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REGULAR ARTICLE

Energy, knowledge and economic growth

John Foster

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 is viewed as the outcome autocatalytic co-evolution of energy use and the application of new knowledge associated with energy use. It is argued that models of economic growth should be built from innovation diffusion processes, unfolding in history, rather than from a timeless aggregate production function. 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' following the industrial deployment of fossil fuels on a large scale in the 19th Century. Also, the evidence suggests that large and sustained movements in energy prices have had a very significant long term role to play.

Keywords Macroeconomics · Economic growth · Economic development · Economic evolution · Innovation diffusion · Energy · Fossil fuels · Capital stock

JEL Classifications B52 · E11 · O11 · O33 · O40 · Q32 · Q43

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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).

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 perspective on growth 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 wide adoption in the literature on economic growth. Solow (1957) famously found, using neoclassical economic theory and a Cobb-Douglas production function, that about 80 % of economic growth was unexplained by the growth of capital and labour when he modelled 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 neoclassical micro-analytical perspective on economic behaviour as had Solow, with all its attendant problems (Fine 2000). 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.[1] 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 (2007) recently pointed out, 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).

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[1] 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.

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 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 universally true that populations of species in organic-based systems that exploit a free energy source follow a sigmoid growth path to a capacity limit. 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 (Dopfer 2006). 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 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 evolutionary macroeconomic methodology, which replaces the production function with the innovation diffusion curve at the core of growth modelling, is designed to discover simple aggregate representations of the behaviour of complex economic systems that are not based upon ‘simplistic’ neoclassical micro- foundations (Foster 2005), as is the case in the Solow model and variants built upon it, but on historical tendencies that are observed when knowledge cumulates and there is a source of energy available to allow growth in economic activity to occur. Here it is 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. (2010) and Stern and Kander (2012) where economic growth is also modelled using very long samples of time series data. However, the methodology adopted in both studies is in sharp contrast to that adopted here. In both, the modelling is constructed on Solow's theoretical foundations.

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, b) 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 that unfolds in historical time. Instead of thinking of economic growth simply as an aggregation of the behaviour of a 'representative agent' engaged in constrained optimization in a timeless setting, it is viewed as being initiated through entrepreneurship, innovation and the adoption of new skills (Baumol 2002).[2] Since this involves a great deal of uncertainty, constrained optimization is impossible over long periods (Foster and Metcalfe 2012).

From radical innovations there follow diffusion processes that involve increases in the organized complexity of an economic system. The outcome of much learning-by-doing, incremental innovation and competitive selection, all processes taking place in historical time, is a range of viable economic activities that yield productive processes and products that grow in number, at falling cost. These economic activities are consolidated in effective organizational structures that are 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 is applied when it is feasible but, given the sheer complexity of any networked productive organization, this is very difficult to do in any general way. 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 be built with this historically-based evolutionary economic process at its core, not upon an idealized representation of constrained optimization and a timeless production function.

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[2] It is instructive that Aghion and Howitt (1998), who hijacked the term 'Schumpeterian' for their endogenous growth theorizing, do not even have 'entrepreneur' or 'entrepreneurship' in the index of their 190 page book.

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 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 not just another ‘factor of production.’ It is a magnitude that is the end 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 other kinds of new knowledge can be developed and applied, for example, in organisational innovations and the development of new skills.

The existence of a capital stock makes it possible to apply a flow of non-human energy to generate economic value, as measured by GDP, in excess of that possible by application human effort alone. The capital stock is a durable and multi-use structure which offers the opportunity for many other 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 any productive process in terms of its inputs and outputs, there can be no meaningful ‘equilibrium’ association between them over long periods when structural change is significant.

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 oscillating around a long run equilibrium path. Such a series is wholly dependent upon its past history. Undeterred, proponents of economic theories that predict input-output equilibrium solutions search for ‘co-integration’ between such time series. This, it is argued, provides evidence in support of a ‘long run equilibrium’ relationship between the chosen variables. Often, but not always, an ‘equilibrium correction model,’ is estimated using stationary first-differenced data, plus an equilibrium correction term (commonly the residual error in an estimated co-integrating equation). Interestingly, when a Solow style equilibrium growth equation is estimated with a significant constant term, the latter is usually deemed to represent ‘technical progress’. But, from an equilibrium correction methodological perspective, such an equation has no long run equilibrium solution yet, theoretically, it is still viewed as an ‘equilibrium growth model’. 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.

