HOW TO SUPPORT GROWTH WITH LESS ENERGY

Mark Barrett, Robert Lowe, Tadj Oreszczyn and Phil Steadman
Bartlett School of Graduate Studies
University College London

Abstract

There is considerable potential to support growth with less use of primary energy and lower carbon emissions. This can be achieved through technical solutions (existing and new), as well as behavioural change. The goal of securing growth with lower carbon emissions is just one of several strategic goals that need to be satisfied. Of the others, the need to develop alternatives to an energy system heavily dependent on oil and natural gas and to maintain security of energy supply are likely to be the most important.

The strategic goals are to achieve major reductions in the energy intensity of transport, buildings in use, and to achieve corresponding reductions in energy intensity of the major building materials. Key challenges associated with these strategic goals include:

- the development of technologies to produce carbon-free cement, carbon-free steel, carbon-free glass
- enabling infrastructural developments that provide a framework for a wide range of low-carbon technologies and increase energy diversity and security of supply
- identification of key energy-efficiency tipping points and the construction of technology policy
- development of methane-fired modular fuel cells
- improved capabilities to model whole energy systems, i.e. adequately modelling both demand and supply, social/economic as well as technical, and assessing the impact outside of the UK system boundary
- better low-carbon planning and improved co-ordination of planning, building control and other policy tools
- better monitoring and feedback on the real performance of energy efficient technologies.

The implication of the Energy White Paper goal of reducing CO_2 emissions by 60% by 2050 is a six-fold reduction in the carbon intensity of the UK economy. In the longer run, it is clear that we will move towards a carbon-free economy. Within this transition, developments in supply, distribution and end-use technologies will be multiplicative, while action to constrain demand growth is crucial to the rate of the overall transition.

Definitions and interpretation of brief

'How to support growth with less energy' is not an easy topic to discuss without initially defining what is meant by 'growth' or 'less energy'.

'Growth' is usually taken to mean economic growth as represented by, for example, gross domestic product (GDP). GDP does, however, have limitations, it does not fully account for quality of life, biodiversity loss, pollution, unsustainable resource use, except insofar as they result in current expenditure. Also, services like transport (passenger kilometres) or thermal comfort, which don't have a market value, are not directly accounted for.

'Less energy' can be interpreted as less primary, delivered or useful energy and may include finite fossil, renewable (with or without passive solar), and all commercial energy sources.

Systems boundary. A key element of any discussion around growth with less energy is where the system boundary is drawn – around the world or the UK? For example, it could be argued that the UK's significant growth over the last 20 years with minimal additional energy use has been in part as a result of exporting much of our heavy energy-intensive industry such as steel and cement production to other countries and, instead, moving to low energy-intensive manufacturing (e.g. information technology) and services (e.g. pop music).

We have identified two possible interpretations of the brief:

Interpretation 1 *How to support growth in energy use with less primary energy*: this is often interpreted as **how to support energy efficiency***.* We use energy to provide health, productivity, comfort and have fun, the more of this we do the more growth in other indicators such as GDP we are also likely to have. Improving energy efficiency has, over the last 30 years, been a key goal for both research and policy, although the definition of energy efficiency has been somewhat vague during this period, as highlighted by the recent House of Lords Select Committee on Energy Efficiency (2005) '*… in placing such weight on energy efficiency, the Government appear to have no clear view on how to measure and thereby manage it.*'

Interpretation 2 A more pertinent question to today's energy problems is: **how to support growth in energy use with an absolute reduction in primary energy consumption and carbon emissions, or, in other words, growth with less carbon**. This is a far more challenging interpretation and, in the long run, requires more than energy efficiency alone. Ultimately, it requires a switch to non-carbon-emitting energy sources. Over the last 30 years, energy efficiency has not resulted in a reduction in primary energy consumption. For example, the heat loss of the UK domestic stock has decreased by 30% and the efficiency of heating systems has improved by 30%, but primary energy has increased by 30%. This is because we use twice as much energy in our homes today as we did 30 years ago. We have more and bigger homes, which we heat to higher temperatures, light to higher levels and have new categories of energy use, such as infotainment. We appear to have an innate ability to think up new ways of using energy that almost always outstrip efficiency improvements. In this interpretation, defining what is useful or wasteful energy use becomes very complex. If I design a space such as a conservatory that everybody loves but which overheats, is it wasteful to then air-condition it? Air-conditioning in offices to 24ºC or lower is useful if dress conventions require the wearing of western-style suits. But this convention can be changed. The Japanese Government now encourages the wearing of light suits and no ties in summer (http://en.wikipedia.org/wiki/Cool_Biz_campaign), thereby making it wasteful to cool below 28ºC. In the UK, it appears there is still legislation on the statute book that makes it illegal to heat public buildings above 19ºC, but this has never been enforced.

