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Energy, efficiency and economic growth: a coevolutionary perspective and implications for a low carbon transition

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Contents

Abstract. This paper reviews recent strands of work arguing that high quality energy inputs and their efficient conversion to useful work have been key drivers of economic growth. This is important for understanding how a low carbon transition could be achieved and resulting implications for economic growth. An increase in energy input costs, due to declining availability of cheap oil and the need to switch to low-carbon alternatives, will have profound, but insufficiently understood, economic impacts. The paper argues that a useful way forward for understanding these impacts would be to combine insights from a coevolutionary economic understanding of the drivers of economic growth with those from socio-ecological approaches that emphasise the material and energy reliance of modern industrial economies.

Keywords: energy, economic growth, exergy, co-evolution

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1 Introduction

The extent to which a transition to sustainable, low carbon energy systems will either reduce economic growth or, alternatively, provide a stimulus to a new wave of economic growth is central to policy analyses of the feasibility of a transition (N. Stern, 2007). This paper reviews recent work arguing that the past rates of economic growth have depended on higher quality forms of energy inputs and the increasing efficiency of their conversion to useful work (Ayres and Warr, 2009; D. Stern, 2011; Warr and Ayres, 2012) and, complementarily, that high rates of economic growth depended on high ‘net energy’ returns (Hall and Klitgaard, 2012). We argue that this work is important for understanding how a low carbon transition could be achieved and resulting implications for economic growth. This prospective suggests that if energy costs significantly increase in future, as a result of carbon pricing and/or increasing costs of fossil fuel inputs, then a return to past rates of economic growth may not be possible. This would imply the need to manage a process of change to economic systems less dependent on high rates of growth. We argue for the need to combine these ideas on the ecological basis of economic activity with a coevolutionary economic analysis of feedbacks between coevolving systems (Foxon, 2011), in order to analyse the challenges and opportunities of a low carbon transition. This would provide a basis for further analytical and modelling work to explore these issues in more depth.

In a series of papers and a book, Robert Ayres, Benjamin Warr and colleagues have argued that the increasing availability of cheaper and higher quality forms of energy inputs (measured by their exergy content), and the efficiency of their conversion to useful work, have played a key role in driving economic growth in industrialised and emerging economies (Ayres et al., 2003; Ayres and Warr, 2005; Ayres et al., 2007; Ayres and Warr, 2009; Warr and Ayres, 2012). This builds on the work of economic historians, who argued that the availability of cheap coal in relation to high labour costs in the UK in the 18th Century stimulated R&D and investment in the development of steam engines that helped to drive the industrial revolution (Allen, 2009), and socio-ecological theorists, who argued that this transition represents a step change in the scale of systems of production and consumption (Haberl et al., 2011). Hence, we need to better understand the future availability of exergy inputs and whether or not conversion efficiencies will continue to increase (Brockway et al., 2013).

In a complementary strand of work, Charles Hall, Cutler Cleveland and colleagues have argued that the ‘net energy’ provided by fossil fuels, as measured by their energy return on energy invested (EROI), has been an important driver of economic growth (Hall et al., 1986; Cleveland et al., 2000; Hall and Klitgaard, 2012). However, they point out that EROI is now declining for fossil fuels, as the most easily accessible sources are extracted, and that most low carbon energy technologies also have low ‘net energy’ provision, which could have important economic implications (Hall et al., 2008; Gupta and Hall, 2011).

However, these two strands of work are not well represented in mainstream economic analyses of the implications of a low carbon transition on future rates of economic growth, which we argue is an important omission. Hepburn and Bowen (2012) recognise that there may be energy and resource limits to growth in the material economy, but argue that growth in the non-material ‘intellectual economy’ can continue indefinitely and is necessary to drive the investment needed for a low carbon transition. To better understand if this is the case, or if there are energy and resource limits to all economic growth, we need to develop analytical approaches and modelling tools that incorporate the above ideas on the role of energy in the economy. This paper argues that the above ecological economic perspective can usefully be combined with ideas from evolutionary economics within a coevolutionary framework (Nelson, 2005; Beinhocker, 2006; Foxon, 2011). This also helps to clarify a partial misunderstanding of the role of entropy in earlier coevolutionary economic analysis (Beinhocker, 2006).

Ayres et al. (2007) argued that cheap energy and its efficient conversion have been both a cause and consequence of economic growth, through positive feedbacks or virtuous cycles between decreases in energy input costs and increases in economic activity. A co-evolutionary perspective adds insights into how this has led to the developments of economic systems and institutions that are predicated on maintaining high rates of economic growth. This means that physical and economic constraints on useful work from energy coming into the economy will require new institutions and business models for new modes of economic functioning. Changing trends in exergy availability and conversion efficiencies will result in changes in economic production, and for these to be managed appropriately for society, a change in institutions. A coevolutionary approach enables examination of feedbacks between changes in energy provision and economic systems, and their implications for a low-carbon transition.

The paper is structured as follows. Section 2 provides a critical overview of mainstream economic growth models, arguing that they neglect the role of energy inputs. Section 3 presents coevolutionary theories of economic growth and their relevance to a low carbon transition. Section 4 examines recent approaches that argue for a significant role of energy inputs in contributing to economic growth. Section 5 emphasizes the importance of the quality of energy inputs and not just their energy content. Section 6 examines potential systems feedbacks under a coevolutionary approach. Section 7 concludes by identifying research questions and challenges raised by applying a coevolutionary perspective to energy inputs and economic growth models.