The evolutionary macroeconomic approach to modelling economic growth starts with complex systems theory which immediately tells us two things. Firstly, all economic systems are, necessarily, dissipative structures, importing free energy and exporting entropy, and, as such, they will grow in the presence of useable energy and the flow of energy is something that we can measure (Brown et al. 2011). Secondly, we also know that an economic system can only become more complex, and, thus, be able to grow, if new knowledge can cumulate and be applied in useful 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 flow of entrepreneurial activities associated with new knowledge. Knowledge is not a stock but, rather, a virtual structure that can be drawn upon by the innovative and the entrepreneurial to generate economic value. We know from innumerable studies of innovation that ‘radical’ applications of new knowledge result in growth until a limit is approached where the innovative niche is filled. Such growth is widely observed to follow a sigmoid ’innovation diffusion curve’ with respect to historical time. As output expands, productivity rises and unit costs fall. 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 to acknowledge 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 mainly physical work, fuelled by a food energy gradient. However, humans in modern times have devised 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 in physio-chemical dissipative structures, the energy gradient available to living organisms is not always exogenous. Following the terminology of Foster (2005), at the 3rd Order of Complexity, humans, almost uniquely, apply non-genetically transmitted creative knowledge to generate economic value and run down energy gradients that have been deliberately accessed. But to get beyond the application of 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 the deliberate exploitation of 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 in the 19th Century.

It follows that, for humans, growth has become heavily dependent upon the creation of what we can label as a ‘knowledge gradient’ that is specifically ‘economic’. 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 (Georgescu-Roegen 1971). The relative cheapness of such energy per joule, compared to the organic and solar sourced energy relied upon previously, offered unrivalled opportunities to accumulate and use 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.

The creation and use of new capital goods has shifted physical work away from human effort to a greater reliance on non-human energy flow. This has involved the construction of a knowledge gradient that could be reduced by historical processes such as: learning-by-doing, in the context of the production and use of new capital goods; incremental technical innovations that made capital goods more productive and diverse in their application; and organizational, institutional and product innovations. A knowledge gradient differs in nature from an 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. Also, the capital goods in which it is embedded can become obsolete as time passes. For example, there is no point in 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 can 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.

3 The super-radical innovation diffusion hypothesis

The hypothesis that is offered here is that the industrial deployment of fossil fuels at scale in the early 19th Century gave rise to a ‘super-radical innovation diffusion process’ that resulted in explosive economic growth. However, 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. The Watt steam engine was a very radical innovation because it both provided an increase in mining productivity and a powerful device to use fossil fuels in a range of applications.

From the 17th Century, on in the United Kingdom, which will be our main focus here, economic growth increased because of changes in the nature of knowledge which also increased 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, recirculate 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.

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

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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.

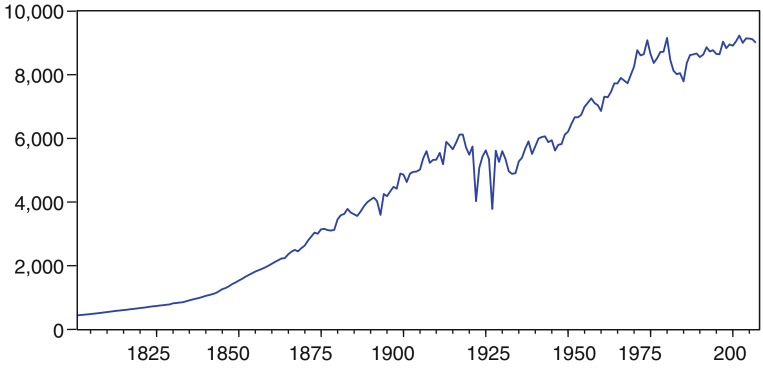

Fig. 1 UK energy consumption 1800–2010 (in Petajoules)

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 the War. Afterwards, 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.

Coal production had peaked in 1913 at around 300 million tons but by 2010 it had fallen to just over 20 million tons. 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 (Fouquet 2008). After the 2nd World 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 what looks like a sigmoid curve for energy (Fig. 1), there was an oil-related 'sub-sigmoid' diffusion curve after the 2nd World War. By the early 21st Century, total energy consumption had plateaued.

Despite the interwar slowdown, the longer term tendency for economic growth to occur at a high and sustained rate was relatively unaffected (Fig. 2). 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 it effectively and in new ways.[5]

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[5] Field (2011) has provided convincing evidence that, in the US case, this resulted in a sharp rise in inventive and innovative behaviour in the 1930s.

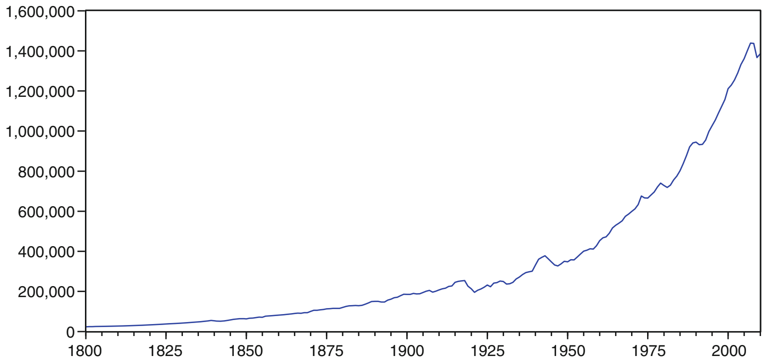

Fig. 2 British real GDP: 1830–2010 (US$ million, 1990 prices)

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.

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. 3, 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 required to design and construct new capital goods, as well as the productive and industrial systems that they operate in and 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 significantly higher than previously.[6] So, the knowledge gradient, built upon knowledge embedded in capital goods, has not been static but has been continually growing. Thus, the 'niche' that GDP could grow into has continually increased.

