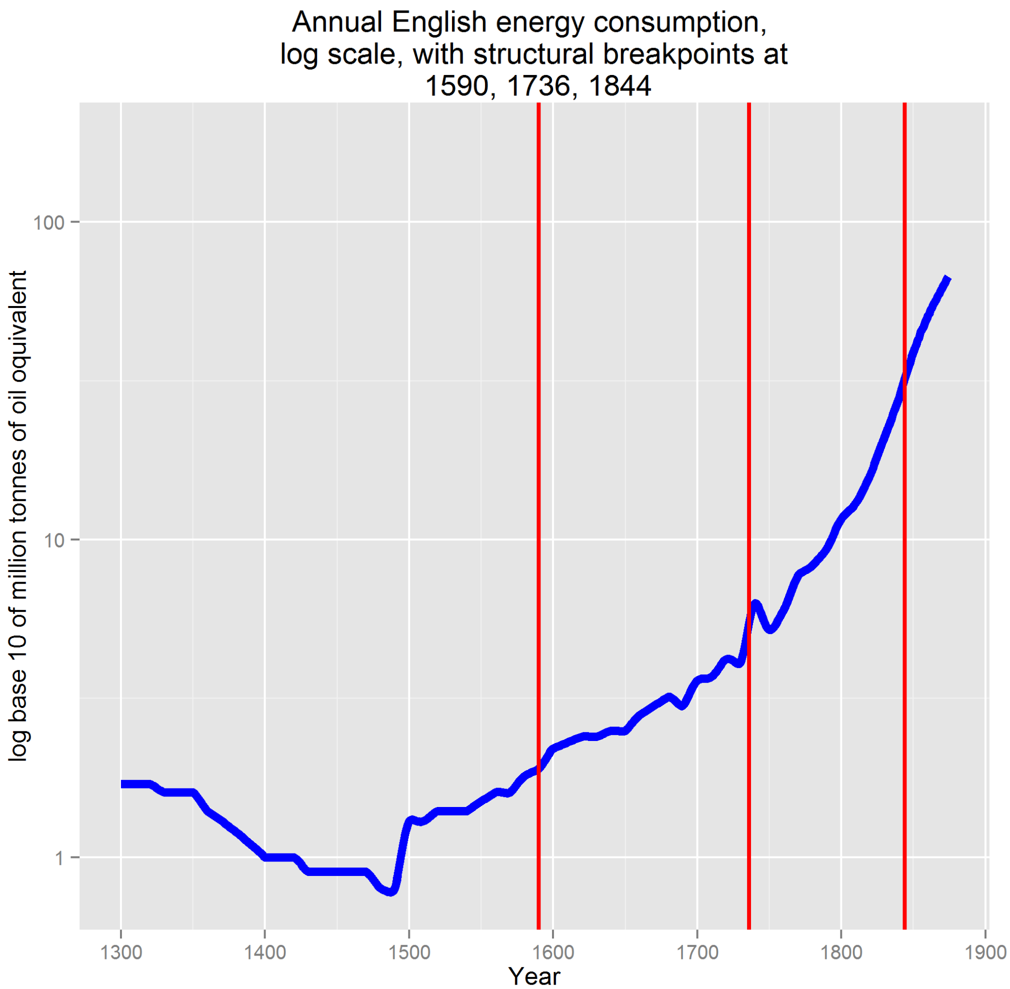


Figure 6: Energy consumption vs. standarized GDP

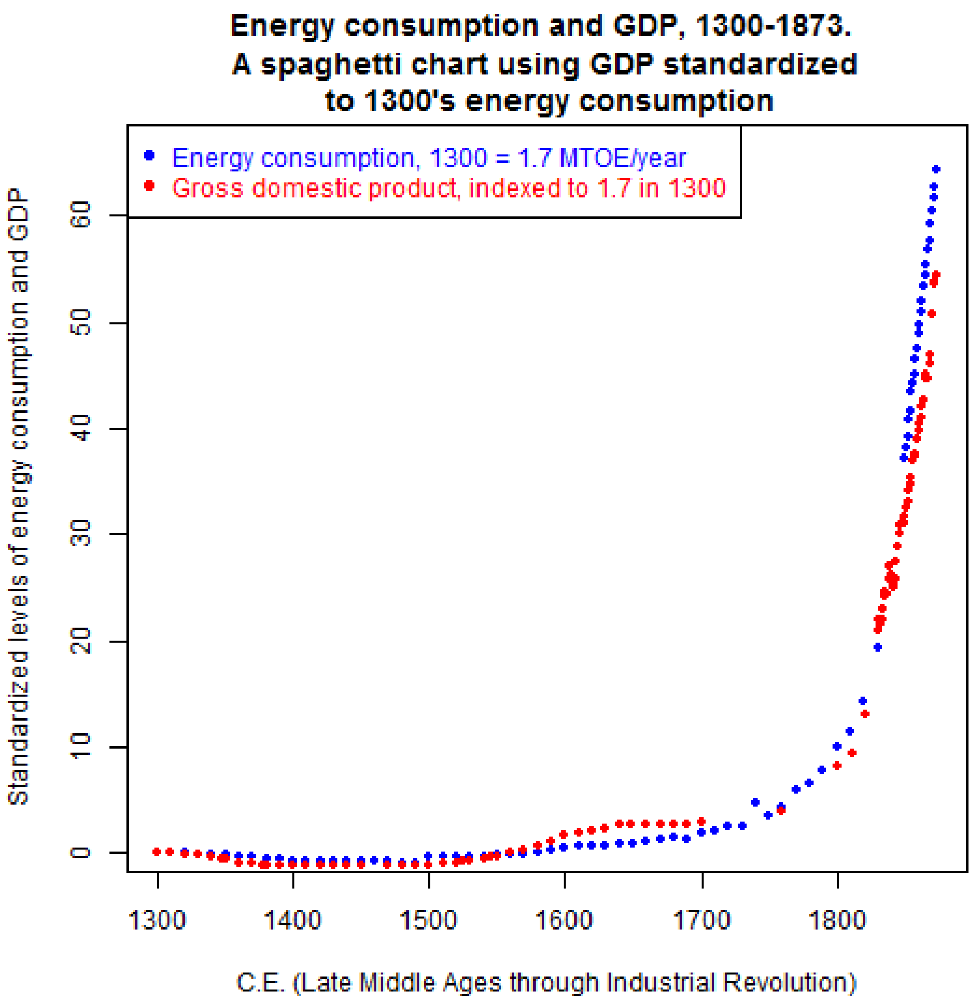


Figure 7: Energy consumption vs. standardized GDP, differences

