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Energy, Knowledge and Economic Growth

by

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Energy, Knowledge and Economic Growth[1]

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Abstract

It is argued that the explosive growth experienced in much of the World since the middle of the 19th Century is due to the exploitation and use of fossil fuels which, in turn, was made possible by capital good innovations that enabled this source of energy to be used effectively. Economic growth, it is argued, has been due to an autocatalytic co-evolution of energy use and the application of new knowledge relating to energy use. A simple 'evolutionary macroeconomic' model of economic growth is developed and tested using almost two centuries of British data. The empirical findings strongly support the hypothesis that growth has been due to the presence of a 'super-radical innovation diffusion process.' Also, the evidence suggests that large and sustained movements in energy prices have had a very significant long term role to play. The paper concludes with an assessment of the implications of the findings for the future prospects of economic growth in Britain and the possible lessons that can be learned about the future of the global economy.

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1. Introduction

> "As long as supplies of both mechanical and heat energy were conditioned by the annual quantum of insolation and the efficiency of plant photosynthesis in capturing incoming solar radiation, it was idle to expect a radical improvement in the material conditions of the bulk of mankind" (Wrigley, 2010, p. 17).

> "The development of mechanized industry concentrated in large units of production would have been impossible without a source of power greater than what human and animal strength could provide independent of the vagaries of nature…Coal and steam did not make the industrial revolution, but they permitted its extraordinary development and diffusion" (Landes 1969, p.41)

Over the past two decades, there have been many studies of the determinants of economic growth. They have been predominantly based upon endogenous growth theory. These studies have built upon the earlier 'neoclassical' growth theory developed by Robert Solow, stressing, in particular, the importance of 'ideas' (Romer (1986)) and the relatively low cost of transmitting them and, more recently, the importance of institutions has also been acknowledged (see, for example, Glaeser et al (2004) and Acemoglu (2009) for a review). Also, there has been a tendency to use human capital proxies rather than 'labour' to better reflect the skills in the workforce, following the work of Lucas (1988). There is little doubt that these developments and the accompanying large literature that has emerged have provided mainstream macroeconomists with a better way of understanding of how economic growth comes about. However, endogenous growth theory does not involve a revolutionary shift in thinking about economic growth. It is built up from standard neoclassical microeconomic foundations. As Fine (2000) and Ayres and Warr (2009) pointed out, this involves a set of extremely strong abstract assumptions that disconnect theory from real historical experience. It is built upon the notion of an aggregate production function, frequently of the Cobb-Douglas form, with all of its attendant, and well-known, abstract assumptions.

There has been a considerable amount of empirical research, using growth accounting data, which attempts to test the validity of hypotheses derived from endogenous growth theory. However, unlike the work of Solow, the bulk of this research has not used time series data but, instead, cross country data, averaged over decades. This is no surprise because it is very difficult to find any support for neoclassically-based growth hypotheses, endogenous or not, using time series data for one country (see Ayres and Warr (2009) and Madsen *et al* (2010)). The problem with using cross country data is that any chosen sample does not contain consistent information since different countries are all at different stages of development, conditioned by their unique evolutionary histories. Some attempts have been made to alleviate this problem by splitting global data up into sub-samples or by introducing dummy variables, or some other proxies, to reflect obvious institutional, cultural and socio-political differences (see, Bluhm and Szirmai (2012)). But the bottom line is that economic growth, as a historical phenomenon, cannot be directly examined in such studies.

Furthermore, it has been known, since at least the 1970s, that there are serious aggregation problems involved in using a capital stock measure in an aggregate production function that is based upon neoclassical microeconomic theory. Also, definitions of the capital stock tend to vary significantly across countries. Perhaps more fundamentally, it is questionable whether a capital stock measure should be used at all in a production function because it involves *flows* of labour services and capital service input flows, not *stock* variables. Stocks are not good proxies for these flows because capital and labour utilization vary significantly over business cycles. This problem is often avoided by making the simplifying assumption that stocks of capital and labour are fully employed but this is entirely unrealistic in the real world of oscillating economic growth.

It is well accepted in the conventional literature on economic growth that, as time passes, we have upward movements in what is viewed as an aggregate production function, as the substitution of new capital for old raises productivity. The problem with this is that shifts of, and movements along, aggregate production functions are very difficult to disentangle using historical data. So what is quite a useful analytical construct for application in short periods at the microeconomic level of inquiry, is not an appropriate vehicle for understanding aggregate economic growth over long periods despite its almost universal adoption in the literature on economic growth. Solow famously found, using a neoclassical economic theory with a Cobb-Douglas production function, that about 80% of economic growth was unexplained by the growth of capital and labour when he used US time series data. In other words, the upward shift of the aggregate production function was massively more important than shifts along it. This upward shift, by force of logic, was the most important factor in explaining economic growth, yet it was deemed by Solow to be outside economic theory and vaguely referred to as due to 'technical progress'.

In the 1980s, endogenous growth theorists noted the inadequacy of the Solow model and began to explore what the technical progress 'black box' might contain and how its contents might be expressed theoretically. But, in doing so, they started from the same 'constrained optimization' micro-analytical perspective on economic behaviour as had Solow. By making a range of clever, but very restrictive, assumptions, this kind of conventional economic theorizing came to be employed with little cognizance of the kinds of behavioural motivations that actually drive the entrepreneurship and innovation that lie at the core of the evolutionary process that generates economic growth.[2] Because of this, the conclusions contained in the endogenous growth literature turn out to be somewhat pedestrian: we need more 'ideas', more R&D, more education, more training. This is a rather obvious list and, as Solow recently pointed out (Solow (2007)), the importance of these drivers was well understood back in the 1960s, if not before (see in particular Denison (1974) for a backward look and update).

Because this kind of theorizing is ahistorical at its core, it cannot tell us much about the actual historical processes that result in economic growth and, thus, it provides little guidance as to where we are likely to end up in the future. This is a very serious problem because, as population growth surges, as output per capita rises rapidly and as environmental degeneration accelerates, we really need to know how the economic processes that result in growth actually work and where they are likely to drive us in the future. Even a cursory glance at the remarkable exponential growth path that the world has been on since the mid-19th Century raises a fundamental question: when will such growth come to an end? We know that continual exponential growth is an arithmetical and logical impossibility. Indeed, it is almost

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[2] Galor and Michalopoulos (2012) claimed that it is possible to capture entrepreneurship in a neoclassical model. Typically, their highly mathematical model contains many very abstract assumptions that invalidate its relevance to the history that they discuss.

universally true that populations in organic-based systems, reliant on limited sources of free energy and adaptive capability, follow a sigmoid growth path, where only the early growth phase is approximated by exponential growth. And we know that there have already been human civilizations in the past 10,000 years that have hit growth limits with some even collapsing (see, Diamond (2005), Landes (1998) and Tainter (1988) for examples).

Looking at economic growth as an outcome of a historical process draws us towards theoretical approaches that connect directly with history. We require what Dopfer (1986) called a ‘histonomic’ approach. A historical process is, necessarily, a non-equilibrium one, characterized by a degree of time irreversibility and continual structural change, sometimes slow sometimes fast. Historians tell us that such change is not random, and evolutionary economists see it as the outcome of an evolutionary economic process that involves economic self-organization, which generates a vast variety of economic processes, goods and services, and competitive selection, that resolves this variety and, in so doing, raises productivity, raises quality, lowers costs and, ultimately, leads to organizational concentrations that have economic power. This is a truly ‘endogenous’ perspective on economic growth (Foster (2011a)).

The purpose here is to apply this ‘evolutionary macroeconomic’ perspective to understand the astonishing and unparalleled economic growth explosion that has occurred over the past two centuries.   This perspective centres upon the co-evolutionary relationship between the growth in energy use and the expansion of knowledge to facilitate such growth. This was discussed in Foster (2011b) which, in turn, was inspired by the theoretical approach to growth in all ‘dissipative structures’ by Schneider and Kay (1994), popularized in Schneider and Sagan ((2005), and Smil (2008). The outstanding empirical work on economic growth by Robert Ayres and Benjamin Warr, reported in a series of articles and consolidated in Ayres and Warr (2009), also motivated the research reported here. The modelling methodology used is econometric, as developed in Foster and Wild (1999a).

The goal of the evolutionary macroeconomic methodology is to discover simple aggregate representations of the behaviour of complex economic systems that are not based upon 'simplistic' neoclassical micro- foundations (Foster (2005)). Here it will be shown that it is possible to find empirical support for a very simple evolutionary macroeconomic explanation of economic growth using almost two centuries of data. These findings can be compared to those in two recent articles by Madsen et al (2009) and Stern and Kander (2012) where economic growth is also modelled using very long samples of time series data. The methodology adopted in both studies is in sharp contrast to that adopted here. There are numerous unrealistic assumptions, analytically convenient functional forms and heavy demands on sparse and poorly measured data in the econometric testing. These studies are both interesting in their different ways but their reliance upon ahistorical and restrictive neoclassical micro-foundations renders their findings contestable because the theory used is not directly connected with the historical processes that underlie the time series that they investigate.

Many evolutionary economists are dubious of the value of econometric exercises conducted at high levels of aggregation where it is not possible to capture the evolutionary mechanisms that they believe are only observable at the micro and meso levels of inquiry. However, there has continued to be an interest in 'long waves' in evolutionary economics, following on from Schumpeter (1939), and the modelling here is very much in the spirit of this tradition, recently enlivened by the work of Freeman and Louca (2002) and Perez (2002). Regrettably, the virtual absence of theory and evidence concerning the evolutionary macroeconomics of economic growth in the literature has resulted in the term 'Schumpeterian' being hijacked by endogenous growth theorists (in particular, Aghion and Howitt (1998)). Here the goal is to begin to reclaim this territory.

2. The Evolutionary macroeconomic perspective on growth

Foster (1987) proposed an 'evolutionary macroeconomic' approach to analysing the determinants of economic growth. This was operationalized as an empirical methodology in Foster and Wild (1999a, 1999b) and is summarized in Foster (2011a). Economic growth, as measured by GDP growth, is looked on, not as an aggregated behavioural entity, but as a statistical aggregation of the measurable economic value that arises out of a complex and irreducible process of economic evolution. To think of the data on economic growth as an aggregation of the behaviour of a 'representative agent' engaged in constrained optimization in a timeless setting is viewed as entirely without scientific meaning. All economic growth is initiated in entrepreneurship, innovation and the adoption of new skills (Baumol (2002)). Since this involves a great deal of uncertainty, constrained optimization is impossible (Foster and Metcalfe (2012)).

From radical innovations there follow diffusion processes that involve increases in organized complexity of an economic system. The outcome of much learning-by-doing, incremental innovation and competitive selection is a range of viable economic activities that yield processes and products that grow in number, at falling cost, over historical time. These economic activities are consolidated in effective organizational structures dominated by sets of routines which, inevitably, introduce a degree of time irreversibility or 'lock-in' (Arthur (1994)). In such processes, there is little doubt that constrained optimization occurs when it is feasible but, given the sheer complexity of any productive organization, this is very difficult to do. To establish order and a productive capability, the operation of rules and routines has to dominate, as Nelson and Winter (1982) explained so vividly. So it is essential that any theory of economic growth, and associated empirical methodology, should the built with this evolutionary economic process at its core, not an idealized representation of constrained optimization (Foster and Metcalfe (2012)).

Conventional economists try to answer questions about economic growth starting with an aggregate production function that contains stocks of 'physical capital' and 'human capital.' But, as already noted, there are serious problems with such an approach once we acknowledge that we are dealing with continual structural change and the formation of productive structures with irreversible features in historical time. The capital stock clearly has a very important role to play in economic growth but it is a physical magnitude that is the product of acts of inventiveness, entrepreneurship and innovative creativity and, as such, it is a complex network of 'structured knowledge' that has cumulated over time in physical capital (Arrow (1962)). It is the physical core upon which new knowledge that is not embodied in the capital stock can be developed.

The existence of a capital stock makes it possible to apply a flow of human and non-human energy to generate economic value, as measured by GDP, in excess of the application human effort by itself. The capital stock is a durable, networked structure which offers the opportunity for many kinds of new knowledge to be generated that can produce economic value and, thus, it creates a ‘niche’ into which GDP can grow in the future. Economic growth is not just about ‘more of the same’ it is about ongoing qualitative change in the economic system. Thus, although we can think of the productive process in terms of inputs and outputs, there can be no meaningful ‘equilibrium’ association between them over long periods when structural change is significant and this is, of course, very clear in the Solow (1957) study, where GDP deviates significantly from input measures, right through to the endogenous growth literature, with its emphasis on ‘economies of scale’.

Indeed, over the past two decades, it has become well understood that many macroeconomic time series do not have simple deterministic trends which they regress to. The hypothesis that such series have ‘unit roots’ often cannot be rejected, i.e., there is no support for the hypothesis of a deterministic trend and, therefore, such a series cannot be viewed as tending to an equilibrium path. Such a series is dependent upon its past history. Undeterred, proponents of economic theories that predict input-output equilibrium solutions began to search for ‘co-integration’ between such time series. This, it was argued, provided evidence in support of a ‘long run equilibrium’ relationship between the chosen variables. Often, but not always, an ‘equilibrium correction model,’ was estimated using stationary first-differenced data. However, as Foster and Wild (1999a) pointed out, it is often the case that first differenced variables are correlated without there being co-integration in levels when non-equilibrium, evolutionary economic change is occurring.

Interestingly, when a Solow style growth equation is estimated with a significant constant term, the latter is deemed to represent ‘technical progress’. From an equilibrium correction methodological perspective, such an equation has no long run equilibrium solution yet, theoretically, it is viewed as an ‘equilibrium growth model.’ But the presence of a significant constant in a growth equation implies that there can be no long run equilibrium relationship between the specified input variables. This is precisely the disconnection between modelling and conventional economic theory that Davidson et al

(1978) pointed to in developing their equilibrium correction methodology over thirty years ago. The correct interpretation of the Solow evidence is that economic growth is the outcome of a non-equilibrium, historical process and it must be treated as such.