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 sigmoid growth

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[6] It has been commonly assumed in a number of neoclassically-based 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.

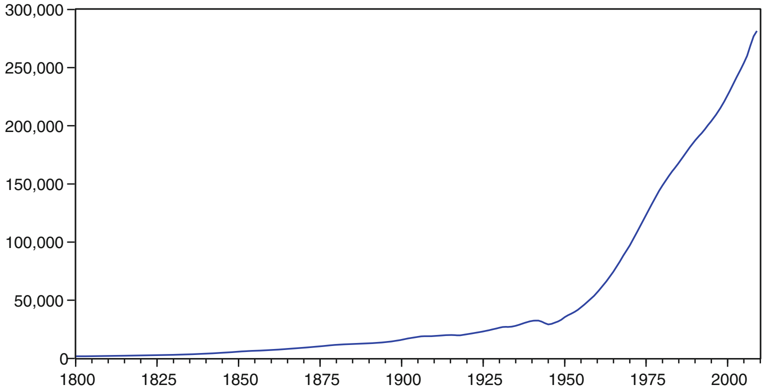

Fig. 3 British net capital stock: 1800–2010 (£Million, 1990 prices)

path. 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 radical innovation diffusion hypothesis for only one, very important country. The United Kingdom was 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 industrial revolution 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. By the early 20th Century, coal energy began to be used in all sectors via electrical power generation. 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

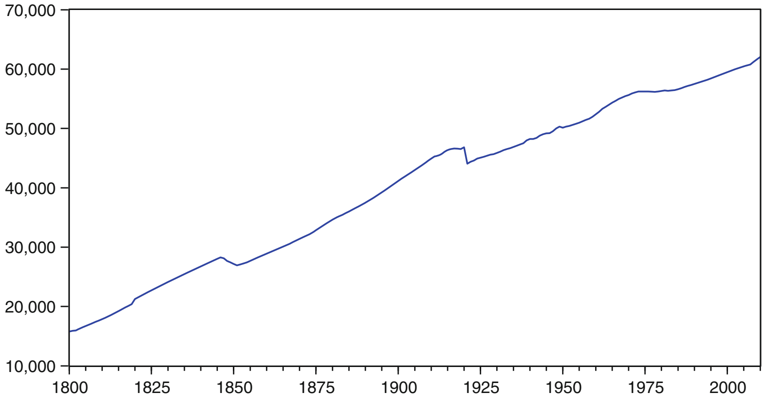

Fig. 4 UK population: 1820–2010 (Thousands)

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.

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. 4).[7] So population has grown ever more slowly than GDP per capita (Fig. 5) which is a very 'un-Malthusian' finding.[8]

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. 6). The ratio rose prior to 1880, because of the significant investments in new mines, steam driven machinery and associated infrastructure which took time to fully utilize.

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. 7 that, labour hours trended upwards until 1919 after which they oscillated around a fairly 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 mainly labour to a more capital intensive economy in relation to the provision of physical energy. Before the War, there was still a significant role for horse and human physical labour. We saw in Fig. 3 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.

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[7] The two negative blips are caused by the potato famine (1845-1852) and Irish independence (1922).

[8] 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.

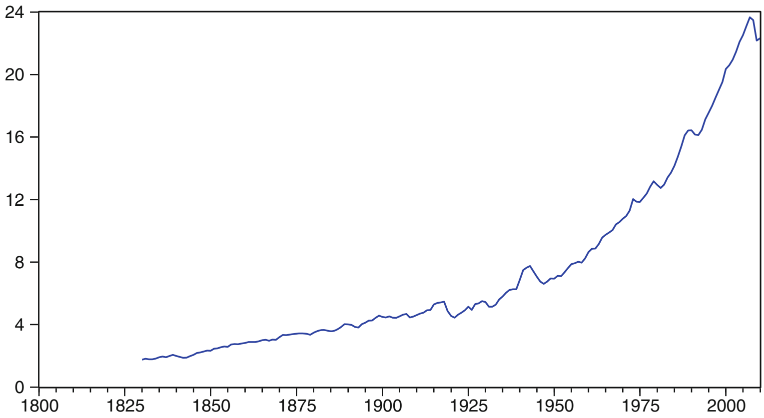

Fig. 5 British real GDP per capita 1830–2010 (US$ thousand, 1990 prices)

So do these charts suggest that a super-radical innovation diffusion process may have been in operation? As has been pointed out, in the presence of a diffusion process with a growing K-limit, we need not observe a sigmoid curve in the case of GDP until the K-limit stops increasing. However, a sigmoid curve is in evidence in the case of energy consumption. This has been paralleled by a steady fall in the price of energy (see Fig. 8, in Fouquet (2011)). By 2007, energy was about one sixth of its real price in the early 19th Century. This is a typical finding in the presence of an innovation diffusion process, with price falling as scale rises and increases in efficiency, both in production and use, occur.