2 Mainstream economic growth theories

Accounting for growth has long been a central goal of macro-economics. In this paper, we do not attempt to review the history of this endeavour; instead we highlight past efforts that are relevant to our focus on the role of energy in the economy. In the next section, we consider implications that co-evolutionary ideas would have for these models.

The macro-economic mission of finding an accurate expression for economic growth, based on productive factors in the economy (the “production function” approach) has been surprisingly difficult. The choice of appropriate, measurable factors, which are conceptually distinct from one another, led to the adoption of labour L and capital K as the main factors of production. The main problem with L-K based production functions is that they fall short in estimating historic growth trends: economic growth is always larger than can be modelled with L and K alone, with deviations appearing on the scale of a few years rather than decades.

The established economic solution to this conundrum was famously introduced by Robert Solow (1956, 1957) and Trevor Swan (1956), working independently from each other, who introduced an extra term, A, to model what is now known as the “Solow residual”: the gap between real economic growth and the output estimated from capital and labour improvements alone. The A term is often given the name

“Total Factor Productivity,” although as Ayres & Warr (2009) point out, to name something is not to understand it or explain it, and as Abramovitz (Abramovitz 1956) famously stated, the Solow residual is merely the measure of our ignorance.

Total Factor Productivity and the Solow residual constitute the evidence that labour and capital are not the sole defining factors of economic output, but that other factors are equally, or more, important. The interpretation of the Solow residual has often been that it represents technological progress and institutional conditions, both of which are of the central concern of co-evolutionary analysis. In modelling terms, the *A* factor is an *exogenous* representation of technological change: it is not based on quantitative measures of technological advances, it merely gauges the gap between real economic growth and that expected based on improvements in *L* and *K*.

Since the late 1980s, there has been an increase in the interest of some economists in *endogenising* technological change and Schumpeterian ideas (Aghion and Howitt 1998). This is generally done by modelling investment in research, as well as a probabilistic (rather than smooth, or proportional to research investment) occurrence of innovations. Quantitative verifications of these types of models often rely on patent statistics, or similar measures of innovation. Although these models show some level of success in a more realistic model of economic growth, they do not measure institutional and technical progress itself.

Other recent approaches have examined the role of energy in the economy by linking detailed energy technology models with macroeconomic models, for example by using a constant elasticity of substitution function to examine substitution between energy, capital and labour (Kemfert, 2005). However, this type of model does not easily incorporate physical constraints on energy inputs, or feedbacks between industrial structure changes and energy inputs.

3 Co-evolutionary theories of economic growth

Co-evolutionary theories of economic growth have proceeded along a radically different path to that of mainstream economic growth theories, discussed in the previous section. Building on the work of Schumpeter (1911/1934), Abramovitz (1989) and others, Nelson (2005, 2008) argues that economic progress is driven by a process of co-evolution of technologies and institutions. Murmann (2003) provides an example of this at a meso-level with his analysis of the co-evolution of technologies, institutions and firms’ strategies in the historical development of the synthetic chemical dye industry in UK, Germany and the US in the late nineteenth and early twentieth centuries. In this conception, technologies, institutions and firms' strategies each form an evolving system consisting of a population of entities. They coevolve by virtue of the causal influences between the systems. These causal influences can take effect either by altering the selection criteria in another system or by changing the replicative capacities of individuals in a population.

Building on Nelson's work, Beinhocker (2006) argued that the coevolution of physical technologies, social technologies (institutions) and business plans has driven the creation of wealth in Western industrialised countries. He interpreted economies as 'complex adaptive systems', with the following properties:

- *dynamics*: economies are open, dynamic systems, far from equilibrium;
- *agents*: they are made up of heterogeneous agents, lacking perfect foresight, but able to learn and adapt over time;
- *networks*: agents interact through various networks;
- *emergence*: macro patterns emerge from micro behaviours and interactions;
- *evolution*: evolutionary processes create novelty and growing order and complexity over time.

Beinhocker (2006) argues that physical technologies co-evolve with social technologies (institutions), i.e. ways of organising human interactions, such as property rights, limited liability companies and venture capital, and with business strategies for more effectively organising physical and social technologies for creating and meeting human needs and wants. He argues that this explains the huge expansion in the scale and scope of economic activity in industrialised countries that we measure as economic growth.

Beinhocker (2006) builds on the work of Georgescu-Roegen (1971) to argue that these co-evolutionary processes create economic value through irreversible, locally entropy-reducing transformations and transactions that create artefacts and services that 'fit' with human needs and wants. Beinhocker (2006) thus invokes "three conditions for creating economic value:

1. Irreversibility: All value-creating economic transformations and transactions are thermodynamically irreversible.
2. Entropy: All value-creating economic transformations and transactions reduce entropy locally within the economic system, while increasing entropy globally.

(3) Fitness: All value-creating economic transformations and transactions produce artefacts or actions that are fit for human purposes."