Introduction

There are two main methods of achieving growth with less energy: technological and behavioural/cultural. The technological options provide the same service levels with less energy or less carbon by the application of energy efficiency and renewable energy. The behavioural options reduce energy either by reducing or changing service level, or by switching from one service or commodity to another with lower energy intensity.

Energy-efficient technology

There is no doubt that there is considerable potential to utilise existing energy-efficient technology and to develop even more energy-efficient technologies. Table 1 attempts to capture this potential for some of our current major energy uses.

Table 1:

Technology	Average UK performance	Best commercially available efficiency	Technically feasible for ≈2030
Electricity generation	39% mean electricity generation efficiency, equivalent to carbon intensity of 0.47 kg (CO_2)/kWh	49% (gas-fired combined cycle gas turbines) equivalent to 0.44 kg (CO_2)/kWh	≈63% (gross cv) using technologies such as hybrid solid-oxide fuel cell/gas turbine,[1] equivalent to ≈0.3 kg (CO_2)/kWh
Transport via car	32 mpg[2]	Audi A2 (1.4 diesel) 65.7 mpg Prius 65.7 mpg	Work by RMI suggests that in excess of 100 mpg is feasible. German engineers currently designing 187 mpg diesel car
Domestic space-heating	72% (mean central-heating space-heating efficiency) 0.27 kg (CO_2)/kWh	90%-efficient gas condensing boiler 0.22 kg (CO_2)/kWh	300%-efficient electric heat pump, <0.1 kg (CO_2)/kWh in conjunction with grid electricity at <0.3 kg (CO_2)/kWh

Technological measures change the total expenditure on a service; a low-energy refrigerator might reduce the total cost of cooling food, an aerogenerator might increase the total cost of lighting. If the total cost of a service is decreased, the money saved will be directed elsewhere – the 'respending' effect. If the money saved is spent on a commodity with greater energy intensity, there will not be growth with less energy. Technically, this phenomenon is one aspect of what economists refer to as the take-back, or Khazzoom-Brookes effect (Brookes 2000).

Behavioural change

Can easily have as large an impact as technological change but can be more difficult to implement socially and politically, in particular where they constrain consumer choice and behaviour, such as limiting air travel or road speed limits. Buying smaller, more-fuel-efficient cars can reduce fuel consumption directly by 15% or more. Reducing internal temperatures in buildings can save of the order of 10% of space heating – more in highly insulated

[1] http://www.powergeneration.siemens.com/en/fuelcells/hybrid/index.cfm

[2] http://www.dft.gov.uk/stellent/groups/dft_transstats/documents/page/dft_transstats_609948.xls#'3.4'!A1

dwellings. Replacing airline flights with videoconferencing and alternative, low-carbon leisure activities can save ≈90% of direct energy use.

More strategically, the valuing of goods that are presently un- or undervalued can, in principle, allow continued gross national product (GNP) growth with little or no increased carbon emissions. Mishan (1967) argued persuasively that a large proportion of growth in GDP stemmed from the internalisation of goods that were previously not traded in the market, for example, care of children, the sick and the elderly. A decision to place an explicit economic value on quiet would compete directly with road and air travel. The resulting adjustments would simultaneously increase GDP and reduce energy use and carbon emissions.

Despite the importance of behaviour, much of this paper focuses on the potential of technological change. Apart from our wish to reflect the requirements of the original brief, this is for two main reasons:

- Despite recent developments, our work is primarily about technology.
- Improved technology makes large reductions in emissions possible. We can identify combinations of technologies that have the capacity to reduce the carbon intensity of particular categories of final demand by factors of the order of 10. We believe that such combinations of technologies[3] are potentially potent drivers of change throughout the economy.