So can we model economic growth at all once we accept that it is the product of a non-equilibrium, evolutionary process? Clearly, there is a great deal that we can learn about economic growth just through detailed historical inquiry, but our capacity to discover a simple quantitative behavioural model of the complex, interconnected processes involved in economic evolution is strictly limited. From an econometric perspective, the whole process is in a 'black box' since the evolutionary drivers of the process involve non-average behaviour by heterogeneous decision-makers, often operating in radical uncertainty that cannot be modelled at the macroeconomic level. So trying to construct a realistic model of economic growth from economic behavioural foundations seems to be a scientific impossibility.

However, complex systems theory tells us that there are systemic features of all economic systems that will tend to make them grow in certain tractable ways. First of all, because all economic systems are, necessarily, dissipative structures, importing free energy and exporting entropy, we know that, as the output of any evolving system changes and grows, it will consume more energy and this is a flow that we can measure (Brown et al (2011)). Secondly, we also know that an economic system can only become more complex, and, thus, able to grow, if new knowledge is applied in new ways. This is much harder to measure.

Although various proxies for the 'stock' of knowledge have been used in the endogenous growth literature, such as patents and education, it is not possible to measure the actual 'knowledge flow' that occurs in entrepreneurial projects. Knowledge not a stock but, rather, a virtual structure that enables physical and human elements to be connected in productive and distributive networks, subject to the technological, organizational and institutional rules that exist. However, we know from innumerable studies of innovation that the process whereby new 'radical' knowledge is applied successfully tends to result in a tractable growth path until a limit is approached. It is this that yields the widely observed sigmoid 'innovation diffusion curve' with its expanding scale of output, rising productivity and falling unit costs. At the macroeconomic level of inquiry, a multitude of these curves can average into a smooth macro growth curve which, itself, as famously suggested by Joseph Schumpeter, can follow a sigmoid path in the wake of a radical innovation of fundamental importance (Perez (2002), Freeman and Louca (2002)).

We have recognized the thermodynamic character of all economic systems: there must exist an 'energy gradient' which can be drawn upon to allow a system to do work. All dissipative structures attempt to reduce such gradients (Schneider and Sagan (2005)). For a long time in human history, a large proportion of the population did physical work fuelled by a food energy gradient. However, humans in modern times predominantly use capital goods to do physical work using flows of non-human energy. Work now is only minimally physical in nature: the 'machine operator' and the 'knowledge worker' are now the norm.

Unlike physio-chemical dissipative structures, the energy gradient faced by living organisms is not always exogenous. Following the terminology of Foster (2005), at the 2nd Order of Complexity living organisms, through the operation of competitive selection, acquire genetic knowledge that enables them to access higher energy gradients and increase the size of their populations. At the 3rd Order of Complexity, humans, almost uniquely, apply non-genetically transmitted creative knowledge, embodied in capital goods, to generate economic value and run down energy gradients that have been accessed. But to get beyond the application hand tools and capital goods related to animal power, humans have had to operate at a 4th Order of Complexity whereby they are able to cooperate in economic organizations using 'understandings' to enable the creation and use of very complex capital goods that enhance their capacity to generate greater amounts of economic value. Starting with wood, charcoal, wind and water power, humans developed a capacity to overcome the thermodynamic limit of a finite 'organic' energy gradient. But this did not have a dramatic effect on economic growth until fossil fuels, which had been known about and used for a long time, became applied at large scale using efficient and versatile steam engines.

It follows that, for humans, growth has become heavily dependent upon the existence of a 'knowledge gradient' that is specifically 'economic' (Georgescu-Roegen (1971)). For example, there was always coal and oil available in the ground, it was only when knowledge of how to extract and use such energy became available that it could enable economic growth. The relative cheapness of such energy per joule, compared to the organic and solar sourced energy relied upon previously, offered unrivalled opportunities to accumulate new knowledge that could generate economic value. This relied almost entirely on the human ability to create capital goods to mine fossil energy more effectively and to create and use others to generate economic value. Thus, the 'core knowledge' that has created opportunities for rapid growth using fossil fuels has been that embodied in energy-using capital goods.

We know that, for economic growth to occur, there must be growth in the use of non-human energy flow and/or increases in human work time and/or a rise in the application of knowledge that can increase the productivity of one or both. The creation and use of radically new capital goods has shifted physical work away from human work time to a greater reliance on non-human energy flow. This has involved learning-by-doing, in the context of the production and use of new capital goods, incremental technical innovations that make capital goods more productive and diverse in their application and organizational, institutional and product innovations that have raised GDP per capita. These are often summarized in conventional economics as 'dynamic economies of scale'. All of these ongoing impacts of a radical innovation tend to result in growth that follows a sigmoid logistic or Gompertz time path towards a zero growth limit. We see this clearly in the literature on innovation diffusion and product cycles and it lies at the heart of studies which identify the presence of 'long waves' at the macroeconomic level of inquiry.

The knowledge gradient differs in nature from the energy one because, as endogenous growth theorists have stressed, using knowledge does not diminish it in a literal sense. However, knowledge does get 'used up' as the potential applications of it become exhausted. The goods in which it is embedded become obsolete as time passes and, therefore, there is no longer a niche to enter using that knowledge. For example, there is no point in deciding to produce this year's fashion goods next year or using the very best knowledge concerning the production of steam locomotives in a world of electric trains.

In reality, it is not easy to discover and reduce a knowledge gradient that has the potential to generate economic value. Only entrepreneurial individuals and groups do this by combining ideas and skills in imaginative new ways with the goal of making money. Only a minority of them is successful. The knowledge gradient that makes GDP growth possible begins with the embodiment of technical knowledge in capital goods but its full extent is dependent on a complex interaction of cultural, social, political and economic understandings that is specific to different countries, regions and cities (Acemoglu and Robinson (2012)). It is this which determines whether a new capital good sparks off multiple applications in future economic interactions or just sits unused to rust. Indeed, interacting cultural, social and political factors can even prevent the innovative development and/or use of capital goods, utilizing non-human energy, because of the threat posed to vested interests.

So we know that the ongoing application of new knowledge augments the impacts of energy flow and labour hours worked. It manifests itself qualitatively in the shifting relationship between these core inputs and GDP. So there must always be a growth ‘residual’ unexplained by input flow growth but, unlike that in Solow (1957), we can attribute it directly to the innovation diffusion process that must occur when new knowledge is being applied following a radical capital good innovation, such as Watt’s steam engine. Here, we are not dealing with a ‘production function’, somehow aggregated up from the optimising behaviour of firms. Instead, we are acknowledging the thermodynamic relationship that must, necessarily, exist between the application of human and non-human energy if human activity of any kind is to occur. For economic activity to occur, as reflected in a measure such as GDP, the key relationship is the co-evolutionary one between energy flow, made possible by the presence of an energy gradient, and the ongoing application of new knowledge, made possible by the existence of a knowledge gradient.

3. The super-radical innovation diffusion hypothesis

The hypothesis that is proposed here is that the explosive growth we have witnessed since the early/mid- 19th Century has been due to a 'super-radical' innovation diffusion process that became possible because of the availability of very cheap fossil fuel energy. To see growth as stemming from a radical innovation is not a novel claim – it is well recognized that there have been Schumpeterian growth surges because of radical innovations, reaching back into the 18th Century (Freeman and Louca (2002)). What is novel is the claim that, for almost two centuries, we have been on a very long innovation diffusion trajectory that has been an 'envelope' within which long waves have been contained. The super-radical innovation diffusion process was not the about deployment of fossil fuels, which had occurred much earlier, but the large scale commercial use of fossil fuel energy, firstly, coal and gas and then petroleum. Fossil fuels have a massive capacity to generate heat, relative to the energy required to mine, transport and process them, compared with previous direct and indirect solar sources of energy. However, the effective exploitation of fossil fuels was only made possible with suitable technical, organizational and institutional innovations that created appropriate capital goods both for the extraction of fossil fuels and for their use in providing goods and services. An energy gradient cannot be exploited without a complementary knowledge gradient. Thus, activities that were uneconomic in the restricted world of organic and solar energy sources became viable. So the opportunities for innovation and entrepreneurial success began to expand rapidly and cumulatively in the 19th Century as powerful fossil fuels became cheaper and more widely available.

The importance of fossil fuels in the industrial revolution is not a new idea – a debate in economic history has been raging for decades on this topic and, indeed, claims that energy was the sole driver of explosive economic growth are unconvincing even amongst those historians who attribute a vital role to fossil fuels in the industrial revolution (see, for example, Allen (2009) and Wrigley (2010)). The application of new knowledge is essential for economic growth but the application of a very powerful energy source opened up possibilities in the application of knowledge that were never previously attainable. The work of historians such as Mokyr (2002) and McCloskey, (2010), claiming that a revolution in the composition of knowledge and related cultural change that commenced as early as the 17th century, was of primary importance, is not denied here. It is not likely that the scientific and engineering advances using fossil fuels in the 19th Century would have happened without the radical shifts in the knowledge base that governed economic activities in the 18th Century (see Chapman (1970)). For example, without the 'Scottish Enlightenment' cultural development in the 18th Century, it is unlikely that James Watt would have developed his superior steam engine.

Indeed, from the 17th Century, on in the United Kingdom, which will be our main focus, economic growth increased because of changes in the nature of knowledge and related increases in agricultural productivity (particularly the growing of potatoes which yielded about three times the food energy per acre compared to other foodstuffs (Nunn and Qian (2011)). Early industrialization involved the creative design and construction of capital goods, as did agriculture, but growth in what some historians label 'the first industrial revolution' was ultimately curtailed by limits on knowledge of how to deploy more powerful capital goods economically.[3] Wood and charcoal became scarce, useful sites for water driven mills became harder to find and the horsepower required began to limit the amount of agricultural land available for food growing. In contrast, coal mining did not take up large amounts of land and a miner could produce about 100 times more energy than an agricultural worker. However, the novel capital investments necessary to make mining more productive, to transport coal and to build the capital goods to use it effectively were massive challenges.

In 19th Century Britain it was remarkable how these challenges were met. It was a century of radical creative destruction: horses, water mills, windmills, wood burning and charcoal production and all the trades associated with them began to be swept away in favour of Watt's improved steam engine to pump water out of mines, re-circulate water in mill races, drive trains, generate electricity, etc.[4] This 'creative destruction,' that enabled the effective and economic use of fossil fuel energy, was intensified in the early 20th Century with expansion of the use of gas in heating and the shift to oil for transportation, electricity generation, etc. The combustion engine and the electric motor took over from the steam engine as the key power drivers in capital goods.

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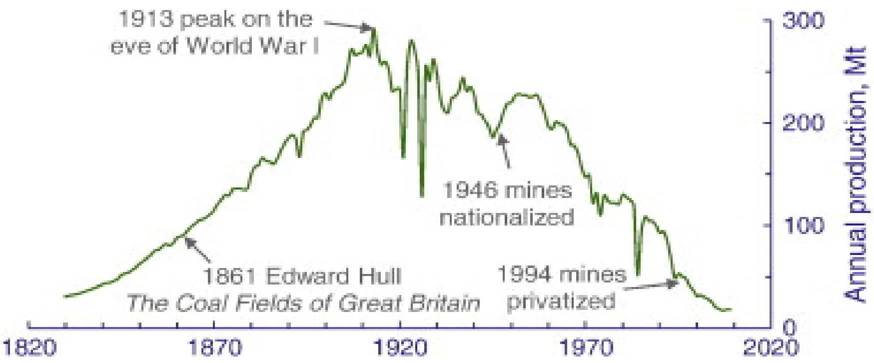
[3] See, for example, Deane (1969), Harley (1982), Crafts (2005) and Wrigley (2010) for extended discussion concerning the existence, or otherwise, of the first industrial revolution.

[4] Harris (1967) pointed out that steam engines were used extensively in the 18th Century to pump water out of coal mines, even though they were relatively inefficient, because they used 'waste' coal fragments that had little commercial value.

But such a transition involved socio-political traumas and Europe became a continent that suffered all of the political pressures that came with a radical structural transformation that involved a sustained shift away from labour and horse power to fossil fuel driven machine power. The occupational churning and rapid increase in capital investment and mining capacity, stimulated by the First World War, ultimately resulted in large amounts of excess capacity and structural unemployment in the 1920s and 1930s. The coal driven economy experienced serious problems. Coal consumption in the UK peaked in 1914 and mining over-expanded in World War One. After the war, British coal prices were held up to maintain miners' wages but this only exacerbated an excess supply situation resulting in the bankruptcy of many privately owned mines. Business investment in new capital stock was cut back because of the relatively high real price of both energy and labour and associated uncertainty. This generated an effective demand problem, as identified by John Maynard Keynes in 1936. This transitional problem was not fully eliminated until the stimulative effect of the Second World War operated.