We argue that conception partially mis-reads Georgescu-Roegen, as it neglects the vital role of low-entropy inputs, such as fossil fuels, into the economic process. As Georgescu-Roegen (1971) rightly pointed out, economic processes create flows of goods and services by converting low-entropy inputs, i.e. energy and natural resources, into high-entropy outputs, i.e. wastes: "since the economic process materially consists of a transformation of low entropy into high entropy, i.e. waste, and since this transformation is irrevocable, natural resources must necessarily represent one part of the notion of economic value" (Georgescu-Roegen, 1971, p.18). These goods and services create economic value by meeting human needs and wants (even though sometimes only delivering short-term satisfaction). He stressed that low entropy "is a necessary condition for a thing to have value, [but] is not also sufficient" (Georgescu-Roegen, 1971, p.282), and that value should be assessed by the extent to which these flows contribute to human wellbeing. We agree with Beinhocker's basic argument that this process of coevolution of physical technologies, social technologies and business plans has enabled more effective and efficient ways of meeting human needs and wants (and in some cases creating new wants to satisfy). However, this process of economic value-creation is offset by the increasing depletion of natural resources and creation of wastes, such as greenhouse gases, that threaten to diminish the natural ecosystem services, such as a stable climate, on which human wellbeing depends.

Whereas Beinhocker's focus is the economic value created by the lowering of entropy within the economic system (at the expense of the global increase in entropy), our focus here is the contribution to economic value from low entropy inputs to the economic system. As Georgescu-Roegen emphasises, the chemical energy of low entropy resources, such as coal, is 'free' or 'available' energy, in the sense that it can be transformed into mechanical work. In more modern treatments, this free or available energy in fuels or other energy sources is measured by its exergy content, defined as the maximum work possible in a (reversible) transformation process (Smil, 2008). For a fully thermodynamically consistent treatment of economic value creation, it is thus necessary to consider the exergy content of energy sources and the efficient conversion of this into useful work. Furthermore, as the economic process of energy (exergy) extraction requires energy (exergy) inputs, these inputs must also be accounted for in an energy-economic analysis. As we discuss in subsequent sections, energy return on energy invested (EROI) provides one way of accounting for this.

Hence, in order to fully understand the future macro-economic opportunities and challenges that will be created by a low-carbon transition, we argue that it is necessary broaden the co-evolutionary framework to include the contribution to economic value provided by low-entropy, high exergy inputs to the economy. One way of doing this is to include the coevolution of ecosystems with technologies, institutions, business strategies and user practices, as was proposed in an earlier paper by one of the authors (Foxon, 2011), represented in Figure 1. In this paper, we begin to examine how the role of low-entropy, high quality energy inputs could be incorporated into this co-evolutionary understanding.

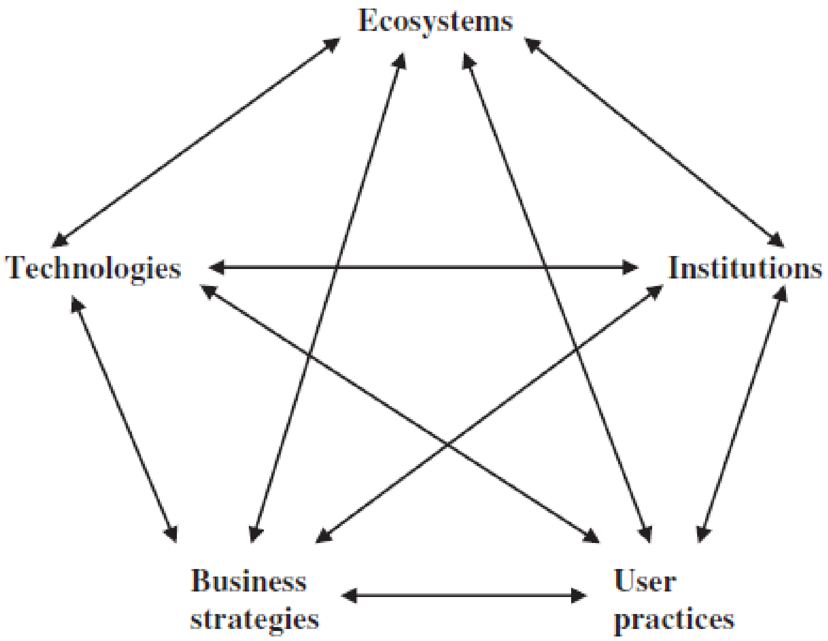

Fig. 1. Coevolutionary framework for a low carbon transition (Foxon, 2011)

In the next two sections, we review two important strands of work that could inform this analysis – firstly, on the economic value of useful work derived from efficient conversion of energy inputs, and secondly, on the role of high net energy inputs into the economy.

4 The role of energy and conversion efficiency in economic growth

In order to be able to combine a coevolutionary perspective on economic growth with an ecological economic understanding, we now examine recent work on energy as a factor of production in formal models of economic growth (Ayres and Warr, 2009), which builds on the work of Rolf Kümmel (1989, 2011) on the roles of energy and entropy in economic production.

Ecological economists, most prominently Georgescu-Roegen (Georgescu-Roegen 1971), have long pointed out the fallacy of attempting to understand and model economic processes in abstraction from their material underpinnings, in particular their embeddedness within, and dependency upon, the natural environment of the biosphere. The emphasis on sustainability within planetary limits led Herman Daly (Daly 1997) to differentiate dependency between renewable and non-renewable resources, and the rate of their use compared to the existing reserves (stocks and flows concepts).

