Queen Mary University of London

Centre for Globalisation Research
School of Business and Management

Energy Transitions, Directed Technical Change and the British Industrial Revolution

CGR Working Paper 91

Ravshonbek Otojanov

Abstract

This paper provides an alternative view on the transition from stagnation to growth by building a two-sector model of the British Industrial Revolution. The sectors differ only in the use of input factors, wood and coal. The model characterises the transition from stagnation to high growth as a direct consequence of the transition from biomass to coal use in Britain. Formalising the accounts of economic historians, technological progress is modelled as an endogenous process driven by the cost differentials between wood and coal. As wood price rises and coal price remains stable it becomes profitable to innovate in coal-using technologies and hence, innovation shifts to the coal-using sector. The model is calibrated to match the main features of the British economy in the transition period between 1550 and 1849. The model reproduces one of the important characteristics of the First Industrial Revolution – transition from low growth to high growth. Counterfactual analyses indicate that, absent coal reserves and low cost coal supplies, growth would have been slower and income per capita would have been 53% of that observed in 1849. Also, the model does a good job in explaining the timing of structural transformations in the British economy.

Keywords: Industrial Revolution; Economic Growth; Directed Technical Change; Innovation; Energy Transitions.

JEL codes: O30, O41, Q43, D50

http://www.busman.qmul.ac.uk/cgr

CGR Working Paper Series

Energy Transitions, Directed Technical Change and the British Industrial Revolution

Ravshonbek Otojanov
Queen Mary University of London
r.otojanov@qmul.ac.uk

Abstract

This paper provides an alternative view on the transition from stagnation to growth by building a two-sector model of the British Industrial Revolution. The sectors differ only in the use of input factors, wood and coal. The model characterises the transition from stagnation to high growth as a direct consequence of the transition from biomass to coal use in Britain. Formalising the accounts of economic historians, technological progress is modelled as an endogenous process driven by the cost differentials between wood and coal. As wood price rises and coal price remains stable it becomes profitable to innovate in coal-using technologies and hence, innovation shifts to the coal-using sector. The model is calibrated to match the main features of the British economy in the transition period between 1550 and 1849. The model reproduces one of the important characteristics of the First Industrial Revolution – transition from low growth to high growth. Counterfactual analyses indicate that, absent coal reserves and low cost coal supplies, growth would have been slower and income per capita would have been 53% of that observed in 1849. Also, the model does a good job in explaining the timing of structural transformations in the British economy.

Keywords: Industrial Revolution; Economic Growth; Directed Technical Change; Innovation; Energy Transitions.

JEL codes: O30, O41, Q43, D50

1 Introduction

Britain was the first country to industrialise its economy (Crafts, 1985; Allen, 2009; Wrigley, 2010). However, there has yet to be a consensus on why it was the first country to break free from the low income, low growth economic system of the previous periods, or how the process of transition to a modern growth economy progressed in a short span of time. This study aims to extend our understanding of the industrialisation of Britain by characterising the transition process as the outcome of the transition from reliance on biomass to coal. In doing so, this study quantifies and extends the cliometric accounts of Allen (2009), Wrigley (2010) and Kander *et al.* (2013). These researchers promote the idea that the transition from wood to coal was central to explaining the industrialisation of Britain[1]. They have documented a set of cliometric evidence that has been subjected to growing criticism from other economic historians (Clark and Jacks 2007; Crafts, 2007; Mokyr, 2009; McCloskey, 2010; Jacob, 2014). The objective of this study is to construct a model of directed technical change to quantify and formalise the historical and cliometric accounts on the importance of the transition from wood to coal use in the British Industrial Revolution.

The micro-foundations of the model are based on the ideas and accounts of Fouquet (2008), Allen (2009), Wrigley (2010) and Kander *et al.* (2013). These authors, in particular Wrigley (2010) and Kander *et al.* (2013), suggest that the increase in output growth during the Industrial Revolution was the (inevitable) consequence of the transition from organic sources of energy to coal use. Availability of previously used energy, derived from organic sources (food and fodder for muscle energy and wood for heat energy), was subject to climate,

[1] In the context of the British Industrial Revolution, the importance of energy transition has previously been highlighted by Nef (1932), Nef (1977), Cipolla (1978), Wrigely (1962; 1988) and Pomeranz (2000) among others. Allen (2009) and Wrigley (2010) were the first to provide detailed cliometric accounts of how the transition to coal enabled the British economy to break free from the constraints imposed by the organic source of fuel. Bob Allen's seminal research on the topic dates back to 2006, an unpublished manuscript is available at https://www.nuffield.ox.ac.uk/users/allen/unpublished/econinvent-3.pdf. This original version was later published in his book entitled "*The British Industrial Revolution in Global Perspective*" in 2009. Allen (2009) mainly focuses on a set of energy-using and labour-saving technical changes in the Industrial Revolution. This was analysed in the previous chapter of this thesis. In this chapter, the focus is on the energy transition only.

environmental conditions and the productivity of land; whereas, coal was inherently efficient, flexible and its availability did not depend on photosynthetic inefficiencies. Thus, the expansion in the supply of energy allowed Britain to break free from the constraints of the previous energy system.

The theoretical model formulated in this paper draws on the directed technical change framework developed by Acemoglu (1998, 2002) and then applied in the context of energy, environment and growth in Acemoglu *et al.* (2012). The framework builds on the earlier work on the price-induced technical change theory of Hicks (1932) and combines the micro-foundations of the endogenous growth theory of Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992). The framework allows for modelling the technical change in multiple sectors as the endogenous outcome of agents' optimisation decisions. In this paper, it is assumed that there are two sectors in the economy. One sector uses only wood (biomass) and the other uses coal as an input in the production of sectorial goods[2]. The sectorial goods are combined to produce the final good of the economy. Using the framework, this study shows that if the goods produced in the sectors are complements, innovation in the larger sector increases the demand for energy (coal or wood) used in that sector. The availability of energy and hence the energy price determines the direction of innovative efforts. Therefore, the research intensity in each sector depends on the price of the energy used to produce the (sectorial) goods in each sector.

How did directed (biased) technical change play a role in the Industrial Revolution? Britain was endowed with vast amounts of coal deposits; however, until the mid-eighteenth century there had been little use of coal in the industry. The national market for coal was mainly limited to demand for coal for blacksmithing, salt making and lime burning (Allen, 2009, p. 81). Coal-based production was limited and coal-using technology that could be used in the wider industry to produce work was not developed until the early decades of the eighteenth century (Kander *et al.* 2013)[3]. Therefore, charcoal was the main source of heat energy but it was relatively more expensive than coal (Fouquet 2008, p. 221). Average charcoal price

[2] This study abstracts from the use of muscle, water and wind power.
[3] Here, the use of coal to produce work refers to the conversion of thermal energy into kinetic energy or, simply, to convert heat into motion (Kander et al. 2013, p. 133).

increased further in the eighteenth century, and the widening gap in the cost of fuels made wood-based manufacture more expensive. This led to the emergence of the market for coal-based technologies as low cost coal input reduced the price of the capital goods (sectorial goods)[4]. The net result of this process was the shift of innovation from wood-using technologies to coal-using technologies. Innovators, determined to benefit from the emerging market for coal-coal based technologies, increasingly directed their efforts towards inventing coal technologies and this sustained the technological progress (Allen, 2009).

An example of such a situation can be drawn from the British iron industry. The main source of heat for smelting iron was wood in the form of charcoal prior to the classic period of the Industrial Revolution (Hammersely, 1973; Fouquet, 2008). Historically, average wood price was higher than that of coal, and increased over time during the seventeenth and eighteenth centuries (figure 2). High fuel costs increased the cost of producing iron products. In the local market, the British iron industry failed to compete with suppliers from Sweden and Russia in the seventeenth and eighteenth centuries (Fouquet, 2008, p. 61; Griffin, 2010). Iron produced in Britain was more expensive than that imported from the Baltic; for them, wood was a cheaper input in iron production. As such, the cost of energy was the main factor determining the price of iron. Naturally, in order to compete with the foreign suppliers, British ironmasters directed their efforts towards saving the most expensive factor, charcoal, to reduce the price of locally produced iron. The outcome of the sustained efforts and experimentations was the invention of coal-based iron smelting[5]. Britain was endowed with coal deposits and the market for coal, albeit small, had already been established. Moreover, coal was much cheaper than wood and its adoption in the iron industry coincided with the revival of the British iron industry (Fouquet, 2008, p. 62).

Recent research on the economics of the British Industrial Revolution provides many other examples in both the industry and household sectors where directed technical change played an important role[6]. The direction of technical change in most of the developments was the

[4] For instance, charcoal iron was relatively more expensive, the cost of iron began declining after the industry shifted to coke smelting in the 1750s (Fouquet 2008 p. 62).
[5] Also called coke iron smelting technique invented by Abraham Darby in 1709 but only became commercially viable in 1750s (Fouquet 2008, p. 62-64).
[6] Fouquet (2008) provides a detailed discussion of innovations that enabled households to use coal for domestic heating and cooking. The present study focusses on the uses of coal in the industry only. Kander *et al.* (2013, p.

result of the innovative efforts driven by potential economic incentives[7]. For instance, the development of steam technology early in the eighteenth century offers another example of directed technical change. The efficiency gains in steam technology were of paramount importance as the cost of energy even after the transition to cheap coal was a major part of production costs[8] where steam technology provided power. The potential market for steam technology was immensely wide given coal was available at low cost and iron became cheaper in the eighteenth century[9]. At the early stages, steam technology was expensive to use outside the mining industry and could only be used in the proximity of coal mines. Nevertheless, its application in coal mining stabilised the coal prices as the market for coal expanded. Low cost coal meant that the demand for coal-based technologies expanded over time (Allen 2009, p. 138). Sustained low coal prices and the innovative efforts of entrepreneur engineers reduced the cost of power provision. Therefore, the market for coal-based steam generation was more attractive than the one based on organic sources of power such as water, wind and animals as well as wood. The shift to coal made steam and iron cheaper and enabled the wide scale mechanisation of cotton textiles (Allen, 2009).

Allen (2009) interprets the development of coke iron smelting as the response of the ironmasters to the high price of wood and the existence of profit incentives in switching to coal use. Similarly, advances in steam technology were a response to profit incentives as the market for steam technology combined with the cheap coal was larger than that for wood-based technology[10]. In the eighteenth century, coal became a common fuel in Britain, coal-using technologies had been adopted in many industries and coal became the basis of the

135) state that the greatest use of coal was on the production side of the economy and the largest share of coal was in the manufacturing of intermediate goods like still, iron, clothes, chemicals etc.

[7] Allen (2009) argues that the low cost of coal made it more profitable to invent in technologies that used coal. Since the market for coal had already been expanding by the seventeenth century, demand for coal-based technologies was on the rise.

[8] Fouquet (2008, p. 89) states that the desire to reduce costs was a major drive for the inventions in the provision of industrial heating.

[9] One could think of the mechanisation of cotton textiles whereby machines were initially powered by water wheels. They effectively limited the productivity gains due to the limited availability of suitable locations for water wheels. The transition to steam technology provided the potential for greater return on investment as the mills and the factories could have been built anywhere on the land and coal was cheaper and available abundantly.

[10] In this study, wood-using technology can be thought of as the methods of production that rely on wind, water and animal muscle power. For instance, mills could be powered by animals, wind, humans or water wheels and in the same vein can be powered by wood powered steam engines. As will be shown in Figure 1 in section 2, more than half of the energy consumed in 1500 was non-wood and non-coal energy.

engineering industry (Allen 2009, p. 83). The transition to coal use in the eighteenth century set in motion the modern growth era in Britain. Given these examples, the directed technical change framework is suited to characterising the changes in the growth patterns as driven by endogenous technical change.

Following Acemoglu (1998) and Acemoglu *et al.* (2012), the production technology and innovation process are formulated based on the quality ladder model of Aghion and Howitt (1992). In the model, technical change arises from the directed efforts of the innovators to improve the quality of machines (used in the production of the intermediate goods) that use either coal or wood as input. The outcome of the innovative efforts is uncertain and a successful innovation results in the quality improvement of the machines employed in the sectors. It is assumed that a minimum level energy is needed to operate machines and there is a finite amount of woodfuels available to extract. Therefore, economic growth depends on the supply of fossil fuels in the long run. The model does not have a balanced growth path as the resource stocks are not renewable, but reserves can be expanded over time. Once the maximum extractable reserves are exhausted, unless the economy shifts from coal to another source of energy, growth stalls or declines. The implication of this assumption is that endogenous technical progress is resource dependent.