Fig 1

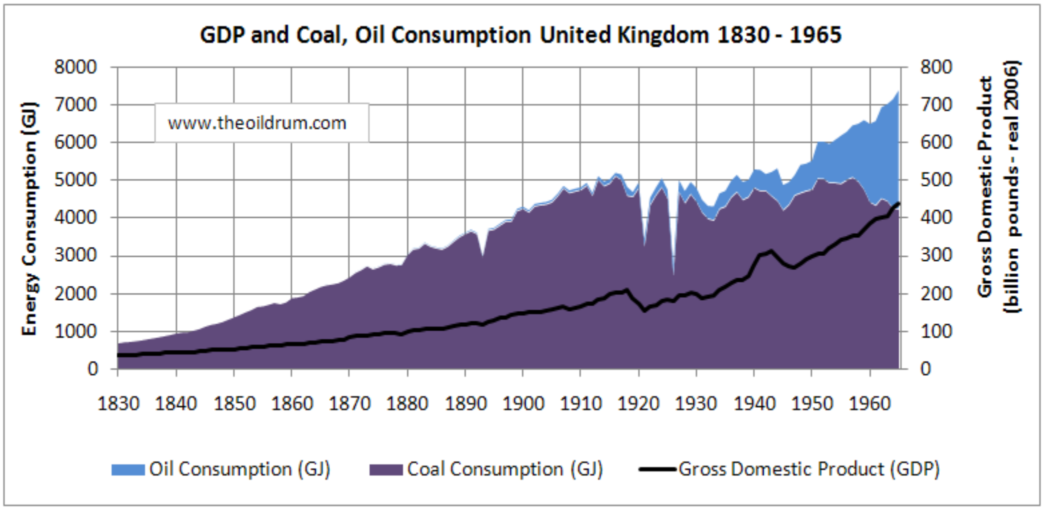
UK Coal Production



Source: BP Statistical Review of World Energy, (2010)

As can be seen in Fig. 1, in terms of production, coal peaked in 1913 and reached the end of its era of growth. The UK became more and more dependent on imported coal, particularly after the Second World War, but the price of coal remained fairly stable – it was still at around its 1880 real price in 1967 after which it rose about four and a half times by 2008 (Fouquet (2009)). After the war, oil consumption grew rapidly and coal became mainly dedicated to the generation of electricity with tar, coke and gas as by products. Dependence on imported oil also increased although this was moderated with the emergence of North Sea supplies in the 1970s. In Fig 2, the rapid rise in the proportion of oil in energy consumption in the early post World War Two era can be seen.

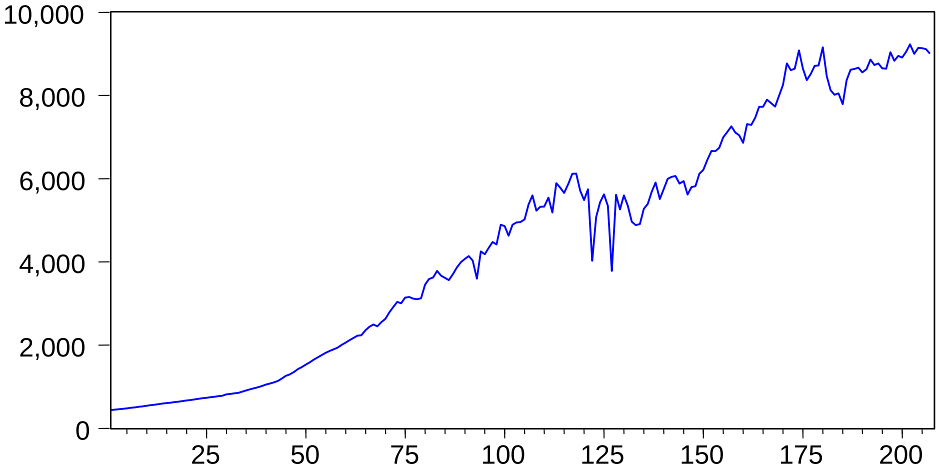
Fig. 2



Source: Ryland et al. (2010)

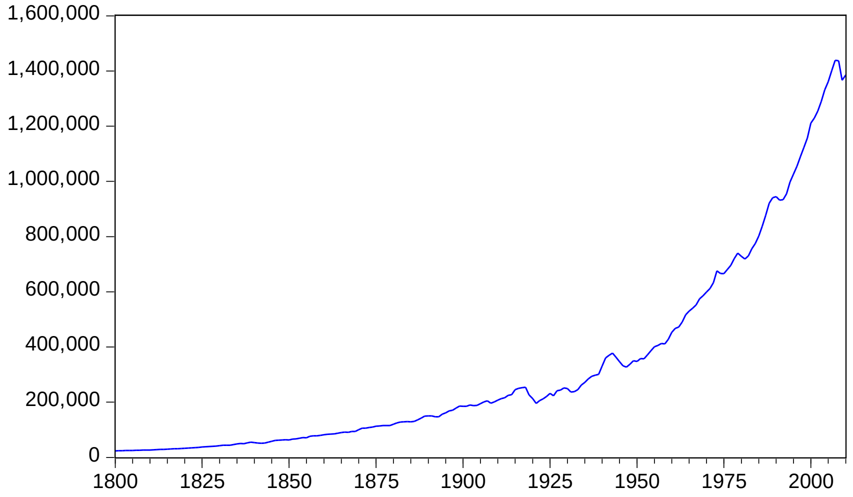
Data on all energy consumption charted in Fig. 3, indicates that growth in oil consumption stopped in the 1970s and we can see that it constituted a 'sub-logistic' diffusion curve within an overall logistic curve for total energy. By the early 21st Century, total energy consumption had plateaued.

Fig. 3
UK Energy Consumption 1800-2010
(in Petajoules)



Despite the interwar slowdown, the longer term tendency for economic growth to occur at a high and sustained rate globally was relatively unaffected (Fig. 4). The interwar period was not one where energy was in short supply but rather there was a lack of new knowledge as to how to extract energy more economically and to deploy effectively and in new ways. Field (2011) has provided convincing evidence that this resulted in a sharp rise in inventive and innovative behaviour in the 1930s.

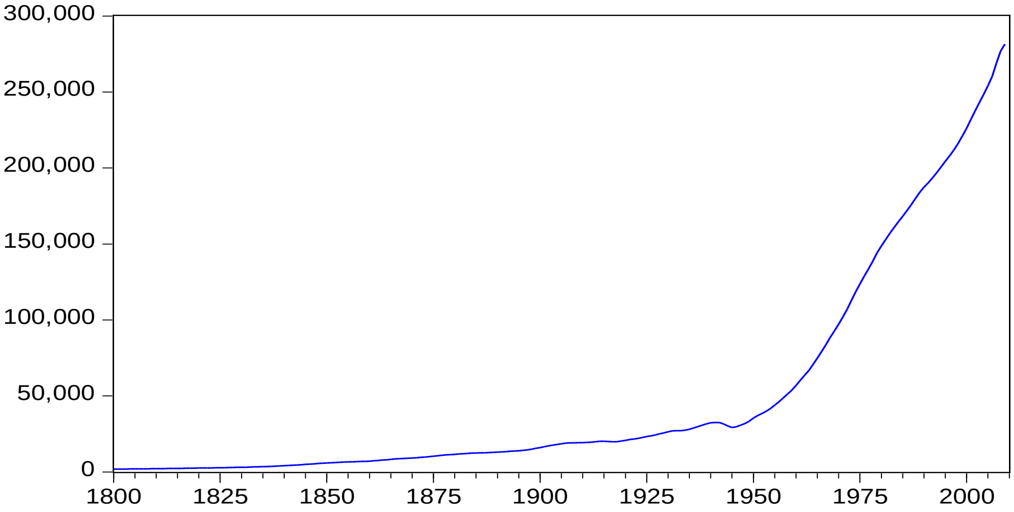
Fig. 4
British Real GDP: 1830-2010
(US$ million, 1990 prices)



19th century economists, such as Stanley Jevons (1866), had worried about the implications of the heavy British dependence on coal but he seriously underestimated the durability of the growth of knowledge process that had started. Institutional innovations are generally slow in agrarian societies, but not so in 19th Century industrial communities in the UK where the gains from investing heavily in new capital goods and reorganizing society to take advantage of fossil fuel power were so attractive. Anthropological evidence suggests that human beings in modern societies are neither more imaginative nor creative than they were previously (Boyd and Richerson (2005)). The spark seemed to be the availability of a massively powerful source of energy in a country with a recent socio-cultural history in which knowledge had been permitted to accumulate concerning the mining of coal and the design of capital goods for use in mills and factories.

Capital goods have been identified as the primary vehicle for catalysing economically valuable knowledge in the presence of a fossil fuel energy gradient. In Fig. 5, the upsurge in the net capital stock in Britain is very clear. The massive release of unskilled labour that this implied allowed a shift in employment towards service activities which provided the specialized expertise to design new capital goods and the systems that they operate in, as well as the provision of a large range of services for mass consumption. This shift was most marked after the Second World War when growth in the capital stock was higher than previously. [5]

Fig. 5
British Capital Stock: 1800-2010
(£Million, 1990 prices)



So, it is clear that total energy consumption, in the case of the UK, has followed a logistic path but, economic growth has not. It has followed a quasi-exponential path which is only approximated in the pre-inflexion phase of a logistic diffusion path. However, the super-radical innovation diffusion hypothesis is not about a fixed curve. The knowledge gradient, built upon knowledge embedded in capital goods, is not static but, as we can see in Fig.5, has been continually growing. Thus, the 'niche' that GDP could grow into continually increased, so a simple logistic curve should not be observed even though we are dealing with a logistic *process.* Let us see what the evidence tells us.

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[5] It has been commonly assumed in a number of neoclassical studies of economic growth that the capital-output and/or the capital-labour ratio have been approximately constant. In the British case, the former in 2010 was about 2.5 times greater that it was in 1900 and the latter about 12 times greater.

4. The United Kingdom: a suitable case for treatment

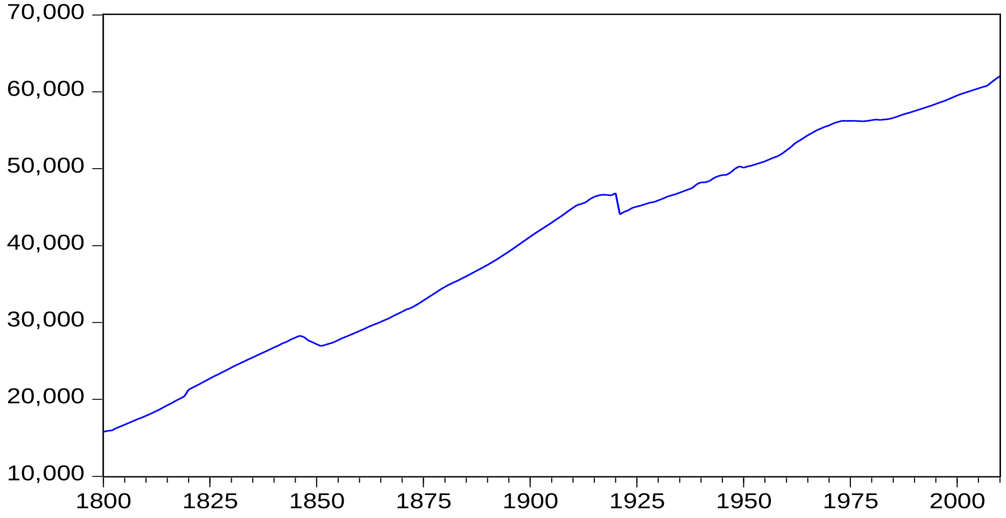
The idea that global economic growth has been on a long sigmoid diffusion curve is not new, recently Miranda and Lima (2011) and, before them, Boretos (2009) explored this possibility using global data. However, the problem with global studies is the paucity of long time series and it is not clear that the relatively small segment of time series data available to these researchers is actually on a logistic growth path, even though it is intuitively obvious that real GDP growth cannot continue to be exponential or faster at the global scale indefinitely. Also, since each country's growth experience is unique, we can only understand global growth by looking at each of them separately and understanding the interactions between them. The global economy is a network structure connected by production and trade. But it is a very incomplete network which has become more connected and, thus, more complex and organized over time. Only careful historical study of every country can track how this global process has unfolded and how related cultural, social, institutional and economic circumstances have shifted over long periods of time (Acemoglu and Robinson (2012)). Here we report the results of tests of the super innovation diffusion hypothesis for only one, very important country.

The United Kingdom was the country selected for study for two reasons: firstly, it was first into the 'industrial revolution' and is now a stable, advanced 'post-industrial' country. It has exhibited the longest 'explosive' growth path of any country and, over the past two centuries, it has not been disturbed by serious internal political crises or invasions. Secondly, there are available long data sets that stretch well back into the 19th century that can shed light on our hypothesis.

The United Kingdom was first to experience an 'industrial revolution' and this was, in large measure, due to technical, organizational and institutional innovations that had their roots back in the 16th Century. In the early 18th Century about 80% of global output of coal was produced in the UK (Wrigley (2010)). At that time, coal was used largely for domestic heating. Steam engines, although they existed, remained relatively inefficient. But the British developed a lead in coal mining technology and a key driver of the development of Watt's much more efficient steam engine was the need to pump water quickly and effectively out of coal mines. By the 19th Century, although many factories were still powered by water because costs had been sunk and marginal cost was very low, new industrial sites began to be powered by steam engines, fuelled by coal. The widespread use of coal energy would have to await its large scale translation into electrical power in the early 20th Century. The availability of combustion engines using distillates also began to transform economic production in radical ways in the early 20th Century because of revolutionary new transportation capabilities. Innovators could profit from designing machines that used powerful fossil fuels, directly or indirectly, and, in an autocatalytic way, the increasing demand for fossil fuels lowered their cost as scale economies, learning by doing and incremental innovations, in exploration, mining and delivery, did their work.

