The role of energy and efficiency in economic development: policy implications

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Abstract

Energy policies in industrialised countries are now seeking to promote a transition to providing low carbon, secure and affordable energy services. This requires a fundamental reassessment of the role that the availability and efficient conversion of energy sources into useful work plays in economic development. Recent work (Ayres and Warr, 2009) has shown that the increasing availability and efficient conversion of cheaper and higher quality forms of energy inputs has played a key role in driving economic growth in industrialised and emerging economies. This perspective has serious implications for economic growth projections, since we may be at a turning point in affordable, easily available energy: fossil fuel sources are becoming increasingly expensive due to depletion of easily accessible reserves and the imposition of higher carbon prices, and the generation from low carbon energy sources is still relatively expensive. Thus the continuation of past trends in economic growth rates cannot be assumed. This paper applies a coevolutionary framework (Foxon, 2011) to raise the issue of the contribution of the efficient conversion of energy sources to long-term economic growth and examine positive feedbacks or virtuous cycles between changes in energy input and conversion costs and changes in economic activity. This analysis highlights the importance of both energy efficiency improvements and changes in end-use consumption patterns to ensuring continuing economic prosperity as countries undergo a transition to low carbon energy systems.

Introduction

Achieving high levels of energy efficiency is recognised as a key component of a transition to a low carbon society, and is also argued to be a strong driver of economic growth. This means that a better understanding is needed of the drivers and barriers to the adoption of energy efficiency measures at the micro level, and of the macro-economic implications of energy efficiency improvements on the demand-side and supply-side. Recent work (Ayres and Warr, 2009) has shown that the increasing availability and efficient conversion of cheaper and higher quality forms of energy inputs has played a key role in driving economic growth in industrialised and emerging economies. In this paper, we review some of the relevant literature, and consider the links between economic growth and energy efficiency policies from a coevolutionary perspective (Foxon 2011).

Review of 'green growth' arguments

The issue of energy efficiency and its promotion horizontally across consumption types and vertically along supply chains is intimately connected with the very basis, structure and definition of industrialised economies. The links between energy efficiency improvements, resource productivity more broadly, and macro-economic growth are thus key to understanding the potential for efficiency strategies for reducing the dependency of developed economies on energy inputs.

In past decades, and certainly since the "Limits to Growth" report of the Club of Rome (Meadows et al., 1972), the challenge of reconciling growing population, economies and their energy requirements with environmental limits has been framed as a competition of rates: what growth rate levels are

acceptable, and how do various growth rates compensate for each other. Sustainable development is divided into 'weak' or 'strong' sustainability based on the type of compensation allowed: natural and man-made capital are allowed to substitute for each other in the weak version of sustainability (but not in the strong), implying that depletion, or negative growth rates, of natural capital, is acceptable as long as man-made capital is growing at least as fast, or faster (Daly 1997).

In recent versions of the sustainability debate, these arguments have been crystallized into their most simple form. 'Green' growth is defined as good economic growth: growth that is consistent with decreases in energy inputs and pollution outputs, whereas 'brown' growth, or bad growth, implies increases in energy and emissions (Victor 2010). The concept of a green economy, moving towards green growth, was a central topic of the Rio 2012 conference. UNEP put out a series of reports on the Green Economy building up to the conference (UNEP 2011), emphasizing necessary macro-economic changes. Hepburn and Bowen (2012) describe the macro-economic theories and debates around green growth or degrowth, and conclude by agreeing with Herman Daly (1991): that the important aspect is reaching a steady state of zero growth in the material economy, including fossil fuel based energy, with growth in other aspects ('development' according to Daly, the 'intellectual economy' according to Hepburn & Bowen) remaining possible and even desirable. Others have argued that as GDP is a distorting measure of progress, we should do away with it as an indicator (van den Bergh, 2011).

