Energy Policy 36 (2008) 4600–4604

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Energy and economic growth: Grounding our understanding in physical reality[☆]

David G. Ockwell [*]

Sussex Energy Group and Tyndall Centre for Climate Change Research, SPRU, University of Sussex, Freeman Centre, Falmer, Brighton, East Sussex BN1 9QE, UK

ARTICLE INFO

Keywords:
Energy economics
Rebound effect
Ecological economics

ABSTRACT

This article attempts to summarise the complex, wide ranging and unresolved debate within the economics literature on the possibility of decoupling economic growth from energy use. It explores the difference between neo-classical and ecological economic worldviews and highlights how the ecological economic approach attempts to ground its analysis within the physical limits implied by the laws of thermodynamics. Once these laws are accounted for, the possibility of decoupling economic growth from energy use seems more limited than neo-classical economics implies. Analysis of empirical evidence also demonstrates that observed improvements in GDP/energy use ratios in the USA are better explained by shifts towards higher quality fuels than by improvements in the energy efficiency of technologies. This implies a need to focus on decarbonising energy supply. Furthermore, where energy-efficiency improvements are attempted, they must be considered within the context of a possible rebound effect, which implies that net economy-wide energy savings from energy-efficiency improvements may not be as large as the energy saved directly from the efficiency improvement itself. Both decarbonising energy supply and improving energy efficiency require the rapid development and deployment of new and existing low-carbon technologies. This review therefore concludes by briefly outlining areas of economic thought that have emerged as a result of engagement between economists and experts from other disciplines. They include ecological, evolutionary and institutional economics, all of which can make policy-relevant contributions to achieving a transition to a low-carbon economy.

1. Introduction

Sustained economic growth is a mantra for governments worldwide and is seen as having a key role to play in poverty alleviation. But economic activity is predominantly linked to the use of energy, principally from fossil fuels, which account for over 60% of global greenhouse gas emissions. This implies an urgent need to decouple economic growth from energy use.

This review provides an overview of our current understanding of the relationship between energy use and economic growth. This understanding is fraught with controversy, particularly between neo-classical and ecological economic viewpoints (Sorrell and Dimitropoulos, 2007). Here I focus on the implications of the difference between neo-classical and ecological economic understandings.

I begin by exploring the differences between neo-classical and ecological economic worldviews and the implied relationship between energy and economic growth, before exploring some empirical evidence on decoupling and the implications of the 'rebound effect'. I conclude by briefly outlining relevant emerging areas of economic thought that have policy-relevant contributions to make towards achieving a transition to a low-carbon economy.

2. Neo-classical views of economic growth

The neo-classical economic worldview sees the economy as a closed system within which goods are produced by inputs of capital and labour, and then exchanged between consumers and firms (red square in Fig. 1). Economic growth is achieved by increasing inputs of labour or human capital. It is also feasible that growth could be achieved by improvements in technology or in the quality of capital and labour inputs. More recently, the role of natural capital in economic growth has also been considered. From the traditional, neo-classical perspective, natural capital consists of renewable and non-renewable natural resources such as water, fossil fuels and primary biological productivity.

[☆] While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

[*] Tel.: +44 1273 873541; fax: +44 1273 678166.
E-mail address: d.g.ockwell@sussex.ac.uk

0301-4215/$ - see front matter © 2008 Queen's Printer and Controller of HMSO. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2008.09.005

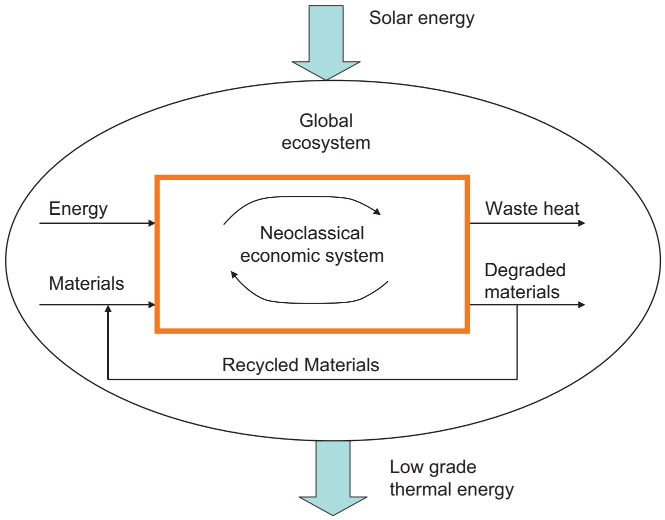

Fig. 1. Opposing worldviews of economic production (based on Hall et al., 1986).