However, we also address the problem of energy price. In our view, price is a primary determinant of behaviour, and as important of the direction and intensity of scientific and engineering endeavour and the course of innovation, particularly in the long term. Here, we appeal to Jevons' analysis. The problem of resource use has, at minimum, two dimensions: the cost of the resource and efficiency of its use. Much historical analysis has treated the problem as having only one dimension: efficiency. The proponents of such views will always be confused and disappointed by the failure of energy/resource use to be reduced by the application of technology. The upshot of our analysis is that we believe that 'factor 10' technology allows us to have our cake and eat it, but only if application of the price mechanism constrains the direction and rate of growth of the cake.

Transport

Much work has been carried out during the last three decades on the potential for reducing carbon emissions from road transport, either through traffic management (road pricing, parking and access restrictions, investment in and subsidies for public transport, park-and-ride schemes, etc.), or else through longer-term changes in land use. The moves in planning policy and practice towards the 'compact city' in Europe, and towards 'transit-oriented development' in the USA, have served to implement some of these ideas. Such policies build on the theory that raising urban densities will have the effect of making mean journey lengths shorter, and will encourage transfers from cars, with high emissions per person kilometre, either to vehicles with lower emissions per person (buses, trains) or to non-mechanised modes (walking and cycling).

Unfortunately, although numerous theoretical analyses and much practical experience has shown many of these policies to be effective in cutting trip lengths and shifting modes in the short run, these gains tend to be quickly overtaken by growth in car ownership and growth in total distances travelled per year. The recent EC-funded PROPOLIS study (Lautso et al. 2004), which modelled the land-use/transport systems of seven major European cities, showed this effect very clearly. The only 'policies' that actually reversed current overall trends

[3] In passing, we note that all of the technology on which we base our prognostications exists.

in car use, according to PROPOLIS, were very large rises (by 100% and more) in the real price of motoring.

For urban planners and traffic managers, these may be melancholy conclusions. But they are difficult to deny. As with energy use in buildings, there is a relentless year-on-year growth in the total quantity of travel (distance per person per year), not just in the UK but worldwide. A study of the future mobility of the world population by Schafer and Victor (1997) of MIT collected statistics for total annual distances travelled by all modes, in different regions of the world, in the period 1960–1990. The figure below shows these distances (passenger kilometres) against GDP per person ($).

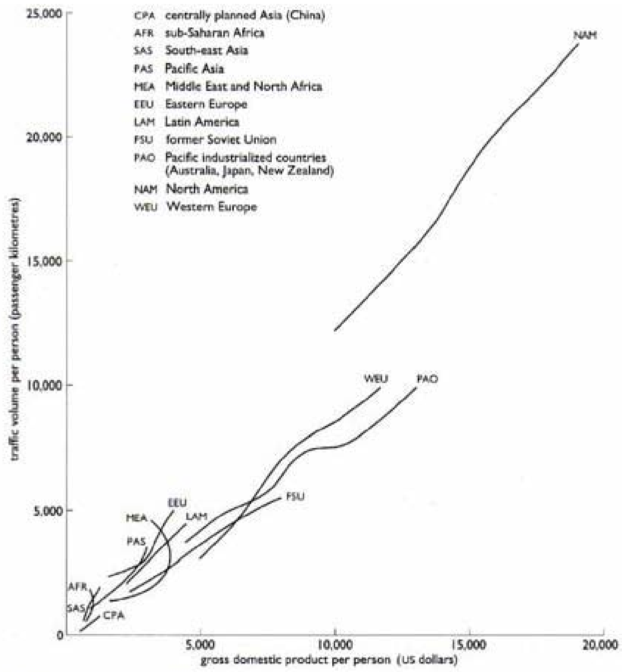

Figure 7.14 Total distances travelled per year by car, bus, train and aircraft, in various regions of the world (vertical scale), compared with average income in US dollars (horizontal scale), 1960–90. There is a close relationship: as incomes rose, so distances travelled increased in proportion (adapted from Schafer and Victor, 1997a; by permission of Massachusetts Institute of Technology)

There is a strong linear relationship. As incomes have risen, so distances travelled have risen in proportion. What is more, the increased distances reflect typically a transition in transport mode from walking and cycling, through bus and local train, to high-speed train and air travel – i.e. towards progressively less-carbon-efficient modes. People's desire for access to mobility, internationally, is passionate and universal. There are obvious parallels here with people's ever-growing capacity to use more energy in the home.