A useful starting point in thinking about the consistency between economic growth and reducing environmental impacts is the 'IPAT' equation (Ehrlich and Holden, 1971). Focussing on CO_2 equivalent emissions as the main global environmental impact associated with energy use, this decomposes environmental impact I as the product of population P, affluence A, measured by GDP per capita, and technology T, measured by CO_2e intensity of GDP, i.e.

$$I = PAT.$$

In terms of growth rates, this identity implies the growth rate in environmental impact is the sum of the growth rates of population, affluence and 'technology'. Over the past 20 years, at the global level, annual population growth has been 1.3 %, annual GDP per capita growth has been 1.4 %, and CO_2e emissions per unit of GDP have been falling by 0.7 % p.a. (Hepburn and Bowen, 2012). Hence, the relative decoupling of emissions from GDP has been overcome by growth in population and affluence, leading to an absolute increase in CO_2e emissions:

Annual growth in CO_2e emissions
= 1.3 % + 1.4 % - 0.7 % = 2 %.

For emissions to fall at the rate needed to achieve the 2 °C global temperature increase limit, CO_2e emissions would need to fall by around 5 % p.a. This would imply an annual rate of emissions reduction per unit of GDP of around 7 % if historical trends in population and GDP growth continue (Jackson 2009). How this unprecedented rate of emissions reduction could be achieved leads to differences of opinion on the desirability of continuing economic growth, as measured by GDP. Ecological economists, such as Daly (1991), Jackson (2009) and Dietz and O'Neill (2013), argue that Western societies need to move away from a focus on economic growth, in order to create an economic system based on achieving human well-being through greater focus on non-material ends rather than material consumption. They argue that this would enable both more satisfying lives and dramatic reductions in emissions intensities, by focussing on renewable energy sources and more local production of goods and services. Steinberger et al (2012) have shown that high life expectancy and low carbon emissions are compatible, even when emissions are adjusted for international trade – but at levels of GDP below $12,000 per capita. Moreover, according to Steinberger & Roberts (2010), the level of carbon emissions required for high human development is falling dramatically, theoretically enabling universal high human development if the emissions were distributed equitably. However, environmental economists, such as Hepburn and Bowen (2012), argue that continuing GDP growth is necessary, in the form of 'green growth' to generate the levels of investment needed in low carbon technologies, but that this can be done in a way that is consistent with limiting or reducing the physical scale of the economy, as suggested above. Much progress can be made by focussing on the areas of agreement between these two views. However, at a fundamental level, we need a better understanding of the role of energy use and energy efficiency in driving economic growth, in order to be able to fully compare the two views on policies aiming promote physical decoupling or 'degrowth', and in relation to societies thinking about the most desirable way of achieving a sustainable, low carbon transition.

Feedback loops between energy conversion efficiency and economic growth

The central importance of energy to human societies, both modern and ancient, is obvious, but often confusing in terms of practical modelling and quantification. The best reference for a comprehensive study of this dependency and its analysis is Smil's General Energetics (2008). One particularly important point is that it is not only the quantity of primary energy consumed by a society, or its composition, that matter in terms of the contribution of energy to the economy, but the efficiency of its conversion into forms capable of doing useful work. Thus efforts to formally model the dependency of economic growth on energy are bound to fail, or succeed only very partially, unless improvements and changes in conversion efficiency are also taken into account.

This key point has been made very clear by the work of Bob Ayres, Ben Warr and their colleagues (Ayres et al., 2003; Ayres and Warr, 2005; Ayres et al., 2007), summarized in their 2009 book 'The Economic Growth Engine: How energy and work drive material prosperity' (Ayres and Warr, 2009). They have estimated the useful work delivered to the economy by the increasingly efficient conversion of primary energy over many decades (up to a century) for several countries, and have shown that it is possible to model economic growth using useful work as an input alongside labour and capital. They argue that this model explains historical trends in economic growth without an arbitrary 'residual' factor associated with autonomous technological change. Their conceptual model,

described in Ayres et al. (2007), presents the links between efficiency improvements and economic growth as a virtuous cycle, with positive feedback loops connecting the two. The cycle can be summarized as follows: (1) declining unit costs of final energy result in (2) lower unit prices, leading to (3) higher consumer demand and thus (4) to more physical capacity for substituting energy and other resources for labour, which in turn lead to (1) declining unit costs, completing the cycle (Figure 1). The effect of the total cycle is to improve labour productivity and incomes (i.e. growth). Energy efficiency intervenes at points (1) and (4) of the cycle, whereas (2) and (3) are simply the economic mechanisms balancing supply and demand of products and services.