On innovation diffusion curves, unit costs usually stop falling and begin to rise after the point of inflexion, as cost economies become harder to achieve and dominant organizations begin to rent seek. We can see that the real price of energy has now stopped falling and is increasing. It is notable that, up to 1930, the price of energy

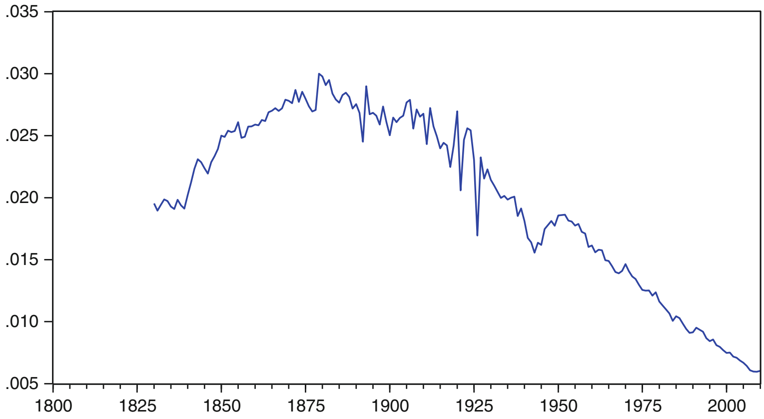

Fig. 6 British energy to GDP ratio: 1830–2010

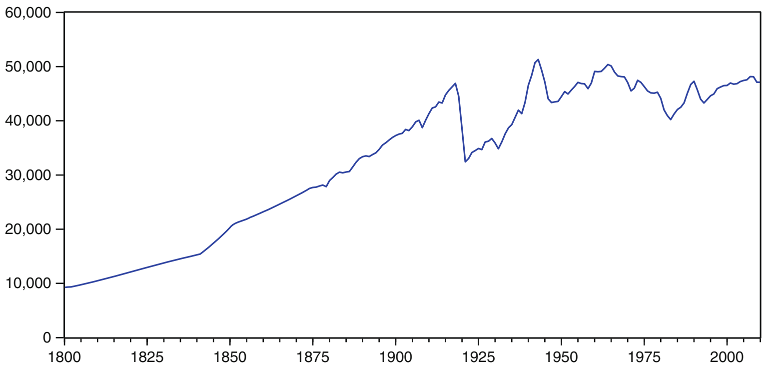

Fig. 7 British total hours worked 1800–2010

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 their 1970s peak range again although they still remain low by historical standards. However, this has not yet held back GDP growth.

5 An innovation diffusion model of long-term 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

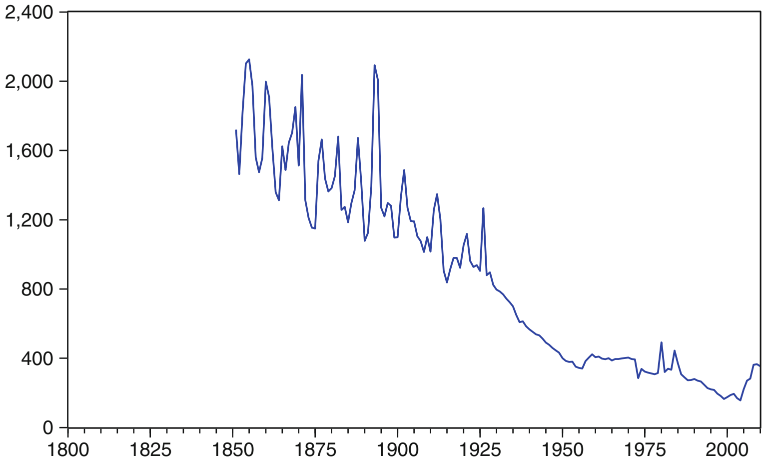

Fig. 8 British average real energy price: 1851–2010 (£in 2000 prices)

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).[9] Both approaches 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.[10] 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.

Here, it is also fully accepted that the capital stock, as a structure containing embodied knowledge specifically designed 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 innovation diffusion. Now, it is commonplace in growth theory to see capital investment (or growth of the net capital stock) as the prime mover but here it is the cumulative level of the net capital stock that determines the energy-related economic potential of a country. It is the conduit through which cheap fossil fuels, directly and indirectly, have facilitated the transformation of materials and human effort into a vast range of goods and services of measurable economic value.[11]

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 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.

So what we have is the reverse of the Solow growth model: the primary source of growth is the innovation diffusion process that Solow consigned to his 'residual.'

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[9] 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.

[10] 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).

[11] Howitt and Aghion (1998) also, saw the capital stock as the main conduit for innovation. However, the neoclassically-based theory that they offer is very different, analytically, to the evolutionary macroeconomic one proposed here and it is not operationalisable econometrically.

