

How to support growth with less energy[☆]

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ABSTRACT

Economic growth with less use of primary energy and lower carbon emissions can be achieved through existing and new technical solutions and by behavioural change. These solutions secure growth with lower carbon emissions and reduce our dependence on oil and gas, thereby improving security of energy supply. The implication of the Energy White Paper goal of reducing CO₂ emissions by 60% by 2050 is a six-fold reduction in the carbon intensity of the UK economy, and further reductions will be needed. Efficient and renewable supply, distribution and end-use technologies have multiplicative effects, but constraining demand growth is crucial to the rate and extent of reducing emissions. Goals include reductions in the energy intensity of transport and buildings and in the energy intensity of major building materials with the development of technologies and demand management. There will also need to be infrastructural developments that encourage low-carbon technologies and increase energy diversity and security of supply, 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, and improved capabilities to model whole energy systems, including demand and supply as well as social and economic issues.

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0. Growth with less energy

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 or unsustainable resource use except insofar as they result in current expenditure. Conversely, GDP values intermediate economic activities such as transport (passenger kilometres) and domestic gas consumption, rather than the goods that those intermediate activities are ultimately intended to provide, such as access and thermal comfort. Finally, it positively values systems and services that have developed to mitigate negative externalities from a range of economic activities, including a significant portion of modern health services, much of the leisure industry, military expenditure and so on, while excluding negative externalities. Mishan's (1993)

critique of GDP as an indicator of well-being remains fundamentally valid.

'Less energy' can be interpreted as less primary, delivered or useful energy and may include finite fossil, renewable (with or without passive solar) or all commercially traded energy. The definition used in framing the primary proposition of this paper affects the conclusions.

Systems boundary: A key element of any discussion around growth with less energy is where the system boundary is drawn. If the boundary is drawn around the UK, a crucial question is whether flows of energy and material across that boundary are accounted for. 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 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 fun. The more of this we do, the faster other indicators such as GDP are also likely to grow. 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 House of Lords Select Committee on Energy Efficiency (2005): '...in placing

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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 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 or more, 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 use 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' (the complex of home computing, television, hi-fi). We appear to have an innate ability to think up new ways of using energy, which almost always outstrip efficiency improvements. In this interpretation, defining what is useful or wasteful energy use becomes very complex. If we 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 24 °C 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 declaring it wasteful to cool below 28 °C. In the UK, it appears there is still legislation on the statute book that makes it illegal to heat public buildings above 19 °C, but this has never been enforced.

1. 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 the service level, or by switching from one service or commodity to another with lower energy intensity. These options have complex interactions, but may be combined into integrated policies that reduce energy related emissions (e.g. Barrett, 2007a). A society that is energy efficient and reliant on renewable energy reduces its exposure to the vagaries of international fuel availability and prices, and thereby protects its members' well-being and facilitates the development of a robust, stable economy.

2. Energy-efficient technology

There is no doubt that there is considerable potential to utilise existing energy-efficient technology and develop even more energy-efficient technologies. Table 1 attempts to capture a sense of this potential for some of our current major energy uses, but note that many technologies have been omitted from the table.

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 re-spending 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 the Khazzoom–Brookes effect (Brookes, 2000; Saunders, 1992; Sorrell, 2007).

3. Behavioural change

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 consumer choice and behaviour are constrained, as with limits on air travel or road speed limits. Buying smaller, more fuel-efficient cars can reduce fuel consumption directly by 50% or more. Reducing internal temperatures in buildings can save in the order of 10% of space heating—more in highly insulated dwellings. Replacing airline flights with videoconferencing and alternative, low-carbon leisure activities is essential to control energy demand and climate forcing in this problematic sector. Barrett's (2007a) low-emission energy scenarios include the effects of such behavioural changes.