All of the growth shown in the figure above happened of course in the era of cheap petrol, and one might speculate as to how the trend might falter in the future with oil prices of $100 per barrel and higher. But so far as energy policy is concerned, the obvious conclusion from the above must surely be to put much heavier emphasis on improving vehicle technology than on any efforts to restrain mechanical mobility through planning. There may be advantages in the fact that the necessary technological changes can possibly be achieved by the commercial market – especially in the face of rising oil prices – while land-use planning is the province of local and central government. There is also the issue of timescale: the national car stock turns over in 10 or 15 years, while substantial change in land use takes place – at least in Europe – over much longer periods.

The question, then, is how to uncouple the demand for mobility from the use of fossil fuels. There are many ways this could be achieved (hydrogen produced with renewables or nuclear, fuel cells, hybrid propulsion, much-improved engine efficiencies, etc.), which are beyond the scope of this paper. One form of transport for which it is difficult at this point to see any substitute for fossil fuels, however, is air travel.

Future advances to 2050 and beyond

There have been a considerable number of future scenarios that have explored the possibilities of achieving environmentally significant (60%) reductions in carbon emissions by 2050 (for example, in the UK domestic sector by Johnston et al (2005), 40% House, and Building Research Establishment) while maintaining growth in energy services due to, for example, increased temperatures, etc. These scenarios often look at technologies that have been investigated since the 1970s but which are only now becoming mainstream. A crucial insight from these studies is the way changes throughout the energy supply, transmission, distribution and end-use conversion system multiply together. Thus, the decarbonisation of electricity supply coupled with state-of-the-art heat pumps, are capable of reducing the carbon intensity of space- and water-heating by a factor of 4 with respect to natural gas burnt in a condensing gas boiler. Coupled with technologically feasible improvements in dwelling fabric, an overall factor 10 reduction in carbon emissions due to space-heating is clearly achievable using currently available technology. Studies have also looked at the potential for renewable and low-carbon electricity generation, into the future, for example, demonstrating the potential to provide 95% by renewables.[4]

Table 3.1: Recent bottom-up energy studies and the potential for savings identified

Study	Year	Country	Energy sector	Savings*
BRE study 1 (Shorrock & Dunster 1997)	1997	UK	Household energy use	14% energy saving 2020 compared with 1995.
University of Oxford 1 (DECADE 1997)	1997	UK	Electricity for lights and appliances	28% electricity from 1996 to 2010
University of Oxford 2 (Fawcett, Lane, & Boardman 2000)	2000	UK	Electricity and gas domestic lights, appliances & water heating	17% carbon /13% energy from 1998 to 2020
BRE study 2 (Shorrock et al. 2001)	2001	UK	Household energy use	17% energy saving 2000-2020 under their 'efficiency' scenario
Energy Saving Trust submission to PIU energy review (Epple 2001)	2001	UK	Household energy use	12.5% energy saving 2000-2010, a further 12.5% 2010-2020 (24% 2000-2020)
European Climate Change Programme (Anon 2001)	2001	All EU	All sectors	16% greenhouse gases from 1990/1995 to 2010
Imperial College study (ICCEPT 2002)	2002	UK	All sectors	60% carbon savings by 2050
German study (Thomas et al. 2002)	2002	Germany	All sectors of the economy, gas and electricity.	Approx. 10% energy saving from 2002 to 2010.
David Johnston (Johnston 2003a)	2003	UK	Household energy use	50% energy and 61% carbon from 1996 to 2050

Source: Fawcett (2005).

Synergies within the energy conversion chain lead to sharp divergence between the capabilities of existing systems and the capabilities of their replacements – in other words to 'tipping points', or 'phase changes' in the energy infrastructure. A key role of government is to identify potential tipping points in advance and to build energy and technology policy and strategy around them.

Other countries have undertaken similar exercises, some demonstrating the great technical potential for improving energy efficiency and reducing carbon emissions, while simultaneously achieving a number of other major strategic goals. For example, in the case of the US, both military security and energy security can go hand in hand. Threats to military power arise from the huge costs and risks associated with supplying energy-inefficient armed services with energy under battlefield conditions. Strategic technologies, such as ultra-high-strength materials, fuel cells, and energy efficiency make possible orders of magnitude

[4] http://www.cbes.ucl.ac.uk/projects/EnergyReview.htm

reductions in cost and risk in the battlefield. The same technologies applied to domestic transport systems make it possible to drive down national demand for oil at a faster rate than domestic supplies fall. The result is that, by 2020, the US could once again become self-sufficient in oil and gas (Lovins et al. (2005).