From an ecological economics perspective, energy and materials are inputs to the economy which, although they are conserved, are transformed to the point where they are unavailable as inputs in the next period. This is made particularly clear by the exergy approach of Ayres & Warr (2009). Exergy, measured in energy units, is defined as the maximum work possible in a (reversible) transformation process as a system approaches thermodynamic equilibrium with its environment (Smil, 2008). As explained by Georgescu-Roegen (Georgescu-Roegen 1971), the economy extracts high quality, low entropy resources from the environment, refines and transforms these through industrial processes which require large inputs of energy (itself a high quality, low entropy resource, refined and transformed), and finally emits low quality, high entropy wastes in to the environment (in the form of waste heat and carbon dioxide, among others). Energy, as a physical quantity, is always conserved, however, it is degraded in terms of its quality by its passage through the economy. From the description of Ayres & Warr, “When people speak of energy consumption or energy production, it is usually exergy that they mean. The exergy embodied in a fuel can be equated approximately to the heat of combustion (or enthalpy) of that fuel. But an important difference is that exergy cannot be recycled; it is used up, or ‘destroyed’ to use the language of some thermodynamicists.” According to Ayres &

Warr, exergy is the real energy input to the economy: the quantity it devours and cannot reuse.

Though exergy may be regarded as an input into the economy alongside labour L and capital K, it has to be converted into useful work U to deliver economic value. Ayres, Warr & Ayres estimate the aggregate *efficiency* of exergy use in the economy, through a painstaking effort of historical technology quantification (Ayres, Warr et al. 2003). Useful work, U is defined as the resource (exergy) flow E into the economy times the conversion efficiency f, which represents the overall technical efficiency of conversion of ‘raw’ exergy inputs into useful work output. In fact, this conversion consists of at least two conversion processes. Primary work is work done by the first stage of energy conversion, e.g. electric power generation by means of a steam turbine. Secondary work is work done by electric devices or machines in producing useful outputs. Exergy conversion efficiency is defined as the ratio of *actual* work (output) to *maximum* work (exergy) input, for any process. Using a similar definition, ‘useful’ heat delivered to the point of use can be thought of as ‘quasi-work’. Useful work can then be divided into several categories, including *muscle work* (by humans or animals), *mechanical work* by stationary or mobile prime movers (e.g. heat engines), *heat* delivered to a point of use (e.g. industrial process heat, space heat, cooking) and *electricity*, which can be regarded as a pure form of useful work, as it can be converted into the other forms of work with little or no loss.

One crucially important aspect of using useful work U as a factor of production is that it is a real, combined measure of both aggregate resource dependency *and* technological performance of the economy. As opposed to the traditional endogenous growth endeavours, which utilize proxies for technological progress, the aggregate efficiency measured by Ayres, Warr and Ayres (2003) is a quantification of technological performance, comparing outputs (useful work) to inputs (total exergy consumed). As opposed to attempts to quantify natural capital alongside man-made capital as a factor of production, Ayres & Warr’s exergy measures only what flows into an economy on a yearly basis: its real-time resource dependency. These measures are interesting because they are quantified using physical units of energy (Joules), rather than focusing on prices or costs.

Ayres and Warr (2005, 2009) argue that a theoretical model of growth in output based on a production function (Kümmel,1989), depending on labour L, capital K and useful work U, fits well U.S. GDP data over the 20th Century. Ayres and Warr (2005) comment “In short, it would seem that ‘technical progress’—as defined by the Solow residual—is almost entirely explained by historical improvements in exergy conversion (to physical work), ... , at least until recent times.” If they are correct, it would mean that there is no analytic need for a mysterious Total Factor Productivity, since it can in fact be measured by energy/exergy inputs and the efficiency of their transformation into aggregate useful work. In recent work, Warr and Ayres (2012) add a factor to their production function relating to inputs from information and communication technologies (ICT), in order to fully explain GDP growth for the U.S. and Japan in recent years, but the key explanatory role of energy/exergy inputs and conversion efficiencies remains.

Ayres et al. (2007) argue that increasing efficiency of exergy conversion is the fundamental driver of economic growth:

“In the longer run, increasing exergy conversion (to useful work) efficiency drives growth via declining prices, thus increasing demand for all products and services. This, in turn, spurs new investment, further economies of scale, learning-by-doing, R&D, and further declines in prices, leading to additional demand.”

This feedback mechanism fits well with the qualitative co-evolutionary theory of economic growth. This suggests that wider changes in technologies, institutions, business strategies and user practices enable improvements in exergy conversion efficiency, which generates further economic activity, likely to promote more technological and institutional changes, enabling further conversion efficiency improvements, and so on.

Conventional models of economic growth assume that technological progress can continue indefinitely, fuelling continuous economic growth. However, the Ayres and Warr works suggests that, if improvements in the useful work available stall, due to physical or economic limits on exergy inputs or conversion efficiencies, then there will be limits to economic growth as we have known it.

To better understand the role of energy in economic growth, we now turn to other work on the quality of energy inputs into the economy.

5 Quality of energy inputs into the economy

5.1 High net energy as a driver of economic growth

Scholars in the field of energy studies have long pointed out that energy sources and vectors are not all created equal: depending on the application, some are much more desirable than others, leading to the concept of “quality” of energy (Smil, 2003, 2008, 2010). Quality here relates both to the physical attributes of the energy source or fuel and to its utility for human purposes. From this perspective, the common physical units are deceptive: for different technical purposes, adding Joules to Joules may be akin to adding apples to oranges. If we want to understand the role of energy in the economy, it is essential to recognise these differences.

Energy sources can be defined as the locus where energy is extracted from the environment and provided to the economy (oil well, coal mine, solar radiation on solar panel, wind or water on turbine). Important characteristics of energy sources include availability and difficulty of extraction, long term security of supply, short term intermittency, storage and transportation requirements, and, for fuels, energy density. Energy density is measured as combustible energy content per unit mass (MegaJoules per kg), and is particularly important in understanding the direction of historical fuel shifts from biomass to coal, then to petroleum and currently to natural gas. Fuel shifts, in the past, have always been in the direction of providing higher energy density inputs into the economy.