The simulation results indicate that the transition towards coal and its availability was pivotal for the acceleration of economic growth. Price signals and economic incentives underpinned the transition from low to high growth in the 1550-1849 period. Endowing the economy with just 1% of the original coal reserves results in an average annual growth rate of 0.12%; whereas, in the baseline scenario, output per capita grows at an average annual rate of 0.33%. The transition to the high growth regime would have been delayed had Britain had no coal reserves. Even when the resource constraints were eased through wood imports from the Baltic, the price of wood would have remained high, but this would not have stimulated energy-saving efforts. The model reproduces the key historical transformations observed during the industrialisation of Britain. Energy could act as a constraint on economic growth as reported by Allen (2009), Wrigley (2010), Kander and Stern (2014) and Froling (2011) but the absence of coal reserves in Britain would have retarded the industrialisation process.

The contribution of this paper is that it provides a number of insights into the economics of the British Industrial Revolution narrated by the economic historians. First, the transition from low to high growth that triggered the First Industrial Revolution can, indeed, be explained as the direct consequence of the energy transition (Wrigley, 2010). Second, resource scarcity and price signals determined the direction of the innovation in the economy. The low price of coal and the growing market for coal-based technologies underpinned the sustained productivity growth in the First Industrial Revolution (Allen, 2009). Third, in the absence of coal reserves, the industrialisation of Britain would have been delayed. Finally, the modelling framework can be used to analyse and forecast the dynamic effects of future energy transitions on the growth paths of modern economies.

The paper is structured as follows. Section 2 presents a review of the existing literature on the topic and highlights the important differences of this study from the literature. Section 3 provides a discussion of the energy transitions and the accounts of economic historians that motivated this study. Section 4 discusses the micro-foundations of the model and builds the model of the economy. In section 5, the model is calibrated with the British data for baseline and counterfactual scenarios; the results are analysed and discussed. Section 6 provides concluding remarks. Appendix presents a detailed description of the data used in this study.

2 Energy transitions and the British Industrial Revolution

The present study is related to the literature on the modelling of the transition from stagnation to high growth. This section provides a review of the existing quantitative studies on the topic. Literature on the topic is relatively new and the efforts were initially concentrated on quantifying the transition from low growth to high growth economic regimes to improve the understanding of the underlying factors that led to the transition from stagnation to growth of the currently developed countries. Galor (2005) states that it has been increasingly recognised that the understanding of the contemporary growth process would be fragile and incomplete unless growth theory could be based on proper micro-foundations that would reflect the various qualitative aspects of the growth process and their central driving forces. The result of the earlier efforts has since been the development of the Unified Growth Theory[11].

To date, numerous studies have attempted to characterise the transition from stagnation to modern growth following the seminal work by Galor and Weil (2000). Other work on the topic includes Jones (2001), Lucas (2002) and Hansen and Prescott (2002) among others. The theory captures, in a single analytical framework, the main characteristics of the process of development: (i) the epoch of stagnation[12], (ii) the escape from the low growth state, (iii) the emergence of human capital formation in the process of development, (iv) the onset of the demographic transition, (v) the origins of the modern growth era, and (vi) the divergence in income per capita across countries (Galor, 2011, p. 4).

Galor and Weil (2000) model the transition from low growth to high growth as an inevitable consequence of economic development. In the model, technological improvement is a function of changes in the size of population and the level of education. It is assumed that, initially, the economy is in a low growth, low technical progress and low education level state. As population grows, technological progress brings about industrial demand for human capital stimulating the accumulation of human capital. Greater accumulation of human capital inevitably facilitates further technological progress. The outcome of this process is a demographic transition that does not halt the growth of income per capita as in the previous periods. Thus, income per capita growth is sustained in the long run.

Hansen and Prescott (2002) provide a model in which the transition from constant to growing living standards is inevitable given positive rates of total factor productivity. The model assumes that there exists two states of an economy. Initially, production is land-intensive, and hence uses land-based sources of energy such as animal power. The final output is produced combining land, capital and labour, and the economy is constrained by the fixed size of the land-based resources. The other state is characterised as capital-intensive, whereby only

[11] Unified theory characterises the process of development in a single dynamic system beginning with an initially stable low growth (i.e. Malthusian) equilibrium which then converges to a high growth followed by modern growth system endogenously. In the low growth system, the benefits of the technological progress are offset by population growth. In the modern growth regime, technological progress and human capital accumulation spur further technological progress in the long run.

[12] Galor (2011) defines the low income growth period prior to the Industrial Revolution as the *Malthusian state*.

labour and capital enter into production and it does not face land-based resource constraints. The transition from stagnant to growing living standards occurs when profit-maximising firms, in response to technological progress, begin employing a less land-intensive production process that, although available throughout history, was not previously profitable to operate.

The proponents of the unified growth theory characterise the period before the nineteenth century as facing diminishing returns to land input as it is a fixed input, and one in which agriculture employs the largest share of the labour force. Recent research by revisionist economic historians shows that the industrial and service sectors accounted for 40% of the labour force as early as the 1380s. A substantial further shift of labour out of agriculture occurred between 1522 and 1700. By 1759, agriculture's share of the labour force had shrunk to 37% and that of industry grew to 34%, and by early 1800, just over 30% of the labour force was in agriculture (Broadberry *et al.* 2013)[13].

Furthermore, unified growth theorists describe the period before the Industrial Revolution as one in which living standards remained on subsistence levels, and a rising population eroded any increase in income per capita. As such, the economy permanently remained in a low growth stagnant state often referred to as *Malthusian trap*. Fouquet and Broadberry (2015) show that there was no such state as *Malthusian* in the past seven centuries, at least not in England. They argue that extended periods of economic growth existed before the nineteenth century, however, economic growth was unsustained each time. They identify long run cycles of output growth and decline which contributed to the slow increase in income per capita. Thus, living standards did not remain constant[14].

Voigtlander and Voth (2006) present a probabilistic two-sector model (i.e. agriculture and manufacturing) where the transition to a high growth state depends on the demographic regime, capital accumulation and the use of more differentiated capital equipment. The productivity of the agricultural sector is subject to weather-induced exogenous shocks that determine the prices and quantities, and wages. Growth is driven by the exogenous

[13] Unified Growth Theory has been criticised for not offering appropriate explanation to the patterns seen in the actual historical data. Perhaps, the harshest critic of the theory has been Nielson (2016) who calls the theory a puzzle and a myth.

[14] Allen (2009) shows that wages grew in the two hundred years prior to 1800 in Britain.

productivity progress in agriculture and by endogenous capital accumulation. Higher output of the manufacturing sector stimulates more capital-intensive production creating context for improving the designs of the existing capital stock, and more differentiated capital stock boosts the productivity growth. Simulations show that Britain's early escape was only partly due to chance, and the study does not find resource endowments to have any effect on the industrialisation of Britain. The study emphasises the importance of chance in inventions, further tinkering, and non-economic motives for innovation.

Another limitation of the unified growth theory is that it does not consider energy as an input to production. Froling (2011) extends the theory by including energy in the production of final goods. Froling develops a model that shows that the switch from biomass to coal use was an important determinant of the transition from stagnation to growth. In the model, the switch between coal and biomass governs the transition to the high growth regime. As in Galor and Weil (2000), the rate of technological progress is the function of population growth. Technical change is underpinned by the accumulation of knowledge input used in the production of final goods and in the conversion of primary energy, coal, to secondary energy. The production of coal and wood is determined by the labour allocated to the energy producing sector only and hence there is no upper bound, imposed by fixed land, to the supply of energy. Energy consumption grows as long as the population grows, and population is employed in the production of primary energy, innovation and final goods. Thus, the only constraint in the economy is population. The production of the final good is modelled as the combination of labour, energy and land. In the model, an increase in the overall level of technology leads to higher growth. Higher energy conversion efficiency spurs the transition from biomass to coal use. Output growth accelerates upon the switch to coal use.

Stern and Kander (2012) provide an econometric test of transition from low growth steady state to one with high growth using data on the Swedish economy for the period between 1850 and 1950. They find that the expansion of effective energy services allowed a higher rate of economic growth than in the pre-industrial period because expanding energy services continually moved the steady state to higher levels of output. Counterfactual simulations show that the scarcity of energy services strongly constrains output growth resulting in a low-income steady state. The expansion of energy services is found to be a major factor in explaining economic growth in Sweden, especially before the second half of the twentieth century.

In another econometric study, Kander and Stern (2014) examine the role of transition from biomass to modern energy use and of differential rates of innovation in the use of each of these in economic growth in Sweden between the years 1850 and 1950. The study measures how important innovation was in the use of each fuel. The results show that the rate of technical change was higher for modern energy; innovation in the use of traditional energy carriers contributed more to growth between 1850 and 1890, since the cost share of traditional energy was so much larger than that of modern energy in that period. However, for the period after 1890 the paper finds that modern energy contributed much more to economic growth than traditional energy did, but, labour-augmenting technological change became the most important single driver of growth.

Eren and Garcia-Macia (2013) provide a quantitative model of the British Industrial Revolution by using an endogenous growth model of directed technical change and natural resources. The model characterises the transition from stagnation to high growth as the transition from wood to coal. Drawing on the cliometric accounts of economic historians, the paper shows that the transition to a cheaper and more efficient energy source, coal, from a less efficient expensive energy source, wood, leads to positive growth effects. While the resource prices play a role in the switching process, the high growth is driven by coal being a more efficient fuel than wood. This assumption, in turn, allows the coal-using sector to be a relatively more productive sector than the wood-using sector.

This short review of the literature does not do justice to the expanding literature on the topic; nevertheless, it provides insights into the related literature. The existing studies have shown that the transition to high growth was not simple, and a range of factors played various roles in the transition process. There does not appear to have been a dominant factor underpinning the transition to growth. However, the role of energy has not sufficiently been addressed so far. The present study is similar in its theoretical and empirical setup to Eren and Garcia-Macia (2013) and Froling (2011). Unlike these studies, this study does not impose differential productivity levels across the sectors driven by the high efficiency content of coal. As will be shown in the following, this assumption is not necessary for the economy to escape the low growth regime. If anything, imposing this assumption accelerates the growth once the coal-using sector dominates the economic activity. The growth accelerates even in the absence of such an assumption.

As narrated by Allen (2009) and Kander *et al.* (2013), the innovation shifts to the coal-using sector due to price signals and the size of the market for goods produced by the sectors. Many industries used organic sources of power including water and animal power alongside coal even after the mid-eighteenth century. The most important factor in the transition to coal, as stressed in this study, was the low cost of goods produced using coal-based technologies[15]. Businesses switched to coal-using technologies because coal as an input to production was cheaper and reduced the production costs (Allen, 2009; Kander *et al.* 2013). Where available wood remained a major source of thermal energy for many businesses during the Industrial Revolution (Fouquet, 2008), the larger market for coal-based products is what underpinned the acceleration of growth. Given the large market, innovators continued tinkering with the new technology and the new technology emerged as the most efficient of the two (i.e. wood and coal-using technologies). While coal was more efficient in providing greater amounts of heat, the growth depended on the extent to which coal based-production reduced the production costs (Fouquet, 2008; Allen, 2009; Kander et al, 2013).

3 Wood crisis and the transition to coal

This paper focuses on the First Industrial Revolution, which was preceded by a period of slow productivity growth and gradual structural change. The gradual nature of the transformation makes this transition process coincide with the gradual transition from wood to coal. Analysing the two overlapping transformations, Wrigley (2010) claims that the Industrial Revolution is the direct consequence of the transition from wood to coal. Allen (2009) provides detailed analysis of the key effects of the energy transition on the growth trajectory

[15] The underlying factor in driving down the prices is the availability of low cost coal in Britain.

