The Economics of Energy (and Electricity) Demand

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Abstract Economic drivers, technologies and demand side management are keys in understanding the long-term trends of both energy and more specifically electricity consumption. This paper discusses some of the important economics foundations of energy demand in general, and electricity in particular. First, we look at the macro-economic context of energy. This reveals how energy and electricity consumption are subject to the same drivers - income and price - over long periods. However, energy demand (and carbon emissions) falls and energy prices rises in one country may have little effect at the world level. Next, we examine the features of energy service expenditures. Despite similarities over time, specific sectors are distinct from one another in terms of consumption profiles, and new sources of electricity demand may substantially change total demand and the way it is consumed. This leads us to a closer look at the micro-economic context of energy demand, and the tension between technically possible energy savings one one side, and the economics and behavioural dimensions on the other side. We conclude by highlighting the various unknowns and uncertainties that characterise the future of energy demand.

Keywords energy demand, electricity demand, macroeconomics of energy, energy services, energy prices, energy expenditures

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1. Introduction

In the UK, electricity demand grew by 2.4% p.a. between 1970 and 2005, to reach a record high of 357 TWh, but then declined to 330 TWh in 2009 following the sharp recession which began in 2008.[3] However longer run trends suggest increasing electricity demand globally in the future, and even in the UK. Figure 1 shows the trends in electricity consumption in the UK since 1960 for the residential; public administration, transport, agricultural and commercial sectors; and industrial sectors. In the residential sector, consumption increased by 59% between 1970 and 2009 (DUKES, 2010). The largest household electricity consumption increase is due to consumer electronics, as will be shown later in this paper. Commercial and public services have used sharply more electricity since 1970, with a rise of 140% to 2009 (DUKES, 2010). Consumption by industry, by contrast, has been decreasing recently, with a steady decrease since 2005, partly due to deindustrialization, the recent recession and increased

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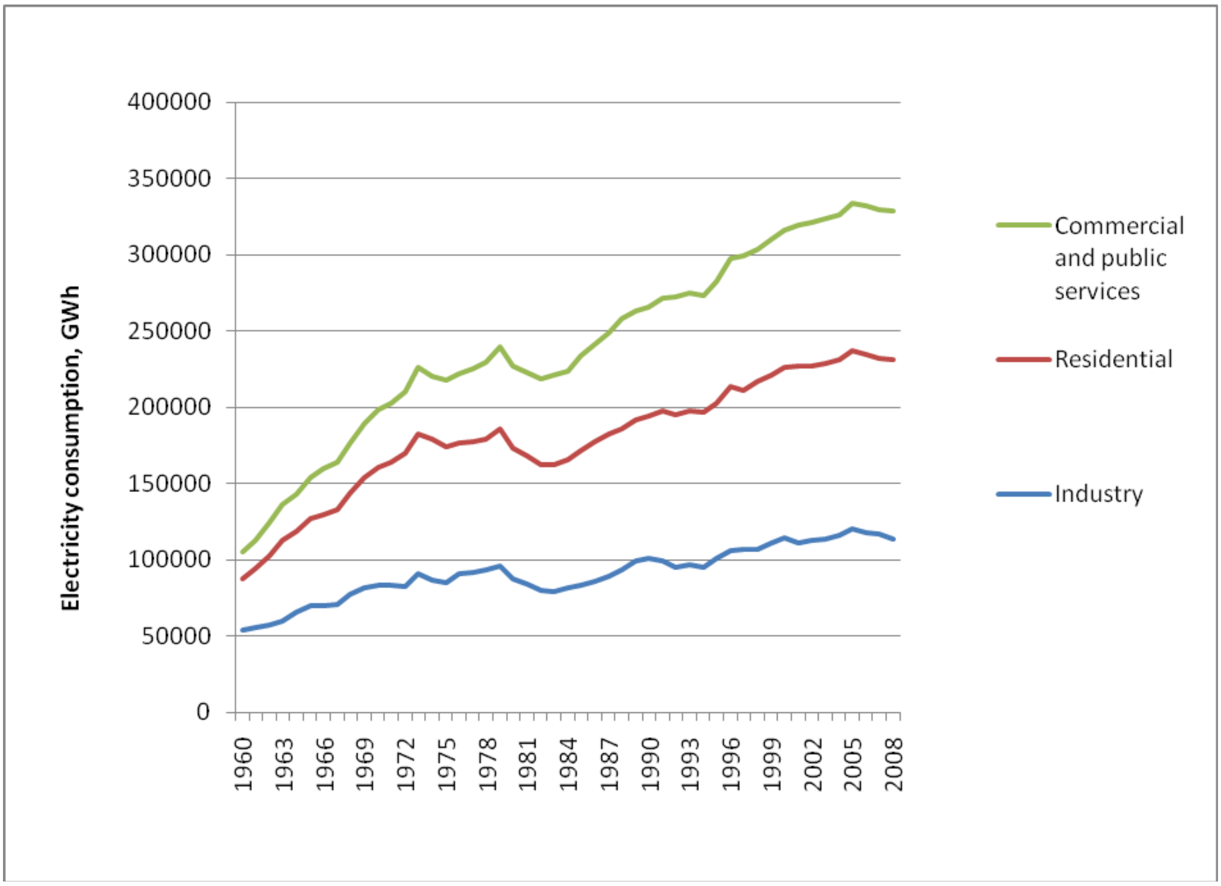
[3] See Table 5.1.2 in "Digest of United Kingdom energy statistics 2010: long-term trends", available at http://www.decc.gov.uk/assets/decc/Statistics/publications/dukes/324-dukes-2010-longterm.pdf, last accessed 15 October 2010.

energy efficiency (DECC, 2010a). In the longer run however electric vehicles and the electrification of the heat sector (should natural gas decline as the heating fuel of choice) will provide significant new sources of growth of electricity demand.

Figure 1: UK final electricity consumption by sector, 1960-2009



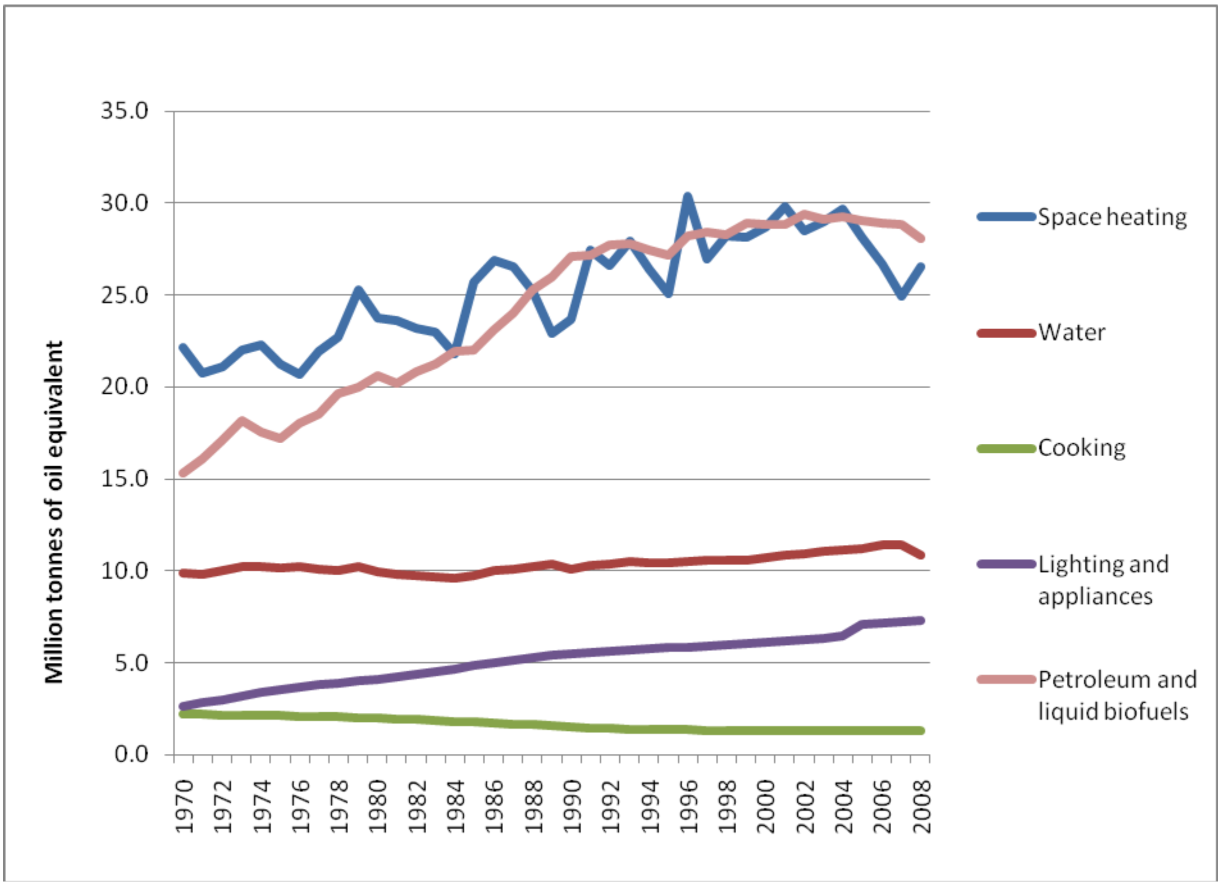
Sources: 1960-2004: IEA (2010a); 2005-2009: DUKES (2010).

Figure 2 shows the scale of the potential impact of electrification of transport and heat on household electricity demand. Household transport demand for petroleum is around four times the energy value of the electricity used for lighting and appliances.[4] Electrification of water and space heating, currently

[4] Given substantial transformation losses in electricity supply, around 2.5 times the amount of raw energy is required to supply a given level of electricity to the home, so Figure 2 exaggerates the relative size of transport demand to lighting and appliance demand, but the scope for increased demand for electricity is clear.

largely (though not entirely) supplied via natural gas would produce a significant rise in demand for electricity.[5]

Figure 2: UK domestic energy consumption by end use, 1970 to 2008



Source: DECC (2010b).

This suggests that income, technologies and demand side management are keys in understanding the long-term trends of energy and more specifically electricity consumption. Future energy trends are central to policy making. This paper intends to uncover what lessons can be learned from the empirical evidence. It looks back at the history of energy demand, discusses key technological and price developments as well as the demand side issues that have led us to where we are now and are likely to continue guiding future energy developments. By doing so, the paper, which is a working paper version of the opening chapter of the book "The Future of Electricity Demand: Customers, Citizens and Loads", lays

[5] Around 80% of households are on the gas network, the rest mainly use oil or electricity for heating.