More strategically, the valuing of goods that are presently unvalued or undervalued can, in principle, allow continued gross national product growth with little or no increase in carbon emissions. Mishan¹ 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 trends to expand 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 emphasis 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 in the order of 10. We believe that such combinations of technologies are potentially potent drivers of change throughout the economy.²

However, we also address the problem of energy price. In our view, price is a primary determinant of behaviour and is as important for the direction and intensity of scientific and engineering endeavour and the course of innovation, particularly in the long term. Here we appeal to Jevons' (1906) analysis. The problem of resource use has, at minimum, two dimensions: 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

¹ This is essentially a restatement of the Khazzoom–Brookes postulate, which, in Saunders' formulation, reads: 'with fixed real energy prices, energy efficiency gains will increase energy consumption above what it would be without these gains' (Saunders, 1992, quoted in Sorrell, 2007). Sorrell goes on to observe that 'If it were correct, the K-B postulate would have deeply troubling policy implications.' This concern is only understandable if one assumes that a policy of active energy price management is inconceivable. We do not believe that this assumption is reasonable.

² In passing, we note that all of the technology discussed in this paper exists.

Table 1
Some actual and potential energy-efficient technologies

Technology	Average UK performance	Best commercially available efficiency	Technically feasible for ≈ 2030
Thermal electricity generation	39% mean electricity-generation efficiency, equivalent to carbon intensity of 0.47 kg (CO ₂)/kWh	49% (gas-fired combined cycle gas turbine) equivalent to 0.44 kg (CO ₂)/kWh	$\approx 63\%$ using technologies such as hybrid solid oxide fuel cell/gas turbine, equivalent to ≈ 0.3 kg (CO ₂)/kWh (Fuel Cells Bulletin, 2006)
Transport via car	2006 car fleet average > 170 g CO ₂ /km (32 mpg UK) (DfT, 2007)	AUDI A2 1.2 TDI, 80 g CO ₂ /km (95 mpg UK) (AUDI AG, 2003) AUDI A2 1.4 TDI 116 g CO ₂ /km (65 mpg UK) (AUDI AG, 2003) Prius 101 g CO ₂ /km (65.7 mpg UK)	The examples given deliver 80–116 g CO ₂ /km. Current technology with vigorous downsizing makes significantly lower consumption feasible
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

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.

4. Transport

At first sight, transport is the most difficult sector in which to reduce carbon emissions, because replacing oil with renewable fuels is technically challenging, because energy efficiency is already a significant design objective in the design of transport technologies, and because the rates of growth are generally high, particularly in international aviation and shipping, where the absence of immediate physical space constraints leads to apparently unlimited demand.

Much work has been carried out over the last three decades on the potential for reducing carbon emissions from passenger transport by road, 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 and trains) or to non-mechanised modes (walking and cycling).

Unfortunately, although numerous theoretical analyses and much practical experience have 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 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 in car use, according to PROPOLIS, were very large rises (by 100% and more) in the real price of motoring.³

³ We note that the policy of the Fuel Price Escalator, which was operated by two successive UK governments from 1993 to 1999, would have resulted in such an increase, even in the absence of rises in global crude oil prices, by the end of the present decade.

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 Schäfer and Victor (1997) of MIT collected statistics for total annual distances travelled by all modes, in different regions of the world, over the period 1960–1990. Fig. 1 shows these distances (passenger kilometres) against GDP per person (\$).

Fig. 1 reveals a strong linear relationship: as incomes have risen, so also 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.

Of course, all of the growth shown in Fig. 1 happened in the era of cheap petrol, and one might speculate how the trend might falter in the future, with oil prices of \$100 per barrel⁴ and higher. But, so far as energy policy is concerned, the obvious short- to medium-term conclusion to be drawn from the above must surely be to put much heavier emphasis on improving vehicle technology than on 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.

Freight transport and international aviation and shipping are generally forecast to grow faster than road passenger transport, and energy efficiency is already at a premium in these transport segments. For example, Barrett (2007a) shows that, by 2050, global warming from aviation may grow to form half of warming due to UK CO₂, despite the application of control measures. There are no efficient and cost-effective direct replacements for oil in long-distance air and marine transport, and these segments are likely to be the last bastion of fossil fuels⁵.