Theory and practice

Many studies demonstrating such alternative technological futures have been undertaken during the last 30 years. Yet none have been realised. Energy use in the UK economy has consistently risen more rapidly than the trajectories explored in energy-efficient futures, and there is considerable potential for this to carry on increasing due to new energy uses, which would generate a significant problem regardless of whether we carry on using fossil fuels, nuclear, renewables or energy-efficient technologies or a combination of all of these. Without somebody defining what energy use is acceptable i.e. defining energy waste, or significantly increasing the price of fuels, the past 30 years will probably be a good example of the coming 30 years. If the problem is to decarbonise the UK economy, whatever mix of supply technologies is ultimately developed, the trick is to stop the demand for energy growing quicker than these low/zero-carbon technologies can be introduced.

There are reasons, other than 'take back', that may explain why theoretical energy-efficiency predictions often do not materialise. There are many causes of overoptimism in future predictions:

1 Computer modelling has often replaced real measurement of performance. This is particularly the case in buildings, which have, in the past, been difficult to monitor and are very often 'one-offs', but where almost half of our energy is used. There is increasing evidence that modelled performance in buildings often does not relate to real energy use (see examples in Figures 2 and 3). The first compares real Department of Trade and Industry (DTI) gas consumption data provided by utilities against theoretical Standard Assessment Procedure (SAP) ratings. Note this data has not been corrected for climatic region or availability of gas but, still, you would expect a better correlation. The graphs in Figure 3 show the predicted and monitored fuel consumption in several thousand Warm Front dwellings with different heating systems and levels of insulation.