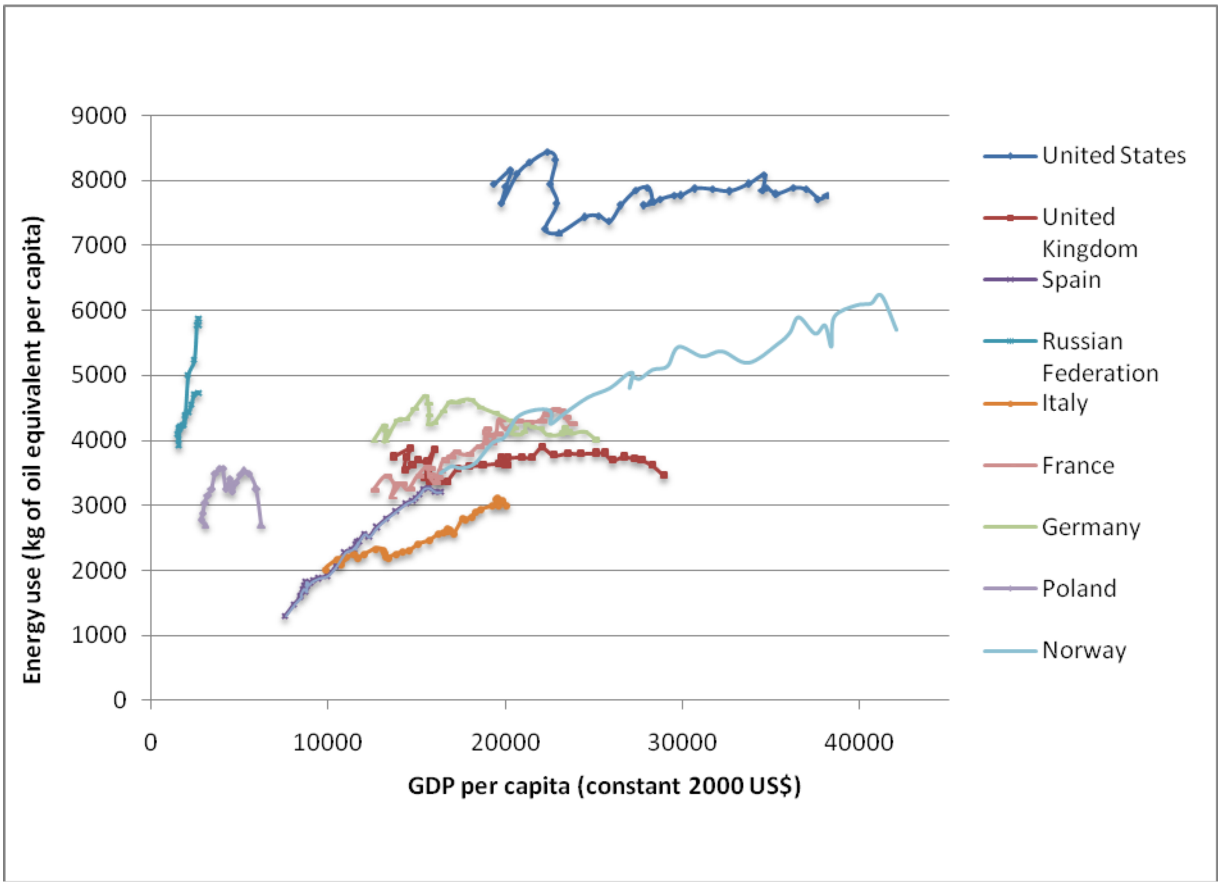
out some economic fundamentals of energy demand, which underpin some of the analysis in later chapters of the book. It is not intended to cover the extensive literature surrounding energy demand (for a recent review of energy demand modelling, see Steinbuks, 2011), but rather to bring together a number of key factors influencing energy demand and reflect on some likely future developments, in light of current challenges. A number of unknowns are highlighted, that testify to the fact that we are now at a crossroads in the history of energy consumption and a number of different paths are possible. The rest of the paper is organized as follows: in Section 2 we discuss the long-run macro-economic context of energy demand; in section 3, we discuss the long-run micro-economic context of energy demand, and offers some initial conclusions in section 4.

2. The long-run macroeconomic context of energy demand

2.1 The drivers of aggregate energy consumption

The 2050 decarbonisation target context in which many energy and climate policies are framed immediately gives rise to a long run comparative view of how energy demand is likely to evolve. It is instructive to examine what the evidence of history says about this. Figure 3 shows the evolution of energy consumption per head versus GDP per head over the period 1972-08. The solid line shows a linear relationship through the data. The data shows the strong positive relationship between energy consumption and income for most countries. Only Germany and the US show significant reductions over longer periods. In Germany this occurs at a high level of income, while in the US this occurs at a very high level of energy consumption and occurs following the oil price shocks of the mid 1970s and mid-1980s. Figure 3 also illustrates (by implication) how rising population contributes to absolute growth in energy consumption.

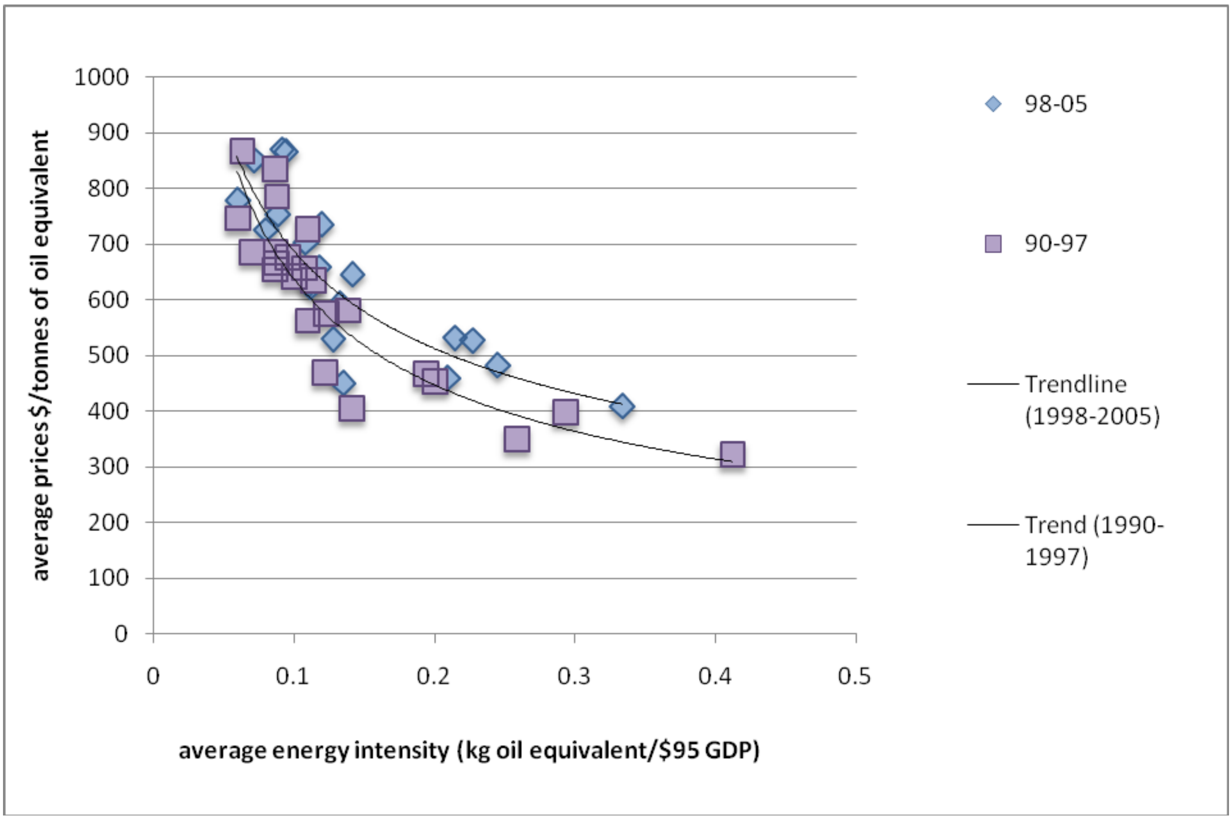
Figure 3: Income as a driver of energy consumption – energy use per head versus GDP per head, 1972-2008



Source: World Bank (2010).

Figure 4 highlights the role of price in explaining the differences in energy consumption between countries. Higher prices are associated with lower levels of energy consumption. Indeed the oil intensity of GDP (units of oil consumed per unit of GDP) is proportionately reduced for proportionate increase in the average energy price (including taxes). Indeed the fitted line shows the price elasticity of demand for units of energy in an economy, which is highly elastic, i.e. 1% increase in average price reduces energy consumption by 2%. Comparison of the 1998-2005 period with the earlier period 1990-97 indicates that the revealed elasticity is increasing between the earlier and later periods. This means that the differences in levels of energy intensity at the same income level significantly reflect price differentials.

Figure 4: Price as a driver of energy consumption – energy intensity versus energy prices

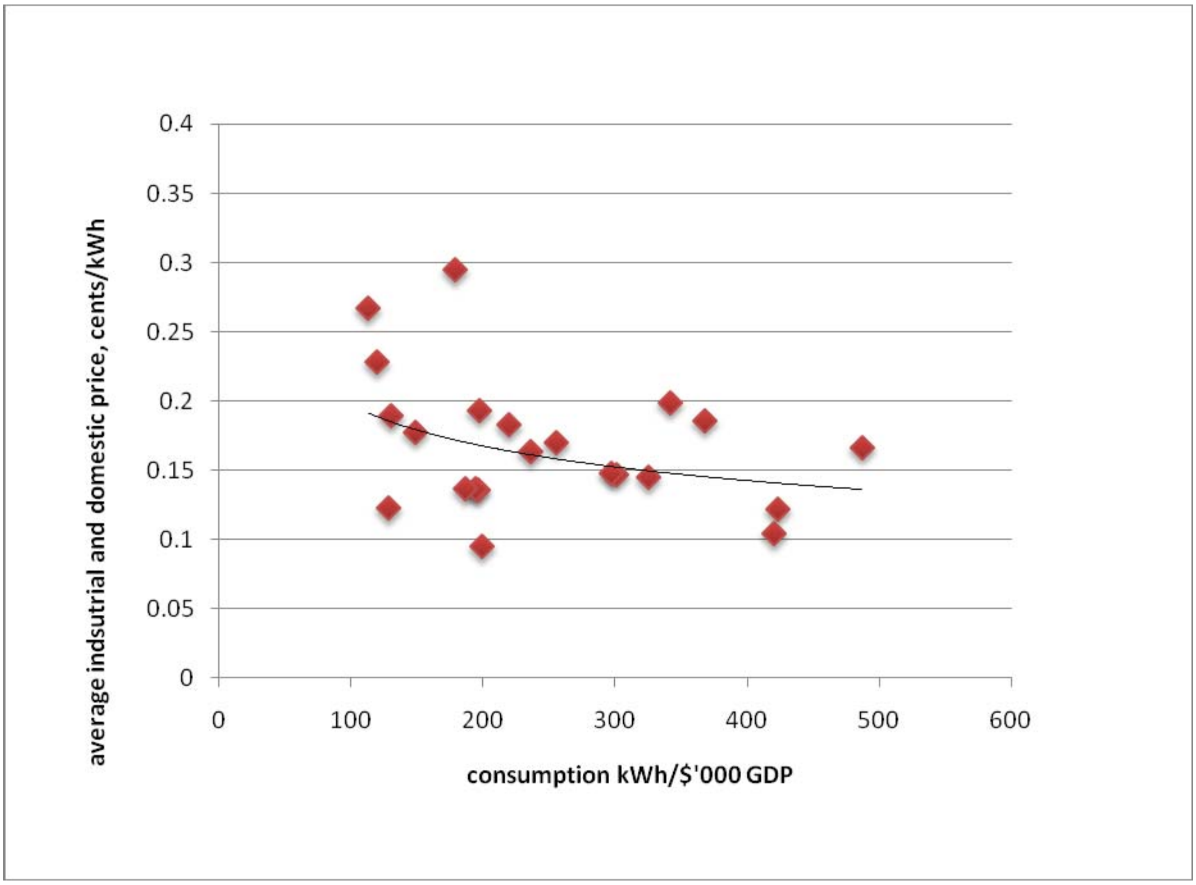


Source: Data from Steinbuks (2010).

