The role of energy in economic development: a co-evolutionary perspective

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Abstract

Recent work (Ayres and Warr, 2009; D. Stern, 2011) has shown that the increasing availability of cheaper and higher quality forms of energy inputs has played a key role in driving economic growth in industrialised and emerging economies. This builds on the work of economic historians, who have 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). This paper examines this issue from a co-evolutionary perspective, in the context of likely future rises in energy input costs resulting from 'peak oil' and the necessary substitution to low-carbon energy sources to mitigate climate change.

Co-evolutionary analyses of economic growth have argued that a process of co-evolution of technologies, institutions and related business strategies has driven the wide availability and reduction in costs of goods and services that have significantly enhanced human welfare (Nelson, 2005; Beinhocker, 2007). Co-evolutionary analysis also demonstrates how increasing returns to adoption have led to the lock-in of economic systems based on high carbon energy inputs (Unruh, 2000), and could provide a useful framework for analysing a transition to a sustainable low carbon economy (Foxon, 2010a). Related work on techno-economic paradigms (Freeman and Perez, 1988) and general purpose technologies (Lipsey et al., 2005) has shown that the full economic benefits of new technological advances with widespread applications are only realised when wider institutions and practices have had time to adapt to these technologies. For example, the economic benefits of information and communication technologies (ICTs) only showed up in productivity statistics as firms adapted their production and retailing processes to capture the potential advantages that these technologies offered. Moreover, political science and historical studies of technological adoption indicate that energy transitions occur only when the power of vested interests representing existing industries is counter-balanced by other forces in society (Moe, 2010).

The paper argues that 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 economic impacts that are not captured in neo-classical economic analyses, as these analyses neglect the role of energy as a factor of production. A co-evolutionary perspective suggests that cheap energy has 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.

Keywords

Co-evolution; technological and institutional change; energy inputs; lock-in; positive feedbacks.

1. Introduction

Joseph Schumpeter's ground-breaking book "The Theory of Economic Development" (Schumpeter, 1911/1934) improved our understanding of the economy as a dynamic, evolving system driven by innovation in new technologies and new organisation forms, led by entrepreneurial individuals and firms. However, in the standard model of economic growth, these technological and organisational factors are subsumed into the 'Solow residual', the gap between total growth in economic output and that which can be explained by labour and capital alone (Solow, 1956, 1957). Recent work on endogenous growth theory also includes 'human capital' or 'knowledge spillovers' as contributors to growth in output (Agion and Howitt, 1998), but this work does not include a wider representation of technological and institutional change or consider the role of physical inputs into the economy. Ecological economists (Georgescu-Roegen, 1971; Daly, 1997) and economic historians (Allen, 2009; Moe, 2010) have argued qualitatively that low-cost, high quality energy inputs, from coal, oil and gas, have contributed significantly to the growth in economic output. Recent work by Ayres and Warr (2005) has given a quantitative argument that including a factor representing 'useful work' from physical inputs can explain the contribution to growth complementary to that of labour and capital represented by the Solow residual in the standard approach.

This paper reviews these arguments and highlights the further research questions raised in the context of understanding the implications for economic growth of a transition to an economy based on low-carbon energy sources. Such a transition is necessary to address the challenge of climate change. A meta-analysis of the expected annual cost of achieving emissions reductions, consistent with stabilising atmospheric concentrations of greenhouse gases at around 500-550 ppmCO_2e by 2050, is likely to be around 1% of global GDP, ±3% (Barker et al., 2006; N. Stern, 2007) (though recent work suggests that a more stringent target is needed to avoid severe climate change impacts). However, the macroeconomic models underlying this analysis generally assume that this would only represent a small decline in the average growth rate of annual GDP relative to a hypothetical 'no climate change' baseline of continuing economic growth. As these macroeconomic models are mostly descendants of the original Solow model, they may not adequately account for the full economic effects of moving to higher cost and lower quality low-carbon energy inputs, and so may underestimate the economic costs of a low-carbon transition. On the other hand, these models also generally do not adequately account for the Keynesian economic stimulus that would arise from high levels of investment in low-carbon energy technologies and infrastructure, which would arguably reduce the economic costs of a low carbon transition (Romani et al., 2011).