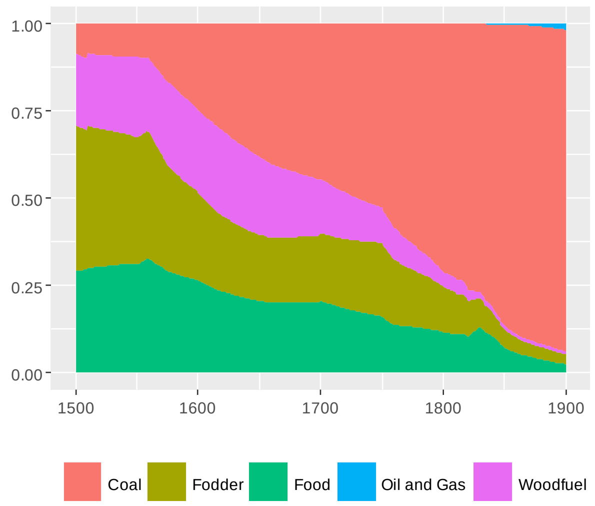

Figure 1 Britain's primary energy composition, 1500-1900.

of the British economy. It is thus important to provide a historical background to the transformation and to provide a preliminary analysis of the data on prices and energy use.

Why did Britain substitute charcoal with coal? Why was the Industrial Revolution bound up by the energy transition? Britain was the first country to shift to a coal-based economy whilst the rest of the world used wood and/or peat for thermal energy (Allen, 2009; 2012). The general historical account of the reasons for the transition to coal use is that the capacity of the land to grow plants imposed a fundamental limit on the economy (Wrigley, 2010). It has also been argued that the transition to coal was inevitable due to the wood crisis Britain faced during the sixteenth century, and the transition was somewhat dramatic (Nef 1932; 1977). Britain was the least wooded country in Europe in the nineteenth century; however, it did not have a wood crisis (Hammersely, 1973). Hatcher (1993) states that the "wood crisis" was mostly limited to certain localities and that the problems associated with transporting wood to the final users increased the cost of charcoal. Fouquet's (2010) cliometric accounts indicate the cost of charcoal was persistently higher than that of coal and the transition towards coal was very slow.

Fouquet (2008) provides a detailed analysis of the energy transitions for the past seven centuries. Figure 1 is adapted from Fouquet (2008), and it provides evidence consistent with the claims that the transition towards wood was not rapid. Little coal was mined until the last

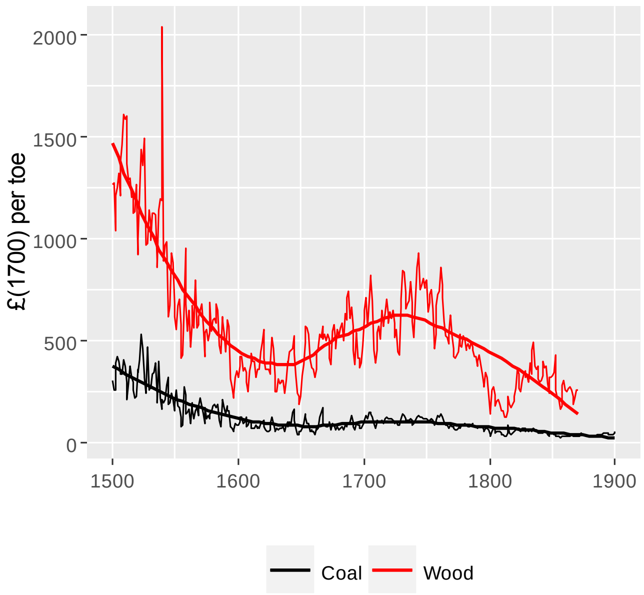

Figure 2 Real price of coal and wood, 1500-1900.

quarter of the sixteenth century and the share of coal in aggregate energy consumption was just over 10%. The main energy sources were human and animal muscle power (represented by food and fodder), and woodfuel. A major source of power appears to have been animals. By the early 1600s, the transition to coal was well underway but it does not appear that wood was being substituted for coal; instead, the share of food and fodder declined rapidly. Demand for woodfuels declined during the eighteenth century; and on the eve of the Industrial Revolution in the 1750s, coal appears to have provided half of the energy. The transition took nearly two centuries, and as can be seen, coal was already a major source of energy even before the classic period of the Industrial Revolution (1760-1840). Coal was used to meet about 90% of energy needs in Britain by 1900.

The transition from biomass to wood appears to have begun in the second half of the sixteenth century, well before the classic period of the Industrial Revolution. Was the transition induced by price differentials? Figure 2 shows the time trend of wood and coal prices for the years between 1500 and 1900. Clearly, coal was cheaper than woodfuels in the whole period. However, the prices appear to have tracked one another, and the gap between the prices was not constant. When the share of coal consumption began rising during the late sixteenth century (Figure 1), the price gap was narrowing. Perhaps, this kept the demand for woodfuels stable, but as the gap widened in the second half of the seventeenth century, the decline in the share of woodfuels markedly accelerated. In this period, the share of other fuels declined as well, but woodfuels' share in the energy mix declined rapidly.

Fouquet (2008) suggests that the substitution towards coal was due to favourable prices of coal for heating, especially in urban centres. In particular, as London grew, the demand for fuel for industrial purposes and domestic heating increased. The trade boom pushed the urbanization rate from 7% in 1500 to 29% in 1800. The growth of London accounted for much of this urbanization. Its population rose from about 50,000 in 1500 to 200,000 in 1600, to half a million in 1700, and reached one million in 1800 (Allen 2012). As shown above, woodfuels provided most of the thermal energy, but as the demand increased, woodfuels had to be shipped over greater distances at increasing transport costs. Transport costs were the main driver of fuel prices[16], and the price of fuel rose as urbanization expanded. Eventually, the price gap widened in the eighteenth century coinciding with the rapid increase in the consumption of coal.

Allen (2012) highlights the crucial role of London's expansion in the transition to coal use. Given that wood had been used for heating in London prior to the transition, coal burning houses had to be redesigned[17]. London's construction boom was underway in the sixteenth and seventeenth centuries and this provided opportunity to experiment with the new coal-using heating technologies. Knowledge sharing among the builders enabled them to extend each other's inventive efforts. As such, collective invention eventually solved many of the technical problems in the transition to coal-based heating (Allen 2012). Had the technical problems not been solved, the market for coal would not have expanded in the seventeenth century. Allen (2012) states that over half of Britain's net coal consumption was used for residential heating in 1700.

As the evidence suggests, there was no wood crisis prior to or during the Industrial Revolution, instead the transition towards coal may have been driven by growing demand for

[16] Fouquet (2008) presents a detailed discussion of the energy costs to the consumers.
[17] Allen (2009) notes the design changes in the layout of a typical English home and the appearance of chimneys in the new homes in the sixteenth and seventeenth centuries.

coal in the household sector. Nevertheless, the transition to coal reduced the burden imposed by a constrained land on a growing population (Fouquet 2011). A widening price gap in the first half of the eighteenth century may indicate the scale of constraints imposed by scarcity of firewood from economically accessible woodlands (Fouquet 2008). Should Britain have continued relying on woodfuels for its thermal energy needs until 1800, it would have had to actively manage a woodland the size of the whole of Britain (Wrigley 2010). Therefore, whether it was induced by prices or other factors[18], the transition to coal enabled the economy to expand its industrial activity that would not have been feasible using scarce and expensive woodfuel. It is possible that the price differentials induced the transition to coal, as it became relatively more profitable to adopt coal in the industry sector (Allen, 2009; Kander *et al.*, 2013).

The price of coal, although remaining low relative to that of woodfuel, markedly increased in the years between 1650 and 1750 (Figure 2). Fouquet (2008) relates the rise in the price of coal to the supply shortages emanating from obstacles in coal mining and its transportation. The major issue in coal mining was flooding, and this slowed down the speed at which supplies could be made available to meet the growing demand. The development of steam engines to pump water out of the mines in the eighteenth century provided a solution to the problem of flooded mines. Steam technology, coupled with the improved roads and extended canals, may have eventually stabilised the price of coal towards the end of the eighteenth century.

With the rapid expansion of demand for coal, coal mining became one of the major industries in Britain[19]. In 1500, coal production was 27,000 toe[20], by 1700 Britain produced 1.5 million toe and in 1800 (Fouquet, 2011). Fouquet (2008, p. 54), citing Hatcher (1993), states that, by the mid-seventeenth century, most industries switched to coal. By the time woodfuel price started to rise, industry was hardly dependent on woodfuels. The transition to coal in each industry depended on industries finding a solution and it being commercially viable (Fouquet

[18] Fouquet (2008) summarises some of the non-price factors that provided impetus for coal mining between 1500 and 1800.
[19] Crafts and Harley (1992) argue that coal mining was a relatively small industry, even in the nineteenth century.
[20] Tons of oil equivalent

2008, p. 99). Some industries such as lime-making, glass making and brick making among others where coal did not come in contact with the materials, adopted coal much earlier. Iron industry, for instance, had to use charcoal until after the 1750s when the technological solution, in the form of coke iron smelting, developed by Abraham Darby in 1709, became cheaper to apply relative to charcoal-based smelting (King, 2005; Fouquet 2008, p. 62).

Power provision outside the mining industry and transport services used organic sources of energy until the first quarter of the nineteenth century (Fouquet, 2008). The delay in adoption of steam technology in these industries was caused by a lack of progress in improving steam technology. Ashton (1955, p. 107) argues that Britain would have had railways before the onset of the nineteenth century had the Parliament not extended James Watt's patent in 1775 for a further 25 years[21]. Watt did not allow other investors to improve the steam technology, discouraged experiment with locomotive models, and was hostile to the high pressure steam technology (Mokyr 2009, p. 93).

In the years following the expiry of Watt's patents, steam technology began diffusing rapidly thanks to sustained innovations and knowledge sharing among innovators. Within two decades, sustained work on high pressured steam engines resulted in the development of the first commercially viable locomotive followed by the invention of steam ships. Construction of the first rail network in the 1830s made freight transport cheaper and more reliable. Railways carried more than 90 per cent of goods, and steam ships provided about 80 per cent of all freight services at sea (Fouquet 2011, p. 7). The adoption of steam technology in the cotton textiles enabled the shift from home to factory based production that boosted labour productivity. In 1700, steam accounted for only 1.5% of total power provision, 30% by 1850 and 71% by 1900 (Fouquet 2008, p. 125). The transition to coal appears to have ushered in the era of rapid technological progress and hence enabled Britain to break free from the constraints on growth.

[21] Originally, James Watt was granted patent in 1769.

4 Transition to coal, induced technical change and the Industrial Revolution

Fouquet (2011, p. 6) argues that the switch to coal was not a simple case of reacting to a lack of land and its products. The substitution towards coal had begun in the sixteenth century for certain industries and households. Instead of fossil fuels spectacularly resolving an energy crisis and driving an Industrial Revolution in Britain, the energy transition was a gradual process, lasting more than two hundred years. The low cost of coal was, however, a major impetus for its adoption in Britain. While it may not have caused rapid industrialisation, the transition to coal was a catalyst for the sustained economic growth in the nineteenth century. The adoption of coke for iron smelting reduced the cost of energy input per ton of pig iron output. Once the efficiency improved sufficiently, the introduction of the coal-fired blast furnace enabled the mass production of iron at low costs (King, 2005).

Shift to coal use in the iron industry made Britain the dominant supplier of non-ferrous metals in the world. Pig iron production did not vary much until the early 1750s when many ironmasters began the transition to coke iron smelting. By 1850, Britain supplied 75% of the world's copper, half of the world's lead and three fifths of its tin (Allen, 2009). According to Kander *et al.* (2013), a low cost iron smelting technique using coke provided comparative advantage enabling Britain to be at the forefront of iron production. Moreover, a cheap supply of iron made it possible to produce low cost capital goods, which were used to mechanise a host of production processes in mills, textiles, mining, metallurgy, and transportation industries.