According to this schematic model, increasing energy efficiency at the macro level will broadly result, in economic terms, in the decreasing costs of products and services (step 1 above), and through the workings of the economy, this will inevitably, or rather usually, result in an increase in the capacity, or physical scale, of the consumption of products and services, and hence the capacity for investment in efficiency measures (step 4 above), including the technical efficiency of energy conversion processes as well as the cost-efficiency of energy production. In energy economics terms, this relation between efficiency improvements and increases in scale of consumption and/or declining costs of energy inputs is known as the rebound effect (Hertwich 2005, Sorrell and Dimitropoulos 2008). However, it is necessary to make a clear distinction between micro-level and macro-level effects, as the macro-level is not simply the sum of everything that is happening at the micro-level. Rather, there are emergent properties at the macro-level that arise out of complex interactions between micro-level activities. As Michael Grubb (2000) argued in his debate with economists on the implications of the rebound effect, just because the overall effect of energy efficiency improvements in the economy is to stimulate economic growth, this doesn't mean that I shouldn't fit an energy efficient light bulb in my home, for fear of causing economic growth.

Nevertheless, the implications of this insight into the role played by efficiency in stimulating economic growth are profound. One conclusion is that pursuing energy efficiency strategies and investment, such as the measures advocated in the EU directive on energy efficiency (OJEU, 2012), would make sense from the perspective of enhancing the macro-economic performance of EU economies. In that view, it does not matter much whether the measures advocated are at the level of efficiency in end-user technology or behaviour (consumption-side) or in the more efficient production and distribution of electricity, heat and transportation (supply-side): both of these could stimulate wider systemic changes that would lead to economic growth and further investment. However, Ayres et al 2007 proceed to advocate for policies focusing on enabling supply-side measures (such as CHP) rather than demand-side ones, mainly because energy costs are a larger fraction of the operating and ownership costs in the energy sector, and the incentives to implement efficiency measures will thus be greater.

Another key implication of such macro-economic understanding of the strong links between energy efficiency and economic growth is that not all efficiency gains will lead to overall energy savings. In fact, the criteria for strong efficiency

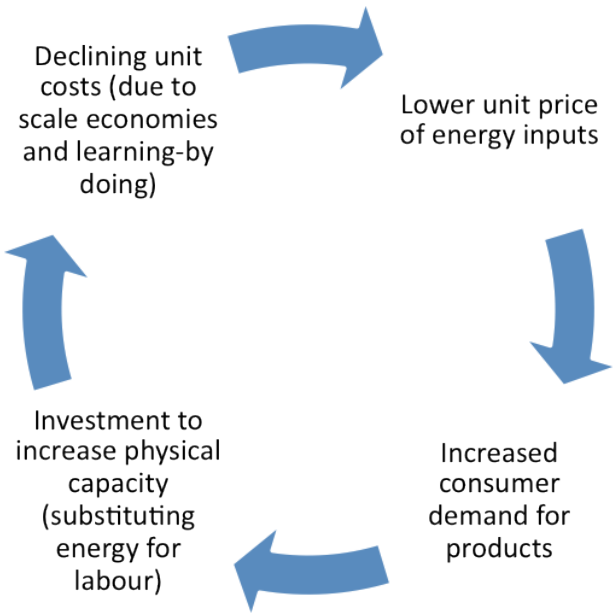


Figure 1. Positive feedback loop driving labour productivity and economic growth (Source: Ayres et al. (1997)).

measures, capable of reducing the total scale of energy use of the economy, are quite stringent: the gains in energy productivity must be higher than the average energy productivity of the economy *both before and after* the efficiency measures are in place, since an improvement in efficiency inevitably leads to higher overall productivity.