Figure 5 suggests that the price relationship for electricity demand across countries is similar to that for overall energy demand. Countries that have very high prices (due to taxation) tend to have lower demand for electricity, while countries that have very low prices (due to subsidy) tend to have very high consumption. We can conclude from Figure 5, that price and income are some of the key triggers for both electricity demand and overall energy consumption.

In order for us to gain perspective on what historians might be saying one hundred years from now we can look further back in to history. In order to evaluate climate policy, historians in 2110 may look back on the national and international efforts to decarbonise energy systems which began to be discussed seriously in 1988 in the run up to the 1992 Rio Climate Change Summit and the many modelling exercises which suggested how carbon dioxide levels should evolve to 2100.

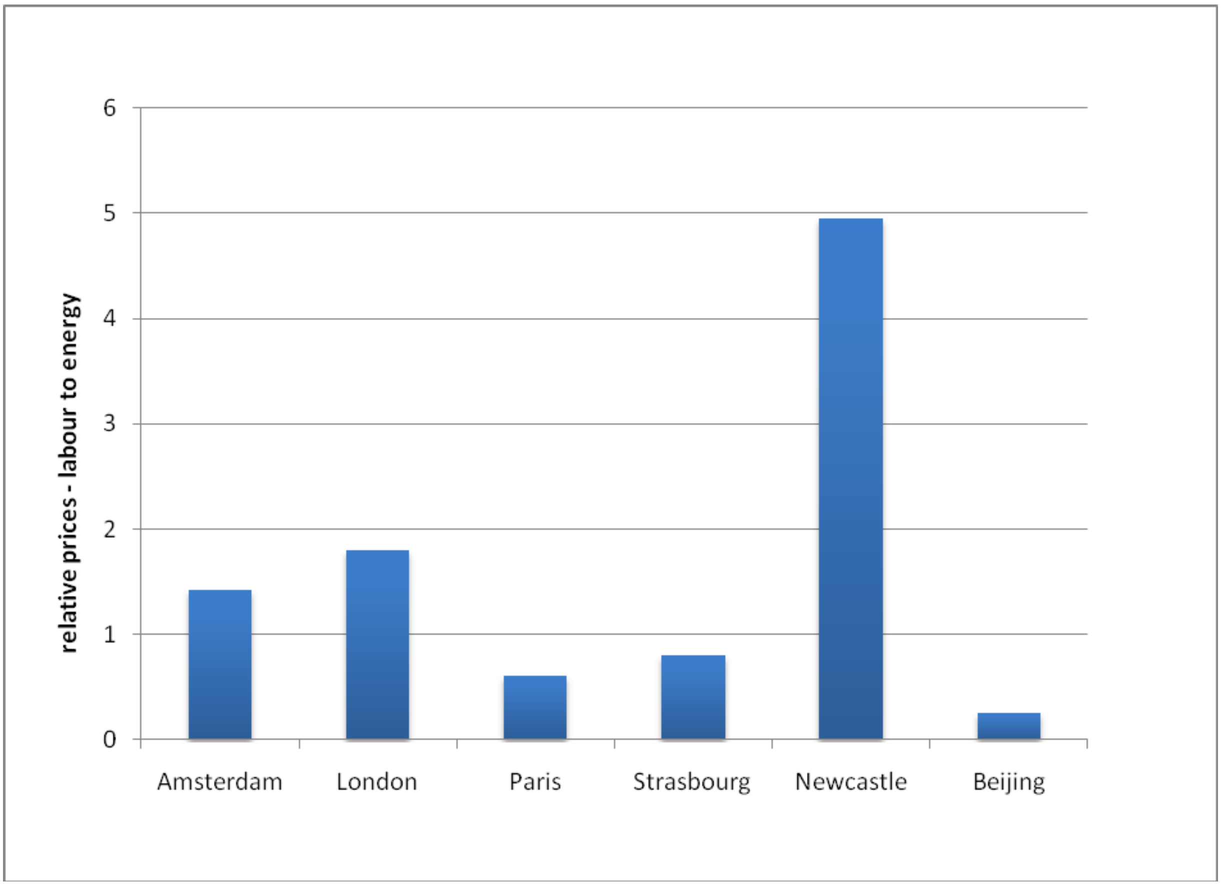
Figure 5: Price as a driver of electricity consumption: 2008 data



Source: IEA (2010b); Countries: Austria, France, Luxembourg, Slovak Republic, United Kingdom, Belgium, Greece, Netherlands, Spain, United States, Czech Republic, Hungary, Norway, Sweden, Denmark, Ireland, Poland, Switzerland, Finland, Italy, Portugal, Turkey.

Figure 6 provides some food for that thought experiment. This figure is taken from Allen's (2009) book where he suggests that the reason why the industrial revolution took place in northern England and not elsewhere was significantly to do with the relative prices of different inputs to production. In northern England a unit of agricultural labour was expensive relative to a unit of energy (due to abundant cheap coal and relatively productive agricultural workers). This incentivised the use of and innovation in labour saving energy intensive technologies (such as the steam engine). Figure 6 shows that in the early 1700s labour was almost 5 times more expensive relative to energy in Newcastle than it was Strasbourg (and more than ten times more expensive than in Beijing). The conclusion which we can draw from this is that energy prices may have triggered some of the key developments that led to the British industrial revolution, and hence are likely to matter for future long run economic transitions. This is a point made supported by Fouquet and Pearson (2006) who look at the history of lighting demand in the UK since the 1300s.

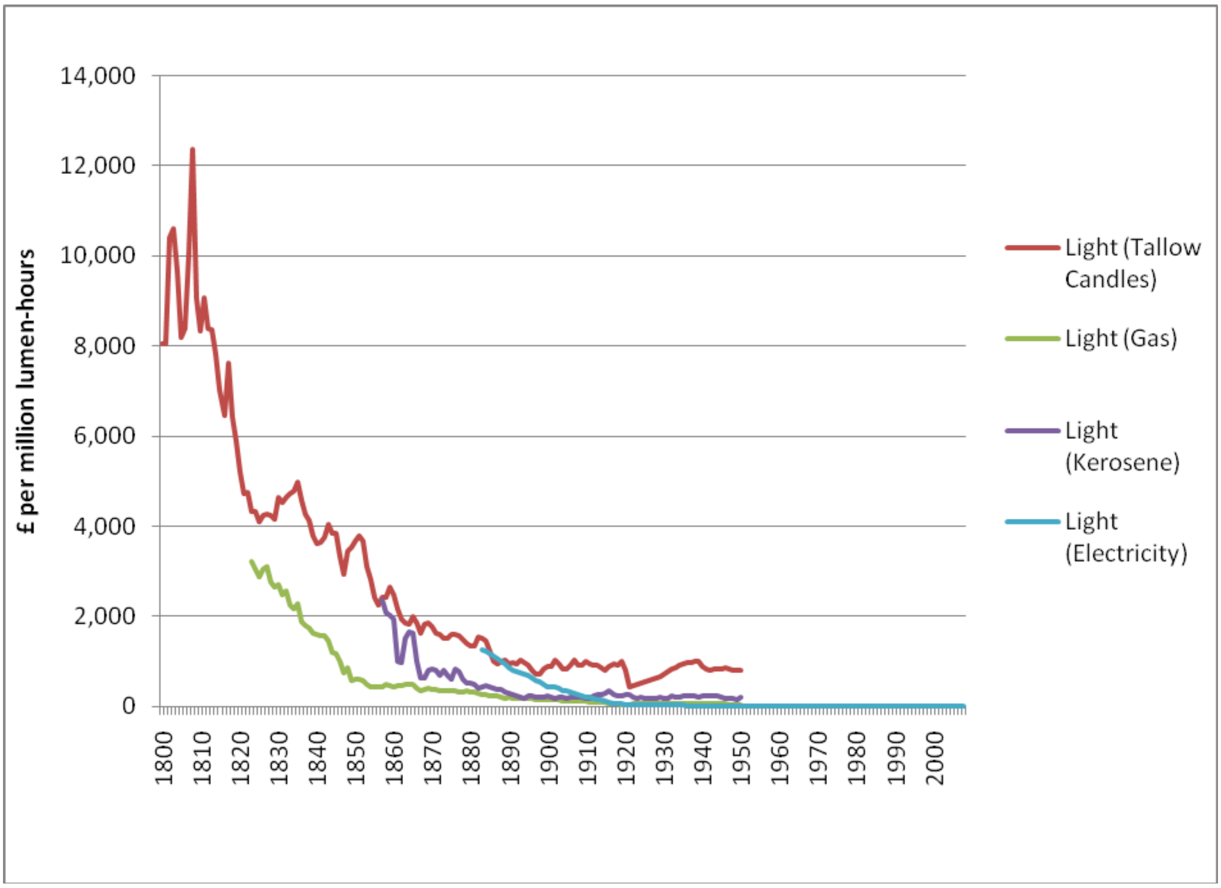
Figure 6: The role of relative input prices in long run economic development: Price of labour relative to energy, early 1700s



Source: Allen, 2009, Table 6.2, p.140.

Fouquet and Pearson focus their discussion of energy demand on the services produced by energy inputs. Energy consumers are not interested in units of energy per se, but rather in the amenities that energy provides (i.e. light, heat, transportation) or *energy services*. Fouquet and Pearson look at how, over a long period, technology changes came about as a result of relative costs of different technologies (cheaper technologies emerged) and how falling costs (and associated falling prices) drove consumption of higher levels of energy services consumption. They focus on lighting and the number of lumen hours (i.e. units of light supplied for one hour). Figure 7 shows how the price evolve of three technologies which emerged over time in the 1800s (initially as niche applications) and then become dominant, as they become cost competitive (on the basis of a mixture of price and convenience grounds). Figure 7 shows the price evolution of energy services from electric lighting which is now the dominant technology. The figure makes the general point that the same technology gets cheaper over time but can be overtaken by a new technology.