This paper seeks to clarify some of these issues at a conceptual level, which, it is hoped, will inform future more quantitative analysis and macroeconomic model development. In particular, it argues that recent work on coevolutionary understanding of long-term economic development provides a useful framework for analysing a transition to a low-carbon economy (see also Foxon, 2011). For example, Freeman and Perez (1988) have identified five 'long waves' of economic development, in which growth is driven by development and application of new technologies and processes, such as the steam engine, electrification and mass production, but for which the full economic benefits are only realised when wider institutions and practices have had time to adapt to these technologies. Similarly, political science and historical studies of technological adoption indicate that energy transitions occur only when the power of vested interests representing existing industries is counter-balanced by other forces in society (Moe, 2010). Richard Nelson (1998, 2005) has identified and analysed the coevolutionary interactions between technological change, institutional frameworks, investment in human capital (skills) and firms' strategies as drivers of economic growth. 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.

Ecological economists have argued for the need to understand economic processes in the context of resources, waste assimilation functions and ecosystem services provided by natural ecosystems (Georgescu-Roegen, 1971; Daly, 1997). In particular, as this paper discusses, the availability of cheap and high quality energy inputs to economies has been argued to be a key source of economic growth (Ayres and Warr, 2009, D. Stern, 2011). However, energy input costs are likely to rise in future due to diminishing availability of cheap fossil fuel sources, commonly referred to as 'peak oil', and the need for rapid substitution to low-carbon energy sources to mitigate climate change, (caused by the scale of anthropogenic greenhouse gas emissions far outpacing the ability of natural processes to assimilate them: the most significant contribution being carbon dioxide released by burning of fossil fuels, which represent over 80% of primary energy use worldwide (IEA 2010).) It has been argued, though, that high levels of investment in low-carbon technologies could stimulate a sixth wave of economic growth, provided that this is accompanied by other changes in institutions, skills, finance and policies (N. Stern, 2011). Hence, we argue that a useful coevolutionary framework for analysing a transition to a low carbon economy should include how ecosystem inputs coevolve with other coevolving economic factors of technologies, institutions, business strategies and user practices (Foxon, 2011). This paper aims to begin the application of that framework to the question of the implications for economic growth of a transition to a low carbon economy.

Section 2 provides an overview of mainstream economic growth models. Section 3 presents coevolutionary theories of economic growth and their relevance to a low carbon transition. Section 4 emphasizes the importance of the quality of energy inputs and not just their energy content. Section 5 examines the role of energy in macro-economic growth models. Section 6 concludes by identifying research questions and challenges raised by combining coevolutionary perspectives, 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 some recent (and less recent) efforts that are relevant to our focus on the role of energy in the economy. We then consider implications that co-evolutionary ideas would have for these models.

One important caveat before we begin: growth models, or models of economic development, are by definition macro-economic. Quantifiable parameters, which are possible to measure and compare in long time series and between different national economies, are the bread and butter of macro-economic development models. It is only through such long-run, reproducible and robust variables that measuring and analysing economic growth makes any sense. There is thus a considerable conceptual challenge in relating the mostly qualitative coevolutionary theory of economic growth to quantitative macro-economic models, but one which is potentially rewarding as well.

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. Indeed, both labour and capital are intuitively necessary for any type of economic production, and they are clearly separate items, although substitutions between them are possible, especially in the long run. 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 and Trevor Swan, 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 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 are clearly germane to coevolutionary economics. They constitute the evidence that raw quantities (of 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 ideas. 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 increases 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.

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. Nelson and Winter (1982) formulated an evolutionary theory of economic change, drawing particularly on the economic themes of Joseph Schumpeter (1911/1934, 1942) and the idea of 'bounded rationality' of firms and individuals promoted by Herbert Simon (1955, 1959). Within this approach, Nelson and Winter (1974, 1982) developed an evolutionary simulation model of economic growth. In this model, firms are represented by their capital stock *K* and a production technique, specified by a pair of input variables a_l and a_k relating to their use of labour and capital. These firms are not assumed to profit-maximise, but instead to 'satisfice', i.e. if the annual return on their capital exceeds a specified value, they retain their existing production technique. If their return on capital falls below this value, they are stimulated to search for an improved production technique, either by an incremental improvement on their current technique or by imitating the technique of a successful firm. Nelson and Winter (1974, 1982) claim that the results of their simulation model match well the data for US economic output from 1909 to 1949 used by Solow (1955) as the basis for his model of how output per capita depends on capital/labour ratio, wage rate, capital share and technological progress function, discussed in the next section. Note that, unlike the Solow model, the

Nelson and Winter model does not assume a moving equilibrium or a well-specified production function of the whole economy.