Fig. 6

UK Population: 1820-2010 (Thousands)

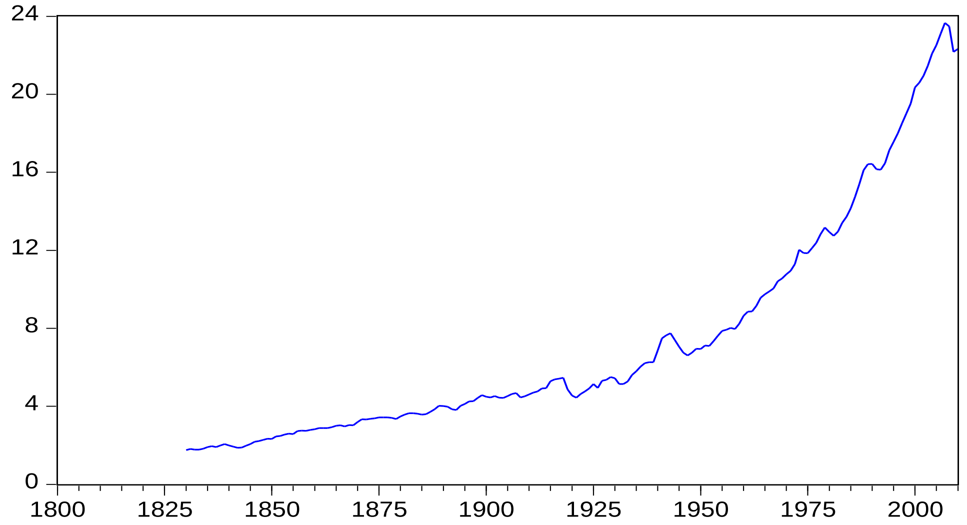


With its early mover advantages, both in having set down appropriate 'meso rules' (Dopfer, Foster and Potts (2004)) that facilitated entrepreneurship and innovation and in having plentiful supplies offossil fuels, the UK began to grow rapidly to become a global power as it employed readily accessible supplies of coal and used it with knowledge embodied in steam driven capital goods. However, its lead was lost by the beginning of the 20th century as Germany, and then the USA, gained industrial strength. Germany also took advantage of extensive reserves of good quality coal but the US to a lesser extent because it still had access to plentiful supplies of wood. However, the spread of fossil fuel driven industrial development did not lead to the decline of the UK in absolute terms since the spread of fossil fuel use globally stimulated trade and the UK, as a major trading nation, was a beneficiary. So, in the 20th Century, the UK maintained a stable growth path, supported by a steadily increasing knowledge base and reliable supplies of fossil fuels, with increased reliance on gas and oil later in the century.

Although real GDP has followed a long period trajectory which is close to exponential, despite the traumatic experiences of a depression and two world wars, population growth has been approximately linear (Fig 6). So population has grown ever more slowly than GDP per capita (Fig 7) which is a very 'un-Malthusian' finding. [6]

Fig. 7

British Real GDP per Capita 1830-2010 (US$ Thousand, 1990 prices)



The consumption of energy in the UK has also increased dramatically but its growth has not been exponential, as we saw in Fig 3. There have been two distinct 'sub-logistic' phases, one associated with the rise of coal and the other with the rise of oil. These come into sharper focus when we look at energy per capita in Fig 8. Also, the energy to GDP ratio, since about 1880, has been falling consistently, reflecting steady increases in the efficiency of the extraction, transportation and use of fossil fuels (Fig. 9). The ratio rose prior to 1880, most likely because of the significant investments in new mines, steam driven machinery and associated infrastructure which took time to fully utilize.

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[6] Interestingly, despite its reputation as a 'mature' economy, the UK continued, up to the recession of 2009, to record a labour productivity growth rate that was not only consistently positive but on a continual rising trend, despite the massive shift towards service sector activities.

Fig. 8

British Energy Consumption per Capita: 1820-2010
(petajoules per Person)

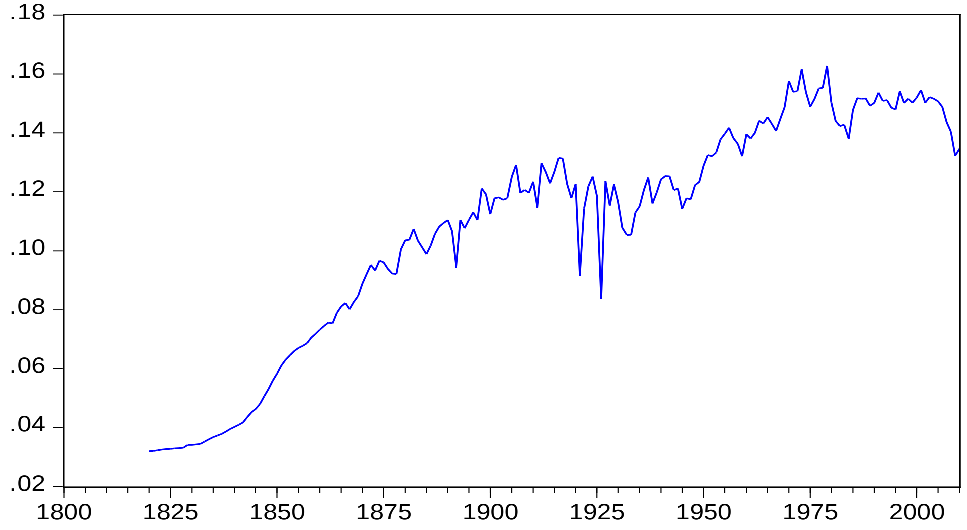
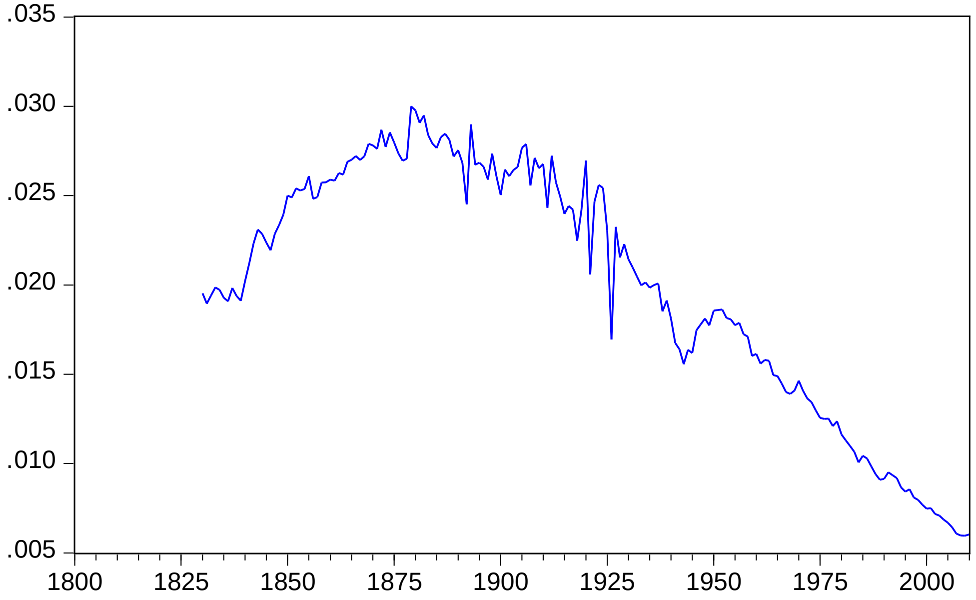


Fig. 9

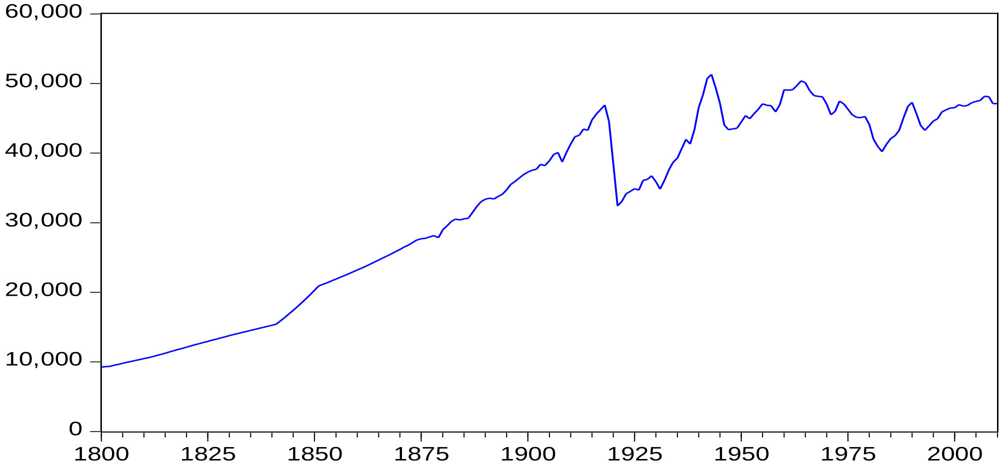
British Energy to GDP Ratio: 1830-2010



Labour effort is clearly fundamental in any economy, whether it is devoted to physical work or to mental activities. It is very striking in Fig 10 that, labour hours trended upwards until 1919 after which they oscillated around a static level up to the present. In 2010, total labour hours were only marginally above their 1919 level. Over the same period, the UK population grew by 33%. Thus, we can see that

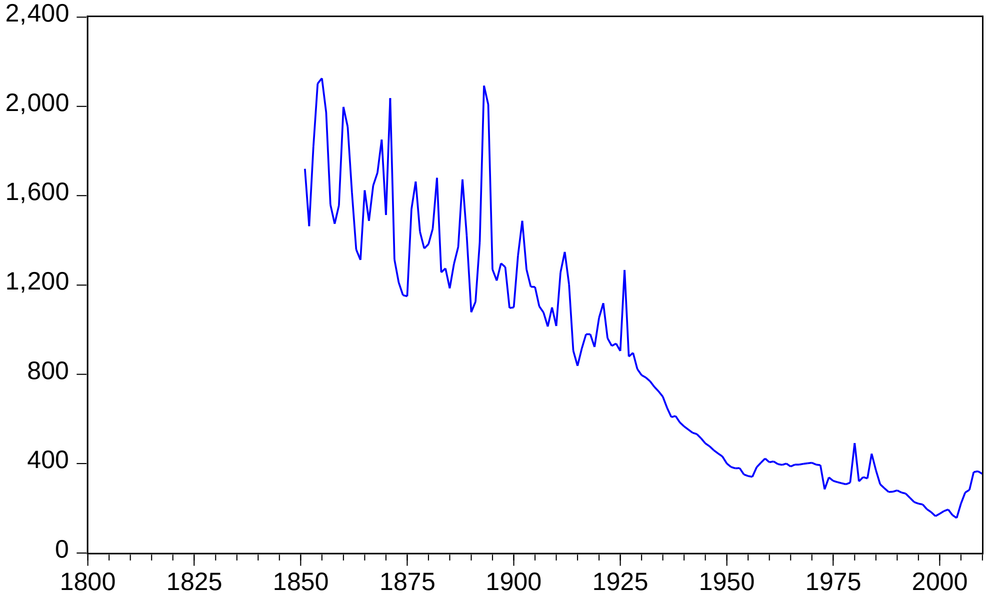
The First World War was pivotal in the shift from a labour to a capital intensive economy in relation to the provision of physical energy.

Fig. 10
British Total Hours Worked 1800-2010



The pre-World War One economy still had a significant role for horse and human physical labour. We saw in Fig 5 that the fast surge in the capital stock, releasing labour into the growing service sector did not occur until after World War Two. The interwar years involved a difficult transition with the capital stock hardly rising and labour hours dropping significantly.

Fig. 11
British Average Real Energy Price: 1851-2010
(£in 2000 prices)



So do these charts suggest that a super-radical innovation diffusion process has been in operation? Well, we saw little sign of this in Fig. 4 but there is little doubt that fossil energy had a big role to play: there was nineteen times more energy consumed in the UK in 2010, compared to the early 19th Century, permitting both population growth and growth of output per capita. An indicator that a fossil fuel based innovation diffusion process may have been occurring is the steady downward trajectory of energy costs. This is a typical finding in the presence of an innovation diffusion process (Figure 11). By 2007, energy cost was one ninth of its 1830 price in real terms.

On innovation diffusion curves, unit costs usually fall up to the point of inflexion, after which they rise as dominant organizations begin to rent seek. We can see that the real price of energy has now stopped falling and is showing signs of a permanent increase. It is notable that, up to 1930, the price of energy fluctuated because fossil energy was in short supply and, thus, sensitive to movements in demand. From the Great Depression on, supplies of coal and oil tended to exceed demand and price became stable and determined by supply side costs. In the 1970s, suppliers, again, had some market power because of the strong global demand that had built up in the post-war boom. Since the global financial crisis in 2008, real energy prices have attained close to their 1970s peak range again although they still remain low by historical standards.

So there are strong indications that energy consumption has followed a logistic trajectory. This is not surprising given that the economically viable fossil fuel component faces a fixed limit. As has been discussed, this is not the case with GDP because knowledge knows no limits. However, given that economic growth is the outcome of a co-evolutionary energy-knowledge process, GDP can still be the outcome of a logistic diffusion process. It will now be explained how this can be tested.

5. An augmented logistic diffusion model of UK growth

Because economic growth is the outcome of a co-evolutionary process, where the application of new knowledge and increased energy use are complementary, we have a methodological choice. We can choose, as in endogenous growth theory, to focus upon the role of knowledge in a general way, or we can focus specifically on the impact of new knowledge on the growth in energy consumption and increases in the efficiency of its use, as in Ayres and Warr (2009) and Stern and Kander (2012).[7] Both approaches can lay claim to explaining most of the 'Solow residual.' For Ayres and Warr (2009), it is energy flow that is important, with the key role of new knowledge being to get energy sources do more work. There is no particular focus on energy in most endogenous growth models although it does figure in some studies (see Pittel and Rübbelke (2010) for a review).

Importantly, in both approaches, it is new knowledge embodied in capital goods that is the key. In Ayres and Warr (2009), it is about the development of more and better capital goods to turn energy into work. In endogenous growth models it is the capacity of people in the R&D sector to produce new capital goods that embody new ideas that drives growth. It is also fully accepted in this study that the capital stock, as embodied knowledge available to use energy to do work, is important. However, the capital stock is not viewed as a direct determinant of economic growth, as it is in the aggregate production function approach, but it is, instead, viewed as a core determinant of the niche that GDP can enter through economic growth. Now it is commonplace in growth theory to see capital investment as the prime mover but here it enters as an indicator of the economic knowledge potential of a country. Focusing on the capital stock in this way might seem to some as rather a narrow perspective on the role of knowledge. Here, it is the key because it is the capital stock which is the conduit through which cheap fossil fuels, directly and indirectly, have been transformed into a vast range of goods and services of measurable economic value.