Roughly at the same time as coke smelting became widespread, steam engines were being used commercially in coal mining. Later, steam engines offered a large source of power that was not geographically constrained, and thus, offered flexibility in the location of factories. Consequently, steam technology powered by coal helped break the geographical constraint imposed on the growth of the new industries (Kander *et al.*, 2013). Previously, water power confined the power intensive industries to areas where it was possible to harness water power. This effectively subjected the productivity to seasonal variations given the water wheels powering the factories required fast flows of water. As in the case of coke smelting, steam engines diffused slowly at first, but the adoption rate took-off in the first half of the nineteenth century (Fouquet, 2008; Griffin, 2010). By 1850, coal had already been used in land and sea transport services provision.

Wrigley (2010) argues that a salient feature of organic economies[22] is their reliance on land to derive energy, and land is in fixed supply. The production of energy resources i.e. food, fodder, firewood expands as a population grows, putting pressure on energy prices. High energy prices coupled with limited supply of land reduces the return to labour and capital. Effectively, organic economies face a somewhat permanent constraint on growth with the absence of alternative sources of energy. A solution to the constraints was the abundant supplies of coal; at low prices, coal stimulated innovative activities. Wrigley (2010) further argues that in the absence of Britain's vast coal reserves, the Industrial Revolution would not have taken place in Britain. British Industrial Revolution was the result of dynamic interactions among various factors, and there is no single element at the core that explains the shift from a low growth to a modern growth regime. Britain's immediate neighbours, France, Scandinavia and Germany had necessary skills and capital, but the modern growth regime did not originate in these regions and countries. Similarly, abundant reserves of coal alone may not be a reason for growth acceleration. Coal was abundant in China, North America and Russia, yet, these regions did not experience the sheer growth acceleration that Britain did early in the nineteenth century. Unlike other countries, Britain had all of the necessary ingredients for industrialisation - abundant coal reserves, skilled labour, capital stock, labour and high wages. Put together with other factors, cheap coal offers a better explanation as to why the Industrial Revolution was British (Allen, 2009; Kander *et al.* 2013).

Availability of coal alone was not sufficient to stimulate growth but it was necessary for directing the technical change (Allen, 2009). An important aspect of the new growth regime was that the innovators were able to convert thermal energy into kinetic energy through innovations (Kander *et al.* 2013). Engineers had known the science of energy conversion for many decades, but its practical application was delayed until the late seventeenth and early eighteenth century. Clearly, the knowledge was not sufficient, and the engineers of the time

[22] "Organic economy" is a system whereby energy is derived from sources subject to photosynthesis.

required incentives to justify the research on steam technology[23] (Allen, 2009; 2012). The development of steam technology required the business environment and conditions conducive to innovation. The growing demand for coal and hence the expansion of Britain's coal industry provided the context and incentives for tinkering with the steam technology. Allen (2012) argues that without incentives, the steam engine might have never been invented in Britain.

Had there not been favourable conditions and incentives for inventive activity prior to the seventeenth century in Britain? Research by the supporters of the "institutions" hypothesis including North and Weingast (1989) and Acemoglu *et al*. (2005) among others show that Britain's Glorious Revolution of 1688 whereby the monarch's powers were limited created the context for innovative activities. The new political system ensured that private property rights were secure and the legal system was flexible, and the government's influence was limited. Engineers were able, for the first time, to patent their ideas and inventions and hence reap the benefits of their hard work. This transformation was promoted as a necessary and sufficient condition for the industrialisation of Britain[24]. However, Mokyr (2009a) questions the effectiveness of the patenting system in Britain, and does not find strong linkages during the time between 1688 and classic period of the Industrial Revolution. In an econometric study, Clark (1996) does not find a significant effect on rates of return on private capital after the Glorious Revolution[25].

Allen (2009; 2011) argues that the French had all the necessary ingredients for conducting scientific experiments, but the prevalence of institutions was not sufficient to incentivise the French engineers to invent steam technology. Coal was more expensive than wood and there was no sufficiently large coal industry as in Britain to warrant a sustained scientific experiment with steam technology. Britain, on the other hand, had an expanding market for coal and this created incentives for innovating not only steam technology but also broad-based coal using technology. Sustained R&D investment in the innovation of coal using

---

[23] Mokyr (2009) writes comprehensively on how advances in scientific knowledge in the era of Enlightenment provided impetus to the innovations that underpinned the sustained growth of the British economy.
[24] In particular, North and Weingast (1989) strongly supports this view.
[25] Pomeranz (2000) argues that private property rights were at least as secure in France as in Britain during this time; in a similar vein, China was not different. Epstein (2004) stresses the ineffectiveness of the patenting system in a historical account of technological progress during the period between 1300 and 1800.

technologies improved energy efficiency leading to the emergence of low cost ground and sea transportation. The adoption of coal-using steam engines for transport reduced the costs of trade and the Industrial Revolution spread to other regions and countries.

5 The Model

The model simulation runs for 300 periods; each period is a year and the simulated series is compared with actual data for the 1550-1849 period. There is no specific date that marks the beginning of the high growth era. However, the consensus is that the classic period of the Industrial Revolution covers the period between the years 1760 and 1830, which has become known as the First Industrial Revolution[26]. Slow but sustained output growth observed in the First Industrial Revolution was the result of many transformations including, but not limited to, the transition towards coal use, application of steam technology in mining, innovations in the iron industry, and the mechanisation of textiles. Some of the transformations took place in the seventeenth century while some were the consequence of innovations that were built on the earlier efforts.

The starting values for the simulations are based on the energy prices observed during the first decade of the sixteenth century, and the model targets to match average annual growth rate of income per capita and the ratio of the estimated energy prices for the 1840-1850 period. The model is constructed such that the fuel price differentials trigger the switch to low cost fuel, coal, from expensive charcoal use. Following the switch, coal-using technologies proliferate and eventually boost productivity growth. In the model, energy is assumed to be derived from firewood and coal only, the stock of wood and coal grow over time through regeneration efforts. Initially, thermal energy is mainly derived from wood and the gap between wood and coal prices is narrow but it expands rapidly. This assumption is made based on the historical price series for the two commodities as shown in Figure 2.

[26] The First Industrial Revolution or the *classic* period of industrial revolution covers the period between 1760/70 and 1830/40. Dating of the Industrial Revolution has been a contentious issue.

5.1 Households

There is a continuum of identical households in the economy comprising of workers and entrepreneur-innovators. Workers work in the production of sectorial goods, entrepreneur-innovators improve resources using machine efficiency. Households do not have a role in the model and the study abstracts from policy analysis. The study only aims to characterise the shift in the growth state as an energy transition process, and hence it is assumed that the agents only care about period by period utility maximisation. However, as will be seen in the following, agents i.e. firms in both the sectors of the economy, are profit maximisers and optimise their production decision on a period by period basis.

5.2 Final Goods

Final good Y_t is produced using two energy intensive inputs $Y_{w,t}$ and $Y_{c,t}$. The aggregate output function is given as:

$$Y_t = \left(Y_{w,t}^{\frac{\sigma-1}{\sigma}} + Y_{c,t}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \qquad 1$$

where, two sectorial goods are produced using either wood (w) or coal (c). This representation of final good production is in line with empirical evidence that production was energy intensive during the Industrial Revolution and that the share of energy in final goods was as high as 25% in the earlier periods and declined to around 13% when liquid fuels were introduced in the second half of the nineteenth century.

5.3 Intermediate Goods

Sectorial goods are produced combining labour, wood or coal energy along with a continuum of machines that use either of the energy carriers. The production functions of intermediate goods are of Cobb-Douglas type:

$$Y_{s,t} = \left(\int_0^1 A\,(j)_{s,t}^{1-\alpha_1} x(j)_{s,t}^{\alpha_1}\, dj \right) E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha} \qquad 2$$

where, $\alpha \in (0,1)$ and $\alpha = \alpha_1 + \alpha_2$. $A(j)_{s,t}$ is the quality (efficiency or productivity) of machine j at time t in a sector that uses energy s, $s \in \{w, c\}$. $x(j)_{s,t}$ denotes the number of energy-complimentary machine varieties or "machines" that can either be used with wood or coal energy. The machines are produced and supplied by monopolist entrepreneurs. Machines depreciate fully after use within one period. $L_{s,t}$ is labour used in sector s at time t, it is mobile between the two sectors and the population is the sum of the labour employed in coal-using and wood-using sectors: $L_t = L_{w,t} + L_{c,t}$. Population is assumed to be given exogenously and is constant; it is set to unity, that is $L_{w,t} + L_{c,t} = 1$. Finally, $E_{s,t}$ denotes the flow amount of energy used in the production of sectorial goods at time t.

The assumption that the population is constant is an abstraction away from the historical pattern of population growth. The growth of coal supply in the eighteenth century was in response to a growing population, the pressures from urbanisation and the demand for a changing economy (Humphrey and Stanislaw, 1979; Fouquet, 2008). In the model, the fuel consumption is determined by the size of each sector, and the size of the sector is partly determined by the labour employed in that sector. Since labour is allowed to switch between the two sectors freely, the demand for fuel is driven by the growth of labour in each sector. As such, the relative growth of labour in each sector is akin to the growth of population in the sector and hence the economy given that in the long run all labour is employed in the single sector. Consistent with the historical accounts, the simulations show that by 1849, almost all labour is employed in the coal-using sector.

The next major abstraction from the historical accounts is that the sectorial production (or the production of the intermediate goods) is modelled as a Cobb-Douglas function. Thus, the share of energy is assumed to be constant in the whole period. Fouquet (2008, p. 269-271) documents that the ratio of expenditure on energy services to output varied between 15% and 35% during the period 1600-1900[27]. Thus, the assumption of constant input shares could not

[27] Here, it is assumed that the cost share of energy in output is reflected in the cost share of energy services in output. This assumption holds given the demand for energy is determined by the demand for energy services and the energy service price tracks the price of energy. Fouquet (2011) shows that the cost of energy and energy services diverged in the late nineteenth century, though the diversion was in the same direction. As such, it is important to note that the temporal behaviour of the cost share of energy in GDP is similar to that of energy services.

be supported by the empirical evidence, but by including energy in the production of intermediate goods, it is assumed that energy is a limiting factor of production. Fouquet (2008) and Kander *et al.* (2013) note that most energy, especially, coal consumption was in the production of intermediate goods including but not limited to iron, cotton, coal, steel among others. Fouquet (2008, p. 90-91) states that, in addition to coal use in iron and steel making, general manufacturing, including non-ferrous metals production, accounted for up to half of the coal consumed in the industry until the nineteenth century. During the nineteenth century, the coal use in the metals industry accounted for one third of the total demand for coal. The next major consumer of coal was the chemicals industry which supplied major inputs to the textiles, glass, pottery, paper and soap industries. Chemicals were also used in the brewing industry as well as in the production of gunpowder, oils and paints.

5.4 Machine Producers

Machines are produced and supplied by monopolist entrepreneurs. An entrepreneur who invents a new machine receives a patent and becomes its unique supplier. The entrepreneur sets a rental price of $\chi(j)_{s,t}$, $s \in \{c, w\}$. As a sole supplier of the machines, the entrepreneur can set the prices above the marginal cost of producing machines. The marginal cost of producing a machine in terms of the final good is assumed to be ϕ. The machines depreciate fully after use within one period and the entrepreneur produces a new machine of the corresponding type to replace the old one. It is assumed that the set of machines used in the production of the two sectorial goods are different in design and operation but are imperfect substitutes; this allows technical change to be biased (Acemoglu, 2002). As it became profitable to use coal for heating in the 1600s, R&D efforts in coal-using technology took off rapidly. Allen (2009) notes that the shift to coal use required re-engineering and re-inventing a new kind of technology. The old technology was wood-using; adopting coal-using technology posed as much of a scientific challenge as an economic challenge directing the flow of resources towards coal using inventions.

5.5 Research and Innovation

According to Allen (2009), after the invention of steam technology, most innovation efforts were directed at perfecting the steam technology and involved many of the most famous engineers of the Industrial Revolution. This phase involved saving all inputs and, in particular, coal, after the 1850s (Fouquet, 2008). Fuel consumption dropped from 44 pounds of coal per horsepower-hour in 1727 to 3 pounds in 1847, and this was the result of engineers building on each other's experience over time. To closely match these developments, it is assumed that the entrepreneur-innovators can conduct research in the coal or wood sector to improve machine quality (or productivity).