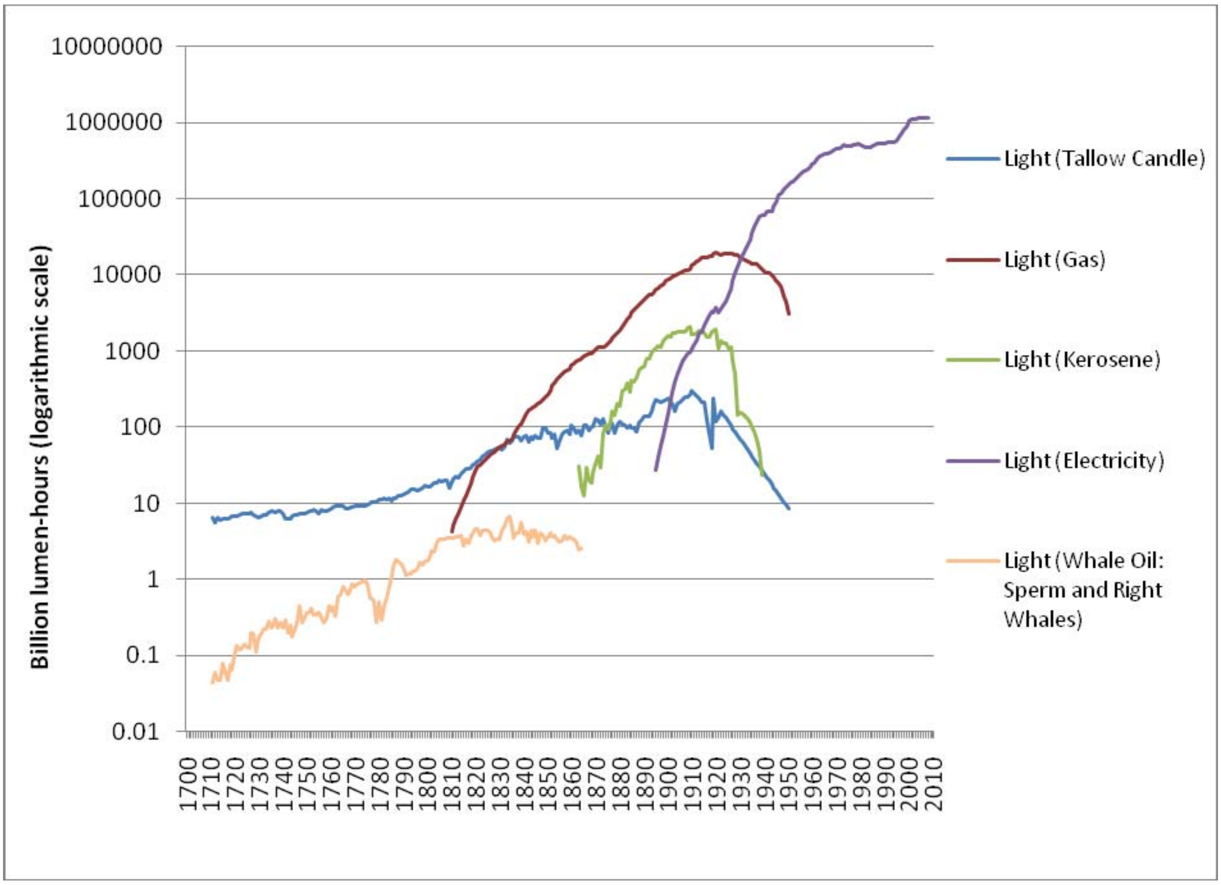
Figure 7: How long run technological change drives prices of energy services: Price of light 1800-1950



Source: From Fouquet and Pearson, 2006, with kind permission.

Figure 8 shows the associated impact of the decline in costs and prices on the demand for lighting services. Fouquet and Pearson show that the price of a unit of lighting services in 2000 was 1/3000 of their real level in 1800 and demand per capita had increased 6500 times. This indicates a very significant price effect (for one element of overall energy demand). This figure shows how long run demand trends are mirrored in long run price trends.

Figure 8: How falling prices have driven long run demand for energy services: Demand for light



Source: Fouquet and Pearson, 2006, with kind permission.

Given the global nature of the climate problem, it is important to think about global energy demand. Price and income effects on energy demand operate globally. Raising the price of energy in one country will have very little effect at the world level (unless it is a very large country). In particular there might be a considerable amount of leakage of energy demand to other countries, such that once the embodied energy (and carbon) in imports is taken into account there is very little reduction in global energy consumption (and carbon emissions). The UK for instance has seen significant reductions in the amount of carbon dioxide it has produced domestically since 1990, however it has also seen a significant rise in manufactured imports from developing countries (and relative reduction in domestic manufacturing). Table 1 shows this sort of effect at the global level (for an earlier period). Total energy consumption in developed countries has risen less than the GDP effect would have suggested (activity effect) due to a combination of structural effect (i.e. de-industrialisation and emergence of developing country manufacturing) and increased energy efficiency (intensity effect). However in developing countries and China there have been significant increases in energy consumption caused by the rise of their industry and some weakness in the energy efficiency of their industry. Table 1 cautions against taking a fall in energy demand in one country in isolation from what is happening elsewhere as a sign of progress worldwide.

Table 1: Global drivers of energy consumption: Increase in energy consumption 1973-1990

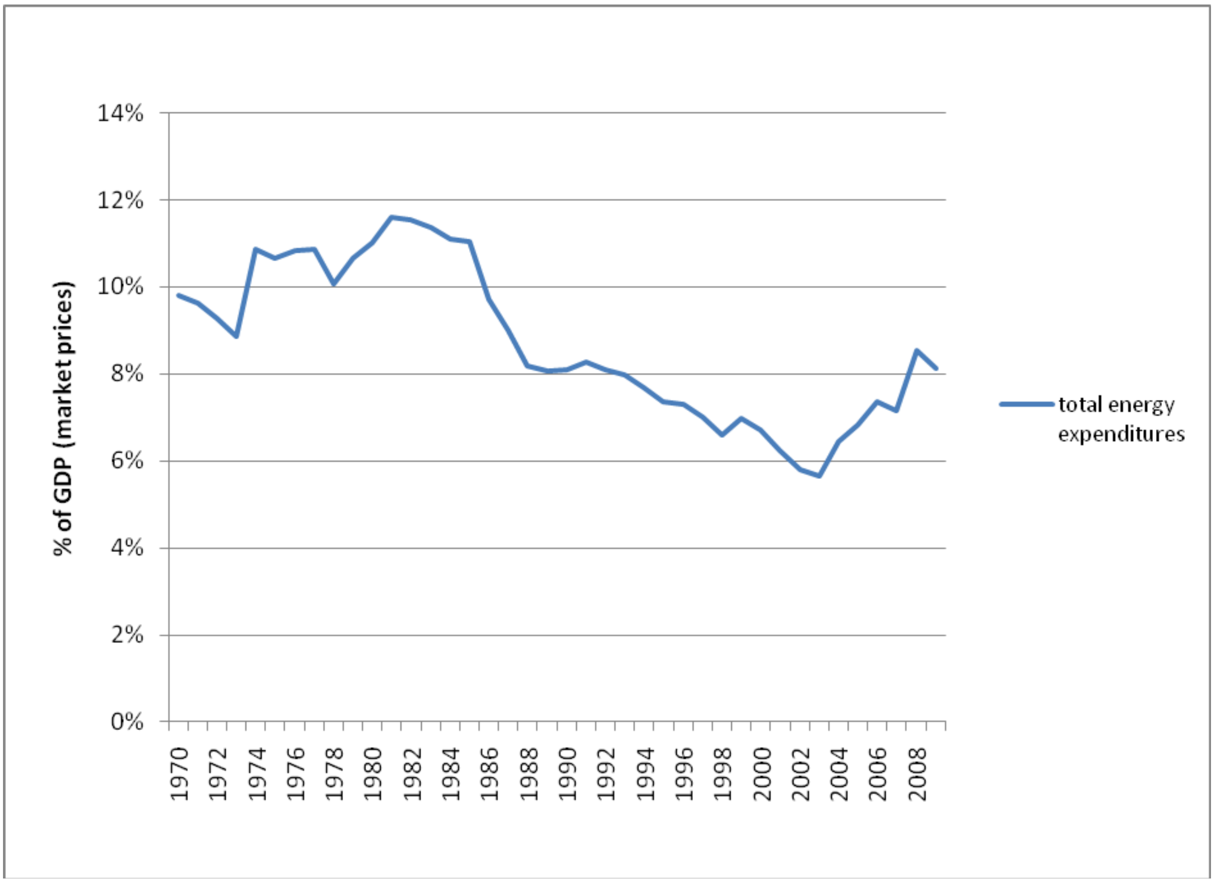
million tonnes of oil equivalent (mtoe)	**Contribution by**			**Total increase**
	Activity effect	**Structural effect**	**Intensity effect**	
Developing	*322.85*	*99.12*	*136.56*	***558.53***
China	*178.65*	*243.90*	*-139.80*	***282.75***
Developed	*1488.21*	*-204.35*	*-1069.16*	***214.70***
Eastern Europe, former USSR	*503.70*	*29.42*	*-210.53*	***322.59***
World	*2493.41*	*168.09*	*-1282.93*	***1378.58***

Source: Sun (1998, p.98).

2.2 Recent aggregate expenditure on energy services in the UK

A basic conclusion of the observation of a stable long-run relationship between energy demand and price and income is that the share of income spent on energy services is roughly constant. High prices favour lower energy consumption as consumers experience 'payment resistance', while low prices incentivise increased consumption of energy services. This is illustrated in Figure 9. From 1970 to 2008, the average share of total energy expenditure (including electricity, natural gas and liquid fuel) as a share of GDP was around 8%, even with the sharp rise in energy prices in the period to 1982, total energy expenditure only increased by 20%. Prices then fell back substantially as energy efficiency improvements continued to come through in the 1980s and 1990s. A recent resurgence of prices since 2003 (substantially increasing energy prices) has only taken energy expenditure as a percentage of GDP back towards the average for the entire period.

Figure 9: UK energy expenditure as a percentage of GDP



Source: Office of National Statistics (GDP at Market Prices) and DUKES 2010 (Table 1.1.6).

In 2009 total energy expenditure was £113 billion of which £17.5 billion was spent on natural gas, £31.1 billion on electricity and £61.2 billion on petroleum (of which £51.5 billion was road transport). Of the total expenditure, a significant share was taxation, with taxes on petroleum being £34.3 billion, with additional VAT being levied on domestic electricity and gas and a climate change levy being raised on industrial and commercial energy use, taking the total tax revenue to £37.3bn in 2009 (DUKES, 2010, Table 1.4). These numbers illustrate two important macroeconomic phenomena. First, that transport fuel is the most significant component of energy expenditure and hence driver of future energy demand (including for electricity). And second, that energy is an important source of government tax revenue, with 7% of total tax revenue coming from taxation on the use of energy.[6] This is in addition to taxation of the profits of energy companies and taxes on the production of oil and gas in the North Sea. Any migration of energy demand from heavily taxed liquid fuels to currently lightly taxed electricity will most likely require substantial tax rises on electricity to maintain the public finances.

Newbery (2005) points out that energy is not efficiently taxed at the moment in the UK, as it does not follows rational approaches of public finance or a sensible carbon tax policy. Indeed, some types of fuels have very high taxes, whereas others are relatively lightly taxed. Thus liquid fuel for road transport has a high tax rate, whereas aviation fuel and gas for heating have very low tax rates. If taxes truly reflected environmental damage costs (of all types) and international security externalities, then taxes would be significantly increased on the less heavily taxed goods. Taxes should be used to give better price signals on the relative environmental damage of different fuels, to give incentives to reduce energy consumption and to raise tax revenue can be recycled to reduce the general level of taxation or to support public expenditure (including measures to help the fuel poor).

Substantial components of overall energy expenditure arise from the industrial and commercial sectors of the economy. Indeed the relative aggregate figures are somewhat misleading as to the position for the household sector. The household sector spends almost twice as much on gas as on electricity (rather than the other way round for the whole economy) and about the same amount on liquid transport fuels as on electricity and gas. This indicates the relative importance of non-transport energy demand for households and the importance of heat demand relative to power demand.