Smil (2010) has creatively argued that another useful way of comparing the quality of energy sources is in terms of their power densities, measured by rate of energy output in Watts per m^2 of land area needed. Typical power densities of thermal electricity generation from coal or gas are of the order of 250-500 W/ m^2, whilst power densities of wind generation are usually less than 10 W/ m^2, and biofuel conversion usually less than 1 W/ m^2. Solar energy conversion via photovoltaics (PV) or concentrated solar power (CSP) has greater potential with power densities of around 30 W/ m^2 for today’s relatively low-efficiency PV conversion in temperate latitudes, with much higher power densities possible in subtropical latitudes and with efficiency improvements in PV or CSP technologies. Power density is also a useful analytic tool in analysing historical economic development and energy trajectories (Krausmann et al 2008).

In relation to the role of energy inputs into the economy, Charles Hall and colleagues have long argued that a key indicator of the quality of energy sources is EROI: energy return on energy invested (Hall et al., 1986; Hall et al., 2001; Cleveland, 2008; Hall and Kiltgaard, 2012). This is a ratio defined as the energy extracted for future use divided by the energy used in extraction (Brandt and Dale, 2011). This is a very interesting quantity, since it measures the efficiency of energy production as a technical process. Energy sources with high EROI are obviously more desirable than those with lower EROI. For example, criticisms of biofuels include their very low EROI (below 2) compared to fossil fuels (around or above 20) (Murphy and Hall 2010), which imply that societies have to use much more of their initial energy reserves to obtain biofuels than liquid petroleum. In industrialized societies, estimates show that agriculture itself often ceases to be a net energy producer, and becomes an energy consumer, due to industrial chemical inputs and machinery: it is thus an example of industrial production using energy (mainly fossil fuels) to create other desirable products (food and fibre) (Pimentel and Pimentel 1996), rather than as a source of energy.

Historically, societies have moved towards higher and higher energy and power densities, lower carbon intensities per unit of energy, and higher EROI, with clear correlations between all of these indicators leading to the preference of fossil fuels over traditional biomass. The trend towards higher energy density fuels, for example, is the main cause behind the trend of decreasing carbon intensity of energy, since higher quality/density fuels also have lower carbon content per Joule. (This lower carbon intensity of energy is, of course, more than offset by the huge increase in energy use, leading to higher carbon emissions.) However, this century-long trend may be slowing or even reversing, as the high availability of coal trumps the other advantages of high quality petroleum and natural gas (Pielke et al 2008). Moreover, the decrease in EROI of petroleum fuels, due to the exhaustion of the highest quality or most readily available deposits, results in higher life-cycle carbon emissions, contributing to the reversion of this trend.

The evolution of industrial societies has been towards higher and higher EROI, with agricultural societies at very low EROI compared to fossil fuel extraction at EROIs of 20 and above (Gagnon et al 2009). As discussed in the next section, these long run trends play an important role in explaining economic expansion: it is hard to imagine a traditional biomass-based society achieving industrial levels of development

(Cottrell 1955). These aspects should thus also be taken into account by coevolutionary theories of economic growth.

As D. Stern (2010) has argued, although the parameters determining energy quality can be described, as above, the quality of different energy sources and fuels is difficult to quantify using a single scale or dimension. One way of trying to do this is to use market prices, where a higher price would indicate a more desirable form of energy. This is done using the Divisia Index to estimate quality-adjusted EROI for the US by Cleveland (2005). Using a weighted index of relative prices of different energy vectors as a measure of their quality, a quality-adjusted measure of energy use more closely correlates to U.S. GDP figures since 1940 than a measure of energy use based on thermal equivalents (Cleveland et al., 2000; D. Stern, 2011). This suggests that a switch to higher quality energy vectors may have been a causal factor in economic growth.

5.2 Declining EROI for fossil fuels and low carbon sources

The above analysis provides complementary evidence that past patterns of economic growth have relied on high net energy inputs. However, net energy returns, as measured by EROI, are now in decline. Here, EROI is used as an indicator of resource exhaustion (Murphy and Hall 2011). The EROI of oil or gas has been decreasing consistently over time, which can be interpreted as a sign that the best, most easily available reserves have been exhausted, and that the remaining reserves are harder and harder (more and more costly in energy) to obtain, either because of their location (deep offshore wells) or quality (tar sands, bitumen). Depleted oil reserves are traditionally considered under the heading of “peak oil,” where the peak is generally understood to apply to conventional oil, rather than the much lower EROI non-conventional sources, such as the Alberta tar sands. Peak oil describes the exhaustion of oil reserves, with many analyses concluding that we are at or past the peak of conventional oil reserves (Murphy and Hall 2011). In the future, dwindling conventional and more impractical non-conventional reserves would lead to competition over a scarce and harder to extract resource, with consequences in terms of prices: due to the widening gap between supply and demand, but also due to the costlier process of extraction of the remaining reserves. Murphy and Hall (2010, 2011) argue that increases in petroleum expenditures at or above 5% of annual GDP are closely correlated with periods of recession. Peak oil, in their interpretation, would drive prices up and thus lead to an end of the quality/growth nexus described by D. Stern (2011). Many low carbon technologies also have low EROIs, e.g. 18:1 for wind, 3-10:1 for solar PV and 0.8-2.1 for ethanol from corn (due to high levels of fossil fuel inputs needed) (Gupta and Hall, 2011). In this way, physical constraints on energy inputs would have serious economic implications, as the price of oil rises and low carbon substitutes, though falling in cost with learning and experience effects, would not be able to deliver equivalent low carbon energy inputs into the economy at the low costs to which economies have become accustomed. Again, this suggests limits to economic growth going forward.