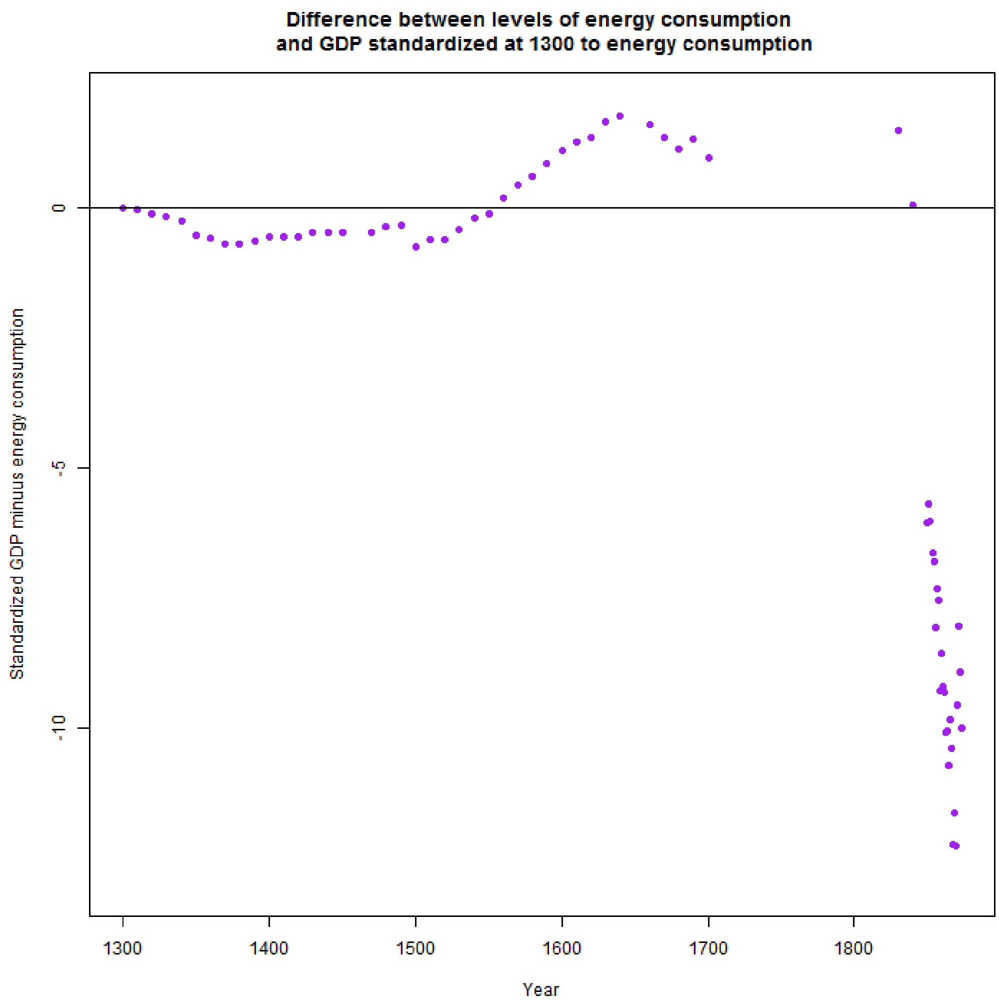


Figure 8: Scatterplot of energy consumption vs. GDP

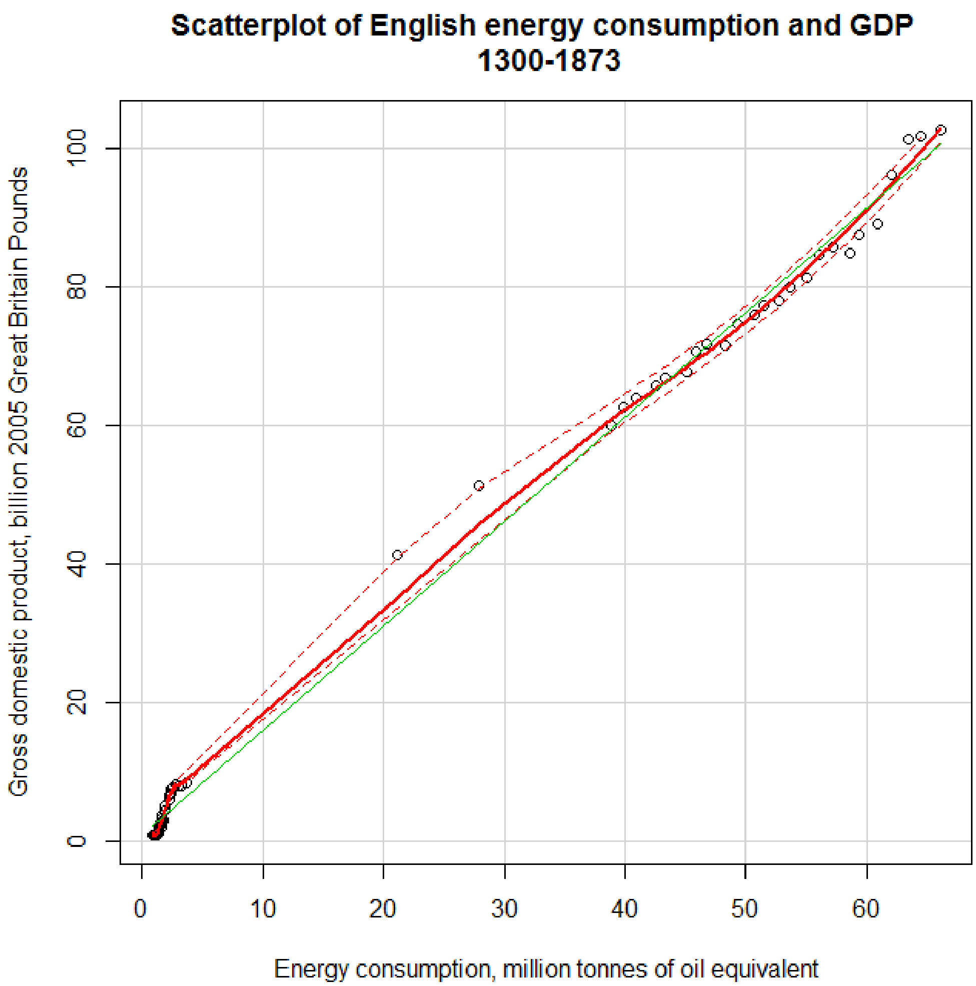


