Economic Complexity and Evolution

Andreas Pyka
John Foster *Editors*

The Evolution of Economic and Innovation Systems

Springer

Economic Complexity and Evolution

More information about this series at
http://www.springer.com/series/11583

Andreas Pyka • John Foster
Editors

The Evolution of Economic and Innovation Systems

Springer

Editors
Andreas Pyka
Chair for Economics of Innovation
University of Hohenheim
Stuttgart
Germany

John Foster
School of Economics
University of Queensland
Brisbane, Queensland
Australia

Some of the contributions have been published in the Journal of Evolutionary Economics, Volume 24 (2), 2014

ISSN 2199-3173 ISSN 2199-3181 (electronic)
ISBN 978-3-319-13298-3 ISBN 978-3-319-13299-0 (eBook)
DOI 10.1007/978-3-319-13299-0

Library of Congress Control Number: 2015934229

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is a part of Springer Science+Business Media (www.springer.com)

Contents

Introduction: The Evolution of Economic and Innovation Systems

John Foster and Andreas Pyka

Abstract The theme of the 14th International Joseph A. Schumpeter Conference 2012 held in Brisbane, was "the evolution of economic systems, through innovation, entrepreneurship and competitive processes." This was intended to be broad enough to encompass a wide range of submitted papers in evolutionary economics and related areas. This book is the outcome of a strong competition among the papers submitted after the conference. The contributions selected show the scope of analysis in evolutionary economics as well as the explanatory power with respect to economic dynamics and long term economic development.

The theme of the 14th International Joseph A. Schumpeter Conference, held from July 2nd to 5th 2012, was "the evolution of economic systems, through innovation, entrepreneurship and competitive processes." This was intended to be broad enough to encompass a wide range of submitted papers in evolutionary economics and related areas. However, perhaps more than in previous conferences, there was a focus upon viewing economic evolution from the perspective of complex systems science, suitably defined for application in economic contexts. This reflected the ongoing interest in complex economic systems that had existed at the University of Queensland for two decades. Some will remember the first 'Brisbane Club' international workshop on this perspective on evolutionary economics at UQ in 1999 and the resultant volume edited by Foster and Metcalfe in 2001. Although having the Schumpeter Conference in Brisbane was viewed by many of us as a fitting conclusion to the Brisbane Club series of meetings, the Club met once again in Vienna in 2013 thanks to excellent efforts of Kurt Dopfer. However, the 2012 Schumpeter Conference was much more than just an extension of this tradition. As with previous conferences, a very diverse range of research questions were

J. Foster (✉)
University of Queensland, Brisbane, QLD, Australia
e-mail: j.foster@uq.edu.au

A. Pyka
University of Hohenheim, Stuttgart, Germany

A. Pyka, J. Foster (eds.), *The Evolution of Economic and Innovation Systems*,
Economic Complexity and Evolution, DOI 10.1007/978-3-319-13299-0_1
Modified and extended version from Journal of Evolutionary Economics 24(2), Springer 2014.

addressed and they stimulated robust discussion and debate. The vibrancy and relevance of modern research in evolutionary economics was there for all to see and this was in no small measure due to the high proportion of early career researchers presenting at the Conference.

The five plenary sessions dealt with: Asian emergence—causes and consequences; innovation policy—evolutionary economic perspectives; knowledge, entrepreneurship and the evolution of markets; modelling macroeconomic behaviour when economic systems are recognized as complex; neo-Schumpeterian evolutionary economics—where has it been going and what is its future? We were very privileged to be able to listen to the following invited speakers: Peter Allen, Ping Chen, Terry Cutler, Giovanni Dosi; Alan Hughes, David Lane, Keun Lee, Deirdre McCloskey, Stan Metcalfe, Jason Potts and Ulrich Witt.

There were 61 parallel sessions including: finance and innovation; economic growth; energy and economic evolution; the evolution of the firm; managing innovation; education and innovation; technological paradigms and evolution; Schumpeter revisited; industry linkages; patents; energy innovation—corporate strategy; demand and consumption; evolutionary perspectives on 'knowledge'; productivity growth; energy innovation—policy; innovation networks; spillovers; innovation case studies; advances in evolutionary economic theory; long waves, finance and global crisis; behavioral perspectives on economic evolution; Chinese economic development; climate change policy; patents, startups and disruption; complex systems; catch up; overcoming socio-cultural obstacles to innovation; new ventures; evolution of the 'green economy'; East Asian growth; spin-offs; innovation policy; emergence in complex economic systems; spatial perspectives on economic evolution; innovation and firm performance; entrepreneurship; energy and green innovation; political economy, law and innovation; history-friendly modeling; the labor market; competition and selection; advances in evolutionary modeling; university-industry collaboration; persistence, inertia and path dependence; complex evolving networks; research collaboration and the emergence of capabilities; human capital; absorptive capacity; development-industrialization; international collaboration on innovation; health; technological spillovers.