5.3 EROI and discretionary expenditure

From the above quantitative assessments, Hall et al. (2008) developed a conceptual and simulation model of the implications of declining EROI for the economy (see also Hall and Klitgaard, 2012, Chapter 15). They treat energy as a basic input to the economy, contributing to the output of the economy which goes into either investments or consumption. Consumption may then be further divided into staples, such as food, shelter and clothing, and discretionary expenditure. Investment flows back either into infrastructure maintenance or discretionary capital investment in the economy, or investment into energy acquisition. They argue that the availability of fossil fuels with high physical EROI implies that relatively little economic output has to be invested in energy acquisition. This is reflected in the fact that energy expenditure is typically only around 5% of GDP for industrialised countries. This means that much economic output is available for discretionary spending and discretionary capital investment, which drive economic growth.

However, as societies move to using lower EROI energy sources, because of depletion of easily accessible fossil fuels and/or the adoption of low carbon technologies, they will have to spend a larger and larger proportion of economic output on investment into energy acquisition. This would lead to a dramatic reduction in discretionary spending and discretionary capital investment. This is illustrated in the outputs from Hall et al. (2008)’s simulation model shown in Figures 2 and 3.

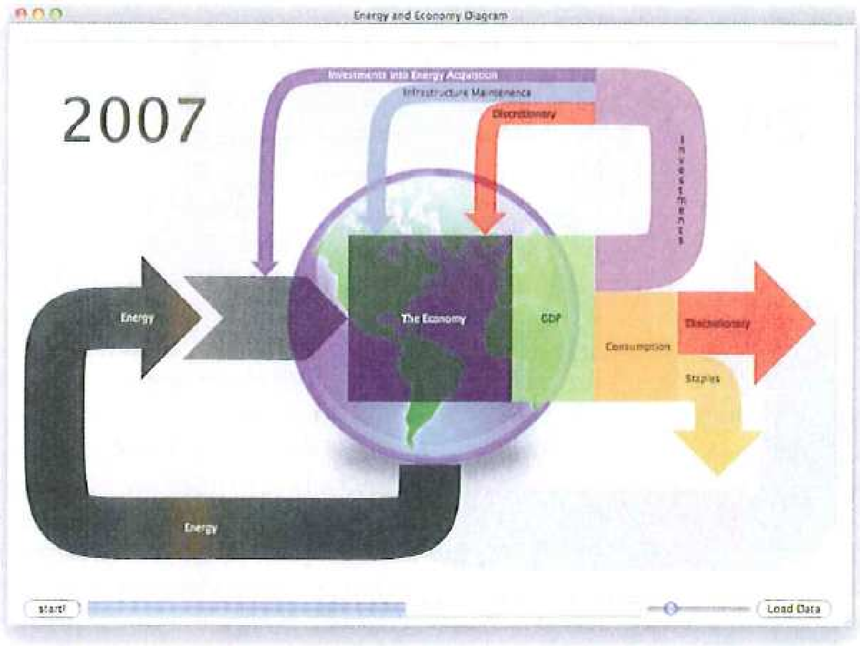

Fig. 2. Low energy investment and high discretionary spending and investment in 2007, with average EROI of 20:1 (Source: Hall et al. (2008))

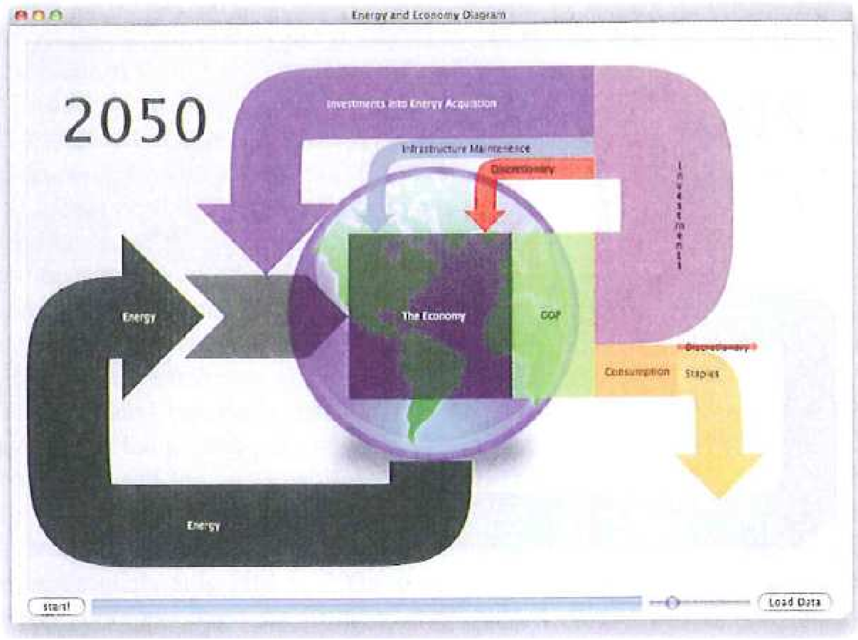

Fig. 3. High energy investment and low discretionary spending and investment in 2050, with projected EROI of 5:1 (Source: Hall et al. (2008))

Hall et al. (2008) argue that this will mean a significant slowdown or halting of economic growth. Under the current dominant macroeconomic model in which national economies with high levels of public and private debt rely on economic growth to create new jobs; this would likely lead to high levels of unemployment and poverty. The technological improvements that have enabled the relatively cheap extraction of shale gas in the U.S. appear to have temporarily halted the decline in EROI, though there is evidence that the majority of shale gas is being extracted from a small number of easily accessible seams that may soon start to decline.