The capital stock is the energy-driven building block that enables technical, organizational, institutional and product innovations to happen. It is the tip of the knowledge gradient iceberg. Think of Henry Ford's re-organization of factory production, the new laws of contract that emerged in the late 19th Century in Britain or the laws that facilitated the formation of joint stock companies. It is because of all

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[7] Stern and Kander (2012) stepped back from the endogenous growth framework, instead, employing a variant of the Solow growth model using a CES production function with time varying elasticities of substitution. They reported that, for Sweden, energy seems to have played an important role in the determination of economic growth over two centuries. Ayres and Warr (2009) also viewed the Cobb-Douglas specification as too restrictive, preferring a more realistic Linex production function to which they add 'useful work' to capture energy flow and energy efficiency effects.

of these innovations that a given capital stock can sustain growth into the future that is not necessarily delimited only by the supply of energy. For example, investments in computers in the 1970s and 1980s made possible large increases in GDP because of innovations in mobile computing power, software development and electronic communications. The massive increase in the proportion of GDP in services has been due to the provision of capital goods which have facilitated the economic delivery of increasingly diverse services and the release of labour to do so.

Our hypothesis is that economic growth has followed a logistic diffusion trajectory following the large scale, commercial deployment of fossil fuels, using efficient steam engines, then combustion engines and electric motors, in the capital stock. To model this evolutionary macroeconomic account of economic growth a 'Schumpeterian' perspective was employed. Economic growth, as a reflection of a process of economic evolution, has no equilibrium solution. It is a 'historical tendency' which, if there is a limit to the capacity to use new knowledge to generate economic value, must tend towards a zero growth state. This is a state that is likely to be structurally unstable if it requires a radical transition to a new knowledge paradigm and the deployment of alternative sources of energy. What this implies is that any 'systemic' statistical model of economic growth that is constructed can only be estimated up to the early stage of the mature phase of a logistic trajectory.

Following Foster and Wild (1999), an augmented logistic diffusion model (ALDM) was employed. This builds upon the Mansfield variant of the logistic equation:[8]

$$Y_t = Y_{t-1} + aY_{t-1}[1 - Y_{t-1}/K] \tag{1}$$

Where **Y** is GDP, ***a*** is the logistic diffusion coefficient and ***K*** is the zero growth limit.

This simple logistic equation is augmented as follows:

$$Y_t = Y_{t-1} + a\, Y_{t-1}[1 - Y_{t-1}/nC_{t-1}] + be_t + gh_t \tag{2}$$

equivalently:

$$(Y_t - Y_{t-1})/\, Y_{t-1} = a - (a/n)[Y_{t-1}/C_{t-1}] + be_t + gh_t \tag{3}$$

---

[8] A Gompertz specification was also estimated but the results are not reported below. The results are similar to those using the logistic specification but the latter explains a little more of GDP growth so it was preferred.

Approximating logarithmically:

$$lnY_t - lnY_{t-1} = a - (a/n)[Y_{t-1}/C_{t-1}] + be_t + gh_t \qquad (4)$$

e is the growth of total energy(***E***) consumption (***$lnE_t - lnE_{t-1}$***), ***h*** is the growth of total labour hours (***$lnH_t - lnH_{t-1}$***) and ***C*** is the net capital stock. GDP can only exist if there is some energy used and some work done. This is a thermodynamic necessity. The extent of the payoff from these flows is determined by the application of knowledge. Economic growth occurs because of some combination of the growth in ***E, H*** and the increase in the application of knowledge which, in eq. (4) is **$a - (a/n)[Y_{t-1}/C_{t-1}]$**. This is the 'net' innovation diffusion effect. ***a*** is the 'gross' innovation diffusion coefficient that reflects all new knowledge 'dynamic' effects that stem from a radical innovation, such as learning by doing, incremental technical, organizational, institutional and product innovations.

The ***K*** limit is hypothesized to be related to the embodied knowledge contained in the net capital stock (***C***). As **Y** approaches a ***K*** limit, the net innovation diffusion effect tends to zero. So what is a 'qualitative' knowledge diffusion effect disappears, leaving only the 'quantitative' impacts of changes in energy consumption labour hours worked. These can push ***Y*** above the ***K*** limit, but this is corrected as **Y/*K*** rises above unity. However, ***K*** rises because embodied knowledge in ***C*** rises, and this is presumed to be a linear association.[9] This enables more economic value to be produced using non-human energy, sometimes independently, such as the operation of a pump, or in conjunction with human work time. So, as the stock of capital grows, the ***K*** limit that ***Y*** tends towards increases. This offsets the inherent tendency for economic growth to slow down to a zero limit.

The presence of the net innovation diffusion effect means that growth in both of the core energy flows may be unnecessary. We have already seen in Fig. 10 that, in the UK case, ***H*** has grown little over the past century and that, in recent years, ***E*** has begun to stabilise (Fig. 3). Although this may be the case, the core importance of both ***E*** and ***H*** flows implies that their fluctuations should always have an important impact on GDP growth.

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[9] In the Gompertz specification, it is log-linear.

Our hypothesis is that explosive growth, from the early 19th century on, was due to the creation and use of a capital stock explicitly designed to extract and use fossil fuel energy that was uniquely powerful. In addition, we saw in Fig. 11 that the price of energy fell sharply up to the end of the 1950s. Falling energy prices should make marginal investment projects profitable, which suggests that we should observe a negative relationship between energy price and the size of the capital stock. However, the capital stock is mostly inherited from the past at any point in time so we can expect it to only slowly adjust to a changing energy price. We can use a 'partial adjustment' model to capture this slow adjustment:[10]

$$\ln C_t^* = w + f(\ln P_t, \ln P_{t-1} \ldots \ln P_{t-n}) \qquad (5)$$

Where C_t^* is the capital stock in a stationary state

$$\ln C_t - \ln C_{t-1} = z(\ln C_t^* - \ln C_{t-1}) + f([\ln C_{t-1} - \ln C_{t-2}] \ldots [\ln C_{t-n-1} - \ln C_{t-n}]) \qquad (6)$$

Where z is between 0 and 1.

Substituting for C_t^* in eq. (6), we get

$$\begin{aligned} \ln C_t - \ln C_{t-1} = {} & zw + z f(\ln P_t, \ln P_{t-1} \ldots \ln P_{t-n}) - z\ln C_{t-1} \\ & + f([\ln C_{t-1} - \ln C_{t-2}] \ldots [\ln C_{t-n-1} - \ln C_{t-n}]) \end{aligned} \qquad (7)$$

Eq. (5) contains an undefined sequence of lagged dependent variables to capture the unstable short term behaviour of capital investment that has been widely observed in business cycle studies. These oscillatory effects are presumed to die out, i.e., it is anticipated that the sum of any significant coefficients on these lagged dependent variables should be less than unity.

Eq. (7) is a very 'sparse' explanation of the capital stock. The only explanatory variable is the price of energy. Without it, there is no partial adjustment and the capital stock follows an oscillating random walk (with drift if there is a significant constant term). Up until the early 19th Century it is likely that the capital stock did, indeed, follow something like a random walk. It was an economy dominated by labour and animal power, fuelled by food. The dramatic game shifter was fossil fuel deployment and the tendency for energy price to fall, resulting in non-random walk behaviour in the case of the capital stock.

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[10] This formulation is similar to the 'capital stock adjustment principle' (Matthews (1959)), not in a cyclical context where GDP is the main independent variable, but operative over the much longer time scale relevant to economic growth.

Partial adjustment specifications commonly include the contemporaneous value of the driving variable. In eq. (6), an unspecified set of lagged prices is included. This implies a double lagging effect. It may take a long time for an energy price to begin to affect the capital stock and a further period before the full effect is felt. Thus, a fall in energy price initiates plans to expand the capital stock, with the current capital stock only being used more intensively at the lower input price. In the face of uncertainty, such planning can last a long time before significant changes in the aggregate capital stock occur, as discussed by Dixit and Pindyck (1994). Furthermore, these commencements are not uniform, they can occur over a lengthy period. We can have no *a priori* view concerning such lags, it is an empirical matter. However, if our co-evolutionary hypothesis is correct we should find that these price impacts have been large.

The speed at which energy price effects impact on the capital stock depends on the capacity of an economy to transition towards a different energy mix. In the 19th and early 20th century, it took a long time to transition away from all the physical capital associated with human and animal power, fuelled by food, towards physical capital driven by fossil fuels. All those horse drawn vehicles, ploughs, blacksmith's shops using wood and charcoal, water driven mills, etc., had sunk cost characteristics that kept them viable while fossil fuel prices were still high. Add to this habitual behaviour, legal arrangements tailored to old technologies and the action of vested interests and the outcome was a slow transition.

Accepting that ***K*** has not been fixed has important implications for how we interpret ALDM modelling. If the capital stock grows faster than GDP, then eq. (4) tells us that this will *raise* the rate of economic growth – so we should observe no tendency for GDP to go towards a limit. If they both grow at the same rate (at a constant ***Y/nC*** ratio that is less than one) then we shall observe the net diffusion effect following an exponential growth path, reminiscent of the Solow (1956) 'residual growth' finding. If GDP grows faster than the capital stock, the ***Y/nC*** ratio will rise and, when it is unity, the net diffusion effect will be zero. Growth can still occur but it will be 'quantitative' growth driven by growth in energy and labour inputs and likely to be temporary in a state of structural transition.

6. Results

The UK is a good source of historical data relevant to modelling economic growth. It is possible to obtain data set was from 1800 to 2010. However, even though it did not make much difference to the results, Eq. (4) was estimated over the period 1831 – 2010 for two reasons. First, the best and most consistent estimates of GDP, by Maddison (2008a), commence annually in 1830 – data before that year seems to involve annual interpolations of decadal data and, as such, they lack real annual variation.[11] Generally, historical economic data before 1830 tends to be very unreliable, interpolated from very fragmentary observations.[12] Second, historical investigation suggests that around 1830 is close to the take-off of the large scale commercial use of fossil fuels. The first public railway for steam locomotives commenced in 1825, from Stockton to Darlington. This signalled the beginning of the wide use of Trevithick's high pressure steam engine at commercial scale.

It is not possible to have a prior view of as to the lags involved in our model so a simple 'general to specific' elimination method was used to obtain a parsimonious representation of the lag structures for each variable. Also, given that there is a significant literature on the direction of causation between energy and GDP, we conducted Granger causality tests and the results are reported in Table 1. The hypothesis that causation runs from energy to GDP, both in levels and rates of change, is strongly supported, in line with the literature reviewed by Stern (2011). [13]

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[11] Irish independence shifted population and GDP time series for the UK in the Maddison data. The impact of this was checked in the modeling and found not to be a problem.

[12] There has been considerable controversy concerning the reliability of data used by 'cliometricians' prior to 1830. See, For example, Allen (2008)

[13] Note that the total energy consumption data used in the modeling was for England and Wales, rather than the UK. So there is an implicit assumption that there is a fixed ratio between the two. Examination of Scottish and UK population statistics suggested that England and Wales, indeed, is a good proxy, especially when it is the rate of growth of total energy consumption that is the explanatory variable used in the modeling.

Table 1
Pair-wise Granger Causality Tests

Sample: 1800 2010, Lags 6

Null Hypothesis:	Obs.	F-Statistic	Probability
E does not Granger Cause Y	205	1.17729	0.32004
Y does not Granger Cause E		2.61405	0.01853

Null Hypothesis:	Obs.	F-Statistic	Probability
$\ln E$ does not Granger Cause $\ln Y$	205	1.75826	0.10968
$\ln Y$ does not Granger Cause $\ln E$		4.51570	0.00026

Null Hypothesis:	Obs.	F-Statistic	Probability
$\ln E_t - \ln E_{t-1}$ does not Granger Cause $\ln Y_t - \ln Y_{t-1}$	204	1.06611	0.38437
$\ln Y_t - \ln Y_{t-1}$ does not Granger Cause $\ln E_t - \ln E_{t-1}$		4.06387	0.00074

Table 2
OLS Estimates of Eq. (4): 1831-2010

Dependent Variable: $[\ln Y_t - \ln Y_{t-1}]$

Included observations: 180

	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.037267	0.005441	6.848969	0.0000
e_t	0.144388	0.029494	4.895454	0.0000
e_{t-1}	0.135865	0.032886	4.131336	0.0001
e_{t-3}	0.053772	0.026907	1.998448	0.0472
e_{t-4}	-0.040560	0.024227	-1.674138	0.0959
h_t	0.653469	0.072939	8.959161	0.0000
h_{t-1}	-0.159623	0.076410	-2.089044	0.0382
$[Y/C]_{t-1}$	-0.002641	0.000576	-4.582648	0.0000

R-squared	0.566438		
Adjusted R-squared	0.548793		
F-statistic	32.10192	Durbin-Watson	1.845354

The general to specific result for Eq. (4) is reported in Table 2. It is a very strong result for a time series specification using first differenced data. The recursive least squares results reported in Fig. 13 show a strong tendency for the parameter estimates to be very stable as the sample size is increased. As early as 1925, all of the parameters become very stable.