This book is both the outcome of a strong competition among the papers submitted after the conference and the result of a thematic focus of the editors on a core issue of evolutionary economics. Some contributions already appeared in Volume 24 (2), a Special Issue of the Journal of Evolutionary Economics. Some of these reprints are additionally extended for this book to provide information that is more detailed and additional backgrounds. Both variants are clearly marked for the reader of this volume. The contributions selected show the scope of analysis in evolutionary economics as well as the explanatory power with respect to economic dynamics and long term economic development. The book is structured in three major sections dealing with the conference topic: The *evolution of economic systems*, the *evolution of innovation systems* and *entrepreneurship and innovation competition*.

In the first section, *evolution of economic systems*, we start with John Foster's Presidential Address entitled "Energy, Knowledge and Economic Growth." He views economic growth as a self-organized process with energy use and new knowledge associated with energy use as major co-evolutionary drivers. Ping Chen's chapter "Metabolic Growth Theory: Market-Share Competition, Learning Uncertainty, and Technology Wavelets" focuses on the trade-off between stability and complexity of an ecological-industrial system. His growth and technological development theory allows for non-linear economic development in waves combining the thinking of Adam Smith, Thomas Robert Malthus and Joseph Alois Schumpeter. To address issues of economic welfare is one of the major difficulties in evolutionary economics because it is hard if not impossible to find a yardstick because of the open development and the uncertainty inherent to all innovation. In his chapter entitled, "Towards a General Model of the Innovation—Subjective Well-Being Nexus" Hans-Jürgen Engelbrecht introduces the concept of procedural utility to overcome the difficulties in addressing welfare issues stemming from uncertainty and dynamics inherent to innovation processes. Esben Sloth Andersen and Jakob Rubaek Holm focus on the varieties of selection processes responsible for economic evolution. In their chapter "The Signs of Change in Economic Evolution", they differ between three selection mechanisms they label intentional, stabilizing and diversifying selection and explain the meaning of each selection mechanism for economic evolution. The last chapter in this section by Zheng Lu and Xiang Deng deals with an application of evolutionary reasoning and regional policy to analyze the impact of policy reforms on the economic system in China since 1999.

The second section of this book also places emphasis on the systemic character of economic evolution and focuses on the important concept of innovation systems. Peter Allen's chapter "Evolution, Complexity, Uncertainty and Innovation" introduces to the varieties of complex systems, the required assumptions and limitations and most important to their explanatory power for economic reasoning. Felix Munoz and Maria-Isabel Encinar highlight the interaction of agents' intentions for emergent phenomena in economic evolution. Their chapter "Intentionality and the Emergence of Complexity: an Analytical Approach" complements Andersen's and Holm's reflections on selection mechanisms by proposing an analytical approach based on agents' action plans to explain emerging patterns in economic behavior. Peter Hall's and Robert Wylie's chapter entitled "Isolation and Technological Innovation" analyze conditions for disruptive change in technological evolution stemming from isolation and introduce to two cases of military innovations to illustrate their reasoning. The following chapter "The Emergence of Technological Paradigms: The Evolutionary Process of Science and Technology in Economic Development" by Keiichiro Suenaga focuses on complex transition processes. He offers an analytical perspective to get a grip on the imponderability of uncertainty in processes of science and knowledge driven paradigmatic changes. Hans-Peter Brunner and Kislaya Prasad apply agent-based models to analyze structural change in South-Asian regions and introduce to policy experiments using this model. Their chapter "Policy Exploration with Agent-Based, Economic Geography Methods of Regional Economic Integration in South-Asia" also offers a link to Peter Allen's varieties of complex systems. Lykke Margot Ricard finally is concerned with a European case of technology diffusion. In her chapter "Coping with System

Failure: Why Connectivity Matters to Innovation Policy" she applies social network analysis to find out how technology platforms emerge and change in the current European energy system.