Clearly, much further work is needed to develop this simple simulation model into a more realistic model of the drivers of economic growth. A recent and very interesting contribution from Dale and colleagues synthesizes a purely biophysical economy as two sectors within a system dynamic model: energy producing and energy demanding, showing an overall reduction in scale of economic activity (as measured by total energy) in the transition from non-renewable, high EROI, to lower EROI and renewable sources (Dale et al 2012a,b). Other recent analysis has applied the biophysical economics approach of Hall et al. to analysing the energy payback of renewable energy technologies at an industry level. Dale and Benson (2013) show that the energy input involved in building up the global solar PV manufacturing industry is expected to be fully paid back by 2020 at current rates of industry growth, after which the industry as a whole will be a net energy provider.

6 Coevolutionary approach and energy inputs

Though the biophysical and exergy/production function approaches described above provide valuable insights, they do not adequately reflect the complexity of the relationship between energy use and economic activity. Here, we argue that the extended coevolutionary approach (Foxon, 2011) can build on the view of the economy as an evolving materials-energy processing system, put forward by Georgescu-Roegen (1971) and Warr and Ayres (2012). The exergy/production function approach of Warr and Ayres results in the identification of positive feedback loops as reductions in the price of exergy inputs lead to the substitution of exergy for labour and capital, and increasing demand for final goods and services, leading to economies of scale and further reductions in the price of exergy inputs. This is consistent with the coevolutionary view of the economy as a ‘complex adaptive system’, which is far from equilibrium and that delivers economic services through the positive feedbacks between the actors, networks and institutions within the system (Nelson, 2005; Beinhocker, 2008).

We argue that a synthesis of these materials-energy processing and coevolutionary views of the economy would provide a strong basis for future work. The energy processing view builds on a key aspect of the ecological economic emphasis on the material and energy basis of the economy, by clarifying the role of useful work from exergy inputs, and constraints from declining EROI. As discussed in Section 3, this fills a gap in the coevolutionary perspective which, whilst recognising the economic value created by local entropy reduction from physical transformation processes, had neglected the value contributed by low entropy, high exergy and high EROI inputs to the system. The coevolutionary view then brings the insights from evolutionary economics, which has investigated in detail how coevolution of technologies, institutions and business strategies gives rise to positive and negative feedbacks leading to system change or lock-in at the industry or whole economy level (Murmann, 2003; Nelson, 2005; Beinhocker, 2008). The addition of ecosystems and user practices to the coevolutionary approach (Foxon, 2011) emphasises the importance of also considering the feedbacks relating to energy and materials inputs and waste production, as well as those relating to changing social practices that are enabled or constrained by other systems changes (Foxon and Middlemiss, 2013).

This application of this coevolutionary framework at the industry level has been demonstrated for the case of the introduction of the energy service company (ESCo) business model in the UK (Hannon, 2012; Hannon et al., 2013). The value proposition for this business model is based on selling energy services such as warmth, lighting or mobility, rather than physical units of electricity or gas. As such, this aligns the incentives between supplier and consumer for providing energy efficient solutions, and so should contribute to reducing greenhouse gas emissions whilst delivering end user services (Steinberger et al 2009). However, in the UK, this business model has largely been confined to niche-level activities, with the majority of energy supply being provided under the Energy Utility Company (EUCo) business model of selling physical units: the higher the volume of energy sales, the larger the profits. Hannon (2012) argued that the lock-in of the EUCo business model could be explained as a result of positive feedbacks between the adoption of this model and elements of the wider UK energy system, particularly the regulatory and financial institutions, as shown in Figure 4. He noted that more recent regulatory and technological changes, such as obligations on energy supply companies and reductions in costs of local sustainable energy generation technologies, such as combined heat and power (CHP) co-generation systems, are beginning to generate positive feedbacks favouring the adoption of the ESCo business model by new entrants and incumbents.

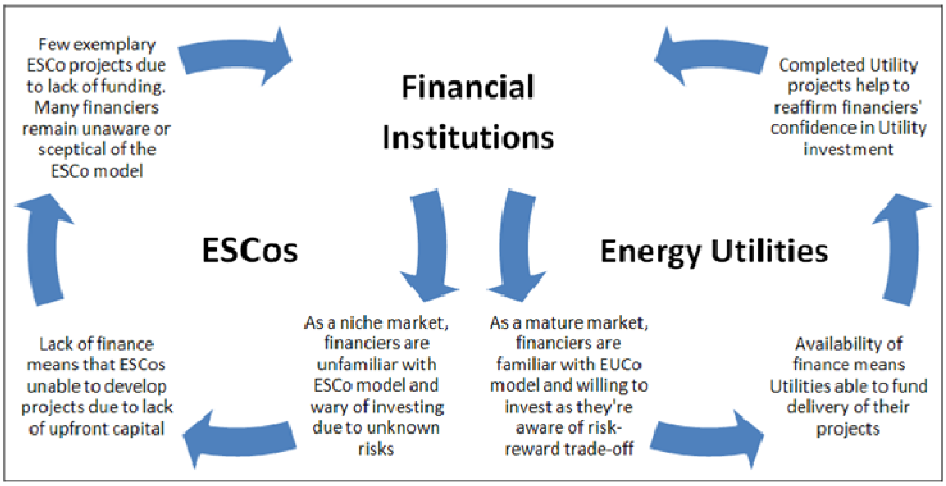

Fig. 4. Co-evolution of ESCo and Energy Utility populations, focusing on financial institutional arrangements (Source: Hannon (2012))