Entrepreneurs in each sector spend $R_{s,t}$ units of final output in research and development, the outcome of which is uncertain. Successful entrepreneurs increase the productivity of machine j by a factor $1+\tau_s$ with probability $\theta_{s,t}$ where τ_s $(0<\tau_s<1)$ is the size of the innovation. Therefore, successful entrepreneurs increase machine quality from $A(j)_{s,t}$ to $(1+\tau)A(j)_{s,t-1}$. On the other hand, if the entrepreneur fails, no product quality improvement is achieved at time t and the existing patent holder produces the old vintage. Thus, the level of productivity remains invariant $A(j)_{s,t-1}$ with probability $1-\theta_t$[28]. Hence,

$$A(j)_{s,t} = \begin{cases} (1+\tau_s)A(j)_{s,t-1}, & w.p. \quad \theta_t \\ A(j)_{s,t-1}, & w.p. \quad 1-\theta_t \end{cases} \qquad 3$$

The probability of successful innovation is:

$$\theta_{s,t} = \nu\left(\frac{R(j)_{s,t}}{(1+\tau_s)A(j)_{s,t-1}}\right)^{\eta} \qquad 4$$

where, $R(j)_{s,t}$ is the amount of final goods spent on conducting research to improve the productivity of machines in sector s at time t, hence the probability depends positively on research efforts given the investment in research. The probability inversely depends on the level of productivity implying that the higher the productivity level, the harder it is to successfully improve the productivity. Essentially, it is not the absolute amount of spending

[28] The equation for the probability of success is adapted from Novales *et al.* (2013, p. 333-337).

that guarantees innovation, but the productivity adjusted R&D expenditure. The η ($0 < \eta < 1$) parameter indicates that an increase in $\frac{R(j)_{s,t}}{(1+\tau_s)A(j)_{s,t-1}}$ raises the probability of success in research less than proportionally and ν is an indicator of productivity in R&D efforts that guarantees the probability of success to be between 0 and 1. Following Acemoglu *et al.* (2012), the technology level in each sector is assumed to evolve according to:

$$A_{s,t} \equiv \int_0^1 A(j)_{s,t}\, dj \qquad 5$$

It can then be shown that the average productivity level of each sector is:

$$A_{s,t} = \int_0^1 \{\theta_{s,t}(1+\tau_s)A(j)_{s,t-1} + (1-\theta_{s,t})A(j)_{s,t-1}\}\, dj = (1+\tau_s\theta_{s,t})\int_0^1 A(j)_{s,t-1}\, dj$$

Next, using the equation for the probability of success (4) and the condition (5) in the above expression, it can be shown that:

$$A_{s,t} = (1+\tau_s \nu r_t^{\eta})A_{s,t-1} \qquad 6$$

So the rate of aggregate productivity in each sector is:

$$\frac{A_{s,t}}{A_{s,t-1}} = 1+\tau_s \nu r_t^{\eta} \qquad 7$$

A successful entrepreneur is granted a fully enforceable patent to monopolistically supply the improved machine to the producers of intermediate goods. The entrepreneur retains the monopoly power in the market for machines until another entrepreneur increases the productivity of the machines further. This set-up closely matches the conditions of entrepreneur engineers such as Thomas Newcomen, James Watt, Richard Trevithick and Richard Arkwright among others who hoped to reap the benefits of their hard work through patenting. For several decades, steam technology had been perfected by these engineers each patenting and commercialising their innovations. Although a number of economic historians highlight the ineffectiveness of the British patenting system, Mokyr (2009a,b) states that patenting was perceived as a way of generating income among the innovators. It provided hope and expectation of greater wealth for each innovator. Also, the assumption that the new "vintage" replaces the older models continuously is also not far from the truth given that the improved steam technology replaced the old models over time during the Industrial Revolution.

5.6 Resource Extraction

Landowners supply wood and coal to the intermediate goods sector in perfect competition. The landowners face resource scarcity but benefit from knowledge spillovers from R&D efforts in the intermediate goods sector.

The stock of resources evolves according to:

$$S_{s,t+1} = S_{s,t} + X_{s,t} - E_{s,t} \quad 8$$

where, $S_{s,t}$ is the stock of resources and $X_{s,t}$ is the additional amount of stock that became extractible at time t. Addition to the stock resources at each time t is $X_{s,t} = S_{s,t}A_{s,t}^{-\lambda}$ and the available stock for extraction is $\tilde{S}_{s,t} = S_{s,t} + X_{s,t}$. $\lambda\ (> 0)$ determines the speed of stock regeneration. It is assumed that temporal productivity gains in each sector allows the landowners to expand resource stock. This assumption accounts for the expansion of coal supply after the application of steam technology in draining mines in the eighteenth century. Depending on the value assigned to λ, the rate of the addition to the existing stock of wood and coal varies.

The evolution of coal stocks in (7) is in line with the claims noted in Allen (2009) and Wrigley (2010) among other economic historians. Notably, coal mines flooded after reaching a certain depth making it impossible to extract more coal. However, the application of steam technology in coal mining allowed the landowners to increase extractible reserves and hence supply more coal to the market. Initially, steam engines were grossly inefficient, according to Allen (2009); however, sustained flow of R&D expenditure made it possible to further tinker with the steam engine and resulted in a more reliable and efficient steam technology. This ensured that supply kept up with the growing demand in the market. Clark (2007) argues that the coal industry was only able to respond to increases in demand in the Industrial Revolution because of technological advances. While Clark did not specify the type of technological advance, economic historians agree that much of the R&D activities was directed towards inventing and improving coal-using technologies during the Industrial Revolution (Allen, 2009; Wrigley, 2010).

It is assumed that the marginal cost of resource extraction changes on the stock of resources. As discussed in the preceding sections and shown in Figure 2, the price of coal remained low thanks to the application of steam technology in mining during the Industrial Revolution. The price for firewood however remained relatively high and increased further in the eighteenth century due to supply constraints (Fouquet 2008). Firewood had to be transported to the centres of industry and town centres from greater distances as deforestation increased. Therefore, the cost of resource extraction ($c_{s,t}$) is modelled as follows:

$$c_{s,t} = \begin{cases} c_{w,t-1}\left(1+\frac{1}{\tilde{S}_{w,t}}\right) \\ c_{c,t-1}\left(1+\frac{1}{\tilde{S}_{c,t}}\right) \end{cases} \qquad 9$$

where $c_{s,t}$ is the marginal cost of resource extraction at the beginning of the period, $s \in \{w, c\}$. In the absence of expansion in extractible reserves, the marginal cost of extraction increases. On the other hand, addition to the existing extractible reserves ensures that the price of the fuel remains low (constant).

6 Solution of the Model

6.1 Final Goods

Final good is produced competitively combining $Y_{w,t}$ and $Y_{c,t}$, and the final good producers solve the following maximisation problem:

$$\max_{Y_{w,t},Y_{c,t}} \left\{\left(Y_{w,t}^{\frac{\sigma-1}{\sigma}} + Y_{c,t}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} - P_{w,t}Y_{w,t} - P_{c,t}Y_{c,t}\right\} \qquad 10$$

where $P_{w,t}$ and $P_{c,t}$ are prices of intermediate goods at time t. In competitive equilibrium, the two sectorial goods are paid their marginal productivities respectively according to the following equations:

$$P_{s,t} = \left(Y_{c,t}^{\frac{\sigma-1}{\sigma}} + Y_{w,t}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{1}{\sigma-1}} Y_{s,t}^{-\frac{1}{\sigma}} \qquad 11$$

6.2 Intermediate Goods

Sectorial goods are produced by perfectly competitive identical firms within each sector. Profit-maximising sectorial good producers solve the following profit maximisation problem:

$$\max_{L_{s,t}, x(j)_{s,t}, E_{s,t}} \{P_{s,t}Y_{s,t} - E_{s,t}p_{s,t} - w_t L_{s,t} - \int_0^1 \chi(j)_{s,t}\, x(j)_{s,t} dj\} \qquad 12$$

where, $x(j)_{s,t}$ is the price of machine type j, $W_{s,t}$ is the wage paid to labour, $p_{s,t}$is the price of energy.

First order conditions with respect to $L_{s,t}, x(j)_{s,t}$ and $E_{s,t}$ imply:

$$x(j)_{s,t} = \left(\frac{\alpha_1 P_{s,t}}{\chi(j)_{s,t}} E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha}\right)^{\frac{1}{1-\alpha_1}} A(j)_{s,t} \qquad 13$$

$$E_{s,t} = \left(\frac{\alpha_2 P_{s,t}}{p_{s,t}} L_{s,t}^{1-\alpha} \int_0^1 A(j)_{s,t}^{1-\alpha_1} x(j)_{s,t}^{\alpha_1}\, dj\right)^{\frac{1}{1-\alpha_2}} \qquad 14$$

$$w_t = (1-\alpha)P_{s,t}E_{s,t}^{\alpha_2} L_{s,t}^{-\alpha} \int_0^1 A(j)_{s,t}^{1-\alpha_1} x(j)_{s,t}^{\alpha_1}\, dj \qquad 15$$

6.3 Machine Producers

Monopolist machine producers choose $\chi(j)_{s,t}$ taking the demand $x(j)_{s,t}$ as given to maximise their profit $\pi_{s,t}$ and solve the following optimisation problem:

$$\pi(j)_{s,t} = \max_{\chi(j)_{s,t}} \{(\chi(j)_{s,t} - \phi)x(j)_{s,t}\} \qquad 16$$

Using (13) in (16) and taking first order derivative with respect to $\chi(j)$ and then rearranging shows that the profit-maximising price is a constant mark-up over marginal cost, $\chi(j)_{s,t} = \frac{\phi}{\alpha}$. Following Acemoglu *et al.* (2012), the marginal cost is normalised to α_1^2 to simplify the calculations. Therefore the monopoly price $\chi(j)_{s,t} = \alpha_1$ maximises machine producers' profit. From (13), the equilibrium demand for machines is then given by:

$$x(j)_{s,t} = \left(P_{s,t} E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha} \right)^{\frac{1}{1-\alpha_1}} A(j)_{s,t} \qquad 17$$

Using (17) in (16) and rearranging yields the equilibrium profit of the machine producers:

$$\pi(j)_{s,t} = \alpha_1 (1-\alpha_1) \left(P_{s,t} E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha} \right)^{\frac{1}{1-\alpha_1}} A(j)_{s,t} \qquad 18$$

and, using the condition described in (3) and (5) in (18), the expected profit of the entrepreneur is given as:

$$\pi_{s,t} = \alpha_1 \theta_t (1-\alpha_1)(1+\tau_s) \left(P_{s,t} E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha} \right)^{\frac{1}{1-\alpha_1}} A_{s,t-1} \qquad 19$$

6.4 Equilibrium research intensity

The machine producer chooses R&D spending $R(j)_{s,t}$ to maximise the expected profit from innovation; therefore, the cost to innovate is $R(j)_{s,t}$. The expected revenue is the probability of innovation $\theta_{s,t}$ times the profit $\pi(j)_{s,t}$. Therefore, the entrepreneur solves the following problem:

$$\Pi(\mathrm{j})_{s,t} = \max_{R(j)_{s,t}} \left\{ \nu \left(\frac{R(j)_{s,t}}{(1+\tau_s) A(j)_{s,t-1}} \right)^{\eta} \pi(j)_{s,t} - R(j)_{s,t} \right\} \qquad 20$$

The first order condition with respect to $R(j)_{s,t}$ yields:

$$\frac{R(j)_{s,t}}{(1+\tau_s) A(j)_{s,t-1}} = \left(\nu \eta \alpha_1 (1-\alpha_1) \left(P_{s,t} E_{s,t}^{\alpha_2} L_{s,t}^{1-\alpha} \right)^{\frac{1}{1-\alpha_1}} \right)^{\frac{1}{1-\eta}} \qquad 21$$

The right-hand side of (21) does not depend on j, therefore, following Novales *et al.* (2010), $\frac{R(j)_{s,t}}{(1+\tau_s) A(j)_{s,t-1}} = r_{s,t}$ and $r_{s,t}$is defined as the productivity-adjusted expenditure in R&D.