⁴ This paper was written during the large oil, gas and coal price increases and fluctuations of 2006–8.

⁵ There are no technologies or abundant renewable fuels in sight for replacing kerosene fuelled aircraft for high speed, long distance passenger transport duties.

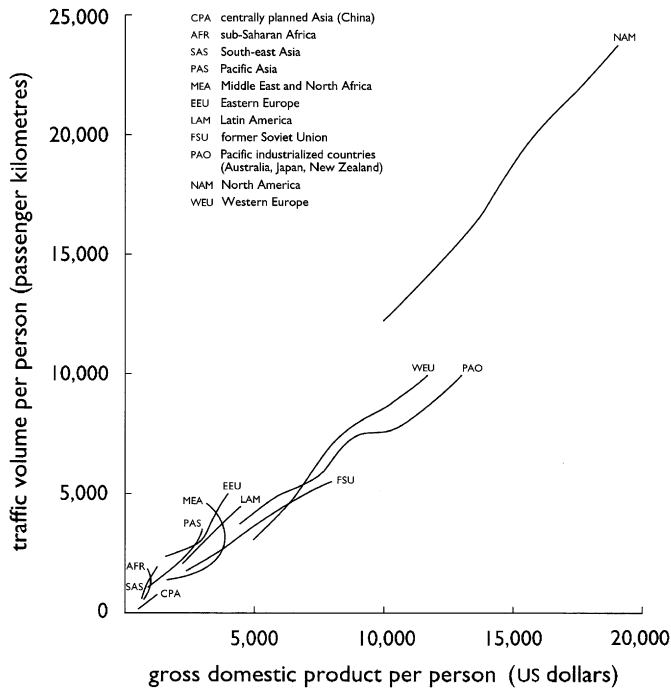


Fig. 1. Total distances travelled by car, bus, train and aircraft, in various regions of the world (vertical scale), compared with average income in US dollars (horizontal scale), 1960–1990. Adapted from Schäfer and Victor (1997), with permission of Massachusetts Institute of Technology.

The question then is how to uncouple the demand for mobility and freight transport from the use of fossil fuels. There are many ways in which this could be achieved—modal shifts from car to train and bus, from aeroplane and truck to train, car downsizing, efficient vehicles, electric vehicles (in the context of decarbonised electricity systems), relocation and relocalisation of activities—though these cannot be detailed in this paper.

5. Future advances to 2050 and beyond

A number of future scenarios have explored the possibilities of achieving environmentally significant (e.g. 60% by 2050) reductions in carbon emissions while maintaining growth in energy services. Some of these are listed in Table 2.

Barrett (2007a) developed low-carbon scenarios to 2050 for each of the 25 EU countries, including the UK, that incorporate behavioural and technological measures. These scenarios look at technologies that have been investigated since the 1970s but which are only now starting to be mainstream. A crucial insight from these studies is the way that changes throughout the energy supply, transmission, distribution and end-use conversion system multiply together. Thus, decarbonisation of electricity supply coupled with state-of-the-art heat pumps is 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 of 10 reduction in carbon emissions due to space heating is clearly achievable using currently available technology. Studies have also looked at the future potential for renewable and low-carbon electricity generation, for example, demonstrating the potential to provide 95% by renewables (Barrett, 2007b).

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. We consider that a key role of the government is to identify potential tipping points in advance and to build coherent 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 USA, it is possible that both military security and energy security may go hand in hand (Lovins et al., 2007).⁶ Threats to military power arise from the huge costs and risks associated with supplying energy-inefficient armed services with energy under battlefield conditions. Strategic technological developments, such as ultra-high-strength materials, fuel cells and energy efficiency, make possible orders of magnitude reductions in cost and risk in the battlefield. The same technologies applied to domestic transport systems might make it possible to drive down national demand for oil at a faster rate than domestic supplies fall. According to the Rocky Mountain Institute (Lovins et al., 2007), such a process could lead, by 2020, to the US becoming once again self-sufficient in oil and gas.