It is thus through this lens that we must consider the effects of such policy documents as the EU directive on energy efficiency (OJEU, 2012), or its national equivalents, such as the UK energy efficiency strategy (DECC, 2012). These seek to promote energy efficiency as both a contributor to mitigating climate change by reducing carbon emissions, and as a contributor to economic growth, by promoting overall economic activity at the macro level. Hence, they sit squarely in the 'green growth' perspective. However, in terms of delivering on climate change mitigation objectives, we need to ask. Do these policy guidelines go above and beyond measures that are economically advantageous, i.e. business as usual, since energy efficiency usually leads to economic benefits? And do they seek out and promote the strongest possible efficiency measures, capable of decreasing the total scale of energy use? Is the decline in relying on energy inputs a clear goal of the overall efficiency strategy? In both the EU and the UK cases, the answer is to the two latter questions is no. The policies advocated are a laundry list of sectors and technologies where efficiency should be implemented. This is not a criticism of these policies as such: they are quite sensible and well-designed for the purpose of improving the energy productivity of the EU and UK economies. However, from a sustainability perspective, they do not take the whole economic system and its scale effects into account, and thus these policies cannot be expected to deliver consistent reductions in total energy use: indeed, that is not their goal.

Coevolutionary perspective

From the above analysis, it is clear that we need a better understanding of both the dynamical feedbacks and the multi-level interactions between energy efficiency improvements and economic growth. Previous authors have shown that a coevolutionary perspective is useful to explore how positive and negative feedbacks lead to systems change and stability. Unruh (2000) argued that fossil fuel based energy technologies have benefited from positive feedbacks or increasing returns to adoption, due to scale, learning, adoption and network effects, and that supporting institutions have co-evolved with these technologies, leading to the lock-in of current high carbon energy systems. Beinhocker (2006) argued that a process of co-evolution of technologies, institutions and business strategies has driven the wide availability and reduction in costs of goods and services underlying economic growth. This provides a broader explanation of positive feedbacks leading to economic growth, which in some ways is complementary to that of the Ayres et al. described above, but we have argued that it neglects or misinterprets the role of low-entropy, high quality primary energy inputs into the economy (Foxon and Steinberger, 2012). Hence, we argue that it is necessary to broaden the coevolutionary framework to include these types of inputs from natural ecosystems, as well as feedbacks leading to ecosystem changes.

To facilitate this, one of the authors has proposed a coevolutionary framework for analysing a transition to a sustainable low carbon economy (Foxon, 2011). This proposes that dynamic interactions between subsystems of the economy can be analysed in evolutionary terms relating to changes in selection environments and replicative capacity arising from mutual causal interactions between subsystems. Five key coevolving subsystems are identified in this framework: ecosystems, technologies, institutions, business strategies and user practices. This framework suggests that the macro-level impacts of changes, such as the adoption of energy efficient technologies, strategies or practices, are mediated through the interactions between these subsystems, which may give rise to emergent systemic changes at the macro level.

This application of this framework 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. 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 Figures 2 and 3.

