Long Run Demand for Energy Services: the Role of Economic and Technological Development

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Long Run Demand for Energy Services:
the Role of Economic and Technological Development

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This paper investigates how the demand for energy services has changed since the Industrial Revolution. It presents evidence on the income and price elasticities of demand for domestic heating, passenger transport and lighting in the United Kingdom over the last two hundred years. It finds that the general trend in income elasticity followed an inverse U-shape curve and in price elasticity was a U-shape curve, as the economy developed and energy service prices fell. However, these general trends were disrupted by energy and technological transitions, which boosted demand (either by encouraging poorer consumers to fully enter the market or by offering new attributes of value to wealthier consumers). This evidence suggests that energy service consumption in developing economies is likely to continue rising rapidly and in industrialised countries is not likely to decline. Thus, in the absence of a full transition to low carbon energy sources and technologies, this implies long run increases in global carbon dioxide emissions.

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1. Introduction[1]

Is the global economy´s appetite for energy insatiable? Will it continue to grow as it did over the last two hundred years? Concerns about energy security and climate stability impel us to look forward and anticipate future long run trends in energy consumption. Key to identifying these trends is an understanding of what factors accelerate or moderate growth rates in energy consumption. A starting point for understanding them is a study of these factors in the past.

Over the last two hundred years, industrialised societies have been freed from dependence on land and wood for heating, humans and horses for power and transport, and sunlight and moonlight for illumination. Technological innovation, mass production of equipment, expansion of energy infrastructures and networks, falling costs of fuels, and rising incomes have revolutionised our ability to heat, move and illuminate.

Many of these revolutions in energy services emerged in Britain (Fouquet 2008). Cheap coal and heating fuelled the Industrial Revolution (Allen 2009, 2012). It also enabled Britons to live standards of comfort in their homes unattainable (for centuries) in most other countries (Crowley 2004). Railways, then the internal combustion engine and most recently airplanes have created opportunities for people to travel and goods to be distributed in ways unimaginable prior to the introduction of these technologies (Bagwell 1974, Leunig 2006). Similarly, the development and spread of gas, kerosene and electric lighting in less than one century lengthened the day in the home, in factories and in the streets (Schivelbusch 1988). Important economic, social and environmental consequences have resulted from these changes in energy service provision.

Having observed such spectacular supply-side transformations (Fouquet 2011), it is worth trying to understand how energy service demands have evolved through time, at different phases of economic development or as a result of other economic, technological, political, social or cultural forces. For the economist, this understanding begins by asking a narrower question: how have income and price elasticities of demand for energy services changed? And, what factors made them change?

In the early days of empirical estimates of demand elasticities, researchers appreciated that demand was constantly changing and that an estimate was an average of a number of years (Working 1925). Limited data sets and the need for statistical significance in econometric analysis implied that many have focussed on producing single estimates, and sometimes assuming the values of elasticities are constant (Marquez 1994). Related to energy demand, some studies have sought to compare point estimates to identify variation in elasticities (Hanly et al. 2002, Goodwin et al. 2004, Hughes et al.

[1]. This line of research has benefitted from advice and encouragement from a number of researchers, including Lester Hunt, Lutz Killian, Bill Nordhaus, Peter Pearson, Steve Sorrell, David Stern, Paul Warde and Charlie Wilson, and I am grateful for their interventions. Naturally, all errors are my own responsibility.

2008). Hsing (1990) tried to develop a series of estimates. The recent increased accessibility of long run data sets reaching back hundreds of years (such as Mitchell 1988) has enabled economists to explore the evolution of key economic variables – including in energy markets (Nordhaus 1996, Fouquet 2011). However, to date, there have been only a few attempts to use long run data to identify the trends in demand elasticities (Fouquet and Pearson 2012, Fouquet 2012a).