Energy services demand is not synonymous with demand for fuel and power. Energy services (e.g. lighting, heating and transport) are provided by a combination of capital equipment and energy. Expenditure on better household insulation or double glazing of windows is expenditure on energy services, because it has a similar ultimate effect to gas-fired central heating in raising the ambient household room temperature in the winter. A car and liquid fuel are

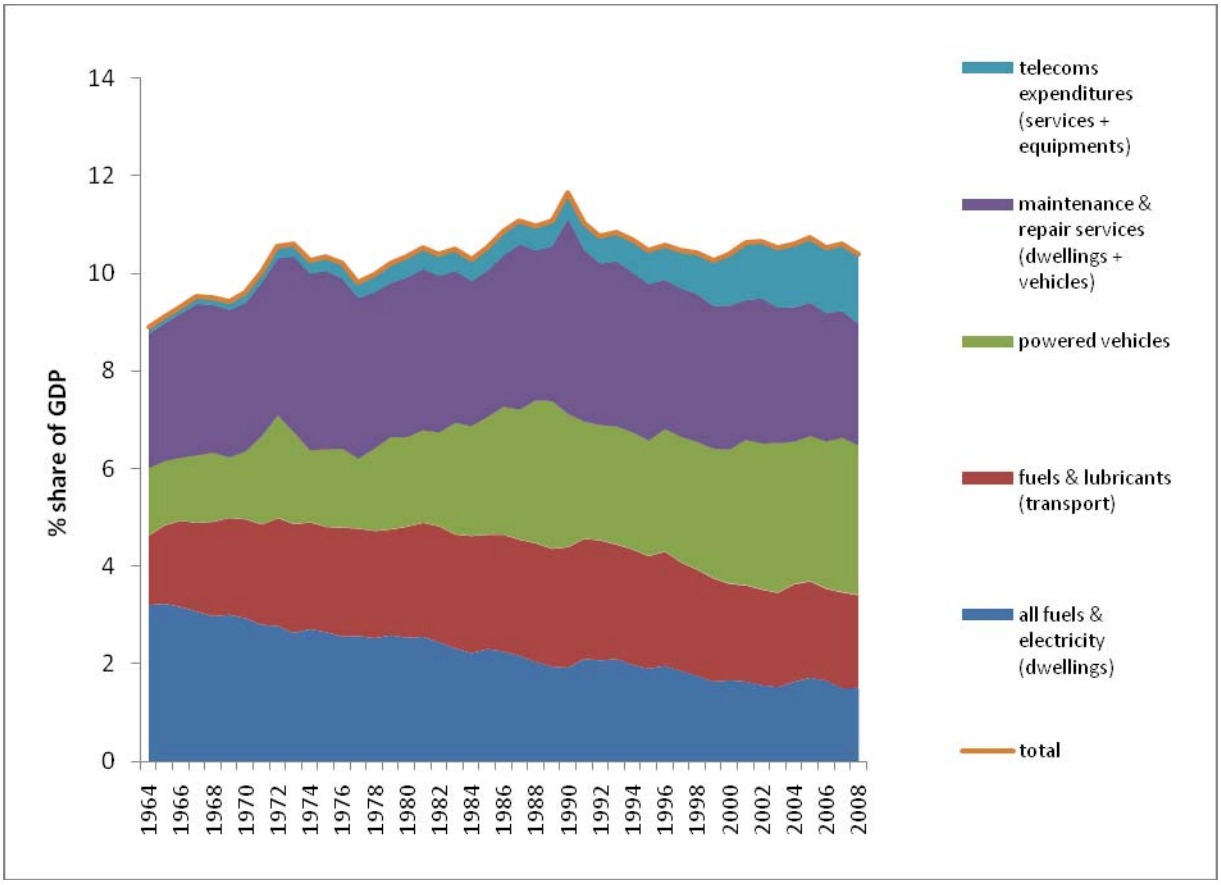
[6] Total public sector receipts were £514bn in 2009-10 (Source: HM Treasury Public Finances Databank).

both required to provide transport services and expenditure on one can be substituted for the other at the margin by spending more on a more fuel efficient vehicle. A low energy light bulb or a more energy efficient domestic appliance will cost more money but use less electricity.

Figure 10 looks at how large the expenditure on energy services is at the household level and its stability over time. From 1964 to 2008 we see that total consumer expenditure on the main categories of expenditure that are associated with energy services (as a percentage of GDP) fluctuated within fairly narrow bounds. We take energy services expenditure to be reflected in maintenance and repair of buildings and vehicles, capital expenditure on vehicles, fuels and other oils for vehicles and fuels (natural gas, heating oil and coal) and electricity. Not all expenditure on the maintenance and repair of buildings will be energy services related, but a substantial part will be related to the provision of thermal comfort and can also be substituted for energy expenditure in the future (e.g. solar panels as part of a new roof). The figure shows that substantial amount of expenditure on transport where expenditure on vehicles and on their repair exceeds expenditure on fuel. It also shows a gentle decline in the significance of household energy.

For comparison Figure 10 shows expenditure on the various components of expenditure on communications services. This we take to be initially postal services (which have declined significantly) and latterly telecoms related. Here there is very little direct expenditure on equipment (as much of the equipment is supplied by service providers in return for the payment of usage charges). We return to communications services as a point of comparison with energy services later in this paper.

Figure 10: UK Energy and Communications services expenditure as a percentage of GDP



Source: Office of National Statistics

An examination of the macroeconomic context of energy demand suggests the size and significance of energy services expenditure. There is substantial scope for diverting the different shares of expenditure between power, heat and transport, and between equipment, maintenance and energy expenditures. While utility companies may be dominant in electricity and gas, major oil companies and major supermarkets are dominant in liquid fuels and a large number of different companies are present in the repair and maintenance of buildings and vehicles. The electrification of heating and transport and the reduction in the size of the markets of liquid fuels will be likely to attract the interest of current liquid fuel incumbents and will create new opportunities for substitution of equipment and repair and maintenance expenditures for expenditure on units of energy.

The first report of the Committee on Climate Change (2008) in the UK illustrated the importance of electricity demand growth and the emergence of new technologies for reducing electricity consumption. In particular the Committee suggested that without attempts to reduce emissions electricity demand might rise by 2.5% p.a. (CCC, 2008, p.55), partly as a result of climate change increasing the demand for air-conditioning. However with the application of new technologies such as LED lighting and efficient air conditioning, electricity demand could be 35% below its baseline figure by 2050 (CCC, 2008, p.55). However, some research on California points to some ambiguous effects. Indeed, it has been shown that newer buildings (subject to stricter energy buildings standards) might enable higher temperature response[7], as they are more likely to be equipped with air conditioners and are often larger, so that the cumulative effect on absolute electricity consumption is ambiguous, and the aggregate temperature response can be predicted to increase with new (and more energy efficient) construction (Chong, 2010). Even within industrial processes the Committee saw scope for the reduction of electricity demand (by 18% below baseline in 2050 – CCC, 2008, p.56). It is worth pointing out that these estimates are highly uncertain and that actual demand will significantly depend on outturn prices and incomes.

3. The long-run microeconomic context of energy demand

We now turn to how the demand for energy (and hence electricity) operates at the level of micro economics. It is worth beginning by discussing the relationship between the underlying physics of energy demand and the economics of energy consumption, and relating this back to individual behaviour and microeconomics.

3.1 The physics of energy consumption and its relation to the economics of energy consumption

MacKay (2008) discusses energy efficiency at the level of the device and the household. He points out that there is a big variation in existing energy efficiencies of transport and of heating and of household power devices. For each of these energy services, electric power is the most energy efficient. Thus for household heating a heat pump can convert one kWh of electricity into up to 4KWh equivalent of heat. This implies that a gas-fired power station running at

[7] Chong (2010) defines temperature response as the percentage increase (relative to usage on a 65◦ F day) in electricity use due to a 1◦ F increase in temperature. Higher temperature response means more incremental electricity use.

53% electrical efficiency might be able to deliver electrical heat using half the gas of gas fired boiler with '90% efficiency' (p.152-153). An electric car uses around 15 kWh per 100 km, around 5 times less than the average fossil fuel car. This implies that even powered by the existing electricity system an electric car produces a quarter of the emissions per km of the average conventional vehicle (p.129-130). Electric household devices are notoriously inefficiently used. In the UK for instance, 8% of all electricity is used by devices on standby (DTI, 2006, p.43), and this could be reduced by a factor more than 10 for many devices. MacKay (p.157-158) gives the example of reducing his own household electricity consumption by 50% by reducing standby and installing energy efficient light-bulbs.

Allwood (2010) looks in more detail into the theoretical potential of energy efficiency by examining underlying material efficiency of production processes. He gives the example of the car where the energy required to power the car is a function of sum of the aerodynamic drag (of the car through the air), the mechanical drag (of the wheels on the road) and the inertia (which must be overcome to get it moving). He suggests how the force required to move the car at a constant speed can be reduced substantially. This can be done by getting the mass of the car down (by 75%), reducing the friction coefficient (by 93%), reducing the drag coefficient (by 75%) and shortening the frontal area of the car (by 25%). He calculates that the energy required can thus be reduced by 91%. This sort of calculation indicates the scale of the efficiency improvements that are theoretically possible in providing the same level of energy service. These fundamental redesigns of the way energy services are provided substantially exceed the efficiency improvements that are possible in industry from simply producing existing energy intensive goods more efficiently. Examination of the energy efficiency savings in the production of steel, cement, plastic, paper and aluminium shows that use of best practice technology and recycling only reduces energy consumption by less than 50% in most scenarios.

The conclusion we can draw from the above is that large physical potential savings in energy use are possible (often involving increases in the scope of use of electricity). However the economics of such savings do not currently stack up. For instance, heat pumps are very expensive and involve very high capital costs, relative to existing gas-fired boilers. They also involve significant running costs, and many would currently be more expensive to run than a gas boiler.[8] There is also the issue of whether the quality of the service provided is comparable. Heat pumps are more intrusive and can take up more space in a household room. Electric vehicles have limited mileage ranges and slower refueling times. A car which weighs 75% less, is less wide and has very low drag (sitting the passenger lower down) will not necessarily be considered as safe, comfortable or stylish as existing vehicles.

Indeed it is clear from history that there is always a wide-range of observed efficiencies in the economy, with the average efficiency of the provision of an energy service being significantly less than the efficiency of the most efficient. Current new fossil fuel cars and gas boilers are 50-100% more efficient than that of the average fleet. Indeed as we saw in Figure 7 technologies tend to persist long after the appearance of apparently superior and more efficient ones (which will indeed eventually become dominant) have appeared. This is partly because initially new technologies are relatively expensive (even for new installations) and partly because of lock-in to existing technologies whereby individuals and companies continue to use existing technologies because they have already invested in them and incurred their up-front capital costs or are uncertain over future energy savings (Hassett and Metcalf, 1993). Thus the average life of energy service equipment, as well as its cost becomes an important determinant of how the average efficiency relates to the highest available efficiency.

3.2 The apparent non-rationality of individual energy consumption

Another important consideration in economics is apparently non-rational behaviour. The idea that energy efficiency measures which reduce cost will necessarily be implemented is based on neo-classical consumer theory, which says that more is always preferred to less and that individual economic decision makers will always take actions which are in their economic interests. There are

[8] If the average price of 20000 KWh of gas is 2.61p/kWh and the marginal price of electricity is 9.62p/kWh (a typical tariff on 17th September 2010). A heat pump would need to have a coefficient of performance of greater than 3.31 to reduce *running* costs below that of 90% efficient gas boiler.

a number of important challenges to this, only some of which are genuinely about irrationality.