However, 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

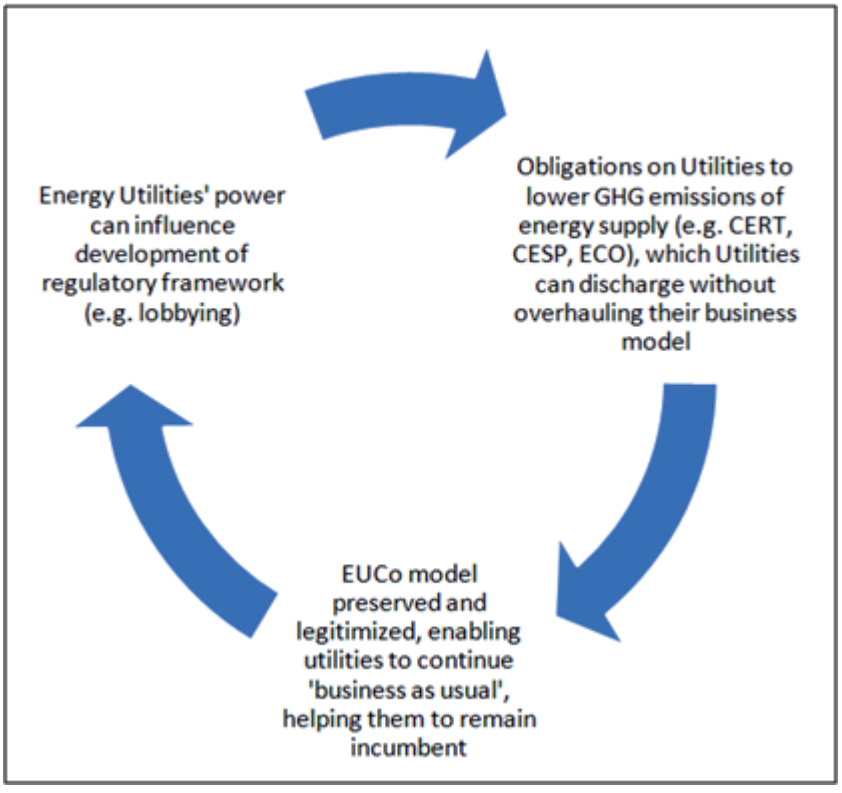


Figure 2. Positive feedback loop between Energy Utility population and UK regulatory framework (Source: Hannon (2012)).

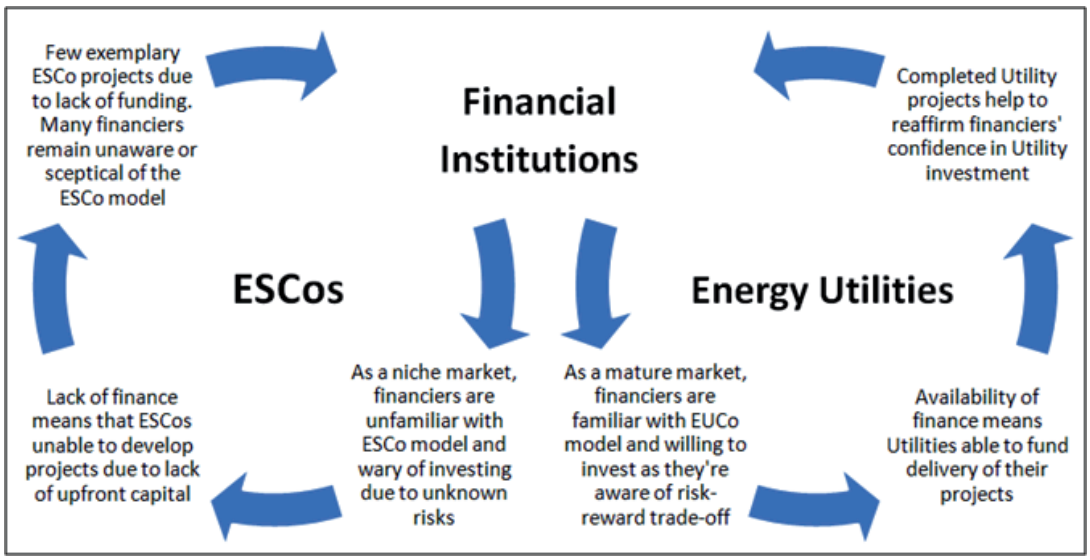


Figure 3. Co-evolution of ESCo and Energy Utility populations, focusing on financial institutional arrangements (Source: Hannon (2012)).

the adoption of the ESCo business model by new entrants and incumbents (Figure 4).

This approach suggests that, to assess the overall impacts of the introduction of energy efficient technologies, strategies or practices on the productivity of the economy, would require an 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. However, even without undertaking a full contextual analysis of this type, it is possible to draw some broad conclusions from this approach, as discussed in the next section.

Discussion and policy implications

This paper has discussed a number of aspects of the relations between efficient use of energy and economic development. We argue that it is important to appreciate these different aspects, in order to be able to get a clearer grasp of the relations between energy efficiency and economic development at macro-, meso- and micro-levels.