Innovation diffusion cannot be just an add-on to a production function – in reality, shifts in production functions and movements along them cannot be separated. It is innovation, due to acts of entrepreneurship, which gives rise to new demands for inputs. So the core of our growth model must be innovation diffusion, not a production function. Foster and Wild (1999a) developed an augmented logistic diffusion model (ALDM) to represent diffusion in the specific context of financial sector development. However, following Metcalfe (2003), industrial development more broadly is better represented by a Gompertz growth model.[12] For the purposes of econometric estimation, the Mansfield sigmoid specification was selected, as in Foster and Wild (1999a), but with a Gompertz representation of innovation diffusion:

$$\boldsymbol{Y_t = Y_{t-1} + aY_{t-1}\left[1 - lnY_{t-1}/lnK\right]} \tag{1}$$

Where **Y** is GDP, $\boldsymbol{a}$ is the logistic diffusion coefficient and $\boldsymbol{lnK}$ is the zero growth limit.

equivalently:

$$\boldsymbol{(Y_t - Y_{t-1})\,/\,Y_{t-1} = a - a\left[\ln Y_{t-1}/\ln K\right]} \tag{2}$$

Approximating logarithmically:

$$\boldsymbol{\ln Y_t - \ln Y_{t-1} = a - a\left[\ln Y_{t-1}/\ln K\right]} \tag{3}$$

However, Eq. 3 is incomplete because we know that, in parallel with this innovation diffusion process, there must be increases in physical work driven by human effort, the application of energy and/or increases in the efficiency of both. This is a thermodynamic necessity. Physical work done comes from two sources: labour time and energy consumption.

Let $\boldsymbol{e}$ be the proportional change in total energy consumption ($\boldsymbol{lnE_t\text{-}\ lnE_{t-1}}$) and $\boldsymbol{h}$ the proportional change in labour hours ($\boldsymbol{lnH_t\text{-}\ lnH_{t-1}}$).[13] Let $\boldsymbol{C}$ be the net capital stock and let us assume that there is a log-linear relationship between it and $\boldsymbol{K}$. Thus, we have an augmented Gompertz diffusion model (AGDM), including a quasi-random shock term, $\boldsymbol{u}$:[14]

$$\begin{aligned}\boldsymbol{\ln Y_t - \ln Y_{t-1}} &= \boldsymbol{a - (a/n)\left[\ln Y_{t-1}/\ln C_{t-1}\right] + b\,(e_t, e_{t-1}\ldots e_{t-n})} \\ &\quad \boldsymbol{+g\,(h_t, h_{t-1\ldots}h_{t-n}) + u}\end{aligned} \tag{4}$$

When the available niche is dictated by the size of a capital stock designed to take advantage of cheap energy, there must be a shift of physical work done, away from labour time towards energy consumption. Released labour shifts into non-physical work activities, raising GDP. This is what we observe in the historical data. In addition to these shifts, induced by innovation diffusion, there are also short term

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[12] The results reported using the logistic specification are very similar but the Gompertz results offer a much more plausible representation of the diffusion process at that has been at work.

[13] Since all product innovations are the outcome of the efforts of labour and there are also continual increases in the efficiency of energy use, making it cheaper per joule, $\boldsymbol{a}$ can be viewed as the sum of two connected diffusion coefficients. Thus, it is possible for GDP to grow at a faster rate than these inputs.

[14] Foster and Wild (1999b) provide evidence suggesting that the errors in an innovation diffusion growth model should not be strictly random.

fluctuations in energy use and labour time. For example, in recessionary conditions, production is curtailed and GDP growth falls, resulting in excess capacity and unemployment. In booms and wartime conditions a given productive structure may be used more intensively and, consequently, its net capital stock may run down at an accelerated rate.

The 'gross' innovation diffusion effect is $\boldsymbol{a}$ and 'net' effect is $\boldsymbol{[a - (a/n)[lnY_{t-1}/lnC_{t-1}]}$. As $\boldsymbol{lnY}$ approaches its $\boldsymbol{lnK}$ 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 and labour hours worked. These can push $\boldsymbol{lnY}$ above the $\boldsymbol{lnK}$ limit, but this is corrected as $\boldsymbol{lnY/lnK}$ rises above unity. In this sense, $\boldsymbol{lnK}$ is a 'soft ceiling.'

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. In addition, we saw in Fig. 8 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 simple 'partial adjustment' model to capture this slow adjustment:[15]

$$\boldsymbol{\ln C_t^* = w + f\left(\ln P_t, \ln P_{t-1 \ldots.} \ln P_{t-n}\right) + u} \tag{5}$$

Where $\boldsymbol{C_t^*}$ is the capital stock in a stationary state.

If there is partial adjustment and we add an undefined sequence of lagged dependent variables to capture the unstable behaviour of capital investment in the short term, we get:

$$\boldsymbol{\begin{aligned}\ln C_t - \ln C_{t-1} = z\left(\ln C_t^* - \ln C_{t-1}\right) + f\,([\ln C_{t-1} - \ln C_{t-2}]\ldots..\\ [\ln C_{t-n-1} - \ln C_{t-n}]) + u\end{aligned}} \tag{6}$$

Where: $\boldsymbol{z}$ is between 0 and 1.