Figure 9: Structural break comparison

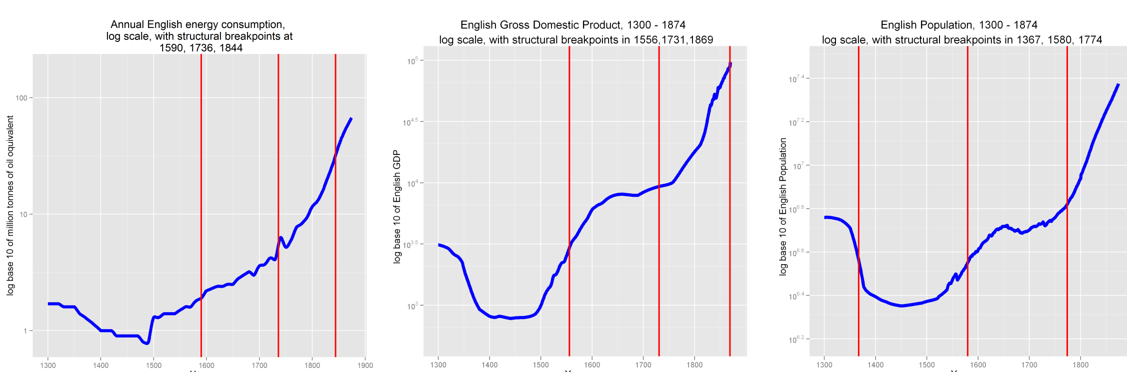


Figure 10: Coal and wood energy sources

Source: Pearson & Fouquet

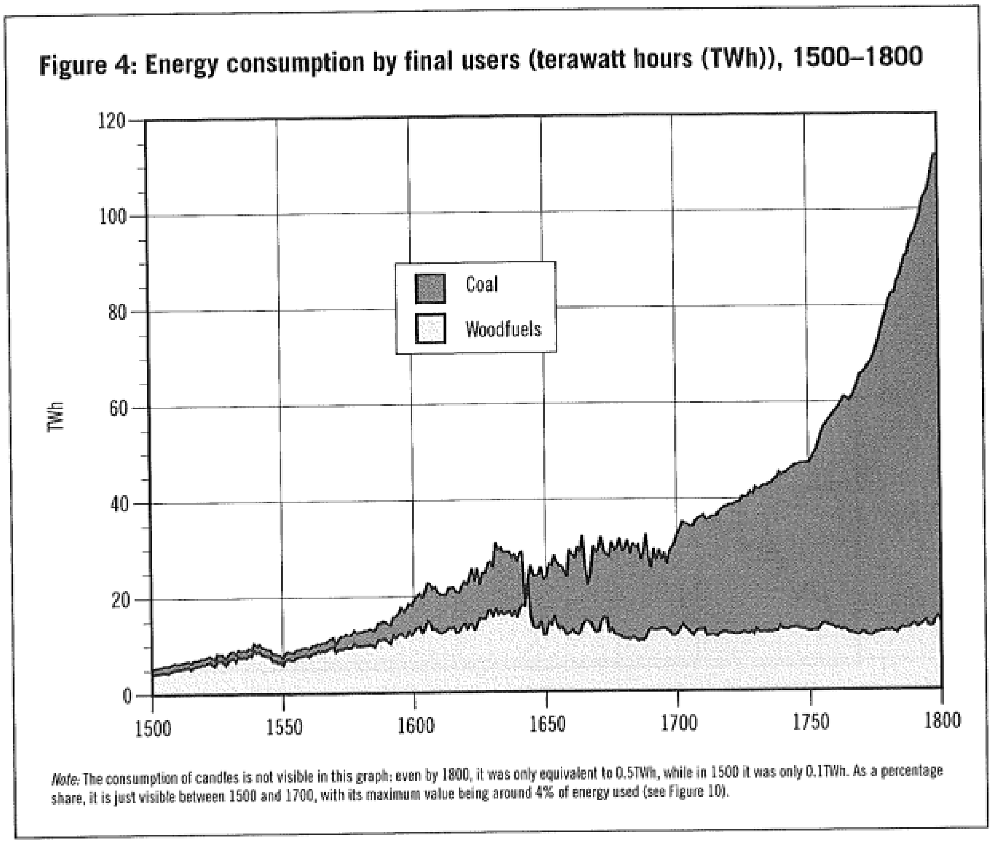