There are essentially three mainstream categories of neo-classical growth models (Stern and Cleveland, 2004). The first focuses on technological change as the only means by which growth can be achieved (Aghion and Howitt, 1998; Solow, 1956; Stern and Cleveland, 2004). All economies grow until they reach an equilibrium level, the point where further returns to capital are no longer possible. Growth beyond equilibrium is then only achievable by increasing returns to existing capital via improvements in technology.

The second category focuses on the consumption of natural capital in determining sustained economic growth. These models assume *a priori* that it is technically feasible to substitute between man-made and natural capital (Stern and Cleveland, 2004). Achieving sustained growth then relies on the correct institutional conditions (including property rights, market structure, means of considering future generations) to ensure that any depleted natural capital is substituted for with the corresponding value of man-made capital.

The final category of growth model considers both natural resources and technological change as determinants of growth. As well as substituting between man-made and natural capital, the possibility of technology improving the output per unit of natural or man-made capital and labour is considered as an additional means by which growth can be sustained (Stern and Cleveland, 2004).

In all three of the above conventional models of economic growth, the contribution of energy to economic activity is only considered relative to its cost within production. In economic terms, the models consider energy to be an 'intermediate good' rather than a 'primary input' into production. In the context of all three of the above models, this implies that decoupling economic growth from energy use is a reasonable possibility, subject, in the case of the latter two models, to various sustainability constraints being conformed to with regard to the consumption of natural capital.

When economists have attempted to calculate economic growth, based on observed inputs of capital and labour weighted by their price, they have found that their models do not match empirical observations. A residual amount of unexplained growth is observed of around 1.2% per year (Simpson et al., 2004). It is therefore assumed that this residual represents technological change and/or qualitative changes in inputs of capital and labour. This assumption, however, is theoretical and has never been proven empirically.

3. The ecological critique—growth and the laws of thermodynamics

Ecological economists criticise the neo-classical worldview as failing to ground economic activity in physical reality. A more realistic view, they argue, is to see the economy as an open subsystem of the global ecosystem (the whole of Fig. 1). This accounts for inputs of natural capital, but takes a broader view of it as including the essential ecosystem services that make human life possible. These include the absorption of waste from economic activity and the maintenance of the climate that facilitates human life. Most importantly, the ecological economists' worldview attempts to account for the laws of thermodynamics.

The first law of thermodynamics, often known as the 'mass–balance principle', asserts that energy cannot be created or destroyed. In the Earth's semi-closed global ecosystem, this means that the only available energy source is solar energy. This can either be used directly, or in an embodied state such as fossil fuels. It also implies that the by-products of the use of embodied energy, such as carbon dioxide emissions from fossil fuels, will be returned to the environment as waste. Solar energy flows into the economic system, and then flows out again into the global ecosystem as low-grade heat and waste. This waste imposes a cost on the environment that is not traded within the closed economic system recognised within the neo-classical economic worldview. The first law also conflicts with two of the three neo-classical economic growth models outlined above, which assume that it is possible to substitute between man-made and natural capital. If the ability of the environment to absorb waste from economic activity is depleted, then the ecosystem services and life-support functions upon which economic activity, and human life, rely may be, and in practice often have been, compromised, sometimes irreversibly. They cannot be substituted for by any corresponding gains in man-made capital. Examples include commercial fish stocks, the provision of clean air, the maintenance of global temperatures and weather patterns, and supplies of clean water.

The second law of thermodynamics, sometimes termed the 'entropy law', implies that while energy and materials can be reused, they will increasingly reach a less useful state, that is, their entropy will increase. It also implies that in order to transform one material to another, additional energy is required. This implies limits to the extent to which energy can be substituted for by other inputs into the production process. At the macro, economy-wide level, this limit to substitution may be even more difficult to overcome. Essentially, in order to manufacture more man-made capital, even without direct reliance on natural capital, energy is required to drive the manufacturing process. Labour is also required, which in turn consumes energy (food and water and often transport, light, heat, etc.). By only accounting for energy in terms of its relative cost within economic production, neo-classical economists may therefore have underestimated its importance for economic activity.