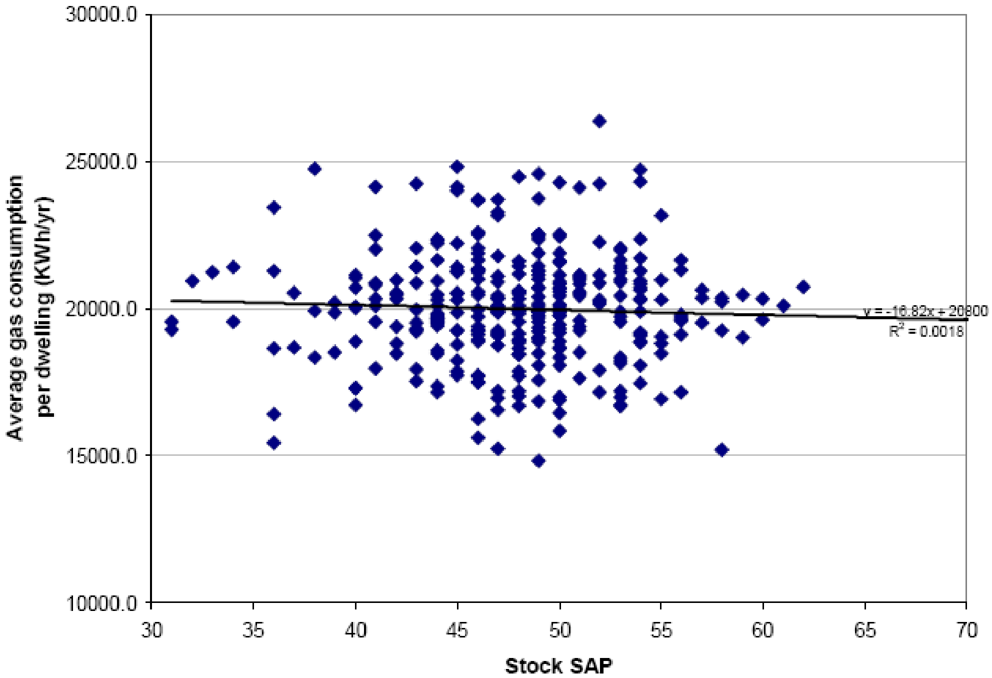

Figure 2: DTI gas consumption versus SAP

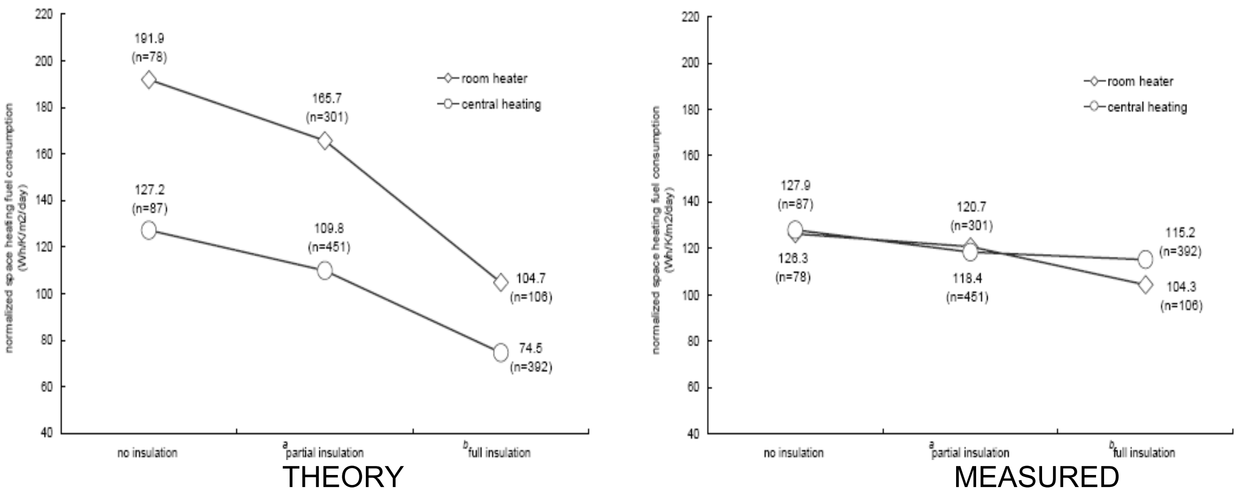

Figure 3: Average SAP versus average annual gas consumption by LA or NUTS4 level (Hong et al. 2006)

2 Performance tests are often undertaken under conditions where it is easy to compare performance but which are not necessarily representative of real operating conditions.

3 Where systems are modelled, it is often assumed that individual component efficiencies are cumulative and there are no losses associated with the interaction of the system.

4 Energy-efficiency improvements do not take place against a static background – culture, society, the economy and the rest of the energy-using infrastructure change continuously. Some of these changes and their implications don't become apparent until years after they begin. For example, higher-density housing appears to lead to longer distribution pipe-runs in dwellings and therefore to higher heat losses from

pipe-work, resulting in system efficiencies that are no better than was achieved 20 years ago, despite the use of high-performance condensing boilers. In addition, high-density housing also leads to more three-storey dwellings, and more party walls, which it now transpires increases rather than reduces space-heating requirements.

A final point is one that was drawn to our attention by our reviewer, Ian Cooper. Achieving performance in the built environment implies:

> 'not only a greater need for enforcement – to ensure that new additions to the stock are built in compliance with approved designs. It also implies a need to monitor the performance of buildings in use in order to understand actual as opposed to predicted performance. Without enforced compliance and monitoring in use, the assumed contribution of additions to the stock to reductions in CO_2 emissions is likely be inaccurate. [But note that such enforcement and monitoring lies at the collectivist end of the dimension shown in Figure 1. Given the UK Government's continued interest in deregulation and voluntary initiatives, movement in this direction is most likely to be driven by EU directives.] Movement in this direction carries with it manpower, skills and training implications that also have to be addressed. In this sense, even seemingly straight technical fixes can have large people-related consequences and come with large behavioural changes attached to them.'

Key goals

Both behavioural and technological changes can result in growth with less carbon emissions. Scientific and technological innovations can be achieved in the following three ways:

1. Doing what we already know how to do in ones and twos but better and in millions
2. Putting together new systems from technology we already have but haven't yet used at any scale – such as local energy centres incorporating combined heat and power, heat pumps and fuel cells
3. Wholly new scientific and technological breakthroughs.

1 and 2 involve existing technological solutions that should be deployed, refined and supported to achieve the strategic goal (growth with less carbon). The urgency of reducing carbon emissions is such that the importance of 1 and 2 must not be forgotten in the excitement of 3.

Key challenges

1. **The study of the potential for divergence of technological trajectories, the strategic nature of technological choices, synergies and conflicts between technologies**. As has been said elsewhere (Lowe 2005): 'At its most basic, technology is the physical expression of human ingenuity, but such a definition would impose too tight a boundary on the discussion. Rather than focus on the physical manifestation of technologies, it may be more useful to focus on the space within which they develop and are appropriated, managed and discarded. This consists of a complex of resources and resource constraints, human needs and desires, scientific knowledge and economic and social processes within the scientific and technological community and in society as a whole. In the long term, the most important constituents of this technology space are the technologies themselves, which interact, compete and cohabit in ways that closely resemble the component species of biological eco-systems.'