Firstly, we reviewed the arguments and different perspectives on 'green growth'. The common ground between environmental economic and ecological economic perspectives is that addressing climate change and resource scarcity issues requires limiting the physical size of the economy, i.e. achieving reductions of the order of 5–7 % per annum in carbon emissions relative to GDP. Debates between these two perspectives centre on whether this can be achieved purely through changing the incentives within current economic structures to promote decoupling of emissions and GDP, or whether a more fundamental structural change is needed to the aims and workings of economic systems. Environmental economists, such as Hepburn and Bowen (2012), advocating the former position, tend to focus on the need, within current economic structures, for growing GDP to enable investment in low carbon and energy efficient technologies. Ecological economists, such as Daly (1991), Jackson (2009) and Dietz and O'Neill (2013), argue that for greater structural change, on the basis that (1) current economic systems are no longer delivering increasing wellbeing to the majority of populations in industrialised countries; (2) other environmental limits, such as depletion of freshwater, soil erosion, biodiversity loss, also need to be addressed; and (3) increasing cost of fossil fuel inputs into the economy, due to resource scarcity, mean that current economic systems are unsustainable.

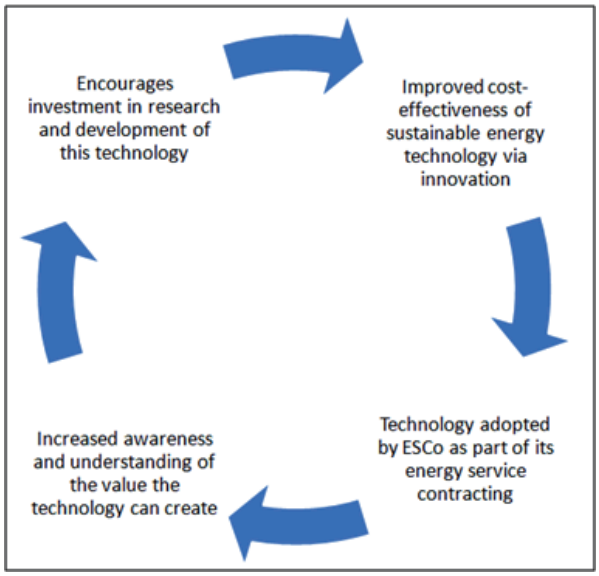


Figure 4. An emerging positive feedback loop between ESCo population and energy technologies (Source: Hannon (2012)).

Secondly, we reviewed the argument put forward by Ayres and Warr (2009) that increasing efficiency of conversion of energy (exergy) inputs into useful work has been a key driver of economic growth. They argued that a positive feedback loop has been created in which increasing energy conversion efficiency reduces the unit costs of energy inputs, leading to increasing consumer demand and stimulating investment in labour-saving technologies, which leads to further energy efficiency improvements and unit cost reductions. Coevolutionary

studies of economic growth, such as Beinhocker (2006), highlight the role of positive feedbacks between changes in technologies, institutions and business strategies, and the importance of increasing energy conversion efficiencies, but neglect the enabling role played by the availability of low-entropy high quality energy inputs, in the form of fossil fuels.

Thirdly, we examined other positive feedback loops that have led to the lock-in of business models based on continuing growth in energy consumption (Hannon, 2012). These type of feedbacks create barriers to the adoption of demand-side energy efficient technologies, strategies and practices, for which the benefits would largely accrue to the consumer, whilst giving incentives for incremental improvements in supply-side energy efficiency, as these are consistent with the economic growth cycle, described above. This is consistent with the observed marginalization of the role of end-use technologies in energy innovation for climate protection (Wilson et al., 2012; Grubler, 2012).

So, what lessons and areas for further research on the roles of energy and efficiency in a sustainable low carbon transition can we draw from this wide-ranging conceptual review?

Firstly, both increasing efficiencies of energy conversion and high quality energy inputs were important to past periods of economic growth, but we need to better understand the respective roles that they have played, and how they interacted with other drivers of economic growth, such as changes in technologies, institutions and business strategies. Up to now, these processes driving economic growth have also driven up the overall level of primary energy use and associated impacts in the form of carbon emissions. This supports the view that there is a significant macro-economic rebound effect, i.e. that increasing energy efficiency at the macro level increases energy use over the long term rather than decreasing it.