The purpose of this paper is to present evidence on the income and price elasticity of demand for domestic heating, passenger transport and lighting over the last two hundred years. This will help identify how consumers have responded and might respond to changes in income and energy prices, and to energy efficiency improvements at different phases of economic development (and in relation to other important variables). This might help establish whether consumers´ hunger for energy has diminished and answer the two questions at the beginning of this article. In addition to forecasting long run energy consumption and carbon dioxide emissions, a deeper understanding of energy service demands would aid the formulation of energy and climate policies.

The next section briefly reviews previous efforts to understand the relationships between economic development and energy demand, and between energy efficiency improvements and energy service demand. Section three presents the sources for the data used in this article, and briefly explains the methodology for estimating energy service costs and consumption. The subsequent section discusses the long run trends in energy service consumption and its most commonly modelled determining factors, income and energy service prices. Section five analyses the demand for energy services, presenting the trends in income and price elasticity of demand for domestic heating, passenger transport and lighting. The final section offers insights based on this analysis.

2. The Demand for Energy Services

2.1. Income Elasticities

The demand for energy results from the desire for energy services, such as space and water heating or cooling, powering of appliances, lighting and transportation (Goldemberg et al. 1985). The demand for energy services reflects individuals´ willingness to pay for warmth, travelling, or illumination. Consumer theory proposes that individuals or households consume in order to maximise their utility subject to their budget constraints and the current prices of goods and services (Deaton and Muellbauer 1980). As incomes and budgets rise, households will increase their consumption more than proportionately for ´luxury´ goods, less than proportionately for inelastic normal goods, or reduce their consumption for inferior goods. Unfortunately, beyond these basic points, neoclassical economic theory offers little information about the size of income elasticities (i.e. the percentage change in consumption for a one percent change in income), or why they are likely to change, except to propose that tastes have changed (Lewbel 2007). In other words, the size and trends in income elasticities is an empirical question and needs to be estimated.

Ernst Engel (1857) produced the classic evidence on how shares of expenditure and consumption differed as income rose (amongst Belgian workmen in the 1850s). Interestingly, though, the share of fuel and light expenditure remained constant across income levels studied – at 5% of the total budget (see Chai and Moneta 2010). Looking at the budgets of households in Massachusetts, US in 1870, Carroll Wright (1875) found a virtually constant share of fuel and light (of 6%) at different levels of income – and proposed Engel´s Third Law: "the percentage of outlay … for fuel and light is invariably the same, whatever the income" (see Stigler 1954 p.99).

Earlier (in the 1790s) British studies found that consumers broadly spent about 5% of their budget on fuel (see Stigler 1954). However, one study showed that the very poorest British rural households (earning less than £20 per year (or £2,000 in 2000 money)) consumed a smaller proportion (2.6%) of their income on fuel (Davies 1795). Another study revealed that urban consumers had to spend more than their rural counterparts on fuel - 5.4% rather than 4.4% - and that there was more variation between income levels – the urban poor (under £35 per year (or £3,500 in 2000 money)) spent almost 8% of their budget on fuel and those earning more than £40 per year dedicated less than 4% (Eden 1797). So, these brief historical studies hint possibly at an inverse-U relationship between income and fuel consumption.

A number of more recent studies have used cross-section data to identify changes in income elasticities. Joyeux and Ripple (2011) found that income elasticity of total energy demand in developing and industrialised countries (between 1973 and 2008) was estimated to be 0.85 and 1.08, respectively; however, income elasticitiy of residential electricity demand in developing and industrialised countries was substantially lower – at 0.56 and 0.42, respectively. Medlock and Soligo (2001) and van Benthem and Romani (2009) found that at early phases of development, industrial energy demand grew rapidly, but then tapered-off; meanwhile, residential and commercial demand although growing more slowly, continued steadily at higher levels of economic development; finally, transport demand expansion appeared to start later than for the industrial sector but increased more rapidly than for the domestic and commercial sector. Nevertheless, in all sectors, they found that growth rates declined at higher levels of economic development. Judson et al. (1999) concluded that, as GDP rises, income elasticities in the industrial sector grew towards one, then (at about $13,000 in 2010 money) fell towards zero. Residential sector income elasticity appeared to be constant at about 0.5, until it reached about $13,000 and then dropped towards zero or even became negative. Income elasticity of energy demand in the transport sector did appear to fall at higher levels of economic development, but only slightly – from 0.75 to 0.50 (Judson et al 1999).