Substituting for C_t^* in Eq. 6, we get

$$\boldsymbol{\begin{aligned}\ln C_t - \ln C_{t-1} &= zw + zf\left(\ln P_t, \ln P_{t-1 \ldots.} \ln P_{t-n}\right) - z \ln C_{t-1}\\ &\quad + f\,([\ln C_{t-1} - \ln C_{t-2}]\ldots.[\ln C_{t-n-1} - \ln C_{t-n}]) + u\end{aligned}} \tag{7}$$

If the lagged dependent variables are short term in their impact, we would expect their estimated coefficients to sum to less than unity.

Equation 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

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[15] 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.

stock follows an oscillating path (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 such a path. 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 significantly.

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 in a complex economic system, 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 $\boldsymbol{K}$ has not been fixed has important implications for how we interpret our AGDM 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 $\boldsymbol{lnY/nlnC}$ ratio that is less than one) then we shall observe the net diffusion effect following an exponential growth path, reminiscent of the Solow (1957) 'residual growth' finding. If GDP grows faster than the capital stock, the $\boldsymbol{lnY/nlnC}$ 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/or labour inputs and likely to be temporary in a state of structural transition.

6 Results

The UK is a very good source of historical data for modelling economic growth. It is possible to obtain data 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 involves annual interpolations

Table 1 Granger causality tests

Sample: 1800–2010, Lags 6

Null Hypothesis:	Obs.	F-Statistic	Probability
$lnE_t - lnE_{t-1}$ does not Granger Cause $lnY_t - lnY_{t-1}$	204	1.06611	0.38437
$lnY_t - lnY_{t-1}$ does not Granger Cause $lnE_t - lnE_{t-1}$		4.06387	0.00074

of estimated decadal data and, as such, they lack realistic annual variation.[16] Generally, historical economic data before 1830 tends to be very unreliable, interpolated from very fragmentary observations.[17] 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 the lags involved in our model since we are dealing with a complex economic system 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, Granger causality tests were conducted.

The results are reported in Table 1. The hypothesis that causation runs from energy growth to GDP growth is strongly supported, in line with the literature reviewed by Stern (2011).[18]

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. Recursive least squares estimation reveals 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. However, the actual-to-predicted graph in Fig. 9 shows that there were some significant outlier years. Historical investigation indicated that impulse dummies for 1840-42, 1856, 1919, 1941 and 2009 were all warranted.

The results reported in Table 3, using 'history compatible' impulse dummy variables, are quite similar to those without. The Recursive Least Squares modelling again reveals strong parameter stability.

Because of the interdependent nature of GDP and energy, the specification was re-estimated using Two Stage Least Squares (TSLS). The instrumental variables were

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

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

[18] 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 2 OLS estimates of Eq. 4: 1831–2010

Dependent Variable:	$[\ln Y_t - \ln Y_{t-1}]$	
Variable	Coefficient	t-Statistic
Constant	0.16	4.66
e_t	0.15	4.94
e_{t-1}	0.14	4.20
e_{t-2}	0.06	2.05
e_{t-4}	−0.04	−1.57
h_t	0.67	9.07
h_{t-1}	−0.17	−2.22
$[lnY/lnC]_{t-1}$	−0.12	−4.27
R-squared	0.56	
Adj. R-squared	0.54	
Durbin-Watson	1.85	

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 ***(gpop)***, 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.[19] 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.

It is noticeable in the actual-to-predicted plots in Fig. 9 that the fit becomes tighter around 1880, which is about the time when the energy to GDP ratio stopped rising and began its secular fall (see Fig. 6). So it seemed sensible to re-estimate to model from 1880 on to check its stability. The results in Table 5 are similar to those using the full sample. Again, the Recursive Least Squares results indicate strong parameter stability.

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.

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 and the fit is excellent (Fig. 10).

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[19] Instrument List: $\boldsymbol{e_{t-1}, e_{t-2}, e_{t-4}, h_{t-1}, h_{t-1}, DUM1840 42, DUM1856, DUM1919, DUM1941, DUM2009, gpop_t, gpop_{t-1}, gpop_{t-2}, gpop_{t-5}, gpop_{t-6}, gpop_{t-7}, E_{t-1}}$

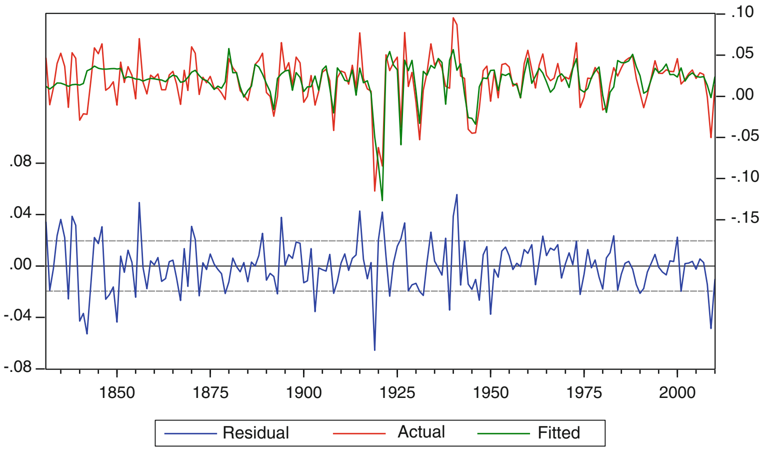

Fig. 9 Actual to predicted chart OLS Estimates of Eq. 4: 1831–2010

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 estimates were obtained by summing the coefficients on the contemporaneous and each significant lagged variable in all three sample periods.