6. Theory and practice

Many studies demonstrating such alternative low-carbon futures have been undertaken over the last 30 years. Yet none has 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 that would generate a significant problem regardless of whether we carry on using fossil fuels, nuclear, renewables, energy efficiency or a combination of all of these. Without a clearer collective conception of what levels of energy use and CO₂ emissions are acceptable, and in the absence of possible future increases in the price of energy, the past 30 years could be rather similar to the next 30 years. If the problem is to decarbonise the UK economy, whichever mix of supply technologies is ultimately developed, the trick is to stop the demand for energy growing quicker than low or zero carbon technologies can be introduced.

There are, however, reasons other than ‘take back’ that may explain why theoretical energy-efficiency predictions often do not materialise and there are many other causes of over-optimism in predictions of energy performance:

- 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 is often not related to real energy use. This is illustrated in Figs. 2 and 3. Fig. 2 compares real DTI gas consumption data provided by utilities against theoretical Standard Assessment Procedure (SAP) ratings. Note that these data have not been corrected for climatic region or availability of gas but still a better correlation would be expected. Fig. 3 shows the predicted and monitored fuel consumption in several thousand dwellings studied in the Warm Front project with different heating systems and levels of insulation.

⁶ Much of the Rocky Mountain Institute analysis hinges on the very high costs of energy supplied to forward battle areas. We are indebted to Bob Everett of the Open University for pointing out that this is a very old concern. Winston Churchill was responsible for a very similar analysis of the cost of biscuits supplied to the British Army at the Battle of Omdurman in 1898.

Table 2
Recent bottom-up energy studies and the potential for energy savings (after Fawcett, 2005)

Study	Country	Energy sector	Savings
BRE study 1 (Shorrock and Dunster, 1997)	UK	Household energy use	14% energy saving 2020 compared with 1995
University of Oxford 1 (DECADE, 1997)	UK	Electricity for lights and appliances	28% electricity from 1996 to 2010
University of Oxford 2 (Fawcett et al., 2000)	UK	Electricity and gas, domestic lights, appliances and water heating	17% carbon/13% energy from 1998 to 2020
BRE study 2 (Shorrock et al., 2001)	UK	Household energy use	17% energy saving 2000–2020 under 'efficiency' scenario
Energy Saving Trust submission to the Performance and Innovation Unit's Energy Review (Epple, 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)	All EU	All sectors	16% reduction in greenhouse gases 1990/95–2010
Imperial College study (ICCEPT, 2002)	UK	All sectors	60% carbon saving by 2050
Thomas et al., (2002)	Germany	All sectors of the economy, gas and electricity	Approximately 10% energy saving 2002–2010
Johnston, (2003), see also Johnston et al. (2005)	UK	Household energy use	50% energy and 61% carbon 1996–2050
40% House, Environmental Change Institute, University of Oxford (Boardman et al. 2005)	UK	Household energy use	60% CO ₂ reduction by 2050
Barrett (2007a)	Each EU25 country	All sectors except international transport	80% CO ₂ reduction by 2050

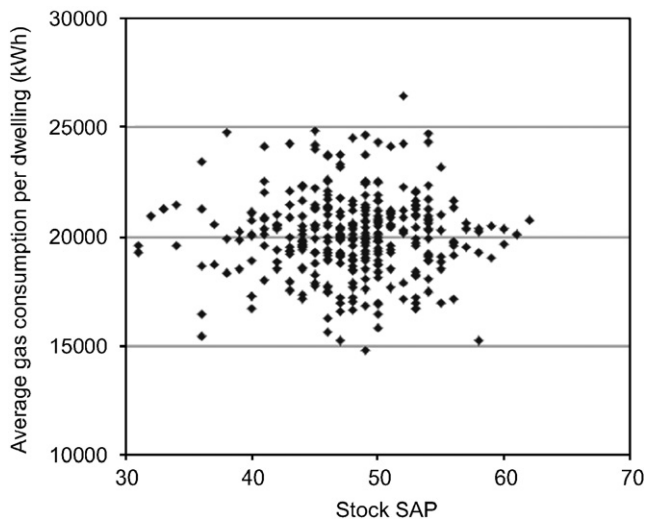


Fig. 2. DTI gas consumption vs. SAP index (Summerfield et al., 2006).