An interpretation of these results is that, at low levels of economic development, most goods and services were luxuries relative to basic foods. So, as incomes rose, except for basic foods, consumption for all goods and services increased more than proportionally. Certain goods and services, such as shelter and cooking, might be seen as urgent needs and, as budgets increased, these services were met first (Chai and Moneta 2012). So, one might expect the income elasticities associated with these services to have increased first. As income increased further, declining marginal utility associated with consumption led to saturation effects making households want proportionately less shelter and cooking, as well as fewer basic foods, and more other goods and services. In principle, still higher income levels would have generated new saturation effects implying that consumption and expenditure of many previously "luxury" goods and services grew less than income (Moneta and Chai 2010). Thus, looking over a period of hundreds of years, as an economy developed, one might expect a series of waves of income elasticities for different goods and services.

For energy sources, studies have observed that, as incomes grew, consumers reduced their consumption of less desirable basic energy sources (woodfuel, dung, etc..) and increased their use of higher quality ones, including fossil fuels and electricity (Barnes and Floor 1986, Rosenberg 1998). Coupled with this energy 'ladder', Sovacool (2011) proposed that the demand for energy services evolved with income growth: cooking and space heating are fundamental to survival; then, once these basic needs were met, other services such as hot water, lighting, running appliances (including entertainment) were also sought; finally, at higher levels of income, it was proposed that energy services and related equipment might have been (in part) sought for the less tangible objective of enhancing social status.

Indeed, Marshall (1890 p.67) argued that beyond basic needs, one of the key drivers of rising consumption was the desire for social distinction, and new levels of economic well-being led to the creation of new wants, as a means of distinction. Later, Leibenstein (1950) and Duesenberry (1949) showed more formally how individuals´ consumption patterns were compared both with their peers and their previous standards of consumption. Thus, the adoption of new energy sources and technologies may have been driven, in part, by the desire for social distinction, amongst the wealthier, and emulation, amongst the rest of the population; then, once acquired, these levels of consumption became an individual´s habits, lifestyle and expected standard of living.

2.2. Price Elasticities and Energy Service Demand

Now, turning to the effect of changing prices, consumption might increase (following a decline in prices) more than proportionately (elastic demand), less than proportionately (inelastic demand) or, in rare cases, even decrease - for 'Giffen' goods (Deaton and Muellbauer 1980). Price elasticity can be broken-down into the income and substitution effects. The income effect depends on the proportion of the individual's budget spent on the service and how the consumer´s propensity to spend on the service as income rises (which can be negative or positive). The substitution effect indicates that, as the price of a good or service falls relative to other prices, individuals will substitute consumption towards this good (implying the effect is always negative). The more substitutes available for a particular good or service the greater will be the substitution effect.

Again, the standard theoretical explanation for changes in elasticities is relatively limited. For instance, the principle explanation for changes in income effect is changes in preferences as purchasing power rises. As mentioned before, this might be associated with declining marginal utility as consumption of a good or service rises. As Leibenstein (1950) proposed, another explanation for changing preferences is that individual value and demand for goods and service is influenced by others behaviour – in order to achieve social distinction or emulation. Similarly, advertising might also boost preferences for specific goods and services. Also, Lancaster (1971) proposed that goods and services are consumed for their different characteristics or attributes, and that the combination of attributes might change. One reason why the combination of attributes provided might change is technological change.

When looking at the demand for energy, over a number of years, new technologies providing efficiency improvements might alter the relationship between a fixed amount of energy consumed and the utility generated – thus, implying a change in preferences. Indeed, Nordhaus (1996) and Fouquet (2011) have shown that the price of energy and energy services tend to diverge in the long run, as a result of energy efficiency improvements. So, a changing relationship between energy consumed and the utility generated is inevitable in the long run.