First, even neo-classical theory suggests the paramount importance of considerations of who benefits as distinct from who bears the cost of an action. Thus apparently non-rational behaviour may simply reflect the fact that it is not the same individual (or group of individuals) who benefits from switching off the light-bulb or installing energy saving equipment as the individuals who have to incur the inconvenience (however minor) of taking energy saving actions. In the commercial sector and in the rented sector this is often exemplified by the tenant-landlord split whereby it is the landlord who has to decide on and organise investment in energy saving equipment, but it is the tenant who benefits through lower bills (as discussed in Grubb and Wilde, 2008). Within the household there may be competing incentives and perceptions – one of our colleagues was told to remove his energy saving bulbs by his wife who did not like the quality of the light produced by them!

Second, the well-known marginal cost of abatement curve (e.g. Committee on Climate Change, 2008, p.226) suggests that there are large unexploited energy efficiency savings in the commercial and household sectors. However this only values the benefit of the action against its capital cost, not against the time and inconvenience costs which would be incurred to deliver what are often individually small savings which require significant up-front investments of individual or organisational time. Thus even for a commercial business, prioritising energy cost savings may come at the expense of sales enhancing strategies which could have been worked on by the same individuals. Some energy savings may even come at the direct expense of sales, e.g. if keeping shop doors closed (to reducing heating bills) or not visiting clients in person (to reduce transport costs) actually results in less business.

Third, behavioural economics, which looks at how individuals actually behave when making economic decisions, has suggested a number of phenomena which may be increasingly important to take account of in considering the future of energy demand. These include: liquidity constraints, expectations, loss aversion, commitment devices and perceptions. Brutscher (2010) investigates these in the context of explaining top-up behaviour by electricity customers using prepayment meters in Northern Ireland. He starts by observing that individuals top-up by significantly less than is rational given interest rates and the costs of topping up (using a Baumol-Tobin Model). He finds that given fixed costs of topping up (the opportunity cost of time taken to go on-line, telephone or buy credit in-store) versus the lost interest on credit balance, individuals should top up 2.3 times a year at £230 per time. What actually happens is that individuals top-up around 50 times a year, by £13 per time. Liquidity constraints would suggest that the reason why people might do this is because they do not ever have £230. Expectations theory might suggest individuals worry about future changes in prices in ways that might reduce the optimality of their top-ups. Loss aversion might suggest that people worry about the potential for loosing larger credit balances (should the meter malfunction or they have to move house). Commitment device theory might suggest that individuals use low top amounts in order to force themselves to be more conscious of energy use, because they are forced to check their meter more regularly. Perceptions may matter because intuitively people may prefer spending a series of small amounts of expenditures than a one-off expenditure of the equivalent amount. Therefore we might prefer pay-as-you-go expenditures over lump sum contracts, even if the lump sum contract is cheaper (Finkelstein, 2009). Brutscher (2010) finds evidence for perceptions theory as an explanation of actual top-up behaviour in Northern Ireland. One implication of this is that smart meters which facilitate small top-ups may make many consumers less concerned about their energy consumption by making them think they are spending less on energy than they actually are. Behavioural economics may prove to be very significant in both explaining observed energy behaviour (with and without smart meters) and in understanding how best to encourage individuals to make more rational energy decisions. This relates to Thaler and Sunstein's idea of nudge theory (2009), where the way information is presented (rather than the underlying financial characteristics) may be very important for the final aggregate outcome and that small changes in the way information is presented might have very large impacts on behaviour.

Fourth, there are serious issues of poverty and vulnerability in the provision of energy services. An estimated 4.9 million households in the UK are currently in fuel poverty (i.e. spending 10% or more their income on household energy) (see Waddams, 2011). This is around 20% of all households; in some regions the figure is more than 40%. Of those households perhaps half are vulnerable households, i.e. households with sick, disabled, children or elderly people who are more vulnerable to cold-related illness (Bolton, 2010) and hence, for whom adequate provision of energy might have serious impacts on health and for whom rational decisions about energy consumption may not be possible. Fuel poverty may merely be a component of poverty, but it clearly has implications for the future of energy demand. The fuel poor may be exempted from general pressures to raise energy prices to bring about the long-run transition required by decarbonisation targets, or they may be targeted for capital expenditure interventions which reduce their regular expenditure. The poor may exhibit very different income and price elasticities from the national average. Concerns about the nature of the social contract with the poor in transition and developing countries explain large subsidies to reduce energy prices (which are often very poorly targeted). Climate change policy may increasingly come up against such pressures to subsidise final prices for large numbers of customers (and hence raising the cost for others).

Finally, it is worth saying that inefficiency and variability in decision making are a general characteristic of energy markets (and indeed all markets). Wilson and Waddams (2010) analysed the behaviour of household consumers in choosing electricity and gas supplier. They found that a significant number of consumers switched to a higher tariff when they intended to switch to a cheaper one, whereas less than half of those switching to get the cheapest price chose the cheapest tariff available at the time of switching. They concluded that this demonstrated a combination of computational mistakes (the 'bounded rationality' of consumers, following Simon, 1947), the fact that factors other price alone (such as the quality of service) were also important and that companies might make it difficult for consumers to calculate exactly how much they were going to pay under any tariff using so-called "foggy tactics" (Miravete, 2007), hidden clauses, tiny fonts (thereby being an example of a 'confusopoly'[9]). This was in addition to the fact that 50% of customers had never switched

[9] This term was introduced by Scott Adams in The Dilbert Future (1997).

supplier, even though they could have saved money by moving away from the incumbent. It is simply a fact that customers of any given product exhibit high degrees of inertia, value quality of service, are prone to miscalculations or are faced with confusing (and sometimes misleading) information from service providers. Thus apparently optimal solutions only spread slowly through the economy.

One of the ways in which individual energy users might become better informed is via social networks. This could happen for householders through being in touch with other better informed individuals (e.g. friends, family, neighbours, members of social network groups). Or it could happen for companies through interactions with motivated outside stakeholders (such as green NGOs). Zhang and Nuttall (2008) uses agent based modelling to show how a supplier-led smart meter role out might develop as a result of social and economic influences on individual households. Brophy Haney et al. (2009) show how high street retail companies are more likely to have adopted tougher energy and climate objectives, if they have connections with more outside stakeholders of a particular type (most notably academic institutions). Participation in energy saving clubs can be associated with substantially enhanced demand reduction as participants share ideas (though the likelihood of voluntary participation might be low).[10] Social capital and its relation to the encouragement of energy efficiency (and more efficient consumption in general)[11] would seem to be an important idea reflected in these results.

3.3 How to encourage energy efficiency

Now we turn to the underlying micro-economics of energy services to discuss how easy it is likely to be to encourage the uptake of energy efficient products. Energy services are goods which are quantity, place, time and quality specific. They are a derived, or intermediate, demand, in that the final price of the good which requires energy to be used is what consumers in general perceive, rather than just the price of the energy. As the energy cost is less than 100% of the cost

[10] See Ofgem (2010, p.9) for some evidence from the UK.
[11] See Pepper et al. (2009) who discusses the link between green consumption and sustainable consumption in general. Pollitt (2010) argues for the importance of a more holistic engagement with individuals' religious beliefs in eliciting behavioural change related to the achievement of climate change policy targets.

of the service this dilutes the impact of changes in energy prices on the final price to which customers respond. This is further complicated in that, although the marginal cost of consuming the product may be substantially made up of the energy cost, individuals may only consider the average total cost (possibly due to pre-commitment to use the product once purchased and also due to bounded rationality).

3.3.1 Raising prices

Table 2 shows a rough calculation for the costs of energy part of certain energy services in relation to the total cost of the service. It is immediately why low-energy light-bulbs are high up the list of products that individuals are willing to buy in order to save energy. Even for a low energy light bulb costing £1, 94% of the lifetime cost is the electricity consumed. Having an energy efficient gas boiler should be high up the list of actions to take if a £1000 up-front cost is not a problem. Cold storage services provided by fridges are roughly one third energy costs. However for a computer or a mobile phone the energy cost is a small fraction of the total annual cost.

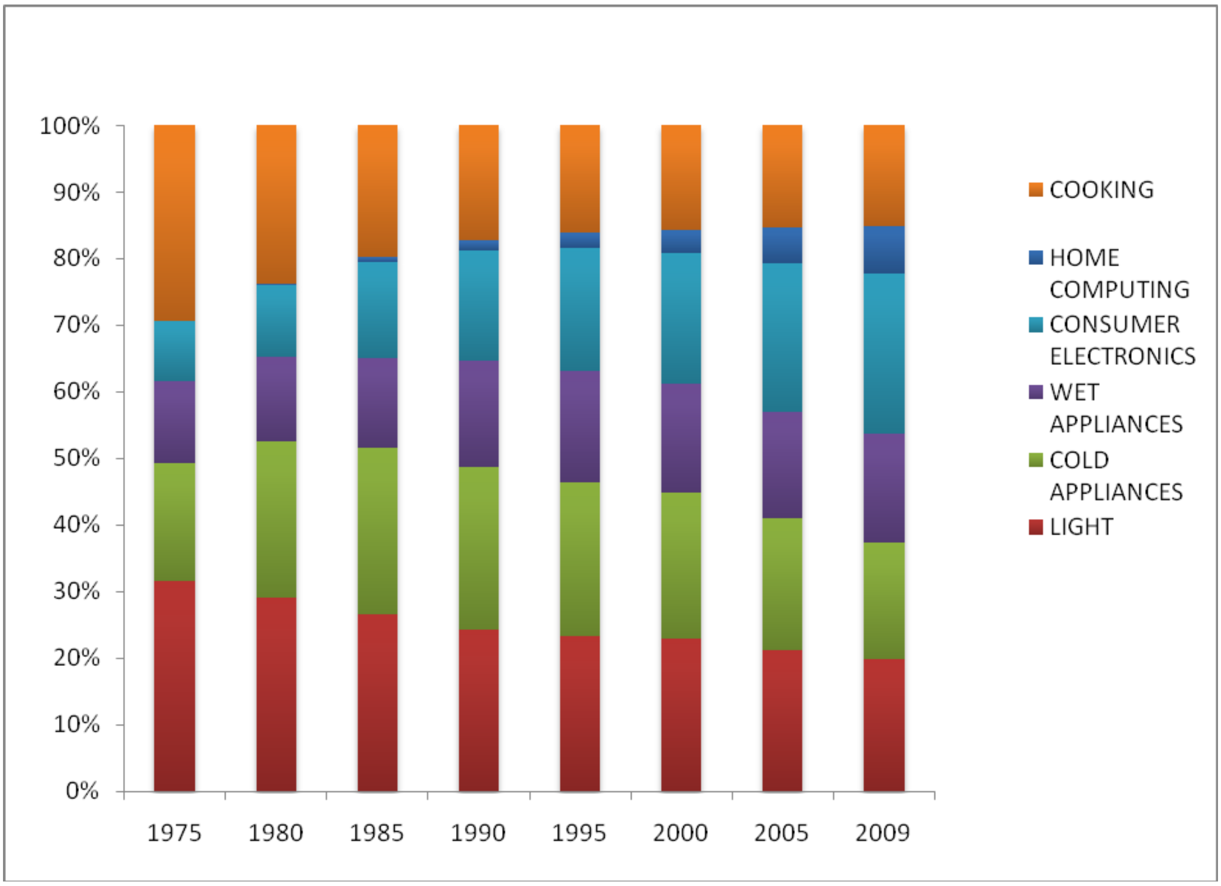
Table 2: Lifetime costs of certain energy related services