- 2 For those systems and components of buildings that are subjected to performance tests, tests are normally undertaken in the laboratory according to protocols that deliberately exclude many of the contextual factors that operate in the real world. The reasons for this are sound—such contextual factors are often difficult and expensive to define and replicate in the laboratory, but their effect is almost always to degrade performance with respect to measurements made under test 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 do not 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 pipework, resulting in system efficiencies that are no better than those

achieved 20 years ago, despite the use of high-performance condensing boilers.⁷ In addition, high-density housing also leads to more three-storey dwellings, and more party walls, which, it now transpires, at least with current construction practice, increase rather than reduce space heating requirements (Lowe et al., 2007).

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 CO₂ emissions are likely be inaccurate. (But note that such enforcement and monitoring lies at the collectivist end of a spectrum, at the other end of which is 'individualism'. 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.'

7. 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.

⁷ Factors in this relationship include the impact of moving from two to three storeys and the fact that higher density tends to result in less external wall area and tighter constraints on siting of boilers. The recent trend towards much larger numbers of wet rooms in modern dwellings is a confounding factor.

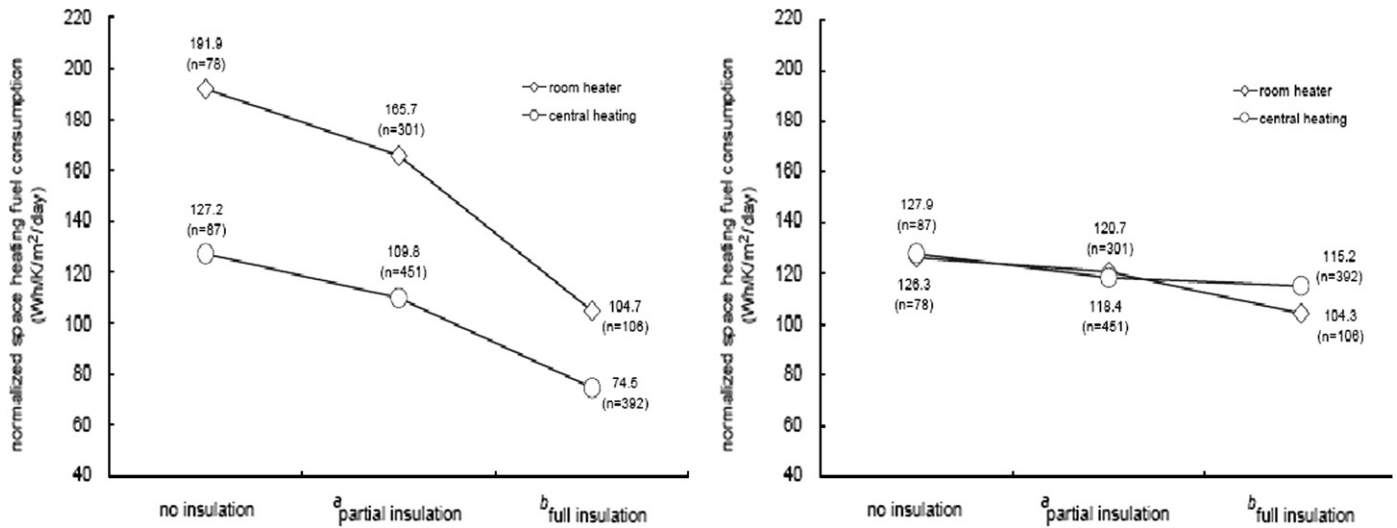


Fig. 3. Theoretical and measured Warm Front normalized space heating fuel consumption disaggregated by primary heating system and insulation level (Wh/K/m²/day) (Hong et al., 2006). ^aPartial loft insulation (< 100 mm) without wall insulation or full loft insulation (> = 100 mm) without wall insulation or wall+partial loft insulation. ^bwall+full loft insulation.