Section three of this book is entitled *entrepreneurship and innovation competition* and the chapters there focus on the sectorial, firm and individual perspective of innovation processes. Compared to the previous sections the following 11 chapters also choose more applied questions or address central issues in an evolutionary innovation-driven economic development. The first chapter authored by Harold Paredes-Frigolett and Andreas Pyka addresses innovation networks and firm entry strategies to knowledge pools organized in networks. "A Generic Innovation Network Formation Strategy" for firms embedded in geographic environments endowed with only poor knowledge and business opportunities can be a re-location into prolific networks which also can be part of a policy strategy. In the chapter "Property Rights as a Complex Adaptive System: How Entrepreneurship Transforms Intellectual Property Structures" David Harper treats intellectual property rights as a complex adaptive system which offers entrepreneurs opportunities and which is changed by entrepreneurial actions. These feedback effects determine meso-levels as structures within the macro intellectual property rights. Gunnar Eliasson and Pontus Braunerhjelm apply their competence bloc theory on economic development in the Baltic Sea region. They show that "Entrepreneurial Catch-up and New Industrial Competence Bloc Formation in the Baltic Sea Region" is possible and require a strong policy orientation on the improvement of the conditions for entrepreneurs. Abiodun Egbetokun and Ivan Savin pick up an old question in innovation economics: why do firms cooperate in innovation if they run into danger to lose knowledge to potential competitors? Their contribution "Absorptive Capacity and Innovation: When is it Better to Cooperate?" introduces to a new model which focuses on knowledge distances, voluntary and involuntary spillovers as well as the required investments to integrate external knowledge. The next chapter of this contributed volume "Innovation and Finance: A Stock Flow Consistent-Analysis of Great Surges of Development" by Alessandro Caiani and Antoine Godin links Neo-Schumpeterian and Post-Keynesian approaches to analyze the finance-innovation nexus which allows to explain the co-evolutionary relationship between technological change, demand and finance acknowledging for structural changes. The chapter "Restless Knowledge, Capabilities and the Nature of the Mega-Firm" by Harry Bloch and Stan Metcalfe adds to the competence-based approach of the theory of the firm important insights from evolutionary economics. In a similar vein Giovanni Cerulli and Bianca Poti address in their contribution "The Role of Management Capacity in the Innovation Process for Firm Profitability". Stefan Hitzschke again introduces a geographic dimension in his chapter "Industrial Growth and Productivity Change in German Cities: A Multilevel Investigation". Despite converging of urban industrial value creation, he founds diverging growth rates in employment for German cities. Bernado Maggi and Daniel Muro also focus on joint and interdependent growth dynamics, this time for European countries. Their chapter entitled "A Dynamical Model of Technology Diffusion and Business Services for the Study of the European Countries Growth and Stability" provides with a detailed description of their statistical approach and with policy conclusions, which can be derived from their analysis. Marcelo de Carvalho Pereira and David Dequech introduce to "A History-Friendly Model of the Internet Access Market: the Case of Brazil". With the help of an agent-based simulation model, they reproduce important dynamics and interactions empirically measured in Brazil. The last chapter "Micro, Macro, and Meso Determinants of Productivity Growth in Argentinian Firms" authored by Verónica Robert, Mariano Pereira, Gabriel Yoguel and Florencia Barletta is an application of the evolutionary feedback story between the different levels in an economy and deals with firm productivity growth in Argentina.

All chapters of this contributed volume of the International Joseph A. Schumpeter Society Conference from 2012 in Brisbane, Australia join the focus on complex adaptive systems as an adequate framework for evolutionary economic analysis. The contributions make clear how far the evolutionary complex methodology is developed and how rich the explanatory power of economic analysis can be with the right instruments: Changes of the system like innovation-driven economic development or economic crisis become endogenous phenomena, which are analyzed immediately without exogenous shocks and/or the application of restrictive assumptions. Interactions among heterogeneous actors and the emergence and diffusion of new knowledge triggers the interesting dynamics and structural transitions which are only analytically accessible with the methodologies and frameworks provided by evolutionary Schumpeterian economics.

Part I
The Evolution of Economic Systems

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.

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).

This paper was presented in preliminary form as the Presidential Address at the International J.A. Schumpeter Society Conference, July2–5th 2012, University of Queensland, Brisbane, Australia. I would like to thank Maxine Darnell for providing advice concerning the treatment of energy in the British economic history literature. Roger Fouquet and Jakob Madsen kindly provided me with their historical data. Thanks are also due to Stan Metcalfe, Jakob Madsen and David Stern for their extensive comments and criticisms of a previous version of this paper. However, all errors and omissions remain the responsibility of the author.

J. Foster (✉)
School of Economics, University of Queensland, Brisbane, Queensland 4072, Australia
e-mail: j.foster@uq.edu.au

A. Pyka, J. Foster (eds.), *The Evolution of Economic and Innovation Systems*,
Economic Complexity and Evolution, DOI 10.1007/978-3-319-13299-0_2
Reprinted from Journal of Evolutionary Economics, 24(2), Springer 2014.