Instead, Stigler and Becker (1977) argued against changes in preferences associated with technological change (as well as other factors, such as advertising), and rather that (usually unobservable) changes in the costs associated with the household production function occurred. For example, by looking specifically at energy service demand, rather than energy, energy efficiency improvements would not change the relationship between consumption of energy services and utility, and would instead lead to a decline in the price of the energy service (Howarth 1997). Thus, when studying the long run, it is important to analyse energy service demand rather than energy demand.

2.3. The Rebound Effect

Furthermore, as Fouquet and Pearson (2012) argued, two "straw-man" examples can be used to show that when we ignore service demand, we are actually making an implicit assumption about the price elasticity of demand for energy services. The `efficiency optimist´ might suggest that if energy efficiency improves by 10%, energy consumption will fall by 10%. The `lazy economist´ might propose that since the price of energy is unchanged consumption of energy will remain unchanged. Both stances ignore the impact on the cost of energy services and the associated income and substitution effects.

However, since the efficiency has improved by 10%, the consumer can get the same quantity of the service with 10% less energy. This implies that the price of the energy service has fallen 10%. For energy consumption to fall by 10%, energy service use must remain unchanged. So, the `efficiency optimist´ implicitly assumes that the price elasticity of demand for energy services is zero.

Similarly, in the case of the `lazy economist´, since the price of this energy service has fallen by 10%, for energy consumption to remain unchanged, energy service use must increase by 10%. So, the implicit assumption here is that the price elasticity of demand for energy services is one. Thus, focussing on energy rather than energy services will lead to misleading estimates of consumer responses to long run energy price and efficiency changes. The same applies to the effects of rising income and economic development. It has been proposed that valuable insights might come from understanding the two-stage relationships, first, between energy service demands, income and energy service prices and, second, between delivered energy services, energy efficiencies and energy consumption (Toman and Jemelkova 2003, Fouquet and Pearson 2012).

The 'rebound effect', as it is now known, was first identified by Jevons (1865) in his classic The Coal Question: "….it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth…. Every improvement of the engine when effected will only accelerate anew the consumption of coal…" There is now a large theoretical literature on the rebound effect (i.e., the effect of energy efficiency improvements on energy consumption), which either implicitly or explicitly analyses the price elasticity of demand for energy services (Saunders 1992, Howarth 1997). Empirical studies have tended to estimate smaller rebound effects than Jevons (1865) argued would exist. This suggests that, in the cases investigated, energy consumption declined, all other things being constant, as a result of energy efficiency improvements (see Greening et al. (2000) and Sorrell (2009) for a review of available estimates).

Ayres et al. (2005) proposed that rebound effects related to 'macro' innovations (i.e. radical innovations, like the steam engine) may have led to large rebound effects and increases in energy consumption; whereas the 'micro' innovations that improve the efficiency of existing technologies tend to lead to smaller rebound effects. Fouquet (2008 p.277) proposed a few historical cases in the United Kingdom (particularly, freight transport between 1715 and the 1930s, passenger transport from the 1840s to the 1920s, and lighting during the nineteenth century – the latter two confirmed in

Fouquet (2012a) and Fouquet and Pearson (2012)) where the rebound effects were very high – partially supporting Jevons' (1865) hypothesis.

Building on these recent studies, this paper brings together estimates of long run trends in income and price elasticities of various energy service demands to develop a possible general explanation for the trends.

3. Data

Identifying trends in the demand for energy services requires statistical information on prices and consumption of heating, transport and lighting fuels, on energy technologies and their efficiencies, and on variables that help to explain service consumption patterns, including population and income. Details about the principal sources and methods used to assemble the data series associated with fuels, prices, consumption and technologies can be found in detail in Fouquet (2008).