	Capital Cost £	Lifetime energy cost £	Total cost	Energy cost %
Lightbulb 100W	0.35	18.98	19.33	98.2%
Lightbulb low energy 100W	1	15.53	16.53	94.0%
Gas Boiler	1000	7629.05	8629.05	88.4%
TV	700	540.01	1240.01	43.5%
Fridge	300	159.56	459.56	34.7%
Car (annual)	2500		3500.00	28.6%
Computer	1000	48.84	1048.84	4.7%
Mobile phone (annual)	360	1.42	361.42	0.4%

Key assumptions: Electricity 13p/kWh; gas 3.5p/kWh; 5% discount rate

Table 2 suggests that doubling the price of electricity or of natural gas is likely to have a significant impact on the uptake of low energy light bulbs or energy efficient boilers and energy use per unit of lighting service or heating comfort. However it is likely to have a negligible impact on incentivising the purchase of energy efficient mobile phones. For these energy related services agreed energy efficiency standards might be very important in encouraging the manufacture and sale of more energy efficient devices. Table 2 has a further implication: as energy efficiency improves it is likely to get harder to influence energy demand via price effects. This is because the share of energy in the cost of the service is likely to drop over time (unless the price rises to compensate) thus reducing the incentive to achieve further efficiencies. Income elasticities for certain energy related services will be very important drivers of energy demand. Income elasticity for additional fridges (at households which already have one) is likely to be low, however only around 1/3 of UK households currently have dishwashers, while demand for personal electronic equipment is likely to be highly income elastic. Interestingly it is also the case that energy consumption is rising fastest for the categories of energy service where the share of energy in total costs is lowest, such as personal electronic devices (see Figure 11). Power for personal electronic devices (including computing) has increased from 19% of total domestic electricity consumption in 1990 to 32% in 2009, by contrast lighting demand has fallen from 24% to 19% over the same period.

Figure 11: Shares of different devices in household electricity demand in the UK, 1970-2009



Source: DECC (2010b).

3.3.2 Electrification of personal transport

New sources of electricity demand may emerge which substantially change the total demand for electricity and the way electricity is consumed by the household. The Tesla Roadster[12] stores 53 kWh of electricity and has maximum power rating of 185 KW (Mackay, 2008, p.129). Typical daily household demand is about 10 kWh with a maximum power of 10 KW. An electric car has a typical charge and discharge efficiency of 85% of the electrical energy used to charge the car. The impact of charging an electric car at home would be to substantially shift electricity demand towards the residential sector and to increase aggregate electricity demand. It would also increase the maximum power drawn by the household, though this would substantially depend on the rate of charge required (53kWh could be delivered overnight in 7 hours at 8.91 KW power). Given the average household consumption at the evening peak in winter is only 1 KW[13], a substantial penetration of electric vehicles charging at home would be a substantial system load. It would also imply substantial infrastructure investments and have significant implications for the grid.

However electric vehicles offer other possibilities. They offer substantial battery storage capacity to the electricity grid, both when stationary at home and when at work. They may thus be very useful in providing short term back-up at system demand peaks or for dumping electricity to the batteries when supply is at a peak (due to the running of large quantities of intermittent renewables). This sort of linkup between intermittent wind generation and electric vehicle demand is being trialled on the Danish island of Bornholm.[14] Electric vehicles also offer the ability to shift the location of consumption around the grid, with cars charging at work and discharging at home or vice versa. Indeed it would possible that commercial loads could be supported by discharging vehicles during the day time and then return home to charge up at night.

[12] The Tesla Roadster is an electric sport car prototype manufactured by Tesla Motors (http://www.teslamotors.com/).

[13] This is based on there being around 25 million homes in the UK and peak household demand of around 25,000 MW (as discussed below).

[14] See www.edison-net.dk.

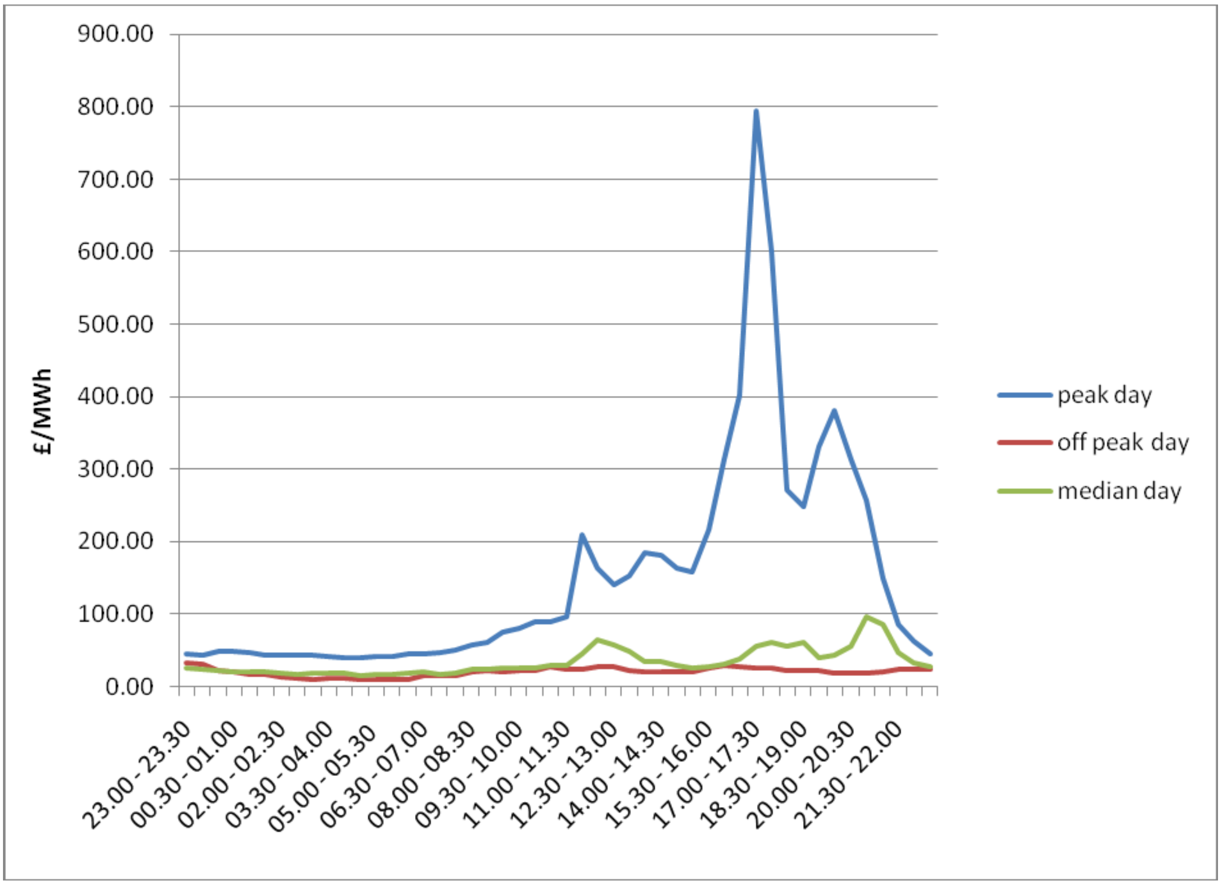
3.3.3 The size of the elasticities

The evidence on elasticity of demand with respect to price and income is large, but difficult to interpret (see Steinbuks, this volume). There is also a substantial difference between the short run and long run responses to a price or income change. Espey and Espey (2004) looked at a number of studies of household electricity demand and found that the median short run price elasticity for electricity was -0.28 rising to -0.81 in the long-run. They found the median short run income elasticity was 0.15 rising to 0.92 in the long-run. This highlights the importance of raising real prices as incomes rise if demand is not to increase over time. For transport Espey (1998) looked at a larger number of studies and found lower median elasticities in the long run. The median short run price elasticity of demand was -0.23 rising to -0.43 in the long run. Espey also found the median short run income elasticity of demand was 0.39 rising to 0.81 in the long run. Given that energy costs are currently a relatively small part of the running costs of a petrol-powered car (see Table 2) and would decline substantially for electric vehicles, electricity demand for transport would not be particularly sensitive to its own price. Indeed over time we would already be expecting to see price elasticities of demand for energy declining as energy became less significant as a share of the total cost of energy related service.

3.3.4 Shifting electricity consumption across time and place

Electricity consumed at different times of the day and time of the year has different underlying resource costs. Figure 12 charts the daily variation in prices for three days in 2009 on the UK power system. Prices vary considerably. On an off-peak day the price per MWh in the power market does not rise above £50 per MWh or 5p/kWh, significantly less than the price paid by residential consumers for each additional unit of power. However on a median day the price varies between £30 per MWh and £100 per MWh for half hour periods across a 24 hour period. On the peak day on the system prices reached £800 per MWh or 80p / kWh. For median days there is a strong incentive for large energy intensive users to use electricity at night rather than during the day. Smart demand response from commercial and residential users could exploit this underlying price differential, either by reducing consumption or by shifting it to a cheaper time. Residential consumers could therefore reduce marginal generation costs.

Figure 12: Demand shifting is potentially important

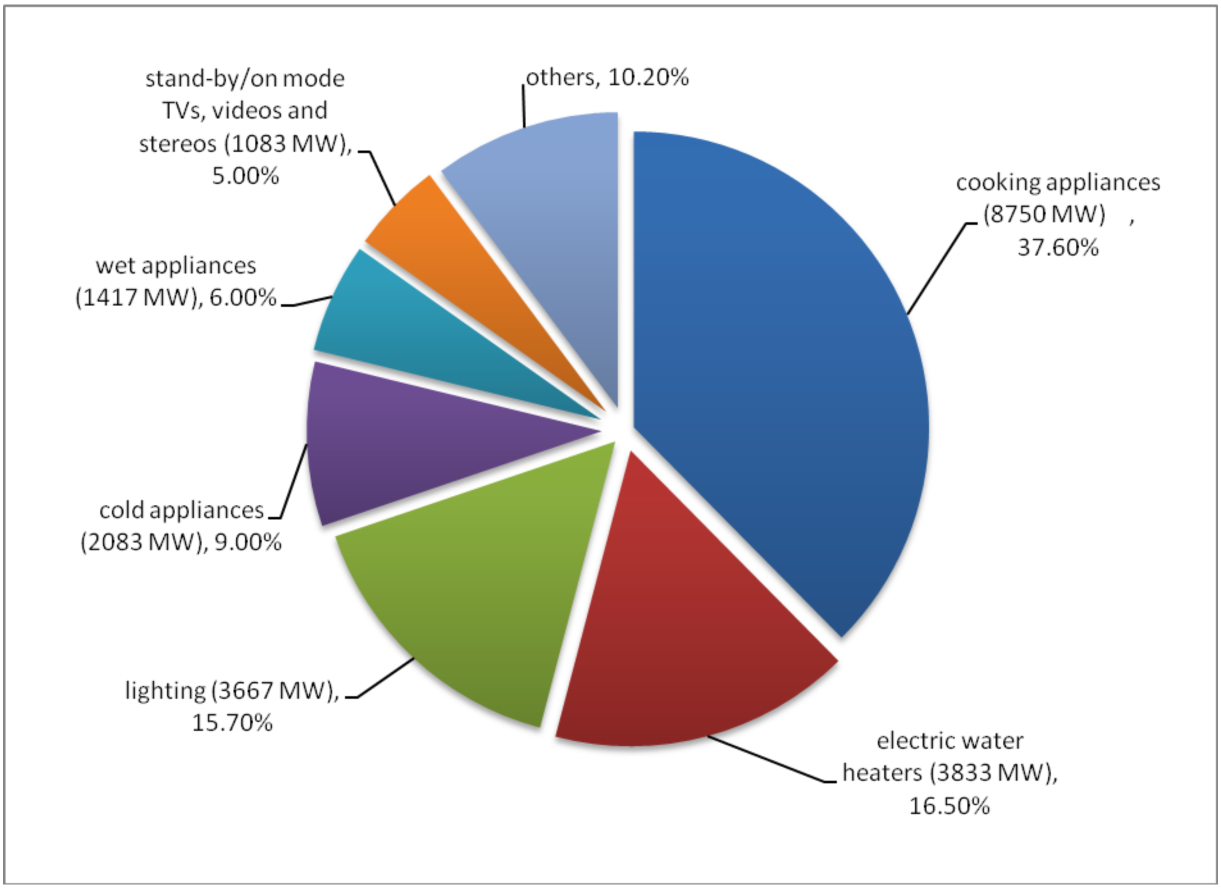


Source: APX (2010).