6.5 Resource Extraction

Energy is supplied competitively as "common raw material" to the sectorial goods producers. It is assumed that the landowners do not take into account the effects of current extraction on future reserves. This assumption is consistent with the economics of resource extraction in England and Wales during the First Industrial Revolution era. Nef (1932) notes that prior to and during the seventeenth century, landowners received fixed rent in the form of royalties and wayleave from colliers. In some instances, landowners received variable rents per unit of output extracted. Rent of a mine was not considered as a payment for the exhaustion of the resource. Hatcher (1993) relates a similar account of lease arrangements, but argues that rent payments varied very much from landowner to landowner and from region to region. On the other hand, Hatcher (1993) too suggests that there is little reason to believe the landowners received compensation for exhaustion of coal reserves; instead, they were concerned with profit maximisation in each period. Therefore, the assumption of "common raw material" is reasonably justified in the model.

Landowners maximise period by period profit and solve the following maximisation problem:

$$\max_{p_{s,t}, E_{s,t}} \{(p_{s,t} - c_{s,t})\, E_{s,t}\} \qquad 22$$

where, $p_{s,t}$ and $c_{s,t}$ are price and marginal cost of resources respectively. $E_{s,t}$ is the flow amount of coal and wood extracted and used at time t, $s \in \{w, c\}$. Since there is a free entry to the extractive sector, the industry generates enough revenue to recover its costs and hence the price of a unit of energy is equal to its marginal cost $p_{s,t} = c_{s,t}$.

6.6 Equilibrium

The equilibrium path of the economy is derived by combining the optimality conditions given the constant parameters and initial values of machine quality, cost of energy and resource stocks. In equilibrium at every time t:

- Given the prices, the producers of the final good, sectorial good and machines maximise their profits;

- Entrepreneur-innovators maximise their expected profits;
- Resource stock evolves according to: $S_{s,t+1} = S_{s,t} + X_{s,t} - E_{s,t}$;
- Labour market clears: $L_{c,t} + L_{w,t} = 1$;
- Goods market clears:

$$Y_t = C_t + \phi\left[\int_0^1 \left(x(j)_{c,t} + x(j)_{w,t}\right)dj\right] + \int_0^1 \left(R(j)_{c,t} + R(j)_{s,t}\right)dj$$

Now, using (11), it can be shown that the relative price of the two inputs satisfies

$$\frac{P_{c,t}}{P_{w,t}} = \left(\frac{Y_{c,t}}{Y_{w,t}}\right)^{-\frac{1}{\sigma}} \qquad 23$$

This equation implies that the relative price of goods produced using coal (compared to goods produced using wood) is decreasing in their relative supply. The elasticity of the relative price response is the inverse of the elasticity of substitution between the two inputs. Following Acemoglu (2009; 2012), the price of final good is normalised to one at each date to simplify the calculations:

$$P_t = \left(P_{w,t}^{1-\sigma} + P_{c,t}^{1-\sigma}\right)^{\frac{1}{1-\sigma}} = 1 \qquad 24$$

Equation (24) can then be used to derive the prices of intermediate goods as the function of each other's prices. The price of coal using input is $P_{c,t} = \left(1 - P_{w,t}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$.

Combining (1) and (11), it can be shown that:

$$P_t = P_{c,t}^{\sigma} Y_{c,t} \qquad 25$$

Combining (2) and the equation for equilibrium demand for machines (17) gives the equilibrium production level of input s as:

$$Y_{s,t} = A_{s,t}\left(P_{s,t}^{\alpha_1}\, E_{s,t}^{\alpha_2}\, L_{s,t}^{1-\alpha}\right)^{\frac{1}{1-\alpha_1}} \qquad 26$$

This equation indicates that the level of output is the function of the size of the market (represented by the combination of demand for energy and labour in the bracket) for the sectorial good and the productivity of the machines used in the sector.

Next, in equilibrium, wages in both sectors are equal; therefore, combining (15) and (17), the relative production of sectorial goods can be written as:

$$\frac{Y_{c,t}}{Y_{w,t}} = \frac{P_{c,t}}{P_{d,t}}\frac{L_{d,t}}{L_{c,t}} \qquad 27$$

Combining (24) and (27) gives the equilibrium relation between labour demand and the price of intermediate good in one sector:

$$L_{s,t} = P_{s,t}^{1-\sigma} \qquad 28$$

Equilibrium demand for energy resources is derived using (17) in (14):

$$E_{s,t} = \left(\frac{\alpha_2}{c_{s,t}} P_{s,t}^{\frac{1}{1-\alpha_1}} L_{s,t}^{\frac{1-\alpha}{1-\alpha_1}} A_{s,t}\right)^{\frac{1-\alpha_1}{1-\alpha_1-\alpha_2}} \qquad 27$$

In the next section, the model is calibrated with the British data.

7 Calibration and Model Dynamics

The model is calibrated with sixteenth-century British data. The aim is to characterise the industrialisation as a direct consequence of the transition from wood to coal use. Parameters of the model along with starting values of variables are chosen so as to match the long run growth rate of GDP per capita and the ratio of the average prices in the 1840-1850 period. The starting values of the parameters and variables are given in table 1.

Share parameters in sectorial goods production functions are chosen to match the historical factor shares. Clark (2010) tabulates income share of labour which fluctuates between 0.51 and 0.69 in the period 1550-1849; therefore, α is set to equal the arithmetic mean of the series 0.6. Also, Hansen and Prescott (2002) and Froling (2011) use this value for the cost share of labour in simulations. The cost share of energy is calculated using the price data and energy

Parameter	Value	Comment
α	0.6	Clark (2010) & Froling (2011)
α_1	0.20	
α_2	0.20	Fouquet (2008) and own calculations
σ	4	Kander and Stern (2014)
τ_s	1	
ν	0.085	
η	0.40	
λ_c	1	Years
λ_w	10	Years
$c_{c,t-1}$	1	Fouquet (2008)
$c_{w,t-1}$	4	Fouquet (2008)
$A_{c,t-1}$	4	
$A_{w,t-1}$	5	
$S_{c,t}$	600	
$S_{w,t}$	600	

Table 1 Starting values for the variables and parameters.

consumption series provided by Fouquet (2011). It fluctuated between 0.13 and 0.28 during the 1550-1849 period; a simple arithmetic mean of the series implies $\alpha_2 = 0.20$ and the share of capital (machines) α_1 is therefore 0.20.

The parameter measuring the size of innovation τ_s is set to 1 in each sector. However, it is sensible to assume a priori that the wood sector technology was more advanced than that of the coal using sector in the sixteenth century. It is thus possible that the potential for greater innovation in the coal sector was higher. This would imply that the rate of productivity in the wood sector was lower than that in the coal sector at the outset. While this assumption is reasonable, as will be shown in the following, it is not necessary to impose such a restrictive assumption in the model. The productivity-adjusted R&D expenditure parameter, $r_{s,t}$, is not observable, it is set to 1 in both sectors. Regardless of the initial values, the interior solutions produce empirically plausible results.

For the measure of the quality of machines $A_{s,t}$, there is no reliable historical set of estimates. Both coal and wood were sources of thermal energy before 1550 but wood burning for heat was more common in all industries. Coal use in industrial production was growing but it was not a common source of thermal energy in the sixteenth century (Hatcher, 1993). Allen (2009, p. 81) documents that coal was used in salt-boiling, lime-burning, brewing and clothes dying among other industries prior to 1600[29]. These industries did not require coal burning machines which converted heat to mechanical energy. The first such machine was a practical steam engine invented and used in draining a coal mine in 1712. It was then possible to measure the quality (or efficiency) of coal burning machines[30]. As there are no historical proxies, the values of this parameter are chosen jointly with $\nu_t$and η_t such that the ratio of average coal to wood price between 1840 and 1849 is matched with the ratio of the simulated series for the same period.

Marginal cost parameter c_s is set to match the ratio of the average wood to coal prices between 1550 and 1560. Average wood price was just under 4 times higher than that of coal. In the baseline simulations, the cost of coal is normalised to 1 and the cost of wood is set to 4 to reflect the actual price gap. Parameter λ_s measures the number of years it takes to expand the resource stock. Extractible reserves of coal are known to have expanded in a very short time so long as the mines are drained continuously. However, wood regeneration required a much longer time. Ashton (1924) observes that the iron industry required wood supplies from mature forests and virgin woods would not have been suitable for ironworks. Also, it would

[29] This has been pointed out by Mokyr (1990; 2009), Hatcher (1993), Fouquet (2008) and Kander *et al.* (2013).
[30] Fouquet (2008) provides historical estimates of the efficiency of steam engines used in the seventeenth century onwards. Also, the term "machine quality" is not limited to the efficiency or the productivity of steam technology. In the present context, it could also reflect the effectiveness and the superiority of techniques used in wood and coal-based production. For instance, prior to 1750s, charcoal iron was perceived to be superior to coke iron (Allen, 2009). The difference in the quality of iron reflected the difference in the progress of improving the smelting methods employed. By directing more efforts towards the improvement of coke based smelting, Abraham Darby and others were able to perfect the method (or improve the quality of the technique) eventually.

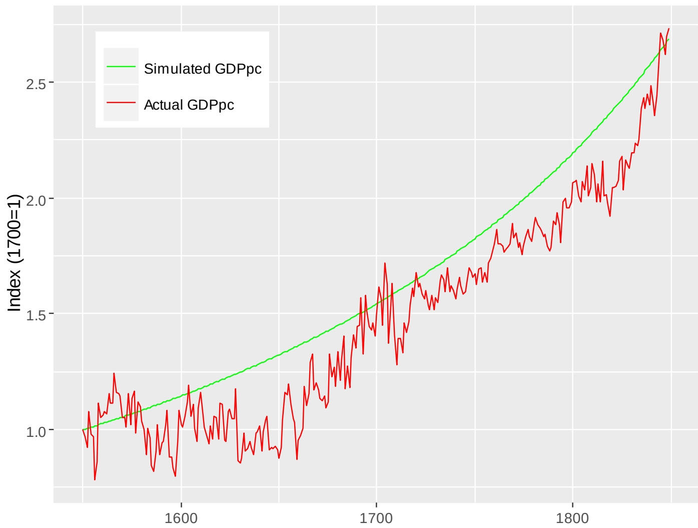

Figure 3 Simulated and observed GDP per capita, 1550-1849.

take around 14 years to fully regenerate a woodland to its original state. To reflect this historical account, taking into account the fact that not all industries would require mature wood for heat generation, a more reasonable value of 10 years is chosen to govern the speed of wood stock regeneration.

There is no reliable estimate of the resource reserves for the sixteenth century. Initial values for the stocks of reserves are chosen such that the simulated relative average prices of wood to coal for the 1840-1849 period matches the actual value of 6.5. Lastly, the elasticity of substitution parameter in the final good production function is set to 4 based on the empirical evidence in Kander and Stern (2014).

8 Baseline simulations

Figure 3 shows the simulated and the estimated GDP per capita. The model is able to reproduce the observed trend in historical output per capita given the starting values. Average growth rate of GDP per capita during the period 1550-1849 is 0.33% according to Broadberry *et al.*, (2015) and the growth rate of the simulated GDP per capita is 0.32%. The model parameters are optimised such that the ratio of average wood price to that of coal in the 1840-

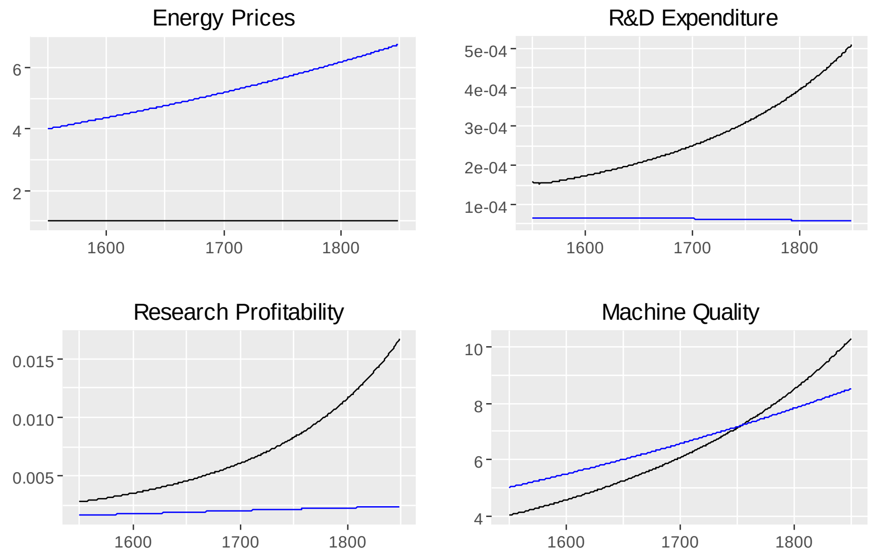

Figure 4 Simulation of the selected variables.