For ecological economists, energy is a fundamental factor enabling economic production. Some commentators even argue that energy availability actually drives economic growth, as opposed to economic growth resulting in increased energy use (e.g. Cleveland et al., 1984). From this perspective, the possibility of decoupling energy use from economic growth seems more limited.

4. Empirical observations on decoupling

Empirical evidence on economic growth in the USA over the last century seems at first sight to suggest some degree of decoupling. As Fig. 2 illustrates, since the 1940s the amount of

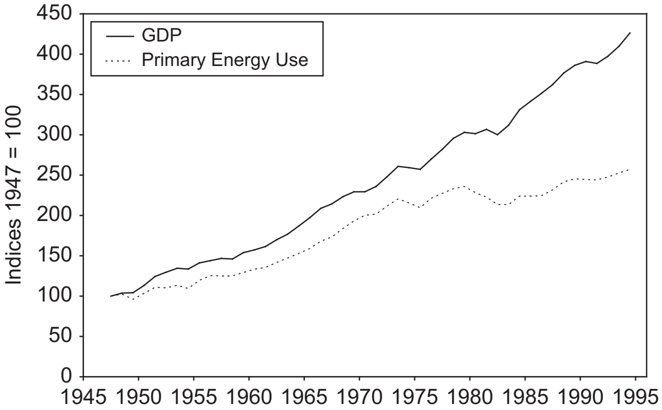

Fig. 2. US GDP and primary unadjusted energy use (*source*: Stern, 2004, p. 39). *Note*: GDP is in constant dollars, i.e. adjusted for inflation. Energy use is the sum of primary energy BTUs.

primary energy used per unit of GDP has declined. This has traditionally been assumed to be the result of the application of more energy-efficient technologies within production processes. Closer examination of this trend has, however, suggested that this apparent decoupling has in fact been achieved largely by a switch away from the direct use of low-quality fuels such as coal to higher quality fuels and energy inputs, electricity in particular (Cleveland et al., 1984; Kaufmann, 1992, 2004; Stern, 1993; Stern and Cleveland, 2004). These fuels provide more units of useful work per unit of thermal input. Roughly speaking, it is possible to assert that electricity is the highest quality energy source available, followed, in order of decreasing quality, by natural gas, oil, coal and wood and biofuels (Stern and Cleveland, 2004). As Fig. 3 demonstrates, once a measure of energy quality is factored into measures of energy use, US GDP no longer appears to have been decoupled from energy use. The contribution of fuel quality to economic growth is a factor that has not, to date, been considered in economic growth theory.

Work by Kaufmann (2004) showed that, together with some contribution from changes in the proportion of household income spent on fuel, changes in energy prices, and a compositional shift towards a service-based economy, shifts away from the use of coal and particularly towards the use of oil can explain the majority of declining US energy intensity since 1929. The idea that a shift towards a service-based economy can achieve decoupling is one that is often put forward (Panayotou, 1993). But this notion ignores the large amounts of energy involved in producing services. For example, offices need to be lit and heated, consumers use energy travelling to work and shops, and some service industries, such as transport, are very energy intensive (Stern and Cleveland, 2004). This implies that a shift to a service-based economy cannot achieve a complete decoupling of energy and economic growth. Furthermore, the potential for a global decoupling of economic growth via a shift towards a service-based economy is ultimately limited by the fact that such shifts in developed countries have partly been achieved by outsourcing manufacturing to developing countries (Stern et al., 1996). Recent work by Wang and Watson (2007) demonstrates that net exports from China account for 23% of its carbon emissions.

The ecological economics worldview and some of the supporting empirical evidence suggests that the extent to which it is possible to decouple energy use from economic growth may be more limited than has previously been assumed. This implies a need to focus on decarbonising energy supplies, as opposed to focusing solely on developing and deploying energy-efficient technologies.