The firm's production technique here is an example of what Nelson and Winter refer to as a 'routine', i.e. a specified pattern of behaviour or activity. In recent work, Nelson has argued that firms' routines consist of the 'know-how' for converting physical inputs into outputs, plus a division of labour and mode of co-ordination of human action necessary for this to be enacted. He refers to the former as a 'physical technology' and the latter as an institution or 'social technology' (Nelson and Sampat, 2001; Nelson, 2005, 2008). In this sense, an institution defines a low transaction cost mode of organisation and co-ordination. As Nelson puts it, an institution is "like a paved road across a swamp", as it constrains behaviour but enables a desired outcome to be achieved. Institutions at the firm level are embedded in wider institutional frameworks consisting of laws, regulations, norms and practices. Firms' routines evolve by searching for novel physical or social technologies, if the ones that embody present production processes no longer 'satisfice' in relation to profit or return on capital. This could lead to routines consisting of new technologies or new institutions, but the technologies and firm-level institutions also need to fit well together and with the wider technological and institutional systems in which they are embedded, in order to deliver economic benefits.

As Schumpeter (1911/1934) argued, economic progress is driven by innovation which consists of breaking from established routines. This is a risky process, but with the potential of high rewards for successful innovation. Broadening from an individual firm level to a systems level, Nelson (2005, 2008) thus 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. These systems evolve by a generalised Darwinian process of selection, variation and retention (Dennett, 1995; Hodgson and Knudsen, 2004). 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 heteorogeneous 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.

As others (Basalla, 1988; Mokyr, 1990; Ziman, 2000) have argued, physical technologies have evolved through a generalised Darwinian process of exploring the design space by 'deductive-tinkering' to reach local maxima, at which technologies better meet human needs and wants. This does not deny the role of serendipity or happy accidents in the course of technological change, as new innovations are adapted to fulfil different needs and wants from those that they were originally designed for. It also recognises that human needs and wants may change over time, and may be actively influenced by firms, for example through advertising. The current economic system relies on incentives for increasing consumption to compensate for technological changes that lead to increases in labour productivity, in order to avoid widespread unemployment (Jackson, 2009).

Beinhocker (2006) argues that physical technologies also co-evolve with social technologies, 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 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 artifacts or actions that are fit for human purposes.”

We argue that conception 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 convert low-entropy inputs, i.e. natural resources, into high-entropy outputs, i.e. wastes, whilst creating a flux of physical and psychological services that 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 also depends. 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 coevolution of ecosystems with technologies, institutions, business strategies and user practices (Foxon, 2011). 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.

In the next sections, we first consider energy quality, then the represesentation energy inputs into economic processes in macro-economic growth models. As we discuss in Section 5, Ayres and Warr (2009) have argued that it is the quantity of useful work that energy inputs deliver that is the key economic variable. However, this analysis is based on the contribution that high quality energy inputs, i.e. coal, oil and gas fossil fuels, have made to economic output over the last century. In the next section, we review other work that has argued that for the importance of the quality, as well as the quantity, of energy inputs into the economy, and that renewable energy sources are likely to be of lower quality.

4. Quality of energy inputs into the economy

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, 2010). Quality here relates both to the physical attributes of the energy source or fuel and to its utility for human purposes. In this sense, 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 important to overview 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 weight (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 higher energy density, with some arguing that hydrogen and nuclear fuel represent continuations of this trend towards concentrated energy sources (although, of course, hydrogen is an energy carrier rather than an energy source, and nuclear fuels need the heavy apparatus of a power plant).

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 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).