Figure 11: Aggregate Supply - Aggregate Demand

Four energy/GDP regimes

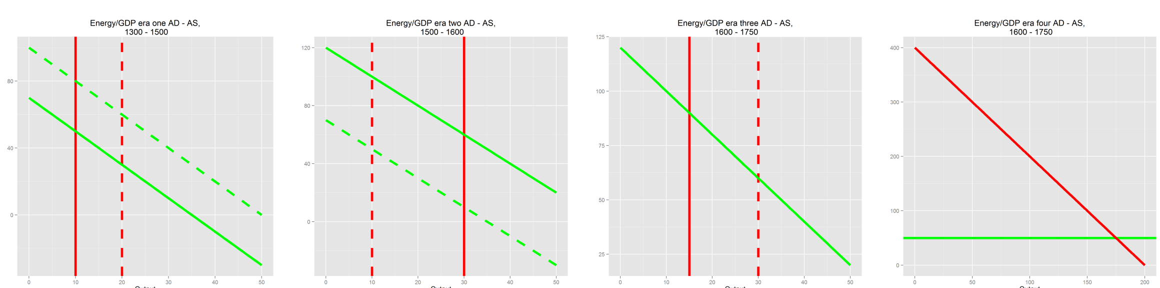


Figure 12: Desagulier manuscript

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

Ooo 2

Lect. XII. Plate 36.

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

Figure 13: Real wage to energy ratios

Source: Robert Allen (2009)