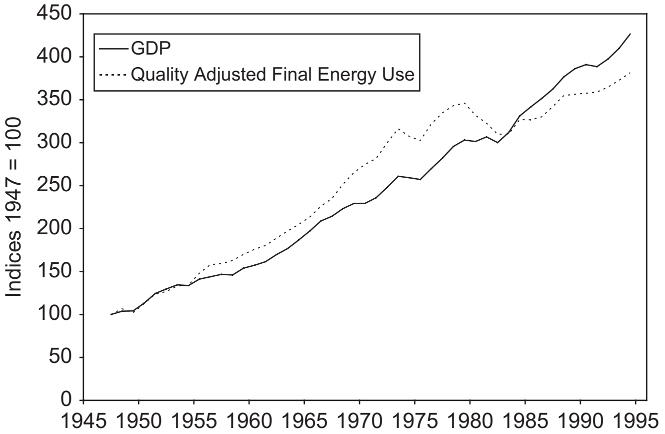

Fig. 3. US GDP and quality adjusted final energy use (*source*: Stern, 2004, p. 41). *Note*: GDP is in constant dollars, i.e. adjusted for inflation. Energy use is a Divisia index of the principal final energy use categories—oil, natural gas, coal, electricity, biofuels, etc. The different fuels are weighted according to their average prices to provide a reflection of energy quality and hence the useful work provided by different fuels.

Where energy-efficient technologies are considered in the context of reducing the energy intensity of economic activity, it is essential that the rebound effect, another emerging insight from the economics literature, be considered. The most comprehensive review of the rebound effect has recently been completed by Sorrell and Dimitropoulos (2007); their findings are briefly summarised below.

5. The rebound effect

The rebound effect refers to the idea that increases in energy efficiency might result in increases in energy consumption. There is a school of thought that has argued that the effect of any energy-efficiency improvements will be a net increase in overall energy consumption (Brookes, 1990; Inhaber and Saunders, 1994). This concept is known as 'backfire'. Rebound effects can be direct, indirect, or economy-wide. An example of a direct rebound effect would be if an improvement in the fuel efficiency of a car resulted in consumers driving the car further due to the reduced cost of driving each mile and therefore, on aggregate, used more fuel than they did before the efficiency improvement was made. An example of an indirect rebound effect would be if the money saved from reduced fuel consumption from more efficient cars were spent on overseas flights. The economy-wide rebound effect is the sum of the direct and indirect rebound effects.

Rebound effects can apply to the production as well as the consumption of goods. A production example would be improved efficiencies in the production of steel. This could result in a decrease in the price of steel, which, in turn, might be reflected in the cost of producing cars. If this cost saving were passed on to consumers, an increase in demand for cars might be observed, as well as a corresponding increase in petrol consumption. When the knock-on effects of improvements in efficiency are considered throughout the economy, the potential implications become both bewildering and extremely concerning.

Some important findings from Sorrell and Dimitropoulos' (2007) review of the rebound effect are as follows:

- Rebound effects are significant, but they need not make energy-efficiency policies ineffective. Backfire is not the norm, so energy-efficiency policies can reduce net energy consumption. But direct and indirect rebound effects are not small (below 10%), as some commentators have assumed, and need to be taken seriously by policy makers.

- Direct rebound effects for household energy services in OECD countries are likely to be less than 30%. But they could be larger for producers and potentially much larger in developing countries.
- The evidence for indirect rebound effects is poor, but nevertheless suggests that they may be significant.
- There is a need for further research in several areas in order to develop a stronger, empirically based understanding of various aspects of the rebound effect.

6. Policy implications and potential future insights

The analysis presented above implies two urgent policy requirements:

- *Decarbonising energy supply*: If energy use is more closely related to economic growth than has traditionally been assumed, as the ecological economics literature suggests, this implies an urgent need to focus efforts on decarbonising energy supply.
- *Developing and deploying energy-efficient technologies*: While some energy-efficient technologies may have the potential to reduce the energy intensity of economic activity, they must be considered within the context of any potential rebound effect. Sorrell and Dimitropoulos (2007) suggest that general-purpose technologies, such as steam engines in the 19th century or electric motors for manufacturing in the 20th century, have the highest propensity to be subject to rebound effects. This implies that efforts should be focused instead on dedicated energy-efficiency technologies, such as thermal insulation.