Another indicator of the quality of energy sources is EROI: Energy Return On (Energy) Invested (Cutler 2008). This is a ratio defined as the energy extracted for use divided by the energy invested in extraction. 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 a source of energy.

Historically, societies have been moving 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. 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). The evolution of industrial societies has similarly 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). These long run trends probably play an important role in explaining economic expansion: it is hard to imagine a traditional biomass-based society achieving industrial levels of development. These aspects should thus also be taken into account by coevolutionary theories of economic growth.

Energy vectors, in contrast to energy sources, are defined as any form of energy which can be used or transformed in an economy, including electricity, heat and refined fuels. Energy vectors can also be compared in terms of their relative qualities, although the most important question to answer in this case is always “for what purpose?” since much depends on the precise technical application. Energy vectors can be compared in terms of their ease of storage and transportation, energy density (especially for transportation, hence the importance of petroleum-derived fuels), environmental pollution (particulates, acidifying emissions of most combustion processes, health concerns in home and urban environments) and versatility of use. In terms of versatility, electricity is the uncontested leader, since it can be used for heat, transportation, illumination, manufacturing, running appliances and communication.

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 doing this is to use market prices, where a higher price would indicate a more desirable form of energy. Using a weighted index of relative prices of different energy vectors as a measure of their quality, D. Stern (2011) argues that a quality-adjusted measure of energy inputs more closely correlates to U.S. GDP figures since 1940. This suggests that a switch to higher quality energy vectors may have been a causal factor in economic growth.

EROI can also be used as an indicator of resource exhaustion (Murphy and Hall 2011): if the EROI of oil or gas decreases consistently over time, this 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).

5. Energy as a factor of economic growth

We now turn to energy as a factor of production in formal models of economic growth. In this section, we are particularly indebted to two recent contributions on energy and economic growth: the first is the work of Bob Ayres and Ben Warr, summarized in their recent book “The economic growth engine: how energy and work drive material prosperity” (Ayres and Warr 2009); the second is the 2011 “Ecological Economics Review” issue of the Annals of the New York Academy of Sciences, in particular the excellent article “The role of energy in economic growth” by David Stern (Stern 2011).

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 use compared to the existing reserves (stocks and flows concepts).

In his review of energy linkages to the economy, D. Stern (2011) explores theories that seek to account for energy reserves as a form of capital, albeit “natural” capital. Because of the difficulties in estimating natural capital, and its remoteness from economic processes (unlike man-made capital, natural capital in the form of energy reserves in the environment does not play a role in economic production), it seems unlikely that the solution to integrating energy into models of economic growth would rely on such a conceptualization.

In order to implement energy constraints on economic growth, David Stern (2011) modifies the Solow model by adding an energy input term to the production function that has low substitutability with capital and labour, while allowing the elasticity of substitution between capital and labour to remain at unity. This model then has two solution regimes. One, in which energy is abundant, corresponds to the Solow model, in which the steady-state level of capital stock and output are determined by the savings rate, the level of labour augmenting technology, and the rate of depreciation. In the other, when energy is relatively scarce, the steady-state level of output is determined by the supply of energy and the level of energy-augmenting technology. In this model, in the era of cheap and abundant energy in the 20th Century, energy supplies would not have played a large role in determining economic growth, and so the original Solow model provides a good approximation. David Stern’s model thus explains the lack of growth of pre-industrial energy-constrained societies, but does not explain the role of energy supply and use in the economic growth of industrial societies. In particular, no link is drawn between the Solow residual and energy use.

In terms of factors of production, it could be argued that resources in general, and energy in particular, are separate to labour and capital, but necessary for both to achieve economic production. However, the place of these physical resources within current economic thinking is far from clear. Most production functions are based on a very schematic model of the economy, consisting of one average sector, with an average ratio of labour to capital, and an average economic output. Introducing physical inputs usually implies complicating this model to involve at least two sectors, at least conceptually, as do Ayres & Warr (Ayres and Warr 2009). Moreover, most ecological economists would view physical inputs to the economy entering the first (primary) sector, which then transforms and refines the energy, and sells them to the next sectors. However, according to D. Stern (Stern 2011)

“Primary factors of production are defined as inputs that exist at the beginning of the period under consideration and are not directly used up in production (although they can be degraded or accumulated from period to period), while intermediate inputs are those created during the production period under consideration and are used up entirely in production. Mainstream economists usually think of capital, labor and land as the primary factors of production, and goods (such as fuels and materials) as intermediate inputs. The prices paid for the various intermediate inputs are seen as eventually being payments to the owners of the primary inputs for the services provided directly or embodied in the produced intermediate inputs.”