The potential for demand shifting, even by a couple of hours, could be substantial. At the system peak time a disproportionate part of the load is made up residential demand (45%, against an average of 36% final energy consumption[15]). Figure 13 shows the components of household demand at the typical daily winter peak (of 52016 GW in this case). 5% of total domestic demand is simply devices on stand-by, while another 6% is wet appliances such as dishwashers and washing machines many of which could be run later at night. Another 9% is represented by cold appliances which could be pre-cooled before the system peak to maintain their target temperature over the peak period before switching back on. Next the 16.5% of demand due to water heaters could also be turned on earlier to have hot water available ahead of the system peak. Pre-loading of devices with energy does imply added energy cost due to energy losses, but with better thermal insulation this cost could be kept low.

[15] 36% is calculated as the domestic share of final electricity consumption in 2007, reported in DUKES (2010, Table 5.1, p.132).

Figure 13: The components of household energy demand at system peak



Source: Lampaditou and Leach (2005).

Residential consumers could also respond to local voltage or national frequency changes (i.e. providing backup demand response equivalent to backup generation response). The National Grid spends several hundred million pounds per year on spinning reserve[16] to maintain frequency in the national transmission system. In theory households could provide a form of virtual spinning reserve. This is possible if fridges, freezers, washing machines and dishwashers could be interrupted for short periods a small number of times per year in return for a payment related to the current payment for spinning reserve.[17]

[16] Spinning reserves refer to generators that can instantaneously increase the power they generate, in case of a decrease in frequency, i.e. when load is greater than generation. Electricity system operators are required to maintain a certain amount of spinning reserves in the case of sudden surges in power demand.

[17] See Samarakoon, K., Ekanayake, J., Jenkins, N. (2010), *A Demonstration of a Load Control Scheme to Provide Primary Frequency Response through Smart Meters*, Poster Presented at Flexnet Annual Assembly May 2010.

A number of economic issues arise with this exploiting this potential for demand response. These include the size of the likely benefit relative to the costs. *Time of use* pricing is relatively straightforward to implement and already exists for a significant number of customers (on Economy 7 tariffs, or the PowerShift tariff in Northern Ireland). This sort of tariff does not require two way communications with the meter; it only requires a clock in the meter so that charging occurs in line with the charge periods. *Real time pricing*, where prices change according to spot prices in the market requires two-way communication with the household meter. This implies additional telecoms costs as well as creating uncertainty about the actual price that the consumer will face. Assuming demand response arising from real time pricing is to be largely automated via sequential switching off particular appliances, this requires additional communications infrastructure within the home, and possibly smart controls on the appliances connected to the meter. Contracts could specify the nature of the demand response to real time prices (e.g. pay a fixed price and get a reduction for limiting consumption to a specified maximum level when the price rises above a certain level on the spot market). Indeed *critical peak pricing* is a limited form of real time pricing whereby strong incentives to reduce consumption are given at certain times of the year. Thus usually involves a known price paid for a measured response at the critical peak. This requires a two-way communication system, but can be quite basic (e.g. a red light on the meter), aimed at soliciting a manual response by the householder to the signal received.

Brophy Haney et al. (this volume) discuss the evidence from trials on the size of the effect from time of use, real time and critical peak pricing. They conclude that peak savings of up to 15% are possible, with demand reductions of up to 10%, though it is not entirely clear how much of the savings are due to improved information on energy use alone. For the UK, the evidence from Northern Ireland is that the introduction of better prepayment meters (which gave clearer information on energy use) reduced demand by up to 5% (Boyd, 2008).

A further overall consideration is the fact that if there is significant responsiveness of demand, this begins to significantly reduce the marginal benefit of further response, flattening the price curve and reducing the cost of spinning reserve. This reduces the value of additional responsiveness and the incentives to respond if responsive demand only receives its marginal value to the system. In short responders create positive externalities for other users which would somehow need to be recycled back to the responders. There may also be issues to do with the fact that rich consumers might have more opportunities to benefit from offering demand response (e.g. because they could afford the state of the art household appliances capable of responding and because they use more non-essential appliances) and hence this would further exacerbate fuel poverty concerns.

Lampaditou and Leach (2005) conduct a simulation, in line with Figure 13 above. They suggest that time of use pricing with water/wet appliances might lead to a 47% decrease in the household morning peak (due to a shift of water heating) and a 6% decrease in the household evening peak (due to a shift of wet appliances). They calculate that this could generate consumer benefits of up to £52 per year per consumer (using average spot prices of random winter day from UK APX 2005). However if there was direct load control (by the grid) of major appliances at 5-6 pm (due to shifting use and better cycling) there could be much greater responsiveness in the evening peak. They suggest that switching off washing machines, tumble driers, dish washers & cold appliances would cause a 15% of household peak reduction (or 3500 MW), rising to a 23% reduction if there was better cycling of water heaters (5500 MW). Clearly these figures represent the upper end of what is technically possible, rather than reasonable estimates of the likely uptake of contracts for such response. Silva et al. (this volume) present more recent simulations of the benefits of responsiveness from domestic appliances.

Actual household demand responsiveness will be driven by consumer willingness to participate in the contracts that might be offered by suppliers for demand response. A large percentage of consumers are likely to show no response (in line with more than 50% of consumers who have not switched electricity supplier).[18] Other consumers will respond depending on the size of the benefits available to them (their ability to respond) and on their view of the level of control they would like exercised by external parties. Remote control of appliances will raise issues of data security, confidence in the technology and the

[18] See Ipsos Mori (2010).

availability of easy overrides. Uptake will also be likely to be a function of the extent to which consumers can understand the contracts being offered. It seems likely that simple contracts will be favoured and that widespread use of real time pricing is unlikely in the current environment. It is also the case that people prefer the insurance that fixed tariffs offer (most consumers currently pay a fixed amount monthly)[19] and hence may well be prepared to pay a premium to avoid exposure to variable tariffs.

A major discussion which has gone on at the transmission level, and to some extent at the distribution level, of electricity networks is the role of nodal prices (location varying) prices (see Pollitt and Bialek, 2008). These prices allow the reflection of marginal congestion costs around the electricity system. Additional demands located at congested nodes impose both short run energy losses and long run expansion costs on the network as a whole. While additional generation at these loads reduces short run losses and longer run expansion costs. Of course it is already possible to differentiate prices by location alone. However truly efficient nodal prices vary by time of day, and hence nodes heavily congested at the national system peak are not likely to be congested off-peak. At the moment most loads and all households pay the same for electricity from a given supplier within the same distribution network area. Thus it would be possible that there is some quantifiable benefit from varying retail prices more by location than they do currently. Estimates from Heng (2010) suggest that locational import and export energy prices might vary significantly within the same distribution network. Location varying charges within distribution networks may be particularly useful in avoiding the need for local network upgrades. All the same issues arise with location varying charging as with time related charging, except that the idea that individuals living physically very close to one another might pay different prices according to the condition of the electricity distribution network may raise fairness issues which may be difficult to explain.

Locational, as well as, time varying prices are particularly relevant to transport demand for electricity. We already have place varying prices for liquid fuel (i.e. every petrol station can set its price independently). It may be very useful to have locational varying prices reflecting the efficient cost of supplying electricity

[19] See Ipsos Mori (2010).

to particular parts of the network. Indeed it is possible that transport demand at high levels of penetration could significantly improve the efficiency of operational and capital expenditure on the distribution networks.

4. Conclusions on the economics of electricity demand

There is much that we can imagine about the potential future of energy demand and its degree of responsiveness. However there are things that we know we don't know about the energy future.

First, the scale of the IT challenge is unclear until we know what we would like the power system to do and the degree of public acceptability for the massive amounts of data transfer that could be involved.

Second, we don't know what outturn response elasticities could be. The previous estimates vary widely. The London Congestion Charge for vehicles actually revealed an elasticity of demand with respect to price of -0.42 against a value -0.15 predicted (Evans, 2008), leading to significantly more price response and significantly lower charge revenue than predicted.

Third, we don't know what innovations might come along in heat and in transport which impact back on electricity demand. The recent revolution in telecoms suggests expect the unexpected (e.g. growth of SMS messaging).

Fourth, we don't know which diversifying entrants will enter (e.g. device retailers, supermarkets, oil and gas majors). Evidence suggests that it is likely that well positioned incumbents in related sectors will enter if profitable entry opportunities present themselves (see Klepper and Simons, 2000).

Fifth, we don't know how consumers will react to the new technological and contractual opportunities. Official trials of smart meters appear to have been disappointing in the UK (see Ofgem, 2010), but this may be because of the way the trials have been set up. It may be the case that actually or apparently non-rational behaviour is likely.

Sixth, we are likely to see the exhaustion of the benefit of new demand technologies at relatively low levels of penetration. It may not be worth signing more people up to a new tariff or equipping them with new technology given the increasing marginal cost of persuading additional householders to participate and the declining marginal benefits of them doing so.

In closing, there would seem to be four important messages from our discussion in sections 2 and 3.

First, higher prices are key to demand moderation. Prices must rise (nationally and globally) as technology improves to avoid a significant rebound in demand arising from more efficient appliances and higher income. The good news is economies can and do adjust to high energy prices and consumers may not notice the difference in the long-run.

Second, price signals should be helped by standards. As income rises and energy service equipment becomes more energy efficient, then prices will become a weaker signal, especially for new sources of demand. Energy efficiency standards will remain important policies driving long-run demand.

Third, shifting electricity demand is worthwhile and may be easier and more valuable than actual reduction. This is especially true if there is a rise in electric vehicles and in renewable penetration, which will make the exact time and place of consumption important as well as the quantity of consumption. This is an area where new business models are required - and already emerging - to fully exploit the potential benefits by inducing behavioural change.

Finally, the full potential for demand reduction and response is unlikely to be fully realised. The demand side of electricity consumption is decided by the interaction of millions of decisions made by human beings with bounded rationality and mixed incentives. Some of the aspects of such diversity of patterns of consumption have beneficial impacts – such as through load flattening for instance. However, it always has been and always will be the case that we will look at the current pattern of consumption and be able to identify significant theoretical scope for savings. The hope is that we can achieve as much demand reduction and response as is possible within the constraints, some of which it may be possible to reduce.

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