Both of these policy requirements necessitate an understanding of processes of innovation and the uptake of new technologies. These are not straightforward issues. There are many advanced energy-efficient and renewable energy technologies available in the world today, but they are not in widespread use. In the UK, the majority of houses do not use energy-efficient light bulbs or have cavity wall insulation. This implies that, as well as understanding how to stimulate innovation in new low-carbon technologies, we also need to understand how to encourage the uptake of new and existing low-carbon technologies.

Several emerging areas of economic thought are relevant to the development and deployment of low-carbon technologies, in particular insights from the literature on evolutionary economics and institutional economics. Their relevance is reflected in considerable cross-fertilisation between evolutionary, institutional and ecological economics. A brief overview of the nature and relevance of some of these emerging insights is attempted below.

6.1. *Evolutionary economics*

Emerging insights within the area of evolutionary economics have made considerable contributions to our understanding of innovation processes and of the uptake of new technologies. For example, the idea of ‘co-evolution’ has illuminated how social, technical and environmental systems have evolved together (see, for example, Kallis, 2007; Rammel et al., 2007). Ideas of path dependency and technology lock-in can then be understood within their broader socio-economic context, and more effective policy options can be developed, which account for the complex interactions between social, technical and environmental systems. Emerging analysis by Watson (2008), for example, highlights the way in which supposedly technology-neutral policy measures favour the development and deployment of certain technologies over others. Other analysts, such as Bauknecht and Sauter (in press), highlight how socio-technical systems imply a need to understand energy infrastructure as a complex system of interacting social, economic and political institutions, as opposed to viewing it as a simple physical entity. This has important implications for the policies required to achieve a transition to a low-carbon economy.

6.2. *Institutional economics*

The transition to a low-carbon economy implies a change in the way energy is produced and used. In order to achieve such a change, we must first understand the social, economic and political institutions that determine our current use of energy, and the development and deployment of existing technologies that facilitate energy use. The literature on institutional economics has an important contribution to make here by facilitating insights into the way that institutional structures determine behaviour (see, for example, Paavola and Adger, 2005). This raises the potential for amending institutional structures, for example by altering financial incentives or creating communication networks, to facilitate individual and collective behaviour that is commensurate with a low-carbon economy.

An important aspect of these emerging areas of thought is the application of interdisciplinary approaches to facilitate effective policy insights. For example, ecological economics requires collaboration between economists and natural scientists; evolutionary economics requires collaboration with experts in science and technology studies and sociologists more generally; while institutional economics requires collaboration with political scientists and psychologists. These insights also imply that economic policy instruments used in isolation from other policy approaches are unlikely to be effective in achieving a transition to a low-carbon economy. This is particularly true if a transition is to be achieved within the limited time frame, which the science implies is now imperative if dangerous climate change is to be avoided.

My emphasis on emerging areas of economic thought is not intended to preclude a role for neo-classical economics in future research. The emerging disciplines I have highlighted are founded on interdisciplinary interactions between neo-classical and other economists and experts from other disciplines. Neo-classical economics has much to contribute, for example to understanding utility and profit-maximising behaviour in relation to various policy options designed to change energy using behaviours, including the uptake of new technologies. What I do intend to emphasise is a need for urgently renewed effort on behalf of all economists to engage with the problem of the physical limits implied by the laws of thermodynamics, and the existing and potential catastrophic ecosystem impacts that result from environmentally unsustainable natural resource use. These include both climate change and the often underestimated, but no less severe problem of biodiversity loss.

7. Conclusions

There is a distinct and unresolved divide between neo-classical and ecological economists as to how to treat the contribution of energy to economic growth, with ecological economists arguing that the neo-classical worldview fails to account for the physical limits implied by the laws of thermodynamics. If the ecological economics worldview holds, the potential for decoupling energy from economic growth may be limited.

Sufficient empirical evidence does not yet exist to provide conclusive support for the claims of either the ecological or neoclassical schools of thought. Breaking down the evidence that does exist suggests that observed improvements in GDP/energy use ratios may be better explained by shifts towards higher quality fuels than by improvements in the energy efficiency of technologies. Furthermore, the potential contribution of energy-efficiency measures to reducing the energy intensity of economic activity is affected by the existence of rebound effects.