This implies that “primary inputs” in the economic sense are incompatible with energy and materials in the ecological economics sense, 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, estimated in energy units, corresponds to the thermodynamic potential of a resource compared to the average of the environment (purity of a refined metal, for instance). 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. Exergy is clearly incompatible with “primary inputs”, as described by Stern above.

Ayres & Warr are not simply content to model the economy as a one-sector exergy user: this would be equivalent to simply adding the primary exergy input into economic growth models, which would satisfy those who argue that resource inputs are factors of production, but would hardly advance the larger goal of including both resources *and* technology. Ayres, Warr & Ayres proceed to estimate the aggregate *efficiency* of exergy use in the economy, through a painstaking effort of historical technology quantification (Ayres, Warr et al. 2003). The parameter they then use as a factor of production is useful work, U. This 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.This requires a conceptual deviation from the traditional single sector economy: “As a first approximation, it is now convenient to assume that the economy is a two-stage system with a single intermediate product, denoted U.” (Ayres and Warr 2009).

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 the more interesting because they are quantified using physical units of energy (Joules), rather than focusing on prices or costs.

The Ayres and Warr model thus has a realistic representation of the role of exergy inputs and conversion into useful work that delivers economic services. However, it does not differentiate between the quality of the sources of exergy inputs. The quality element would only come into their model through the efficiency factor, if higher quality inputs resulted in more efficient conversion processes to useful work. This notion could be related to EROI: the higher the quality of an energy input, the higher its EROI, the higher the likely efficiency of its conversion to useful work *U*.

The production function employed by Ayres and Warr is the LINEX function developed by Kummel (1980,1985). It does not follow the Cobb-Douglas form, where the factors of production are combined through multiplication,

where the exponents are interpreted as the elasticity of output. Instead, the LINEX function starts with energy (or in this case, useful work *U*) and the exponential ratios of L/U and (L+U)/K:

Since the parameters *a* and *b* can be time-dependent, the fits to historical GDP can obviously be extremely good. The parameters *a* and *b* do not have a straightforward economic interpretation. According to D.Stern’s (2011) interpretation,

“Output elasticities are not constrained to equal cost shares and the LINEX production function assumes that as capital accumulates and the economy becomes more ‘automated’ the output elasticity of labor falls. Also labor and energy are assumed to be q substitutes – increases in energy use reduce the marginal product of labor, which can become negative when energy is very abundant.”

D. Stern views these attributes of the LINEX model as disadvantages, but they may well reflect the reality of mature industrialized societies, where the mechanisation of production tends to make all but the lowest-paid labour uneconomical and redundant, and constant increases in the total volume of consumption of non-essential goods is overtly promoted as the only way to stave off mass unemployment (Jackson 2009).

Moreover, Ayres and Warr (2005) comment on the success of their LINEX model with useful work U as an input in modelling US economic growth over a 100 year time span by stating that “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), as summarized in Fig. 2, 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.

Several questions of key importance to coevolutionary economics arise from this research:

- Is it possible to model future or expected changes in efficiency, based on coevolutionary ideas of technological development and institutional constraints?
- What does the Ayres-Warr model tell us about a resource constrained future, where the only levers on growth are efficiency, labour and (mainly existing) capital?
- How can savings and investment be understood in this model?

- How can we interpret past increases in labor productivity? Were these mainly apparent effects due to increases in the availability of useful work, and if so can we expect labour productivity to decrease in a resource-constrained future?

6. Discussion and Conclusions

The results reviewed in this paper present a strong case that the availability of high quality, low entropy and low price energy inputs into the economy 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. For example, as economic historian Robert Allen (2009) has argued, 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. 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 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.

However, the results 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 useful 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.

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