   Synergy tends to becomes progressively more important the more complex the energy conversion system one is considering. Until recently, domestic gas heating has previously been the low-carbon solution compared to electric heating; this may now have now changed – the carbon intensity of useful heat from a gas condensing boiler is compared against electric heat for both the past and the future in Figure 4. This graph suggests that the tipping point to convert to low-carbon electric heating has already been passed. This is due to the reduced carbon intensity of future electricity and future improvements in end-use efficiency for heat pumps, whereas gas condensing boilers are already saturated at close to 100% efficiency. The combination of improved building envelope performance, heat pumps and low-carbon electricity makes it possible to reduce carbon emissions from space- and water-heating by a factor in excess of 10.

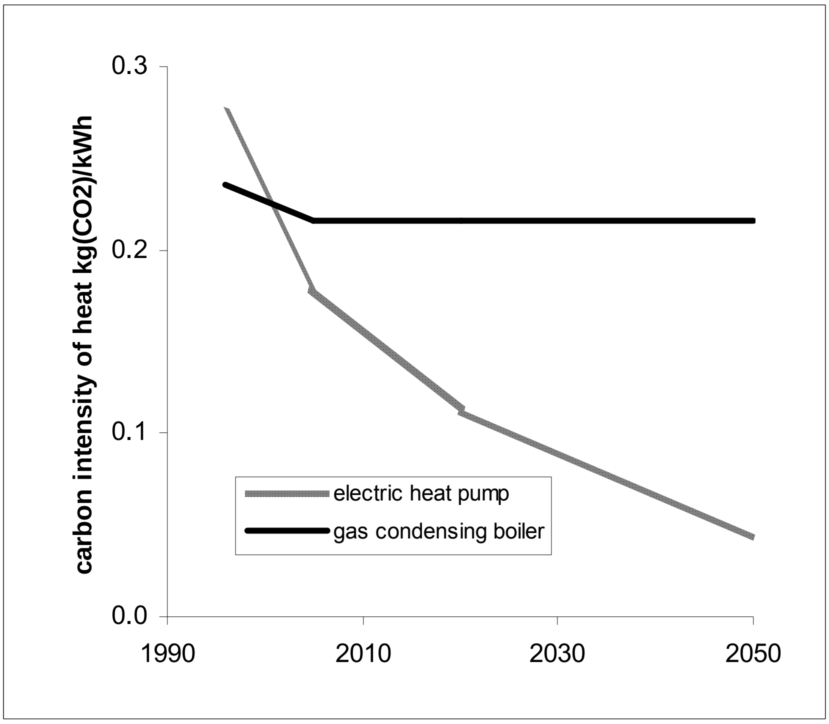

Figure 4: Carbon intensity of space- and water-heating delivered by gas-fired condensing boiler and electric heat pump, assuming modest improvements in heat pump performance and continuation of historical trends in carbon intensity of grid electricity

Such synergies and technological tipping points need to be systematically identified and policy built around them. Further examples include:

a Double glazing used to be, in theory, the least cost-effective energy-efficient improvement in dwellings. However, it is now often more expensive to buy a single-glazed window than a double-glazed window, because most new windows are designed as double-glazed.

b. The clothes we wear determine the energy required to remain comfortable, and the temperatures we have at work define our clothes, which in turn determine the conditions we define at home or at work.

d. We drive heavy inefficient cars, in part because we perceive these to be safer than other inefficient heavy cars. However, Lovins et al (2005) argues persuasively that much of the safety provided by heavy passenger vehicles is illusory, while ultra-light vehicles using advanced composites would be significantly safer than any vehicle that relied predominantly on steel. The example given is the modern carbon fibre Formula 1 car that can be driven into a wall at 200 mph without killing the driver.