Fig. 12
Actual to Predicted Chart
OLS Estimates of Eq. (4): 1831-2010

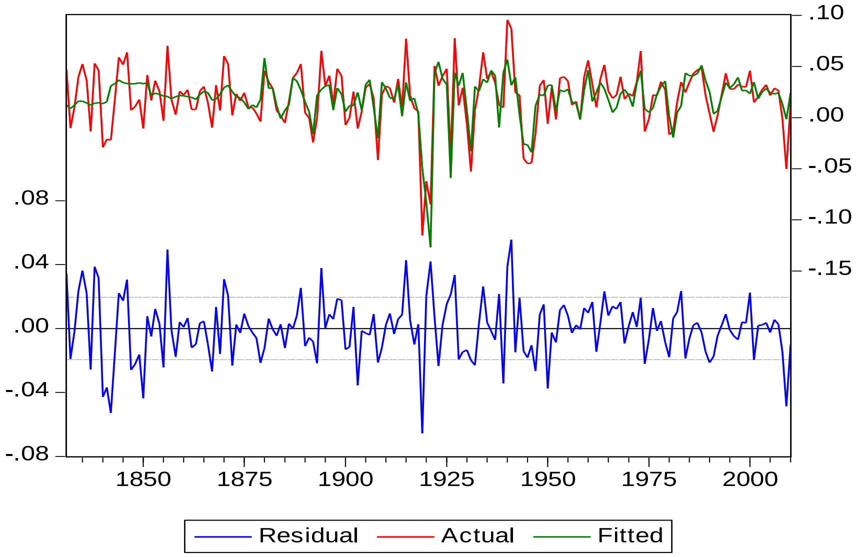
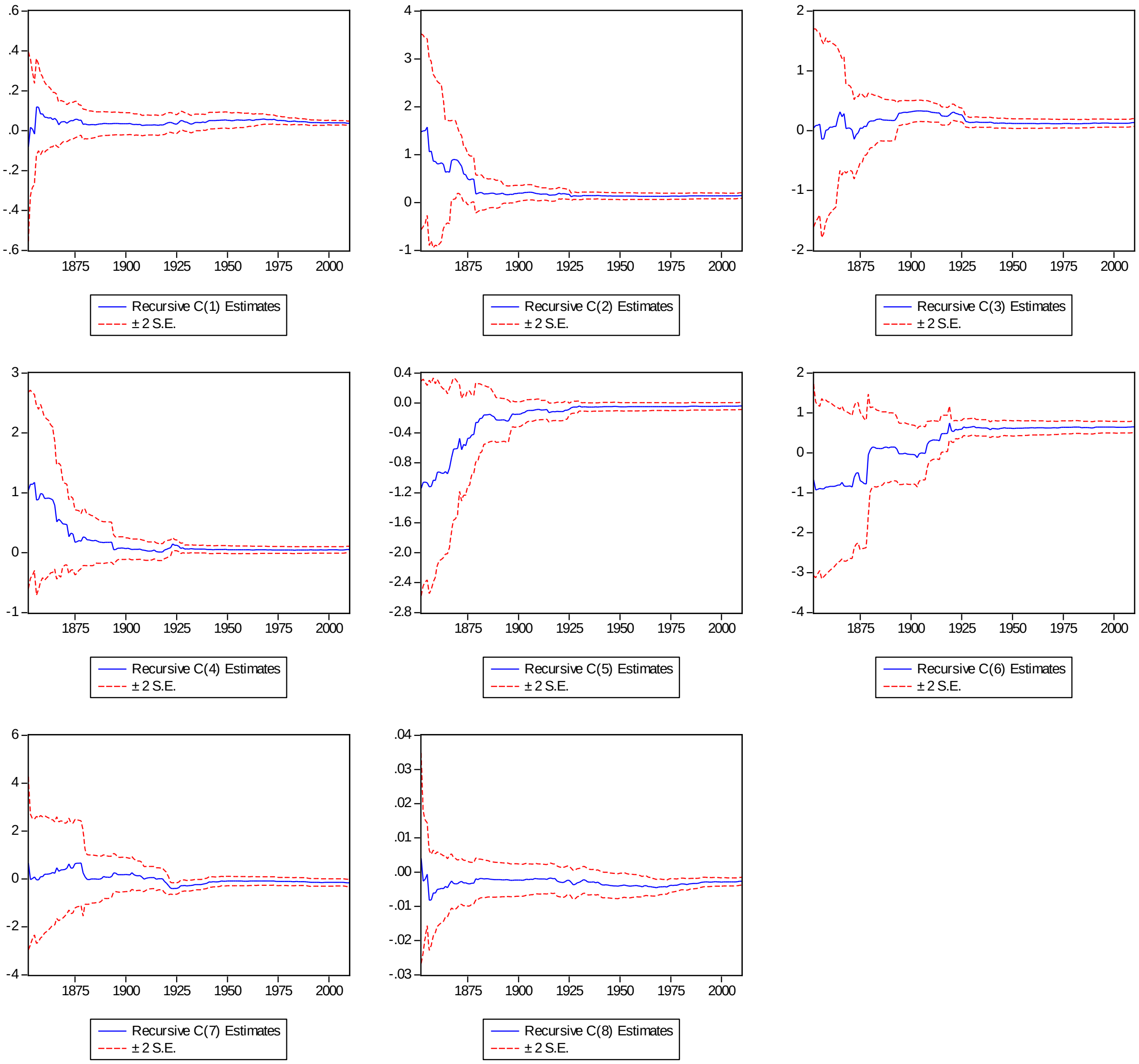


Fig. 13
RLS Parameter Plots
Eq. (4): 1831-2010



The actual-to-predicted graph in Fig 12 shows that there were some significant outlier years. Historical investigation indicated that dummies for 1840-42, 1856, 1919, 1941 and 2009 were all warranted. The model was re-estimated using these five dummies.

Table 3
OLS Estimates of Eq. (4): 1831-2010
With Dummy Variables

Dependent Variable: ***$[\ln Y_t - \ln Y_{t-1}]$***

Included observations: 180

	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.034126	0.004766	7.160657	0.0000
e_t	0.134687	0.025467	5.288790	0.0000
e_{t-1}	0.111600	0.029043	3.842526	0.0002
e_{t-2}	0.038818	0.023329	1.663946	0.0980
e_{t-4}	-0.046004	0.020811	-2.210542	0.0284
h_t	0.601287	0.063988	9.396904	0.0000
h_{t-1}	-0.137659	0.068091	-2.021710	0.0448
$[Y/C]_{t-1}$	-0.002120	0.000508	-4.172147	0.0000
DUM1840-42	-0.045663	0.009968	-4.581069	0.0000
DUM1856	0.048665	0.016863	2.885877	0.0044
DUM1919	-0.073966	0.017723	-4.173511	0.0000
DUM1941	0.055782	0.017163	3.250203	0.0014
DUM2009	-0.050707	0.017110	-2.963586	0.0035
R-squared	0.690494			
Adjusted R-squared	0.668254			
F-statistic	31.04749	Durbin-Watson		1.913932

The results in Table 3 using dummy variables are quite similar to those without. The RLS results (in Fig. 14) again reveal strong parameter stability (the sample was stopped at 2008 to permit RLS testing to start in the 1940s). The Recursive residuals are also reported in Figure 15.

Fig. 14
RLS Parameter Plots
Eq. (4): 1831-2008 with Dummy Variables

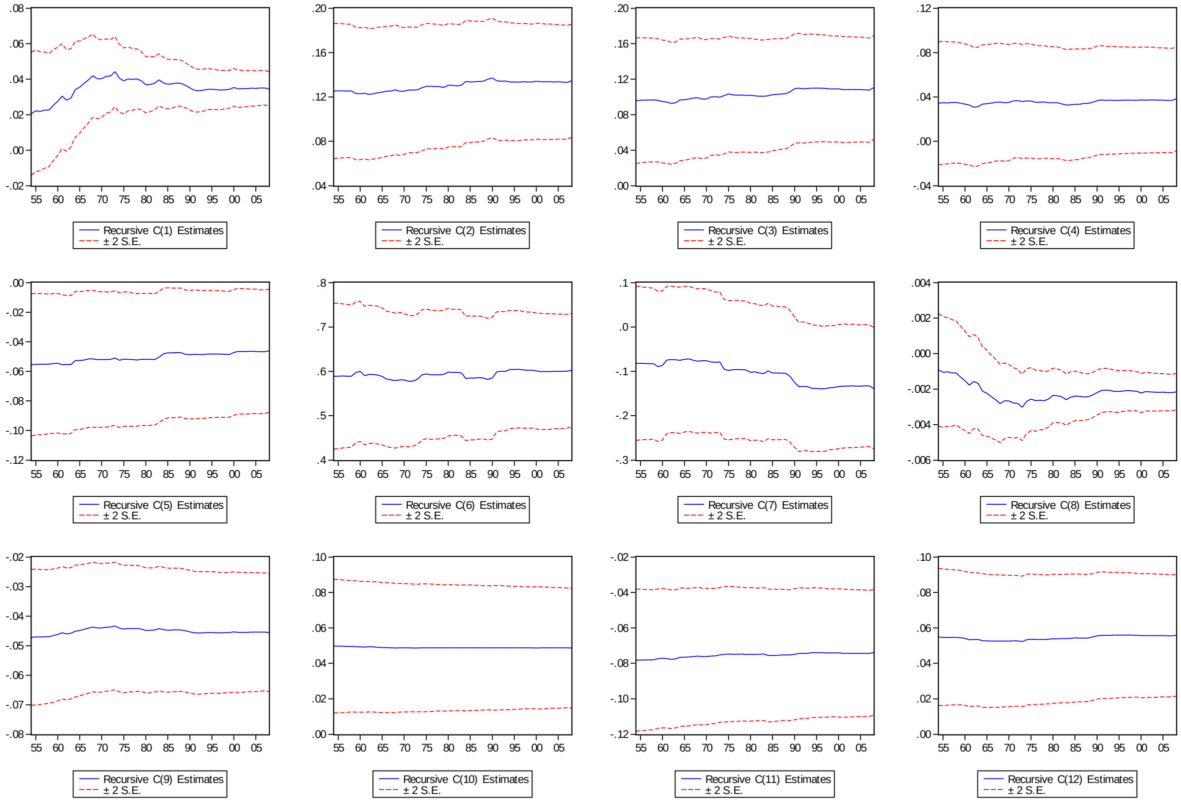
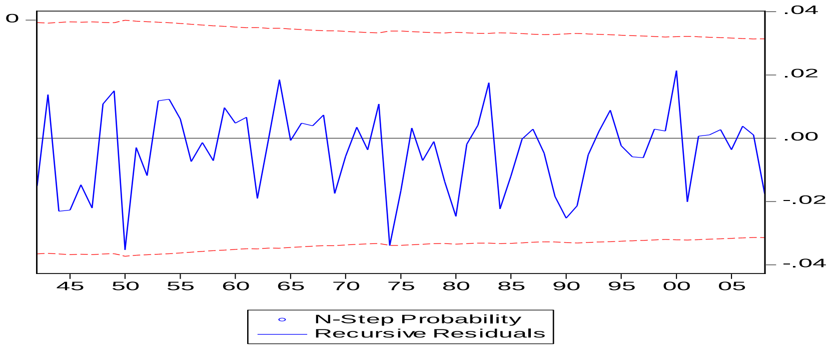


Fig. 15
RLS Plot of Recursive Residuals
Eq. (4): 1831-2008 with Dummy Variables



Because of the interdependent nature of GDP and energy, the specification was re-estimated using Two Stage Least Squares (TSLS). The instrumental variables were chosen on the basis of a well-determined estimated logistic model of the growth in energy consumption which was found to be heavily dependent on the rate of population growth (***pop***), as well as GDP growth. All significant lags, identified using 'general to specific' elimination of variables, were included, plus the level of energy consumption lagged one year, which was significant and negatively signed, supporting the hypothesis that a logistic limit on energy consumption growth was present. As can be seen in Table 4, accounting for the potential endogeneity of the growth in energy consumption does not change the result very much. The cumulative elasticity estimate on energy consumption growth falls from about 0.25 to 0.23.

Table 4
TSLS Estimates of Eq. (4): 1831-2010
With Dummy Variables

Dependent Variable: $[lnY_t - lnY_{t-1}]$

Included observations: 180

Instrument list: e_{t-1}, e_{t-2}, e_{t-4}, h_{t-1}, h_{t-1}, ***DUM184042, DUM1856, DUM1919, DUM1941, DUM2009***, pop_t, pop_{t-1}, pop_{t-2}, pop_{t-5}, pop_{t-6}, pop_{t-7}, E_{t-1}

	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.034018	0.004780	7.116672	0.0000
e_t	0.126508	0.036709	3.446278	0.0007
e_{t-1}	0.107289	0.032219	3.330001	0.0011
e_{t-2}	0.037197	0.023917	1.555240	0.1218
e_{t-4}	-0.047060	0.021095	-2.230812	0.0270
h_t	0.608805	0.068463	8.892455	0.0000
h_{t-1}	-0.135553	0.068451	-1.980306	0.0493
$[Y/C]_{t-1}$	-0.002094	0.000515	-4.066070	0.0001
DUM1840-42	-0.045615	0.009972	-4.574255	0.0000
DUM1856	0.048741	0.016870	2.889158	0.0044
DUM1919	-0.074414	0.017787	-4.183565	0.0000
DUM1941	0.055550	0.017184	3.232592	0.0015
DUM2009	-0.051132	0.017170	-2.977921	0.0033
R-squared	0.690303			
Adjusted R-squared	0.668049			
F-statistic	29.68856	Durbin-Watson		1.913068

It is noticeable in the actual-to-predicted plots in Fig. 12 that the fit becomes tighter around 1880, which is about the time when the energy to GDP ratio stopped rising and begins its secular fall (see Fig. 9). So it seemed sensible to re-estimate to model from 1880 on to check its stability.