Nevertheless, here, the main sources for the data will be presented, first, for heating, then lighting and finally transport. Statistics on energy consumption in the United Kingdom inevitably become less reliable the further back in time we look. Back to 1960, the latest Digest of United Kingdom Energy Statistics (DUKES) provides the necessary information (DECC 2012). Before that, the Ministry of Power (1961) has statistics back to 1923, which can be extended back to 1913 with the Ministry of Fuel and Power's (1951) data, which marks the end of the official annual estimates of fuel consumption. Church (1987) presents estimates of sectoral coal consumption back to 1830. Before this, coal consumption cannot be presented on a disaggregated and annual basis, except on the most approximate basis. Church (1987) also provides data on coal prices between 1830 and 1913. More recent price data can be found in the official sources discussed above (e.g. DECC 2012).

For heating, data was calculated by combining energy consumption (or price) and energy efficiency to generate an estimate of the annual consumption (or price) of the energy service. This implies the need for estimates of the energy efficiency of the equipment used for each service. For example, in the eighteenth century, a tonne of coal could be placed in a traditional fireplace and burnt, generating around ten percent of a tonne of coal in useful heat (Fouquet 2008). With this information, and the price of one tonne of coal (in 2000 money) being equal to £145, we can estimate the price of one tonne of coal equivalent of useful heat – about £1,450.

For lighting, estimates of tallow candle consumption were available between 1711 and 1830, providing a useful early indicator of light consumption (Mitchell 1988 p. 412). Estimates of gas consumption for London were available from 1822 (Williams 1981); they were extrapolated to indicate national consumption. British national consumption data start in 1881 (Mitchell 1988 p.269, BPP, then Ministry of Fuel and Power (1951), Ministry of Power (1961) and DECC (2012, and back copies). Statistics on petroleum consumption start from 1842 (BPP 1896). Kerosene consumption data was based initially on estimates of the proportion of refined petroleum used as a lighting fuel and then, from 1910, actual kerosene data was provided in the statistical digests of the energy ministries. Ministry of Fuel and Power (1951) and back issues of DUKES provided data on actual electricity used from 1924 and 1949. From 1970 to 2010, DECC (2012) provides a highly detailed breakdown of lighting consumption.

From 1823, town gas prices were available from various gas companies, mostly in the South-East of England, recovered from the British Parliamentary Papers (BPP) and, then from the successive ministries (Ministry of Fuel and Power 1951, MoP 1961, and DTI 1991, 1997 and 2001) associated with energy. From 1857, an average refined petroleum price series could be found in the BPP; from 1903, explicit prices for kerosene were presented. Electricity prices were available from 1898 (Administrative Council of London 1920, Ministry of Fuel and Power 1951, Ministry of Power 1961, and DECC 2012).

Just as for heating, energy service consumption can be estimated by combining energy use (or prices) and efficiency associated with different technologies, be they candles, gas or oil lamps, or light bulbs (for additional detail, see also Fouquet and Pearson (2012)). The rate of light emission from a source is the light flux/flow, which can be measured in lumens. A tallow candle emitted about 13 lumens, a sixty-watt incandescent filament bulb about 700 lumens and a fifteen-watt compact fluorescent bulb about 800 lumens (Nordhaus 1996). With these estimates, others in Nordhaus (1996), and the use of a simple diffusion model of generations of lighting technology, time series of the average lighting efficiency (in lumen-hours per kWh) for tallow candles, gas lamps, kerosene lamps and electric lights were assembled. The implicit price or consumption of lighting (measured in lumen-hours) using any particular technology can be calculated by multiplying the associated energy price or use by the efficiency. Building on these data, it was possible to estimate relatively reliable average lighting prices (by taking expenditure-weights for individual source-technology mixes) and lighting consumption (by summing individual source-technology mixes).