In this way, physical growth in the size of the economy relative to ecosystems was strongly coupled to economic growth in value terms, as measured by GDP. However, the existence of ecological limits, including climate change, require limiting or reducing the physical scale of the economy, by decoupling value creation, in terms of 'development' or 'intellectual economy' from the physical scale of the economy. This will require a transition to low carbon and energy efficient inputs. In terms of 'green growth', for this to be consistent with continuing GDP growth, this would require a larger and larger proportion of the economy to consist of low impact activities, or for more activities to become lower impact through improved efficiency. In other words, green growth would need to be self-reinforcing, as growth became greener and greener. This would constitute a significant structural change to economic systems, as it would require less physically intensive activities and sectors to grow faster whilst more physically intensive activities were shrinking (so that the economy as a whole becomes less physically intensive). This would generate economic benefits in some sectors, e.g. green jobs, 'intellectual economy', whilst leading to economic disbenefits in other sectors, e.g. energy and carbon intensive industries and forms of consumption that are energy-intensive from a life cycle perspective. This suggests that economic analysis of a transition to a sustainable low carbon economy needs to examine not just how low carbon technologies can substitute for high carbon technologies in existing forms of economic activity, but also more structural economic change towards low carbon and high energy efficiency activities and sectors.

Though beyond the scope of this paper, the implications of this for employment also need to be considered. In the past, the reduction in employment caused by substituting energy for labour has been offset by the new jobs created through the growth of the economy as a whole. For ecological economists arguing that increasing GDP growth should no longer be the main aim of national economic policy, this implies that, as well as higher investment in low carbon and energy efficiency innovation, investment needs to be reoriented toward more labour intensive sectors of the economy, such as caring for children and older people. These sectors are less productive in conventional economic terms (Jackson, 2009).

Secondly, understanding coevolutionary interactions and resulting feedback loops provides useful insights, but we need to better understand how these interactions and feedbacks at different levels relate. As we have seen, coevolutionary processes at the macro level have helped to drive economic growth (Beinhocker, 2006). Coevolutionary processes at the meso level help to explain the lock-in of fossil fuel based energy systems (Unruh, 2000) and, within that, the lock-in of business models that reinforce higher levels of energy consumption (Hannon, 2012). This suggests the value of a coevolutionary framework that identifies the coevolution of ecosystems, technologies, institutions, business strategies and user practices as key processes to examine (Foxon, 2011). We need to better understand the conditions under which these coevolutionary processes lead to mutually reinforcing positive feedback loops, and the conditions under which lock-in of existing systems resulting from past positive reinforcement can be broken. As we have seen for the case of the energy services company (ESCo) business model, regulatory and technological changes are now starting to reduce the lock-in of the dominant Energy Utility Company (EUCo) business model and give rise to positive feedback loops for the adoption of a business model that is consistent with demand-side energy efficiency improvements.

Thirdly, at least some structural changes, such as those needed to promote energy service company (ESCo) business model rather than the Energy Utility Company (EUCo) business model, are likely to be needed to achieve energy efficiency improvements that also contribute to mitigating climate change. Present policies tend to focus on promoting adoption of energy efficiency measures by households and businesses, and less on promoting such structural changes. There is a need for more bolder policy measures in this area, supported by analysis of potential systemic impacts. For example, the 'pay as you save energy' idea behind the UK's Green Deal for financing household energy efficiency measures was originally seen as a way of promoting the formation of ESCos, but this aim was largely lost, due to the need to get the current large energy companies, who use the EUCo model, on board with the scheme.

We hope that this paper provides a useful contribution to clarifying some of the issues on the relations between energy use, conversion efficiency and economic growth, but we recognise that much further research is needed to fully understand these relations and their crucially important implications for achieving a sustainable low carbon economy.

References

Ayres, R. U., B. Warr and L. W. Ayres (2003). "Exergy, power and work in the US Economy, 1900–1998." *Energy* 28(3): 219–273.

Ayres, R. U. and B. Warr (2005). "Accounting for growth: the role of physical work." *Structural Change and Economic Dynamics* 16(2): 181–209.

Ayres, R. U., H. Turton and T. Casten (2007). "Energy efficiency, sustainability and economic growth." *Energy* 32(5): 634–648.

Ayres, R. U. and B. Warr (2009). *The economic growth engine: How energy and work drive material prosperity*. Cheltenham, UK and Northhampton MA, US, Edward Elgar.