Table 3 OLS estimates of Eq. 4: 1831–2010 with historical impulse dummy variables

Dependent Variable:	$[lnY_t - lnY_{t-1}]$	
Variable	Coefficient	t-Statistic
Constant	0.13	4.34
e_t	0.14	5.31
e_{t-1}	0.11	3.86
e_{t-2}	0.04	1.68
e_{t-4}	−0.04	−2.12
h_t	0.61	9.45
h_{t-1}	−0.14	−2.10
$[lnY/lnC]_{t-1}$	−0.10	−3.84
DUM184042	−0.05	−4.51
DUM1856	0.05	2.95
DUM1919	−0.08	−4.33
DUM1941	0.05	3.14
DUM2009	−0.05	−2.90
R-squared	0.70	
Adjusted R-squared	0.66	
Durbin-Watson	1.91	

Table 4 TSLS estimates of Eq. 4: 1831–2010[20] with historical impulse dummy variables

Dependent Variable:	$[lnY_t - lnY_{t-1}]$	
Variable	Coefficient	t-Statistic
Constant	0.13	4.21
e_t	0.13	3.44
e_{t-1}	0.11	3.33
e_{t-2}	0.04	1.57
e_{t-4}	−0.05	−2.14
h_t	0.62	8.96
h_{t-1}	−0.14	−2.05
$[lnY/lnC]_{t-1}$	−0.09	−3.70
$DUM1840-42$	−0.05	−4.50
$DUM1856$	0.05	2.96
$DUM1919$	−0.8	−4.33
$DUM1941$	0.05	3.12
$DUM2009$	−0.05	−2.91
R-squared	0.69	
Adjusted R-squared	0.66	
Durbin-Watson stat	1.91	

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.[20] The average coefficient on energy consumption growth is 0.26 and that on labour hours growth 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. There are returns to scale, or more accurately in this context, returns to increasing work input, but they are diminishing. The existence of an innovation diffusion process is supported with a strongly significant negative sign on the $[lnY/lnC]_{t-1}$ estimated coefficient (***a/n***). When ***n*** was derived, using the estimate of ***a*** in Table 7, it was also found to be very stable at an average of 1.34 across the samples.

Although there is strong support for the existence of a Gompertz diffusion process, we do not observe a sigmoid curve for GDP. In Fig. 11, the ratio of GDP to ***K***, i.e., ln***Y/nlnC***, is plotted over the 1800–2010 period for ***n*** = 1.34. It is clear that ***K*** rose only modestly relative to GDP up to the 2nd World War but it has risen faster since then in an era dominated by oil and the specialization of coal in electricity generation.

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[20] 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.

Table 5 OLS estimates of Eq. 4: 1880–2010 with historical impulse dummy variables

Dependent Variable:	$[lnY_t - lnY_{t-1}]$	
Variable	Coefficient	t-Statistic
Constant	0.16	4.50
e_t	0.13	5.25
e_{t-1}	0.11	3.73
e_{t-2}	0.03	1.50
e_{t-4}	−0.04	−2.07
h_t	0.61	10.00
h_{t-1}	−0.13	−1.98
$[lnY/lnC]_{t-1}$	−0.12	−4.05
$DUM1919$	−0.09	−4.56
$DUM1941$	0.05	3.34
$DUM2009$	−0.05	−3.22
R-squared	0.76	
Adjusted R-squared	0.74	
Durbin Watson	1.94	

We can see that, prior to 1840, the ***lnY*** to ***lnK*** ratio was 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

Table 6 OLS estimates of Eq. 4: 1947–2010

Dependent Variable:	$[lnY_t - lnY_{t-1}]$	
Variable	Coefficient	t-Statistic
Constant	0.16	2.55
e_t	0.20	3.08
e_{t-1}	0.11	1.77
h_t	0.63	6.01
h_{t-1}	−0.20	−2.07
$[lnY/lnC]_{t-1}$	−0.12	−2.23
$DUM2009$	−0.05	−3.51
R-squared	0.6	
Adj. R-squared	0.58	
Durbin-Watson	1.88	