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).

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

[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.

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.

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

[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.

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, 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.

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 the War. Afterwards, British coal prices were held up to maintain

[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.

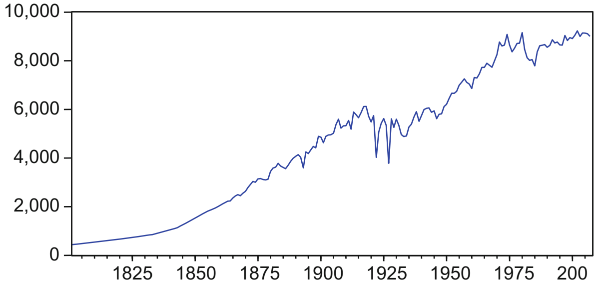

Fig. 1 UK energy consumption 1800–2010 (in Petajoules)

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]

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.

[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.

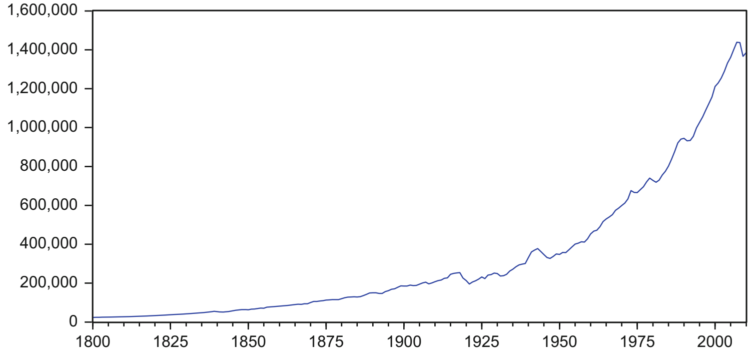

Fig. 2 British real GDP: 1830–2010 (US$ million, 1990 prices)

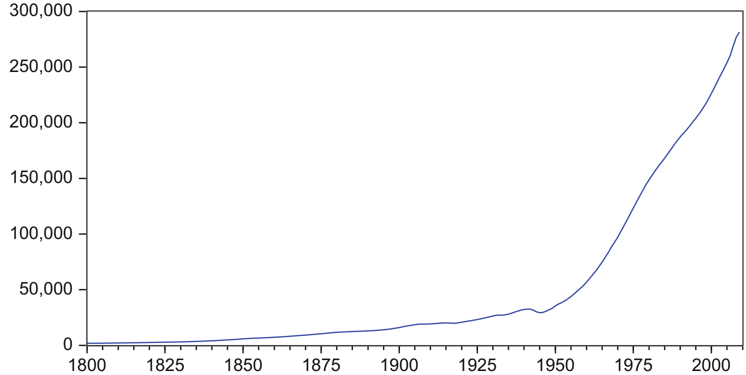

Fig. 3 British net capital stock: 1800–2010 (£Million, 1990 prices)

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

[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.

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 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 powerful fossil fuels, directly or indirectly, and, in an autocatalytic way, the increasing demand for fossil fuels lowered their cost

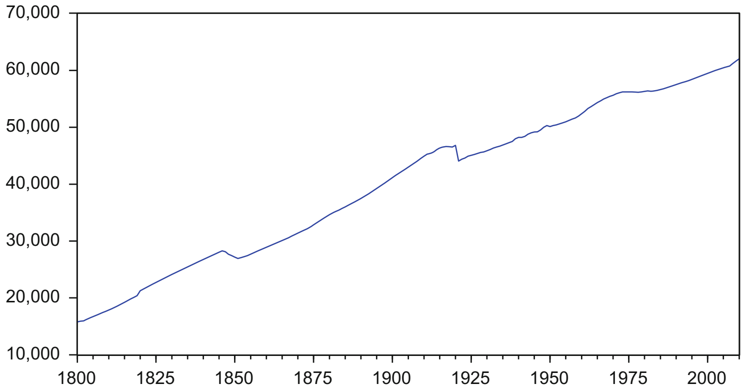

Fig. 4 UK population: 1820–2010 (Thousands)