- 2 Putting together new systems from technology we already have but have not 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 above involve existing technological solutions, which should be deployed, refined and supported to achieve the strategic goal of growth with less energy. The urgency of reducing carbon emissions is such that the importance of 1 and 2 must not be forgotten in the excitement engendered by 3. By constraining cumulative global future carbon emissions, the policy goal set in 2000 requires rapid reductions in CO₂ emissions. Such reductions are perhaps most easily achieved in technology sectors with rapid turnover of infrastructure. Examples include domestic lights and electrical appliances, and personal transport, in both of which the infrastructure turns over more or less completely in less than 20 years. But it is hard to see how rapid reductions in emissions can be achieved without impacting on behaviour and the pervasive expectation that the next fridge, the next TV, the next car will be bigger, faster and more loaded with features compared to the last.⁸

8. Key challenges

1 *The study of the potential for divergence of technological trajectories, the strategic nature of technological choices, and synergies and conflicts between technologies.* It is possible to define technologies, narrowly, as the physical manifestation of human ingenuity, but such a definition would impose too tight a boundary on 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

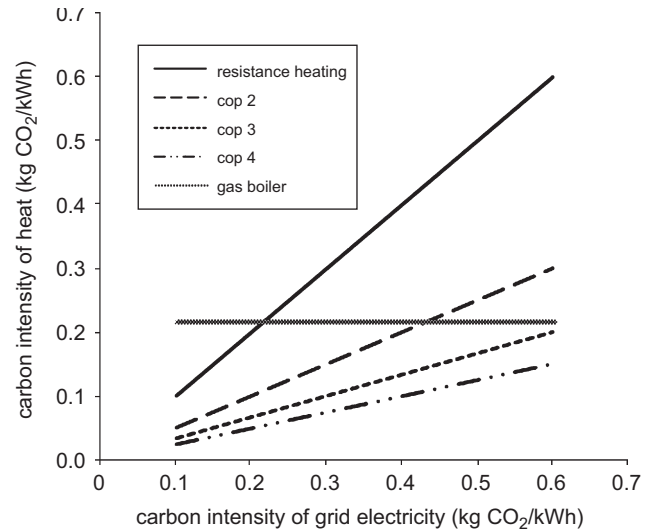


Fig. 4. Carbon intensity of space and water heating: comparison of electric resistance heating, heat pumps with annual coefficients of performance (COPs) from 2 to 4, and gas boiler with an annual efficiency of 90%. Note that electricity required to circulate hot water is ignored in all cases.

interact, compete and cohabit in ways that closely resemble the component species of biological eco-systems (Lowe et al., 2005).

Synergy tends to become progressively more important, the more complex the energy conversion system one is considering. Until recently in countries with predominantly fossil-fuelled electricity systems, natural gas-fired heating has been the low-carbon solution compared to electric heating. In the future, this may change. Fig. 4 compares the carbon intensity of useful heat from a gas condensing boiler against electric heat from electric systems, as a function of the carbon intensity of grid electricity. The graph suggests that a tipping point may be close. The deciding factors will be continued reductions in the carbon intensity of electricity and future improvements in end-use efficiency for heat pumps. The performance of natural gas-fired condensing boilers is close to saturation at 80–90% in-situ efficiency.

⁸ We note that it is now possible to buy showers with integral television sets.

Lowe (2007) has argued that combinations of improved building envelope performance, heat pumps and low-carbon electricity may make it possible to reduce carbon emissions from space and water heating by a factor in excess of 10 (Fig. 4).