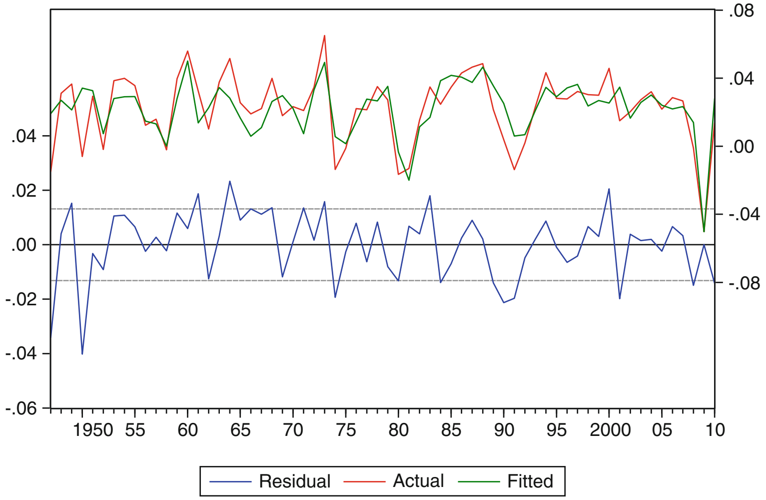

Fig. 10 Actual to predicted chart OLS Eq. 4: 1947–2008

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 about 14 % below unity, still made a significant positive contribution to economic growth via the net diffusion effect in 2010. A steady ratio, at any level less than unity, however, implies that the net diffusion effect is approximately exponential and that was the case in the UK for the three decades up to 2010.

Prior to the World War Two, the ***K*** limit was only about 7 % 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. With a ***K*** limit at 14 % higher than the prevailing level of GDP in 2010, the UK, a mature, post-industrial economy, thus, still seemed to have significant growth potential based upon its past history, even without a further increase in the size of its net capital stock. 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. 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 in

Table 7 Cumulated coefficient estimates in three samples

Coefficient	1831–2010	1880–2010	1947–2010
a	0.13	0.16	0.16
b	0.25	0.23	0.31
g	0.47	0.49	0.51
a/n	−0.10	−0.12	−0.12
n	1.37	1.33	1.32

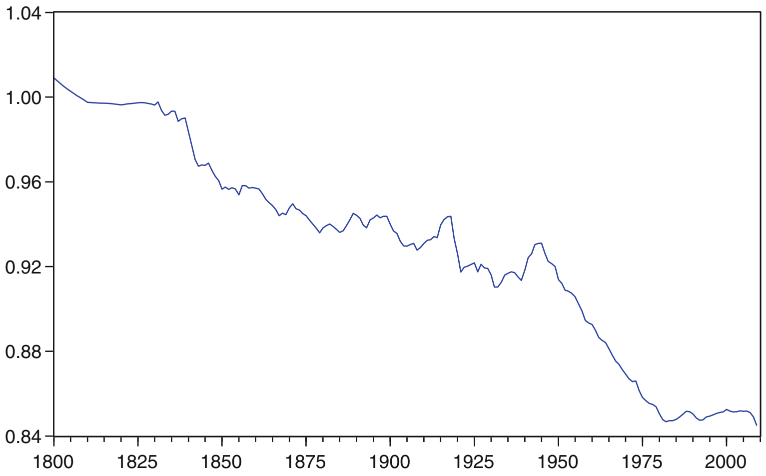

Fig. 11 The estimated ratio ***of lnY*** to ***lnK***

the productive process, 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.[21] 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 -1.8. So these findings suggest that movements in energy prices have 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 concerning the impact of energy prices? 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, would eventually decline by over 25 % in the UK case. This decline would not be sudden, taking 15 years to have a significant effect

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[21] Energy prices are sourced from Fouquet (2011). 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.

Table 8 OLS Results for Eq. 7: 1875–2009

Dependent Variable:		$lnC_t - lnC_{t-1}$	
Variable		Coefficient	t-Statistic
Constant		0.436	5.30
lnC_{t-1}		−0.019	−5.20
lnP_{t-15}		−0.009	−2.57
lnP_{t-19}		−0.014	−3.56
lnP_{t-22}		−0.011	−2.73
$lnC_{t-1}lnC_{t-2}$		1.07	13.45
$lnC_{t-2}-lnC_{t-3}$		−0.30	−3.75
$lnC_{t-5}-lnC_{t-6}$		−0.27	−3.31
$lnC_{t-6}-lnC_{t-7}$		0.21	2.73
R-squared		0.87	
Adjusted R-squared		0.87	
Durbin-Watson		1.84	
Breusch-Godfrey Serial Correlation LM Test:			
F-statistic	1.83	Prob. F(2,126)	0.16
Obs*R-squared	3.87	Prob. Chi-Square(2)	0.14

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 article, a hypothesis has been offered and tested, namely, 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 innovation 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 labour time, and now 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 serious dilemma for the UK and, by implication, for the World as a whole. First of all, future GDP growth possibilities for the UK seem to be available. 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 real 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 ceases to grow, or even falls, then growth will tend towards a zero limit, in line with our super-radical innovation diffusion curve findings.

Already, 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. When the knowledge gradient rises so fast that it overwhelms the natural tendency for the growth of a system to tend to a fixed capacity 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 diffusion limit but do so when price growth is very 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, continuing growth prospects, but with transitional dangers looming on the horizon. 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.[22] However, based upon Angus Maddison's

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[22] 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.

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 fossil 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. From a thermodynamic perspective, the problem lies, not with accessing new sources of energy, but with the availability of entropy sinks. However, 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.

Sources

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, 2011) 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.

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