The extended coevolutionary approach also fits well with other insights gathered from macro-level analysis of long-term energy and economic change. The idea that there have been five long waves of structural economic change since the first industrial revolution follows coevolutionary thinking (Freeman and Perez, 1998; Freeman and Louca, 2001; Perez, 2002, 2013). In each long wave, changes in technological systems interacted with changes in production systems, patterns of consumption and styles of living to drive periods of high economic growth. The first four long waves were associated with new energy sources and technologies, including water-powered mechanisation of industry in the late 18th/early 19th Centuries, steam-powered mechanisation in the mid-19th Century, electrification of industry and the home in the late 19th/early 20th Centuries, and mass production and oil-powered motorisation in the 20th Century (the current 5th long wave is led by information and communication technologies that rely on cheap electricity). These technological changes and associated changes in institutions, user practices and business models helped to drive long-run economic growth in industrialised countries. However, as Moe (2010) has emphasised, these structural changes required vested interests aligned with incumbent technologies to be overcome. These system changes have been associated with significant reductions in the cost of energy services to businesses and households, which have stimulated increasing demands for energy services (Fouquet, 2010). It has been suggested that low carbon technologies could form part of a new 6th long wave of structural economic change (N. Stern, 2012), but, at the moment, low carbon technologies do not appear to possess the properties that drove previous long waves of economic change (Pearson and Foxon, 2012).

Looking at the very long-run history of the rise and collapse of complex societies, Tainter (1988, 2013) has argued for the existence of an ‘energy-complexity spiral’. The availability of surplus energy permits increasing complexity that enables certain societal problems to be solved, whilst often creating new problems. Society then responds by “creating more complex technologies, establishing new institutions, adding more specialists or bureaucratic levels to an institution, increasing organisation or regulation, or gathering and processing more information” (Tainter, 2013, p. 90). Following Hall et al. (2009), he notes that this raises significant challenges for achieving a sustainable society in the face of declining net energy or EROI.

The coevolutionary approach thus suggests that, to assess the overall impacts of the introduction of energy technologies, strategies or practices on the productivity of the economy, requires analysis that takes into account contextual factors and positive and negative feedbacks between subsystem changes, including the role of low entropy, high quality primary energy inputs.

This type of coevolutionary analysis could be applied to examine the evolution of energy-dependent consumption and production systems, by broadening the coevolutionary history of the global economy given by Beinhocker (2006) to include the roles of natural resources and user practices. This would provide an improved basis for better understanding the potential future evolution of industries and economies in a low carbon transition.

7 Discussion

The results reviewed in this paper present a strong case that the availability of high quality energy (exergy) inputs and their efficient conversion into useful work have played a significant role in economic growth in Western industrialised countries. We argue that the increasing ability to harness these energy inputs has co-evolved with other changes in technologies, institutions, business strategies and user practices to enable growth in economic output, through positive feedback mechanisms. This suggests that further research to explore and, where possible, quantify these coevolutionary processes and positive feedback mechanisms would significantly enhance understanding of the challenges and opportunities of maintaining economic prosperity as energy input prices increase. Further investigation into the relations between these coevolutionary processes and capital and labour productivity improvements should yield important insights. Hall et al. (2008)'s simulation model provides a useful conceptualisation of the economic implications of moving to lower quality energy inputs, but more precise specification of the economic relations and the feedback mechanisms in the model would be necessary to inform decision making.

This has important implications for a low-carbon transition, as many of the renewable energy inputs that are needed to substitute for fossil fuels inputs appear to be of lower quality, at least in terms of their EROI and power densities in relation to land area. The intelligent use of renewables in relation to land area, for example, by using cellulosical biomass to minimise competition with food sources, and using urban roof spaces for PV, would appear to be crucial. Further R&D and commercial demonstration of a range of renewable technologies will be needed to stimulate conversion efficiency improvements and price reductions.

However, the results also demonstrate the difficulty of quantifying the contribution of energy inputs to economic output. It would appear that robust measures are needed both of conversion of energy (exergy) inputs to useful work outputs, as Ayres and Warr (2009) have done, and of the quality of different energy (exergy) inputs. Only by developing and applying such relevant measures will we be able to better understand the contribution of energy inputs to past economic growth, and the implications of a transition to low-carbon sources of energy on future economic growth.

We argue that the insights reviewed in this paper have important implications for analysis of whether it will be possible to move to a non-material basis for economic growth, as Hepburn and Bowen (2012) and other have suggested. These insights suggest that the current dominant macroeconomic model based on continuing high levels of economic growth to deliver jobs and prosperity cannot be maintained under lower quality energy inputs – although there is a continuous “efficiency” in the delivery of human development per unit energy over time (Steinberger & Roberts, 2010). An economy driven by growth in a non-material ‘intellectual economy’, powered by low carbon inputs, would look very different to the current macroeconomic model. This supports the need to explore alternative economic models that would deliver high levels of wellbeing and reduced environmental impact without reliance on maintaining economic growth (Jackson, 2009; Dietz and O'Neill, 2013).

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