Beinhocker, E (2006). *The Origin of Wealth: Evolution, Complexity and the Radical Remaking of Economics.* Random House, London.

Daly, H. (1991). *Steady-State Economics: Second Edition with New Essays.* Washington D.C., Island Press.

Daly, H. E. (1997). Beyond Growth: The Economics of Sustainable Development. Boston, Beacon Press.

Department of Energy and Climate Change (DECC) (2012). The Energy Efficiency Strategy: the energy efficiency opportunity in the UK. London, DECC, November 2012.

Dietz, R. and O'Neill, D. (2013). *Enough is Enough: Building a Sustainable Economy in a World of Finite Resources.* San Francisco, Berrett-Koehler/ London, Routledge.

Ehrlich, P. and J. Holden (1971). "The impact of population growth." *Science* 171(3977): 1212–1217.

Foxon, T. J. (2011). "A co-evolutionary framework for analysing transition pathways to a sustainable low carbon economy." *Ecological Economics* 70, 2258–2267.

Grubb, M. (1990). "Communication - Energy efficiency and economic fallacies." *Energy Policy* 18(8): 783–785.

Grubler, A. (2012). "Energy transitions research: Insights and cautionary tales." *Energy Policy* 50: 8–16.

Hepburn, C. and Bowen, A. (2012). Prosperity with Growth: Economic growth, climate change and environmental limits. Centre for Climate Change Economics and Policy Working Paper No. 109/ Grantham Research Institute on Climate Change and the Environment Working Paper No. 93, http://www2.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Working%20Papers/90-99/WP93-prosperity-with-growth-climate-change.pdf.

Hannon, M. (2012). *Co-evolution of innovative business models and sustainability transitions: The case of the Energy Service Company (ESCo) model and the UK economy.* PhD thesis, University of Leeds.

Hannon, M., Foxon, T. J. and Gale, W.F. (2013). The co-evolutionary relationship between energy service companies and the UK energy system: implications for a low carbon transition. *Energy Policy* (submitted).

Hertwich, E. G. (2005). "Consumption and the Rebound Effect: An Industrial Ecology Perspective." *Journal of Industrial Ecology* 9 (1-2, Special Issue on Consumption and Industrial Ecology): 85–98.

Jackson, T. (2009). *Prosperity without growth.* London, Earthscan.

Meadows, D.H., Meadows, D.L., Randers, J. and Behrens, W.W. (1972), *The limits to growth*. New York, Universe Books.

Official Journal of the European Union (OJEU) (2012). Directive 2012/27/EU of the European Parliament and Council on energy efficiency. L315/1, Volume 55, 14 November 2012.

Smil, V. (2008). *Energy in Nature and Society. General Energetics of Complex Systems*. Cambridge, MA, MIT Press.

Sorrell, S. and J. Dimitropoulos (2008). "The rebound effect: Microeconomic definitions, limitations and extensions." *Ecological Economics* 65(3): 636–649.

Steinberger, J. K., J. T. Roberts, G. P. Peters and G. Baiocchi (2012). "Pathways of human development and carbon emissions embodied in trade." *Nature Climate Change* 2: 81–85.

Steinberger, J. K. and J. T. Roberts (2010). "From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975-2005." *Ecological Economics* 70(2): 425–433.

Suh, S. (2006). "Are services better for climate change?" *Environmental Science & Technology* 40(21): 6555–6560.

UNEP (2011). Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication, www.unep.org/greeneconomy.

Unruh, G.C. (2000). "Understanding carbon lock-in." *Energy Policy* 28, 817–830.

Van den Bergh, J. (2011), "Environment versus growth – A criticism of 'de-growth' and a plea for 'a-growth'." Ecological Economics 70: 881–890.

Victor, P. A. (2010). "Ecological economics and economic growth." *Annals of the New York Academy of Sciences* 1185(1): 237–245.

Wilson, C., Grubler, A., Gallagher, K.S. and Nemet, G.F. (2012). "Marginalization of end-use technologies in energy innovation for climate protection". *Nature Climate Change* 2(11): 780–788.

York, R. (2012). "Do alternative energy sources displace fossil fuels?" *Nature Climate Change* 2(6): 441–443.