Coal-using sector series are in black. Wood-using sector variables are in blue.

1849 period is 6.4. The model reproduces the average cost share of energy in output precisely, but underestimates the share of labour. The simulated labour's share is 40% while the estimated value is 60%.

The simulated GDP per capita growth is broadly consistent with the observed growth rates. In the 1550-1749 period, the estimated average annual growth rate of GDP per capita is 0.27% and the simulated rate is 0.28% per year. However, the model produces a lower growth rate than that observed in the 1750-1849. The simulated per capita income growth rate is 0.38% and the estimated actual rate is 0.45%. Essentially, the model reproduces the low growth state; nevertheless, it reproduces the key feature of the British economy in the period 1550-1850, the transition from a low growth to a high growth state.

Figure 4 shows a range of simulated series that broadly conform to the historical and cliometric accounts that characterise the transition from a low growth to a high growth economic system. The price of wood is initially four times higher than the coal price but the price gap widens further over time reflecting the pressures on the supply of wood. The ratio of the simulated average wood price to coal price reaches 6.5 in the last decade closely matching the actual ratio. As explained in the previous section, the price differential

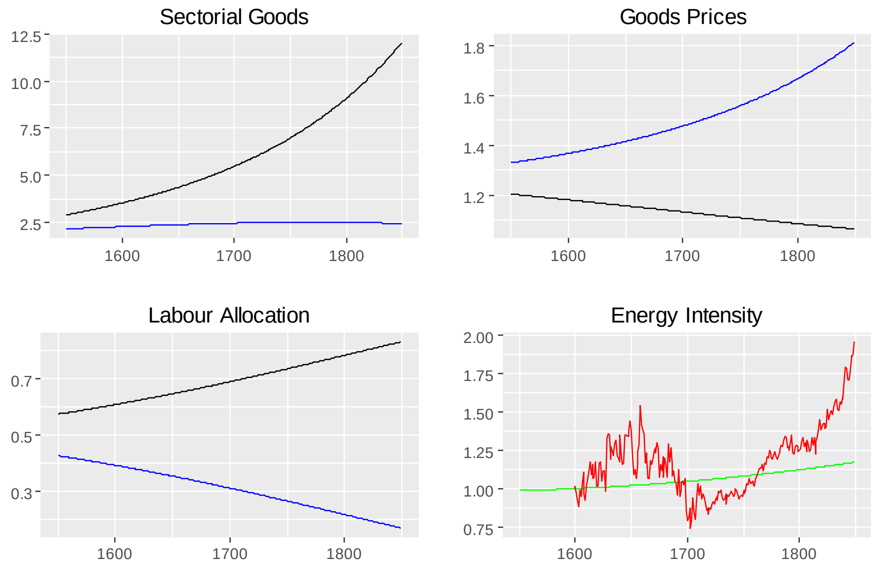

Figure 5 Simulation of the selected variables.

Coal-using sector series are in black. Wood-using sector variables are in blue. In the last panel, the actual series are in red and the simulated series are in green.

determines the direction of the efforts to innovate. Profit incentives to innovate are higher in the sector that uses a cheaper energy source. This is reflected in the graph showing the long run trend of the profitability of conducting research. Since it is relatively more profitable to invent in the coal-sector, the model predicts that the efforts are directed towards innovating coal-using technologies. This results in further increase in R&D expenditure in coal technologies as reflected in the time path of the simulated productivity-adjusted R&D expenditure. The R&D expenditure grows at an average annual rate of 0.3% in the coal-using sector while this figure is -0.05% in the wood-using sector.

The outcome of the sustained efforts and the increased R&D expenditure in the coal sector is an improvement in the quality of machines (or techniques). As can be seen, machines used in the wood sector were of higher quality than those used in the coal sector in the earlier periods. However, the gradual shift of innovation to the coal sector resulted in superior machines in this sector after the 1750s. For instance, draining of coal mines relied on horse and human muscle power early in the seventeenth century. The horse powered gin was, probably, the most effective machine used to drain the mines. However, the machinery was only effective at depths of up to 150 feet, and coal seams at greater depths were not extractable. Steam technology was eventually developed and was more effective than the existing technologies. Newcomen's steam engine was the first practical technology to pump water in much larger quantities and from far greater depths (Griffin, 2010, p. 117). Later, Watt made a number of significant improvements to steam technology improving the efficiency of steam engines. However, steam technology exceeded the efficiency of the technologies that rely on organic fuels much later in the 1850s[31] (Kander *et al.* 2013). Similarly, coke iron smelting technique and iron furnaces were not perfected sufficiently until after the 1750s when the variable cost of producing pig iron became relatively cheaper than that of charcoal based production (Fouquet 2008, p. 62). Also, this period marks the onset of the First Industrial Revolution. The model, however, does not reproduce the historical trend of energy intensity, though it does show that the economy's energy intensity grows at a slow pace.

Equilibrium labour allocation is broadly in line with the historical transformations in the British economy. Initially, employment is similar in both sectors; however, given the persistently high wood prices and increasing production costs, the producers of intermediate goods prefer using coal-using technologies. The results indicate that, in the 1750s, 73% of the labour force is employed in the coal-using sector. It is a plausible result because some of the industrial production was still reliant on non-coal energy sources. Textiles employed a large number of people in cottage based production. The industry relied on hand technology until the 1760s when production began moving to mills and then to factories in the 1830s after the transition to coal powered steam technology (Allen, 2009, p. 182-184). Most power needs were met by horses, wooden shafts and pulleys in the period between 1760 and 1830 (Griffin, 2010, p. 99-113).

During the 1750s, coke iron smelting was being widely adopted in England (King, 2011), and this enabled the production of greater amounts of pig iron at low costs. The model shows that the coal-using industry produces around three times more output than wood using industries in this period. This result closely reproduces some of the transformations in the iron industry. While declining, charcoal iron smelting was common where there was a cheap supply of

[31] Steam engines were run on wood where it was not possible to obtain coal, even in the nineteenth century. Steam technology would not have been developed without the abundant supplies of coal (Kander *et al*. 203, p. 164). Also, Allen (2009, p. 162) states that the availability and low coal was a major factor in the development of steam technology in Britain.

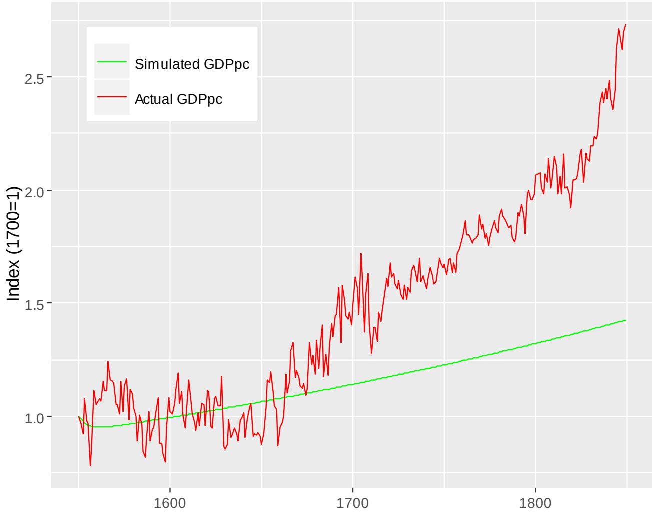

Figure 6 Simulated and observed GDP per capita, 1550-1849.

charcoal, though coal iron production began to dominate the industry (Fouquet, 2008, p. 63). By 1850, 83% of labour was allocated to the coal-using sector. This result is broadly consistent with the observed transition to coal in many industries; for instance, coal provided power for three-quarters of the textiles industry in England and Scotland in 1835 (Griffin, 2010, p. 115). In 1850, coal provided around 41% of the total power in the industry (Fouquet 2008, p. 126). Where a particular source of energy is cheap and plentiful, businesses tend to utilise it instead of switching to coal use. However, Fouquet (2008, p. 54) states that most industrial activity had made a switch to coal by the mid-seventeenth century.

9 Counterfactual Analysis

The results and analysis presented in the preceding section indicate that the transition from low growth to high growth coincided with the transition to coal from wood burning in Britain. Therefore, as conjectured by Wrigley (2010), the transition from wood to coal could explain the British Industrial Revolution. However, a number of economic historians including Mokyr (2009a) and Clark and Jacks (2007) state that coal made a negligible contribution to the growth of the British economy until after the 1870s. Clark and Jacks (2007) provide cliometric accounts of the Industrial Revolution in the absence of coal reserves in Britain. They find that

Figure 7 Simulation of the selected variables.

Coal-using sector series are in black. Wood-using sector series are in blue.

without coal and iron, the expansion of the wonder industry of Britain, cotton textiles, would have been well underway in the 1830s before energy constraints became a significant issue.

The cotton textiles industry has been considered to have benefitted from the transition to steam from water and animal power as it was then possible to mechanise the production on a large scale (Griffin 2010). The production shifted to factories given the constraints of river banks were not an issue any longer by the 1830s. Griffin (2010) further states that the textile factories were built using brick and iron whose sustained supply was dependent on the ability of the iron industry to meet the growing demand. Expensive charcoal iron would not have permitted the expansion of textiles in the nineteenth century. To test these claims, in what follows, the factors that determine the fuel switch, price and stock of coal, are assigned counterfactual values. It is assumed that the economy is in an advanced organic regime implying that it has a backward coal sector. Such a scenario could be plausible if Britain did not have large amounts of coal reserves. Therefore, the initial stock of coal is reduced to 1% of the baseline value while everything else is kept constant. In this scenario, it is difficult to imagine that the coal price would have been lower than that of wood as in the baseline scenario. Therefore, the initial coal price is raised to match the price of wood[32]. This scenario is consistent with the hypothetical computations of Clark and Jacks (2007) and Mokyr's (2009) claim that energy-saving technologies would have been invented in response to resource scarcity in Britain.

The results of the simulations are given in Figure 6 and 7. Average growth rate of income per capita would have been 0.12% in the entire period. In the 1550-1750 period, income per capital grows at an annual rate of 0.09%, and the rate is 0.14% in the 1750-1850 period. Unlike that in the baseline scenario, the growth rate increases marginally and this indicates the First Industrial Revolution would have been delayed or not have happened at all. Income per capita in the counterfactual scenario is 53% of the actual income per capita in 1849. The British economy would have been stuck in the low growth state and the First Industrial Revolution would have been delayed.

Why would have the First Industrial Revolution been delayed? Finding answer elements to this question requires further analysis of the simulated data. As shown in figure 7, machine quality does not improve over time in the coal-using sector as a high coal price suppresses the investment in coal technology. Much of the investment in R&D is then directed towards developing wood-using technology given the market for wood technology is larger. R&D expenditure in the coal-using sector declines at 1.1% per year. Investment in wood-using technologies grows at an annual rate of only 0.1%; as such, it does not offset the declining investment in coal-using technologies. An initial small amount of coal reserves makes coal dearer over time, and the coal price rises faster than wood prices. The coal price stabilises after 1650 as the rate of addition to coal reserves increases, and the demand for coal declines at an average annual rate of 0.2%. The average growth rate of coal price is 0.5% while that of wood is 0.17%.