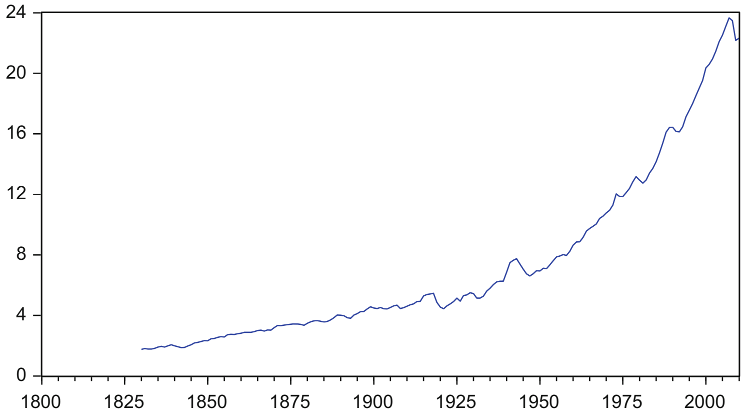

Fig. 5 British real GDP per capita 1830–2010 (US$ thousand, 1990 prices)

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]

---

[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.

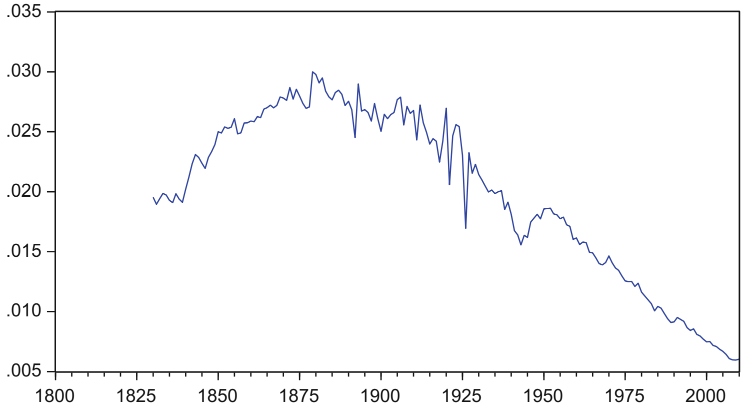

Fig. 6 British energy to GDP ratio: 1830–2010

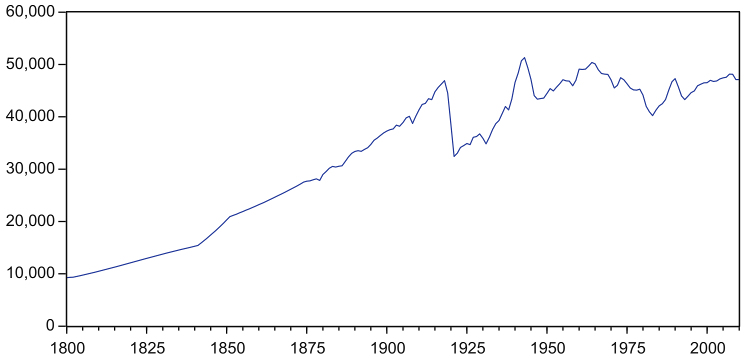

Fig. 7 British total hours worked 1800–2010

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

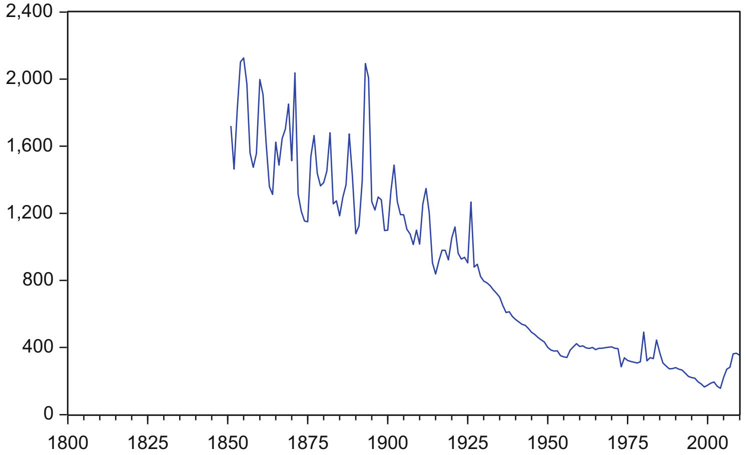

Fig. 8 British average real energy price: 1851–2010 (£in 2000 prices)

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.

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 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 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

---

[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.

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.' 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:

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

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

equivalently:

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

Approximating logarithmically:

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

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 ($\boldsymbol{lnE_t}$ - $\boldsymbol{lnE_{t-1}}$) and $\boldsymbol{h}$ the proportional change in labour hours ($\boldsymbol{lnH_t}$ - $\boldsymbol{lnH_{t-1}}$).[13] Let $\boldsymbol{C}$ be the net

[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