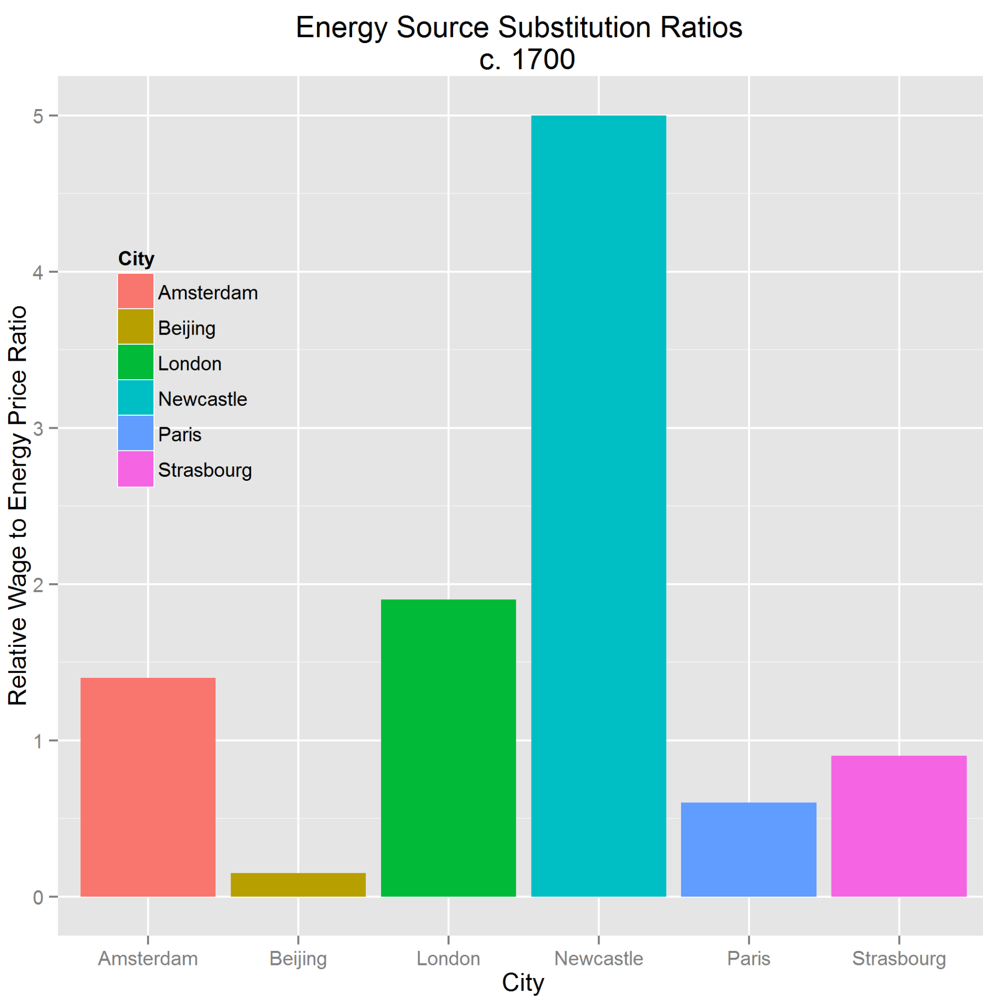


Figure 14: Standardized English energy intensity of GDP

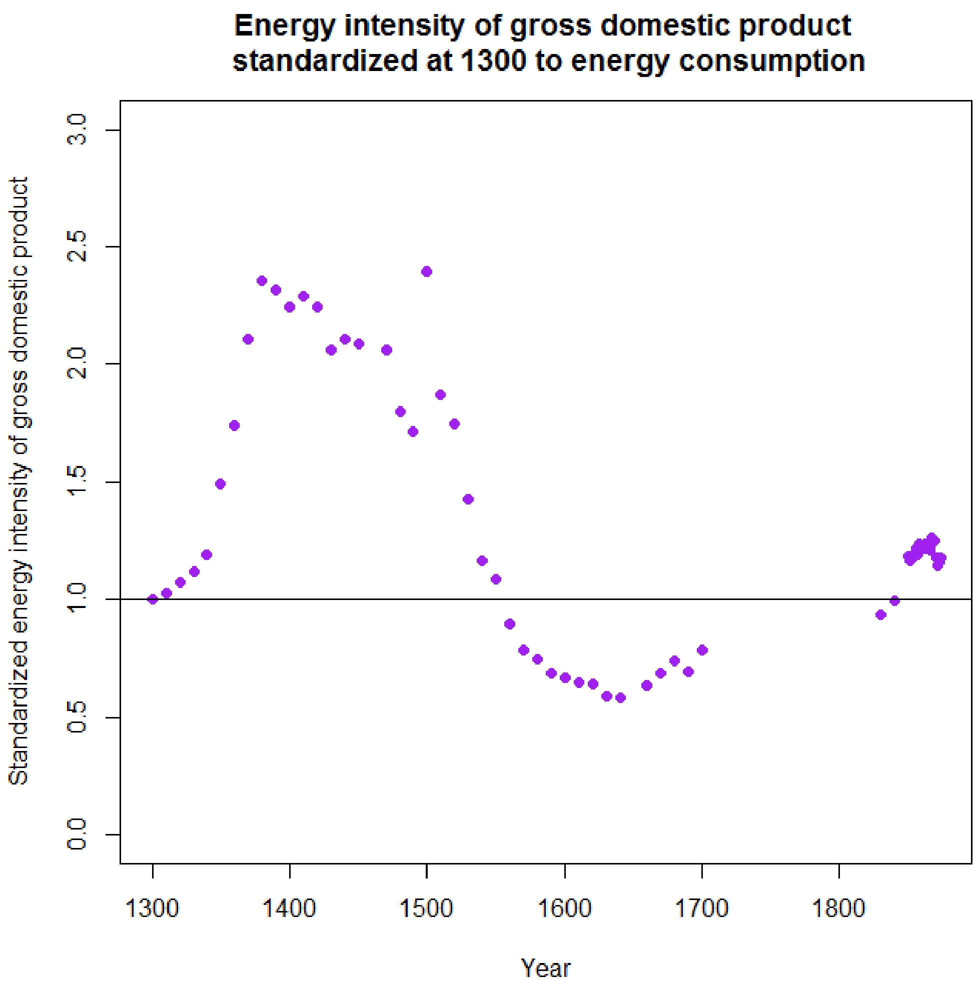
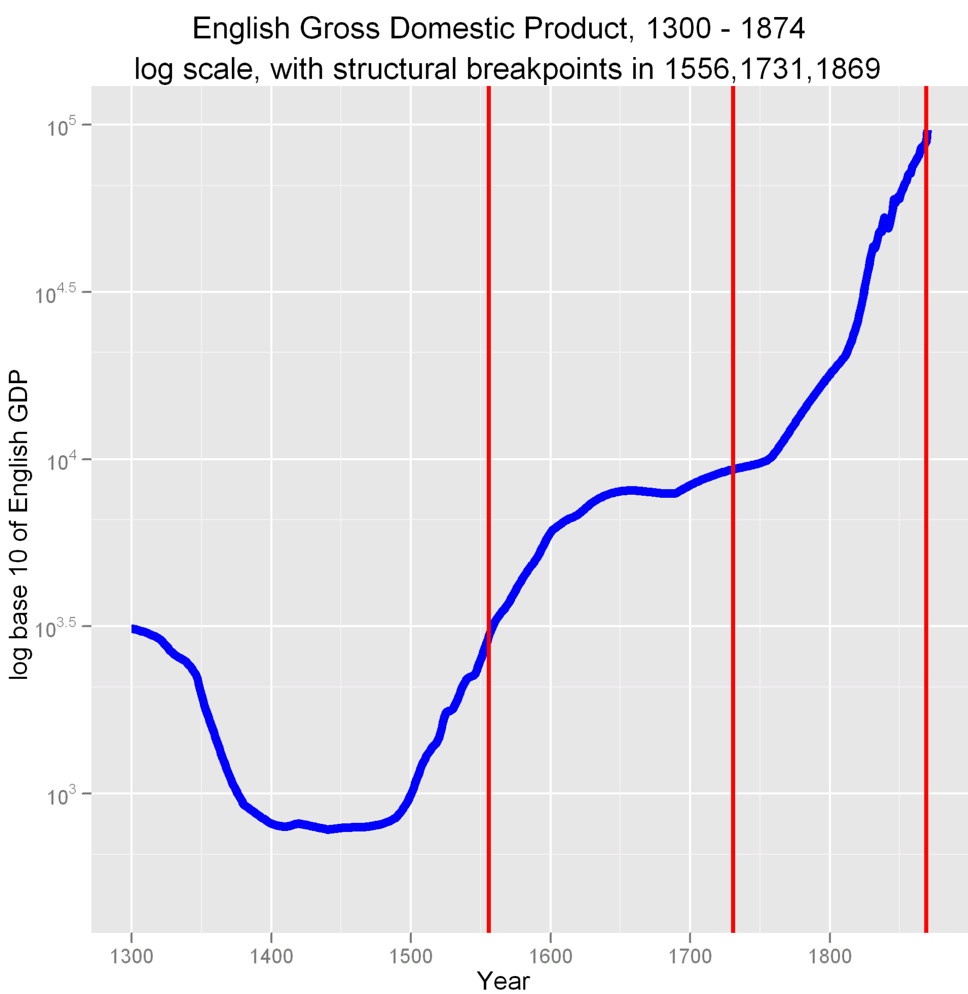


Figure 15: Log of GDP, with structural breaks



10 Equations

$$\frac{\text{Marginal Revenue Product}_{\text{organic energy joule}}}{\text{Price}_{\text{organic energy joule}}} = \frac{\text{Marginal Revenue Product}_{\text{fossil energy joule}}}{\text{Price}_{\text{fossil energy joule}}} \tag{1}$$

11 Appendix A. Detailed Granger test output

12 Appendix B. Time series analyses

13 Appendix C. Future research

survey on institutions/culture

empirical tests of institutional/cultural events