Bearing in mind the uncertainty of existing theoretical and empirical insights into the potential for decoupling energy from economic growth, it would seem prudent to focus on decarbonising energy supplies. This will require renewed effort within existing disciplines to engage in a multidisciplinary context with promising new areas of economic thought, including emerging insights from the ecological, evolutionary and institutional economics literatures. When and to what extent these insights might yield real impacts is dependent on the extent to which such interdisciplinary research is recognised, supported and applied in policy.

Acknowledgements

I owe a large debt of thanks to my colleague Steve Sorrell who has been extremely generous with his time and expertise during the writing of this piece. Steve's impressive review of the rebound effect was also a valuable source of information both on contemporary ideas relating to energy and economic growth and on the rebound effect itself. I would strongly recommend that interested readers consult Steve's work as the most comprehensive review of the debate as it currently stands. I am also very grateful to my colleagues Sigrid Stagl, Markku Lehtonen, Jim Watson and Gordon MacKerron for commenting on my early ideas for how to frame this review. Finally, I would like to express my thanks to one anonymous reviewer and apologise that the length of this piece precluded extensive engagement with their very fair and in-depth comments.

References

Aghion, P., Howitt, P.W., 1998. Endogenous Growth Theory. MIT Press, Cambridge, MA and London.

Bauknecht, D., Sauter, R., in press. Distributed generation: from integration to transformation of the electricity network. In: Scrase, I., MacKerron, G. (Eds.), Energy for the Future, a New Agenda. Palgrave, Basingstoke.

Brookes, L.G., 1990. The greenhouse effect: the fallacies in the energy efficiency solution. Energy Policy 18, 199–201.

Cleveland, C.J., Costanza, R., Hall, C.A.S., Kaufmann, R.K., 1984. Energy and the US economy: a biophysical perspective. Science 225, 890–897.

Hall, C.A.S., Cleveland, C.J., Kaufmann, R.K., 1986. Energy and Resource Quality: The Ecology of the Economic Process. Wiley Interscience, New York.

Inhaber, H., Saunders, H., 1994. The road to nowhere. The Sciences 34, 20–25.

Kallis, G., 2007. When is it coevolution? Ecological Economics 62, 1–6.

Kaufmann, R.K., 1992. A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change. Ecological Economics 6, 35–56.

Kaufmann, R.K., 2004. The mechanisms of autonomous energy efficiency increases: a cointegration analysis of the US energy/GDP ratio. The Energy Journal 25, 63–86.

Paavola, J., Adger, W.N., 2005. Institutional ecological economics. Ecological Economics 53, 353–368.

Panayotou, T., 1993. Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working Paper WP238, Technology and Employment Programme. International Labour Office, Geneva.

Rammel, C., Stagl, S., Wilfinga, H., 2007. Managing complex adaptive systems—a co-evolutionary perspective on natural resource management. Ecological Economics 63, 9–21.

Simpson, R.D., Toman, M.A., Ayres, R.U., 2004. Scarcity and growth in the new millennium: summary. Discussion Paper 04-01. Resources for the Future, Washington, DC.

Solow, R., 1956. A contribution to the theory of economic growth. The Quarterly Journal of Economics 70, 65–94.

Sorrell, S., Dimitropoulos, J., 2007. UKERC Review of Evidence for the Rebound Effect. Technical Report 5: Energy, Productivity and Economic Growth Studies. Sussex Energy Group, SPRU, University of Sussex, Brighton.

Stern, D., 2004. Economic Growth and Energy, Encyclopaedia of Energy, vol. 2.

Stern, D.I., 1993. Energy and economic growth in the USA: a multivariate approach. Energy Economics 15, 137–150.

Stern, D.I., Cleveland, C.J., 2004. Energy and Economic Growth. Rensselaer Working Paper in Economics, no. 0410. Rensselaer Polytechnic Institute, Troy, NY.

Stern, D.I., Common, M.S., Barbier, E.B., 1996. Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development. World Development 24, 1151–1160.

Wang, T., Watson, J., 2007. Who owns China's emissions? Tyndall Briefing Note no. 23. Tyndall Centre for Climate Change Research, SPRU, University of Sussex, Brighton.

Watson, J., 2008. Technology assessment and innovation policy. In: Scrase, I., MacKerron, G. (Eds.), Climate of Urgency: Empowering Energy Policy. Sussex Energy Group, SPRU, University of Sussex, Brighton (forthcoming).