Table 5
OLS Estimates of Eq. (4): 1880-2010
With Dummy Variables

Dependent Variable: $[\ln Y_t - \ln Y_{t-1}]$

Included observations: 131

	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.036646	0.004868	7.527659	0.0000
e_t	0.131242	0.024809	5.290049	0.0000
e_{t-1}	0.106139	0.028235	3.759053	0.0003
e_{t-2}	0.034617	0.022458	1.541388	0.1259
e_{t-4}	-0.041480	0.019837	-2.090984	0.0386
h_t	0.604941	0.060700	9.966131	0.0000
h_{t-1}	-0.121529	0.064166	-1.893979	0.0606
$[Y/C]_{t-1}$	-0.002399	0.000549	-4.372193	0.0000
DUM1919	-0.073623	0.016616	-4.430906	0.0000
DUM1941	0.055093	0.016089	3.424289	0.0008
DUM2009	-0.052082	0.016013	-3.252397	0.0015
R-squared	0.762682			
Adjusted R-squared	0.742906			
F-statistic	38.56509	Durbin-Watson stat		1.954929

The results in Table 5 are very similar to those using the full sample. Again, the RLS results, reported in Figures 16 and 17, indicate strong parameter stability.

Fig. 16
RLS Parameter Plots
Eq. (4): 1880-2008 with Dummy Variables

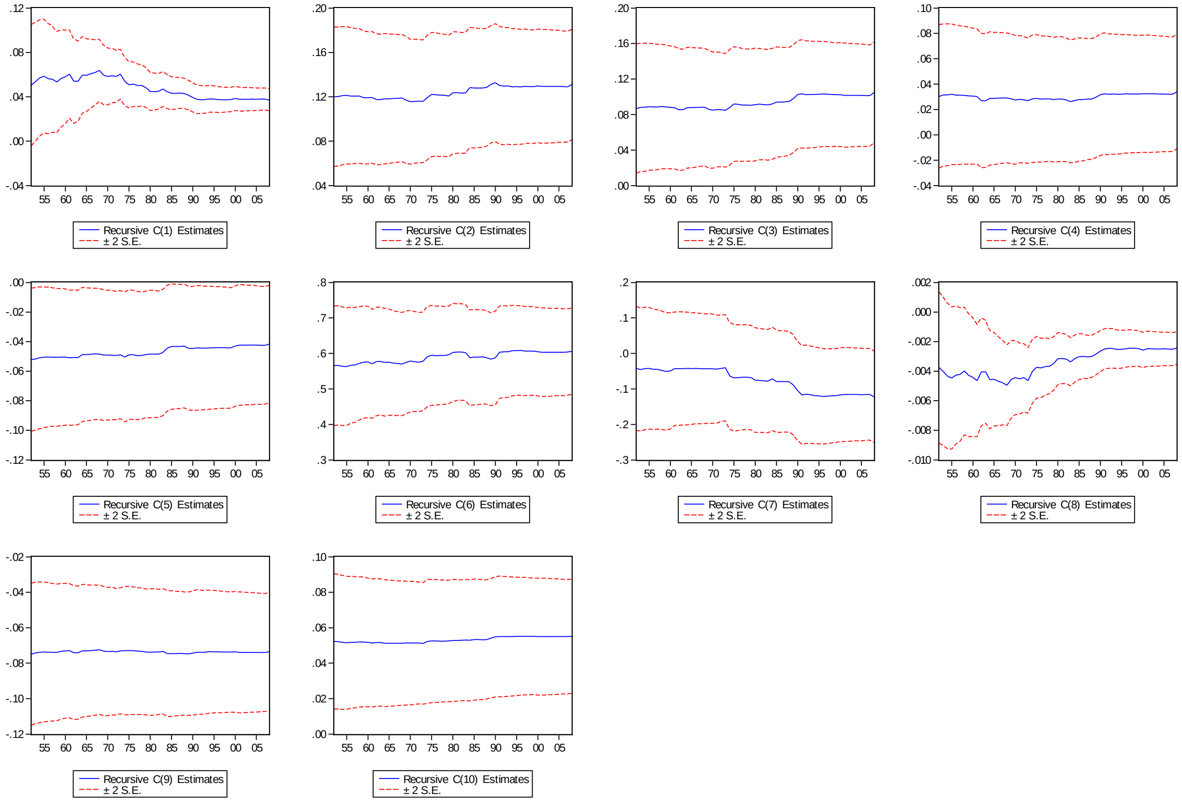
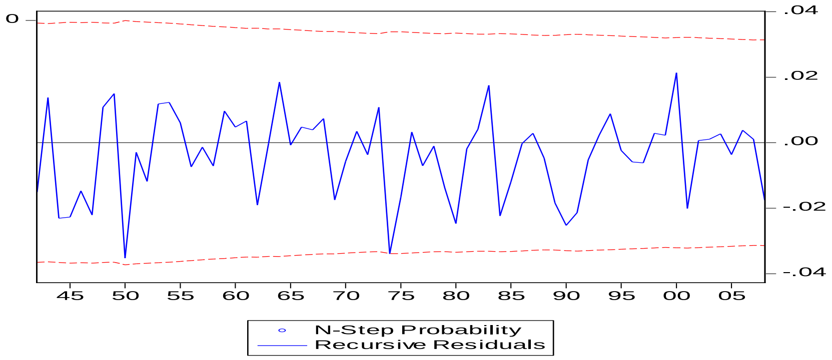


Fig. 17
RLS Plot of Recursive Residuals
Eq. (4): 1880-2008 with Dummy Variables



The final test conducted was to estimate the model over the more recent post World War Two period, when GDP growth was at its highest. Being a much smaller sample, the expectation was that the previously estimated lag structure would be less well-defined and that is what was found Again the sample was truncated at 2008, yielding a specification with no dummy variables, to permit RLS estimation.

Table 6
OLS Estimates of Eq. (4): 1947-2010

Dependent Variable: $[\ln Y_t - \ln Y_{t-1}]$

Included observations: 62

	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.037473	0.006302	5.945983	0.0000
e_t	0.209744	0.063641	3.295768	0.0017
e_{t-1}	0.105513	0.063568	1.659832	0.1025
h_t	0.638838	0.103292	6.184796	0.0000
h_{t-1}	-0.213417	0.094069	-2.268729	0.0272
$[Y/C]_{t-1}$	-0.002590	0.000977	-2.651783	0.0104
R-squared	0.543873			
Adjusted R-squared	0.503147			
F-statistic	13.35456	Durbin-Watson		1.922996

Once again, the results in Table 6 using this recent sample are remarkably similar to those using the full sample. Parameter stability remains very strong, as reported in Figure 18 and the fit is excellent (Fig. 19).

So, overall, very strong support has been found for the super-radical innovation diffusion hypothesis concerning economic growth in the UK, as specified in Eq. (4). Coefficient (elasticity) estimates were obtained by summing the coefficients on the contemporaneous and each significant lagged variable in all three sample periods. These are recorded in Table 7 where derived estimates for ***n*** are also included.

Fig. 18
RLS Parameter Plots
Eq. (4): 1947-2008

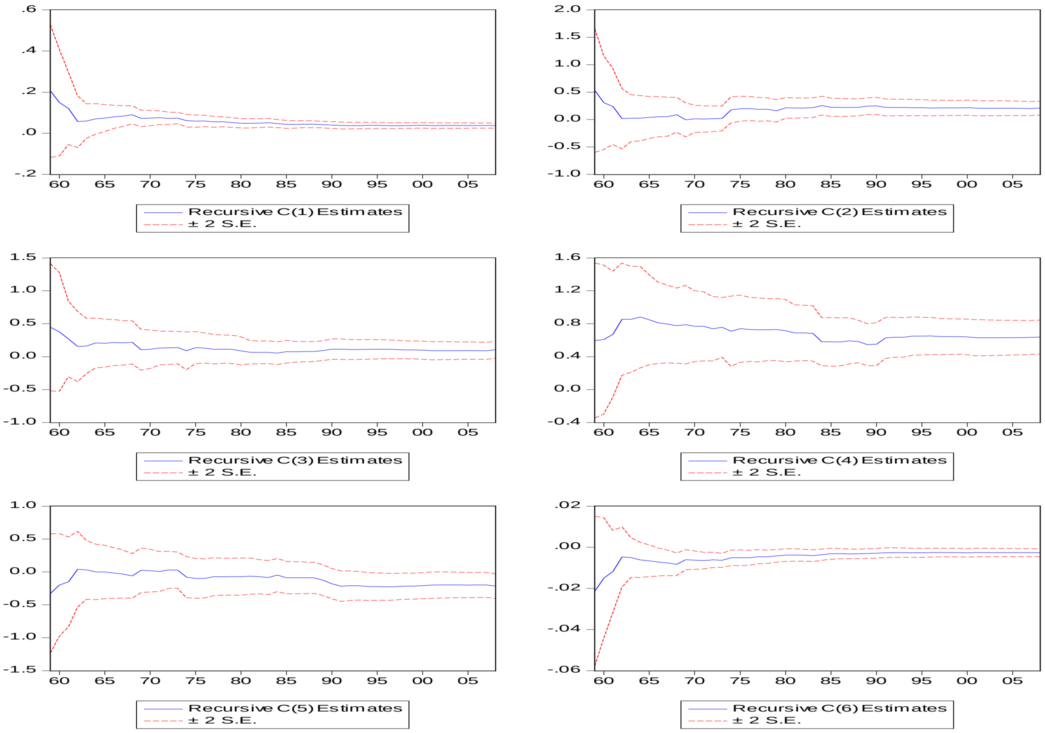


Fig. 19
Actual to Predicted Chart
OLS Eq. (4): 1947-2008

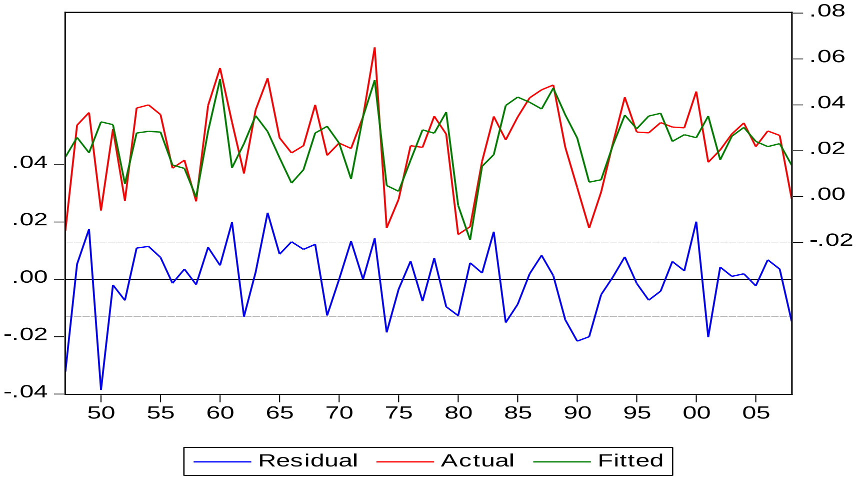


Table 7

Cumulated Coefficient Estimates in Three Samples

Coefficient	1831 – 2010	1880 -2010	1947 - 2010
a	0.037267	0.036646	0.037473
b	0.245	0.230	0.225
g	0.494	0.483	0.425
a/n	-0.00264	-0.00240	-0.00259
n	14.1109	15.2755	14.4683

It is clear from Table 7 that we are dealing with a highly stable model in which the estimated coefficients are all very significant and correctly signed.[14] The summed coefficient on energy consumption is about 0.24 and that on labour hours about 0.49. Although the former estimated coefficient is smaller, it contributed more to GDP growth than the latter which was related more to fluctuations in GDP growth. The sum of the two estimated coefficients is 0.73 so no support has been provided for the existence of a Cobb Douglas production function. Instead, the existence of a logistic diffusion process is supported with a strongly significant negative sign on the $[Y/C]_{t-1}$ estimated coefficient (***a/n***). When ***n*** was derived, using the estimate of ***a*** in Table 7, it was also found to be stable.

Although there is strong support for the existence of a logistic process, we do not observe a sigmoid curve. This is because of the large rise in the ***K*** limit due to the constantly rising embodied knowledge contained in a capital stock specifically designed to obtain and use energy. We can examine this impact over time by using our estimate of ***n*** to see how ***K*** has moved relative to GDP over the sample period. We saw in Fig. 5 how dramatic the rise in the capital stock has been, particularly, since World War Two. Our ***K*** limit is the capital stock, ***C***, times ***n*** and, thus, assumes the same growth path in Fig. 20.

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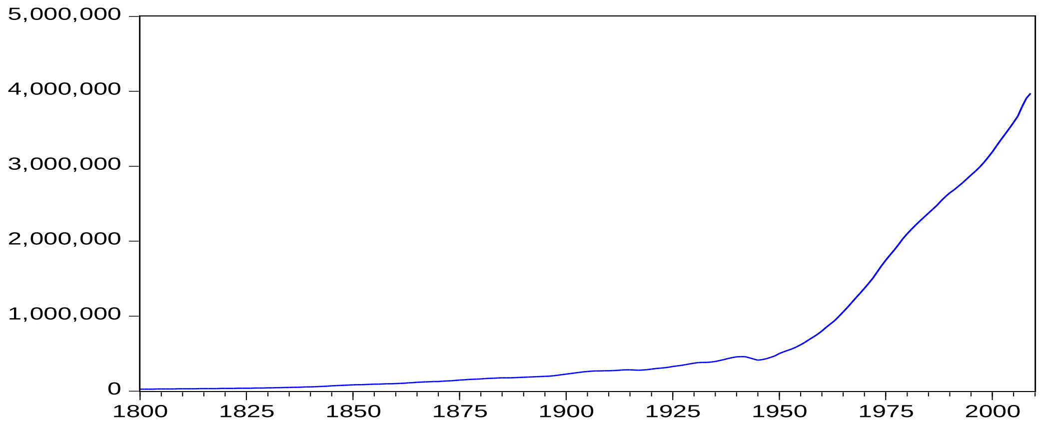
[14] It should be borne in mind that the presence of measurement error in explanatory variables biases estimated coefficients downwards. This is likely to be the case when using long series of annual data. However, it is not possible to assess the magnitude of such bias except to note that the observed stability of estimated coefficients in different sample periods suggest that such bias is likely to be small.