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

- a Double glazing, in theory, used to be the least cost-effective energy-efficiency 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 to be 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.
 - c In general, heavy cars emit more carbon than light ones, and people in heavy cars subject those in smaller cars to a greater risk of injury when they collide with each other; people who choose low-carbon cars are penalised with an increased injury risk. Light, efficient vehicles are critical to low-carbon transport, irrespective of the fuel used. Barrett (2007a, b) shows that downsizing using currently available technology could reduce CO₂ emission from cars by over 50%, which is about 8% of UK total CO₂ emissions.
- 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 being 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 *Low carbon cement* could be produced either retrofitting carbon sequestration to existing cement works, but probably requires re-engineering the process. This might involve co-location of cement works and power stations fitted with flue-gas capture systems. More interestingly, it might be done by replicating the biological processes that enable shelled creatures to produce their shells.
 - b *Carbon-free steel* could be realised by using H₂ 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* could again be realised by using H₂ produced from methane, with carbon capture and storage. Putting these technologies together to achieve the goal of decarbonisation of building materials will require re-engineering and possibly re-locating 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 leading, rather than waiting for, technologies to be developed elsewhere.
- In the area of carbon emissions from buildings in use, the key to progress is not the invention of new technologies but the deployment and integration of technologies that have been available for years and in some cases, decades.
- 3 *Improving practical efficiencies: feedback in use.* Increased monitoring of the performance of energy systems in use is required and this needs to be fed back in an open and

transparent way so that system efficiencies can be improved. Funding is required whereby companies can work with academics to improve efficiencies. There are reasons for believing that models of research such as action research may facilitate such collaboration.

- 4 *Controlling absolute energy emissions: defining and eliminating waste.* Control of absolute energy emissions means that it will be necessary, somehow, to control energy use either directly through carbon rationing/credits or indirectly via the cost of energy 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 sources of these are few and 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; and (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. (2007), restrictions on fossil fuels become complete, fossil fuel inputs go to zero, but this is not important, because the economy is now weaned off its dependency on fossil fuels. The development of key technologies, e.g. the hydrogen fuel cycle, means 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.⁹
- 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 will want to interact, travel and use buildings. It is essential that this type of forward thinking is brought into planning processes. A future goal must be to foster technological and infrastructural flexibility so that future technologies can be incorporated.
- 6 *Improvements in system efficiency as well as single-component efficiency.* There is a need to improve the modelling of the socioeconomic, technological and environmental features of integrated systems of energy demand and supply. This modelling needs to be consistent across national, international and local scales: for example, the reduction of fossil fuel consumption in the UK and Europe will impact on international fuel prices, and thence affect price elastic demand.

9. Conclusions

We consider that, in the absence of catastrophic climate change and the swift onset of fossil fuel shortages,¹⁰ incomes in much of the world will continue to rise. We consider that improved technology can, in principle, result in continued reduction in energy and carbon intensities per economic value. Individual technologies and combinations of technologies have the capacity to reduce CO₂ emissions by factors in the order of 10.

Despite this, 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. One of the many

⁹ We suspect that if such a position was ever to be achieved, economic and population growth would be constrained by other mechanisms. The ‘big rock candy mountain’ will probably always elude us, but the obstacles in our way will almost certainly change and evolve over time.

¹⁰ We note that global oil production has been flat since 2005 and that it is possible that peak oil has already been reached.

possible prescriptions for achieving large absolute reductions in carbon emissions is to apply a steadily reducing cap to CO₂ emissions, and to allow the price mechanism, against the context of current and new technology, to determine the price. It is important to protect weaker members of society from disproportionate harm through the taxation and benefits system and through direct technological intervention. It may be necessary to use tariff barriers to protect national and regional economies from imports from economies in which equivalent action is not taken. The size of any trade block taking such action would need to be maximised through negotiation. It would be possible to add almost unlimited detail to this prescription, but it is unclear how helpful that would be.

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