Given the decline in the rate of investment in the coal-using sector, 88% of labour is allocated to the wood-using sector in 1849. The market for the goods produced by the coal-using sector is small, and wood-using sector supplies 79% of all the goods to the final goods sector. Given

[32] Simulation results with differential prices did not provide significantly different results. Whether the price of coal is kept lower than or equal to the wood price, the model reproduces broadly similar results.

the size of the market for goods produced by the wood-using sector, the demand for wood increases at an annual rate of 0.03% whilst the demand for coal declines at 0.26% per year. These findings imply the availability of energy was crucial for the industrialisation of Britain. This finding is in stark contrast to the claims of Clark and Jacks (2007) and Mokyr (2009). In particular, energy saving efforts do not appear to have grown at sufficiently high rates to maintain the growth observed in the First Industrial Revolution. However, if the model permits importing wood, the counterfactual simulation results may change. The growth of output per capita, again, would depend on the price of wood. If imports do not reduce the average price of wood, an open economy model would have produced broadly similar results to that obtained in this section.

10 Conclusion

This study presents a formal treatment of the role of energy use in economic growth during the First Industrial Revolution. In a general equilibrium model of endogenous growth and directed technical change, energy use is incorporated in the production technology, and technological progress is driven by the availability of energy. The model investigates the breaking of constraints imposed by organic sources of energy in a directed technical change framework developed by Acemoglu (1998; 2002).

The model economy has two sectors, one that uses wood and the other coal, and the prices (of wood and coal) change in the stock of resources. The productivity growth in each sector depends on the investment in R&D, which is determined by the size of the market for sectorial goods. The larger the sectorial goods market, the higher the profitability of conducting research in the sector. The profitability of research is, in turn, determined by the cost of energy. Therefore, the higher the cost of energy, the lower the incentive to develop the technology used in the sector. In the model, high wood prices induce higher innovative activity in the coal-using sector. Coal-using technologies underpin the expansion of coal mining, which then ensures coal prices remain low or constant over time. As long as the price of coal remains low, innovation endogenously shifts to the coal-using sector. In this scenario, the economy eventually switches to a high growth regime as it is dominated by the coal-using sector that does not face resource scarcity.

The model is calibrated with the British data for the 1550-1849 period, and it reproduces the key features of the economy. In the baseline simulations, the model is set up such that the initial values of coal and wood prices match the actual price differential observed between 1550 and 1559. Other parameters are optimised to match the average annual growth rate of GDP per capita. The economy is endowed with equal amounts of resource (i.e. coal and wood) stocks. The model is able to reproduces the key transformations of the British economy. First, the aggregate productivity of the coal-using sector (determined by the quality improvements of machines) grows slowly until 1750, but the rate of productivity growth accelerates after coal becomes the dominant fuel in the energy mix. Similarly, the income per capita grows at a lower rate prior to 1750s, but growth markedly accelerates afterwards. Essentially, the model shows that the transition to coal from wood enabled the economy to escape the low growth state by the mid-eighteenth century. These findings are consistent with Wrigley's (2010) claim that the Industrial Revolution can be characterised as a process of transition from organic to mineral sources of energy. Simulated series closely replicate the historical account of structural change as suggested by Allen (2009).

Second, the model provides useful insights into the British economy. Initially, labour is almost equally distributed between the two sectors. As the wood prices rise and coal prices remain constant and low, the shift of innovation to the coal-using sector gradually redistributes the labour to this sector. This is consistent with the new evidence that the shift of labour from the traditional to modern industries started much earlier than the onset of the First Industrial Revolution. The redistribution was slow, and not all labour was employed in the new industries even by 1850s (see Broadberry *et al.,* 2013). This is not an accidental finding; instead, the results are the outcome of the interaction among the starting conditions, the switching mechanism imposed based on the historical facts and the rational optimisation decisions of the agents.

Would the British economy have escaped the low growth state? A number of economic historians have shown that Britain would have had its First Industrial Revolution without transition to coal (Clark and Jacks, 2007; Mokyr, 2009; McCloskey, 2010). In common with these claims, the model is calibrated with counterfactual parameter values. More specifically, the economy is endowed with only 1% of its baseline coal stock, and the price of coal and wood set to be equal. Remaining parameters are assigned baseline values. The model, in this scenario, fails to reproduce any of the key features of the British economy. The growth rate of GDP per capita is much lower than the observed growth rate. Coal price increases at a faster rate in the earlier periods and then stagnates at a much higher level. Wood price is lower, but when combined with high coal price, the cost of energy provision grows. In the absence of coal reserves, the wood-using sector dominates, but high wood prices slow down the innovative activity. The net result is a near constant low productivity growth. Given that the model characterises the conditions of a closed economy, it is not clear if imported wood would have reduced the tensions arising from resource scarcity. If the wood price remains high even after the wood imports were allowed, the British economy would not industrialise.

Overall, the results show that the availability of energy was crucial for the transition from a low to a high growth regime in the eighteenth century. The idea put forward by Wrigley (2010) that Britain's transition from organic sources of energy to coal was a necessary condition for the British economy to escape from the low growth state is broadly supported by the results. This conclusion follows from simulations of the Industrial Revolution, which show a close fit between historical accounts and model output.

This study extends our understanding of the role of energy in economic growth. Unified growth theorists do not take into account the role of energy in production technology. They suggest that an escape from the low growth state was possible through improving the quality of human capital (see Galor and Weil, 2000). Essentially, in the model, technological progress is conditioned on the level of human capital. The present study provides an alternative view to that put forward by the unified growth theory by abstracting from human capital and capital stock accumulation. Further work may extend the present study by incorporating human capital and capital stock accumulation in the model. One may formulate the accumulation of capital as a positive function of different sources of energy. For the First Industrial Revolution, as shown in this study, capital accumulation did not depend on the type and the source of energy as the machines used either wood or coal, which were substitutes. To characterise the Second Industrial Revolution, and hence the modern growth regime, future research needs to consider the fact that new machines were of a different type and required liquid and gaseous fuels, which are imperfect substitutes for coal. Finally, the modelling framework can be used to analyse and forecast the dynamic effects of future energy transitions on the growth paths of modern economies.

11 References

Acemoglu, D. (1998) Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality. The Quarterly Journal of Economics, 113, 4, 1055-1089

Acemoglu, D. (2002) Directed Technical Change. Review of Economic Studies, 69, 4, 781–809.

Acemoglu, D. (2009) Introduction to Modern Economic Growth. New York: Princeton University Press.

Acemoglu, D. Aghion, A. Bursztyn, L. and Hemous. D. (2012) The environment and directed technical change. American Economic Review, 1, 102, 131–166.

Allen, R. (2009) The British Industrial Revolution in Global Perspective. Cambridge University Press, Cambridge, 2009.

Allen, R. (2012) Backward into the future: The shift to coal and implications for the next energy transition. Energy Policy, 50, 17-23.

Ashton, A. (1924) Iron and Steel In The Industrial Revolution. The University Press. Manchester.

Ashton, T. (1955) An Economic History of England: The 18th Century. Methuen & Co. Ltd. London

Barro, R. and Sala-i-Martin, X. (2004) Economic Growth. 2nd Ed. The MIT Press Massachusetts.

Broadberry, S.N. Campbell, B., Klein, A., Overton, M. and van Leeuwen, B. (2015) British Economic Growth, 1270-1870. Cambridge University Press. Cambridge.

Crafts, N. (1977) Industrial revolution in england and france: Some thoughts on the question, "why was england first?". The Economic History Review, New Series, 30, 3, 429–441.

Crafts, N. and Harley, C. (2000) Simulating the two views of the industrial revolution. Journal of Economic History, 60, 3, 819–841.

Cipolla, C. (1978) The Economic History of World Population. Harvester Press, Sussex

Clark, G. and Jacks, D. (2007) Coal and the industrial revolution. European Review of Economic History, 11, 1, 39–72.

Clark, G. (2010) The Macroeconomic Aggregates for England, 1209-2008. Research in Economic History, 27, 51-140.

Crafts, N. and Harley, C. (2000) Simulating the two views of the industrial revolution. Journal of Economic History, 60, 3, 819–841.

Epstein, S. (2004) Property Rights to Technical Knowledge in Premodern Europe, 1300-1800. The American Economic Review, 94, 2, 382-387.

Eren, E. and Garcia-Macia, D. (2013) From wood to coal may well be from Malthus to Solow. Available at SSRN: https://ssrn.com/abstract=2407255

Fouquet, R. (2008) Heat, Power and Light: Revolutions in Energy Services. Edward Elgar Publications, Cheltenham, UK.

Fouquet, R. (2010). The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy, 38(11), 6586–6596.

Fouquet (2011) A brief history of energy. In Evans, J. and Hunt, L. (Eds.), International Handbook on the Economics of Energy, chapter 1, pages 1-19. Edward Elgar: Cheltenham, UK.

Fouquet, R. and Pearson, P. (1998) A thousand years of energy use in the united kingdom. The Energy Journal, 19, 4, 1–41.

Galor, O. and D. N. Weil (2000) Population, technology and growth: From Malthusian regime to the demographic transition, American Economic Review 90, 4, 806-828.

Galor (2005) From Stagnation to Growth: Unifed Growth Theory. In Aghion, P. and Darlauf, S. (Eds.), Handbook of Economic Growth, Volume 1A, chapter 4, pages 171-285.

Galor, O. (2011) Unified Growth Theory. Princeton, New Jersey: Princeton University Press.

Griffin, E. (2010) A Short History of The British Industrial Revolution. Palgrave Macmillan: Baskingstoke, UK.

Hammersley, G. (1973) The charcoal industry and its fuel 1540-1750. Economic History Review, 26, 593–613.

Hatcher, J. (1993) The History of British Coal Industry, Before 1700: Towards the age of coal. Volume 1. Clarendon Press, Oxford.

Henderson, O. (1969) The industrialization of Europe, 1780-1914. London: Thames and Hudson

Henderson, O. (1954) Britain and Industrial Europe. Liverpool: University Press

Jones, C. (2001) Was an Industrial Revolution inevitable? Economic growth over the very long run. Advances in Macroeconomics, 1, 1–43

Kander, A., Malanima, P. and Warde, P. (2013) Power to the People, Energy in Europe over the last five centuries. Princeton University Press, Princeton.

Kander, A. and Stern. D. (2014) Economic growth and the transition from traditional to modern energy in Sweden. Energy Economics, 46, 56-65.

Lucas, R. (2002). The Industrial Revolution: Past and Future. Harvard University Press, Cambridge, MA.

McCloskey, D. (2010) Bourgeois Dignity: Why Economics Can't Explain the Modern World. Chicago: University of Chicago Press.

Mokyr, J. (2009) The Enlightened Economy: Britain and the Industrial Revolution 1700–1850. Penguin: England

Nef, J. (1932) The Rise of the British Coal Industry. George Routledge and Sons Ltd., London, 1932.

Nef, J. (1977) An Early Energy Crisis and Its Consequences. Scientific America, 140-150.

Stokey, N. (2001) A Quantitative model of the British industrial revolution, 1780–1850. Carnegie-Rochester Conference Series on Public Policy, 55, 55–109.

Stern, D. and Kander, A. (2012) The Role of Energy in the Industrial Revolution and Modern Economic Growth. The Energy Journal, 33, 3, 125-152.

Voigtlander, N., and Voth, H.- J. (2006) Why England? Demographic factors, structural change, and physical capital accumulation during the Industrial Revolution. Journal of Economic Growth, 11, 319–361.

Wrigely, E. (1962) The Supply of Raw Materials in the Industrial Revolution. The Economic History Review, New Series, 15, 1, 1-16.

Wrigley, E. (1988) Continuity, Chance and Change: The Character of the Industrial Revolution in England. Cambridge University Press, Cambridge

Wrigley, E. (2010) Energy and the English Industrial Revolution. Cambridge University Press, Cambridge.

12 Appendix

GDP and GDP Deflator

Data on Nominal GDP and GDP deflator are available from Broadberry *et al.* (2015).

Energy

Data on energy prices and energy consumption are available from Fouquet (2008; 2011) Energy consumption data is comprising of animal muscle power, wood, coal, crude oil and gas. Aggregate measure of energy price is the average of prices of individual fuels weighted by their share in total energy mix. Energy prices are deflated using Robert Allen's CPI index available at http://www.iisg.nl/hpw/data.php.

Wages

Average real wages are composite series based on English and British wage estimates from various sources. Thomas and Dimsdale (2017) splice the data and construct composite series of average wage for Great Britain.