Fig. 20

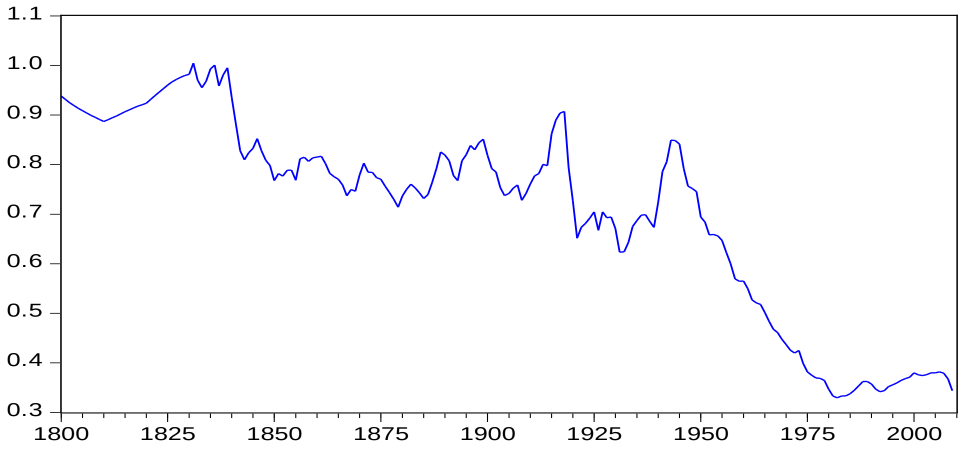
The Estimated K-Limit



It is clear that ***K*** rose only modestly up to World War Two but has risen much faster since then in an era dominated by oil and the specialization of coal in electricity generation. In Fig 21, we provide a chart of the ratio of GDP to ***K***, i.e., ***Y/nC***, over the 1800-2010 period.

Fig. 21

The Estimated Ratio of GDP to K



If we use the approximate pre-1830 data on GDP, we can see that, prior to 1840, the GDP to ***K*** ratio rose up to unity which indicates that the previous innovation diffusion process, sometimes referred to as the 'first industrial revolution,' associated with a capital stock largely driven by solar and organic sources of energy, had come to an end. From 1840 on, the dramatic transition to the fossil fuel driven economy had commenced and we observe the ratio falling along an oscillating path, providing a boost to economic growth with the largest temporary reversals occurring during the two world wars. The sharp reduction in the post-World War Two era came to an end after the energy shocks of the 1970s, but the ratio, being far below unity, still made a large positive contribution to economic growth via the net diffusion effect. A steady ratio, at any level less than unity, however, implies that the net diffusion effect is approximately exponential and that has been the case in the UK for the three decades up to 2010.

Prior to the World War Two the ***K*** limit was only about 25% above the prevailing level of GDP, on average. This is the niche made available for GDP growth by the prevailing capital stock when used in all manner of innovative projects. By 2008, the ***K*** limit was about 170% higher than the prevailing level of GDP. The UK, a mature, post-industrial economy, thus, still has massive growth potential based upon its past history, even without a further increase in the size of its net capital stock. Remarkable as such a finding is, it is not out of line with the post-war growth performance of the UK. Such an increase in real GDP occurred in only a few decades. The massive shift to service sector activity has allowed ***K*** to run well ahead of GDP. This has been particularly marked in the era of computers and associated innovations in data storage and communication. However the behaviour of the recessionary UK economy after 2008 was characterized by near zero growth plus negative growth in labour hours and energy consumption. But, from a historical perspective and the findings of the modelling here, this seems to be only a temporary state. From a longer term perspective, the UK economy seems to be increasing knowledge at a fast enough rate to not require further increases in energy consumption. This is what happened with the other core flow, labour time, in the early 20th Century. This, of course, means that economic growth is much more strongly dependent on growth in the application of knowledge than it was a century ago. Whether this situation can be sustained depends on future movements in the net capital stock which is still largely driven by electricity and distillates produced from fossil fuels.

It has been argued that economic growth has been a result of the large scale exploitation of fossil fuels and that this was due to the availability of energy that was much cheaper per joule than in the past, making previously uneconomic capital good projects viable. This hypothesis, captured in Eq. (7), was tested using 135 years of data.[15]

Table 8

OLS Results for Eq. (7): 1875-2009

Dependent Variable**:**	$lnC_t - lnC_{t-1}$
Included observations:	135 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Constant	0.436139	0.082242	5.303090	0.0000
lnC_{t-1}	-0.018552	0.003568	-5.199728	0.0000
lnP_{t-15}	-0.009184	0.003579	-2.565684	0.0114
lnP_{t-19}	-0.014246	0.004004	-3.557822	0.0005
lnP_{t-22}	-0.011319	0.004146	-2.730207	0.0072
$lnC_{t-1} - lnC_{t-2}$	1.067002	0.079348	13.447120	0.0000
$lnC_{t-2} - lnC_{t-3}$	-0.302082	0.080469	-3.753988	0.0003
$lnC_{t-5} - lnC_{t-6}$	-0.266298	0.080409	-3.311806	0.0012
$lnC_{t-6} - lnC_{t-7}$	0.205327	0.075113	2.733594	0.0072

R-squared	0.873888
Adjusted R-squared	0.866006
F-statistic	110.8714
Durbin-Watson	1.843841

Breusch-Godfrey Serial Correlation LM Test:

F-statistic	1.830523	Prob. F(2,126)	0.1646
Obs*R-squared	3.868266	Prob. Chi-Square(2)	0.1445

The results reported in Table 8 confirm the hypothesis that there is strong inertia in the capital stock, but that it is not a random walk, and that there is a strong negative impact of energy prices. As expected, this impact operates with a very long lag. Only after 15 years is there a statistically significant effect on the capital stock and this effect continues for another 7 years. The cumulative long term price elasticity is found to be high, at -1.87. So these findings suggest that movements in energy prices have

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[15] Energy prices are sourced from Fouquet (2009). It is inadvisable to go further back in history than 1850 because earlier estimates of energy prices, based upon very fragmentary, infrequent and localized data, are notoriously unreliable.

been of key importance in determining long term economic growth possibilities in the UK over the past one and a half centuries.

What are the future implications of this evidence? The International Energy Agency has predicted that the real price of electricity globally is likely to rise by about 15% over the next decade. It is likely that petrol and diesel will rise by more. If we take 15% as a conservative estimate of the overall energy price rise to industrial consumers, and this rise is sustained, our model predicts that the capital stock, at the prevailing state of technology, will eventually decline by 28.5% in the UK case. This decline would not be sudden, taking 15 years to have a significant effect which would be spread over another 7 years. However, the ultimate impact of the lower ***K***-limit on GDP growth would be large. Offsetting this would require a major transition to cheaper energy sources and/or radical breakthroughs in the efficiency of energy use, i.e., raising ***K*** for any given energy-using net capital stock. We know that this has already been happening but it would have to accelerate if energy prices rise significantly and permanently. In many ways, this is a race against time because it can take decades to develop technologies that can be used to drive radical innovation in capital goods and associated methods of using them.

7. Conclusion

In this paper, the hypothesis has been offered that the explosive growth that has been experienced since the early/mid-19th Century was due to the large scale exploitation and use of fossil fuels via the growth of knowledge embedded in a capital stock designed for this purpose. Thus, the energy-driven capital stock is viewed as the key repository of embedded knowledge that made high economic growth possible. Strong empirical support for this co-evolutionary hypothesis has been found in a very well-determined and stable logistic diffusion explanation of economic growth in the case of the UK. The results show that the use of new knowledge has led to very significant economies in the use of labour time and, in recent decades, the same has been occurring with energy consumption. GDP in the UK continues to have a long term growth rate that is approximately exponential, but inputs of both labour time and energy have stabilized. Evidence was also found that movements in energy prices have a large impact upon the size of the capital stock, operative with a long delay.

These findings pose a strong challenge to models of economic growth based upon neoclassical growth theory. In particular, the notion of ‘equilibrium’ growth seems to make little sense when economic evolution, characterized by speeding and slowing structural change, is going on.

The findings in the paper pose a serious dilemma for the UK and, by implication, for the World as a whole. First of all, the future GDP growth possibilities of the UK seem to be very significant. But these findings may be misleading. In the modelling, no account has been taken of the negative externalities associated with economic growth – pollution, congestion, environmental destruction, etc. These are all visibly impacting on the UK, as well as other countries. So it may well be that, even though GDP grows strongly, a rapidly increasing proportion of this growth, and the capital stock utilized, will be devoted to measures that combat such negative externalities. Thus, ‘externality corrected’ GDP per capita could fall, even when GDP is rising. Dyke (1990) referred to this as a state where an ‘entropy debt’ is being paid in order for an economic system to survive.

Secondly, if energy prices are, indeed, shifting up to a higher level, because of the higher costs of delivering more difficult to access fossil fuels, combined with higher costs to access alternative energy sources that are in the early stage of development, then, with a lag of over a decade, there will be a slowly rising but strongly negative impact upon the size of the capital stock. If the capital stock falls, then growth will tend towards a zero limit, in line with our super-radical innovation diffusion curve findings.

Dealing with entropy debt and higher energy prices would, most likely, have severe socio-political repercussions. It has been argued here that significant difficulties were previously encountered in the transition from a solar/organic to a fossil fuel economy in Europe. Already, we are seeing reductions in employment in parts of the British service sector as trade and commerce shift to the internet and reliance on imports of both energy and manufactured goods increases. A different kind of economy is taking shape, as happened in the early 20th Century, but it is not clear what the exact nature of this transition is and what its consequences will be. This is a dangerous state to be in. Again, it was Dyke (1990) who explained that, if an economic system does not address its entropy debt problem in an adaptive manner, it is in danger of contraction or even collapse.

In times of socio-political conflict, when vested interests instinctively defend their territories, the capital stock can become underutilized or obsolete. This is what happened in the Great Depression. Furthermore, political conflicts, both civil and international, can lead to destruction and the premature wearing out of parts of the capital stock, often leaving a previously viable society in relative poverty. However, less dramatic events can also cause the capital stock to diminish. Rapidly skyrocketing energy prices, perhaps because of an international political conflict, can induce political destabilization. If inflation occurs because of public debt problems, as happened in Germany in the 1920s when there was hyperinflation and currency collapse, this can rapidly diminish the capital stock because of a lack of net or replacement capital investment and the accelerating degradation of plant and equipment. In circumstances where uncertainty causes the financial markets and the banking system to function badly, the capacity limit to which GDP tends toward can shrink for any given capital stock. In other words, the knowledge gradient diminishes in a manner comparable to entropy in a physical system.

When the knowledge gradient rises so fast that it overwhelms the natural tendency for the growth of a system to tend to a logistic limit, there is a tendency for such a system to ‘stall’ just as an aeroplane does when it climbs too steeply after take-off. We see this in, for example, the cumulative growth of interdependent, optimistic beliefs in a stock market bubble. Such bubbles don’t burst at a logistic limit but do so when price growth is high and the realization suddenly dawns that the cumulated ‘knowledge’ embedded in stock prices is inconsistent with the state of the real economy. In the case of economic growth, the potential inconsistency is with the capacity of the natural environment to endure ever higher levels of GDP using a larger and larger stock of capital goods. In the past, some environmental disasters have occurred because, environmental exploitation, such as agriculture, was not managed in a way that allowed it to grow steadily to a sustainable limit. Instead, growth was too rapid and, thus, the system became unable to cope with exogenous shocks when they came along. The

'Dustbowl' experience in the US in the interwar years is a good example, as are some of the cases discussed in Tainter (1988).

So the picture that has been provided of British economic growth is one of spectacular past success, impressive possibilities and serious dangers in the future. To what extent can we see parallels in the global economy? As was noted, this is not easy to assess because all countries are in different cultural, social, political and institutional circumstances.[16] However, based upon Angus Maddison's data, Global GDP seems to have taken off about half a century after the UK with the same explosive tendency (Maddison (2008b)). Undoubtedly, the co-evolutionary process of fossil fuel exploitation and the growth of embedded knowledge in the capital stock has also been the key driver of global growth. But there are early indications that cheaply available sources of oil and coal globally are beginning to run out.

Nonetheless, the super-radical innovation diffusion process may not have run its full course yet. Globally, the discovery and exploitation of large stores of unconventional natural gas in shale and coal seams is beginning to compensate for diminishing stocks of cheap oil and may mitigate the tendency for energy prices to rise. So the total energy consumption trajectory may well have a third sub-logistic segment that keeps economic growth going at a brisk pace. However, the exploitation of these new fossil fuel reserves will do little to diminish the threat that cumulating negative externalities pose in a World that seems to be heading towards nine billion people by 2040. Indeed, the provision of new supplies of unconventional gas may well delay an orderly transition to renewable energy at low cost with possibly severe socio-political and environmental consequences. Since all this lies in the domain of radical uncertainty and, thus, beyond the compass of simple modelling exercises using historical data, we can only speculate about such possibilities and the responses that different countries might make to the large structural changes that lie ahead.

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[16] See Gordon (2012) for discussion, using a different perspective, of the prospects of future growth in what is currently the World's leading economy, the United States.

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C: Total UK capital stock (million at 1990 prices), from Madsen *et al* (2010) with updates.

E: Total UK energy index of consumption in petajoules, not including food. From Warde, P., *Energy consumption in England and Wales, 1560-2000*, CNR, (2007) with updates from the UK National Statistical Office

H: Total hours worked in UK (millions). From Madsen et al (2010) with updates

P: Average UK price of energy (£ (in 2000 prices) per toe. From Fouquet (2008) with updates

POP: UK Population (‘000) From Maddison (2008a) with updates

Y: UK Real GDP (million 1990 International Geary-Khamis dollars). From Maddison (2008a), with updates.