2 **Scientific advances** are required in areas where there is greatest theoretical potential for improvements in efficiency. We have already identified one possible combination of technologies that would significantly reduce emissions for space- and water-heating. There is a tendency to view the energy impacts from production of building materials – so-called embodied energy – as much less tractable. However, technologies exist to decarbonise cement, steel and glass, which between them constitute more than 80% of the embodied energy input to the built environment. For example:

a **carbon-free cement.** This could be done either by retrofitting carbon sequestration to existing cement works, but probably requires reengineering the process; or it could involve co-location of cement works and power stations fitted with flue-gas capture systems; or, more interestingly, it could be done by replicating the biological processes that enable shelled creatures to produce their shells – this is an idea of Amory Lovins – chickens make eggshells of astonishing strength at 40ºC.

b **carbon-free steel.** This could be realised by using H_2 produced from methane with carbon capture as the reducing agent. The technology for direct reduction of iron ore using hydrogen has been under development for more than half a century.

c **carbon-free glass.** Again, this could be realised by using H_2 produced from methane with carbon capture and storage.

Putting these technologies together to achieve the goal of decarbonisation of building materials will require reengineering and possible relocating production processes. Over a period of 50 years, such a prospect is realistic since most production facilities will be replaced in any case. Attention needs to be given, at the highest level, to the question of whether there would be a strategic benefit to the UK in taking the initiative, rather than waiting for technologies to be developed elsewhere.

In the area of carbon emissions from buildings already in use:

d **Methane-fired modular fuel cells** with a high ratio of power to heat could be used to provide combined heat and power (and cooling with the addition of absorption cycle chillers) in buildings of any size or in groups of buildings.

3 **Improving practical efficiencies: in-use feedback.** Increased monitoring of in-use performance of energy systems is required and this needs to be fed back in an open and transparent way so that system efficiencies can be improved. The funding of action research whereby companies can work with academics to improve efficiencies is required.

4 **Controlling absolute energy emissions: defining and eliminating waste.** Controlling absolute energy emissions means that we will have to somehow control energy use either directly through carbon rationing/credits or indirectly via its cost or via energy legislation that defines energy waste or restricts the input of carbonaceous fuels into the economy. This would be relatively easy to do technically, since the sources of these are few and they are in the hands of major companies. This would (a) generate an 'access-to-market rent', which would be a source of revenue to government; (b) automatically drive up consumer prices, at a rate governed by the various production functions, the development of energy-using technology and introduction of non-fossil alternative supplies (which would not be limited), and the underlying tendency of the economy to proliferate and intensify energy services. In the longer run, in the kind of future sketched out by Lovins et al. (2005), restrictions

on fossil fuels become complete, fossil-fuel inputs go to zero, but it doesn't matter, because the economy is now weaned of its dependency on fossil fuels. The development of key technologies, e.g. the hydrogen fuel cycle, mean that energy use can continue to grow, fed entirely by renewables. Efficiency then takes second place to a number of other factors, including security of supply and absence of pollution.

5 **Planning for a low-carbon future.** The urban infrastructure that we are currently developing is difficult to change over many decades, yet a low-carbon-expensive energy future will radically change the way we want to interact, travel and use buildings. It is essential that this type of foresight thinking is brought into the planning processes. A future goal must be to foster technological and infrastructural flexibility so that future technologies can be fitted in.

6 **Improvements in system efficiency rather than single component efficiency.** Improved capabilities to model whole-energy systems, leading to models capable of adequately modelling both demand and supply, social/economic as well as technical, and assessing the impact outside of the UK system boundary.

Conclusions

We consider that, in the absence of catastrophic climate change, incomes in much of the world will continue to rise. We consider that improved technology will result in continued reduction in energy and carbon intensities. Individual and combinations of technologies have the capacity to reduce CO_2 emissions by factors of the order of 10.

Despite the latter, it is not obvious that reductions in carbon intensity will outpace growth in demand for energy services by the large factor needed to protect the climate. Among many possible prescriptions for achieving large absolute reductions in carbon emissions, is to: apply a steadily reducing cap to CO_2 emissions and allow the price mechanism, against the context of current and new technology, to determine the price; protect weaker members of society from disproportionate harm through the taxation and benefits system and through direct technological intervention; make use of tariff barriers to protect national and regional economies from imports from economies where such or equivalent action is not taken; maximise through negotiation the size of the trade block that did take action. It would be possible to add almost unlimited detail to this prescription, but it is unclear how helpful that would be.

Acknowledgement

We are grateful for the challenging and generous criticisms of our reviewer, Ian Cooper, on the previous draft of this piece. We hope that we have been able to address at least some of his criticisms.

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