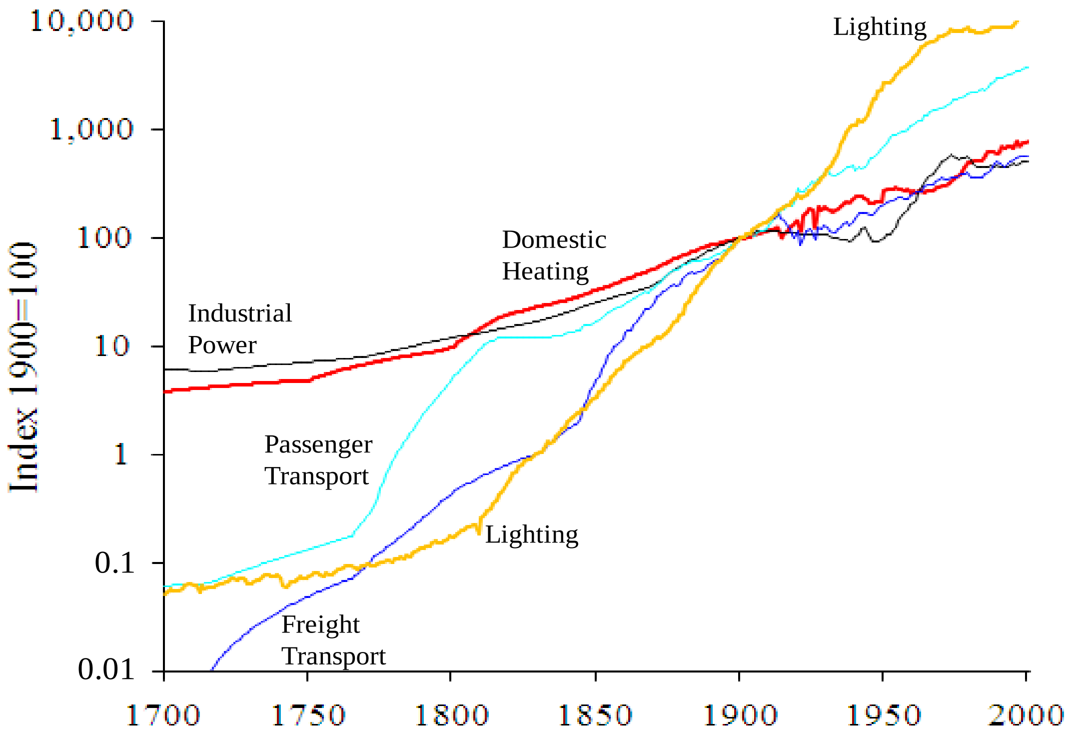
For trends related to transportation, there is often evidence on kilometres travelled (see Fouquet (2012a) for more detail), and do not need to be constructed, as they do for heating and lighting. A long run passenger railway use series from 1842 to 2010 was created based on Hawke (1970 p.47), Munby (1978 pp.106–7), DoT (2002) and DfT (2011). These were also then used to estimate the price of railway passenger services. Mitchell (1988 p.545) has railway passenger receipts (in £m) between 1843 and 1980. These figures can be divided by estimates of total passenger-km travelled to indicate the cost per passenger-km of using railways. DoT (2002) and DfT (2011) had estimates of the price to 2010.

For twentieth century road travel, DoT (2002) and DfT (2011) presented data on passenger travel (e.g., buses, cars, motorcycles, etc…) between 1952 and 2010. Before the early 1950s, data needed to be pulled together based on Mitchell (1988 pp.557–8). Passenger road transport 'prices' are more complex in the second-half of the twentieth century. Rather than identifying the cost of buying a train or bus ticket, as more travellers used their own cars, a number of different expenditures were involved. The price of driving a car one kilometre was estimated by dividing passenger fuel expenditure (in million tonnes of oil equivalent (mtoe)) by distance travelled (DECC 2012).

Throughout the paper, prices are quoted in *real terms* (i.e. in £(2000) money). The retail price index is from the data used for Allen (2007), and then updated using ONS (2012) data. Thus, the costs of using different fuels and of producing services are broadly comparable across time.

4. The Growth in Consumption of Energy Services

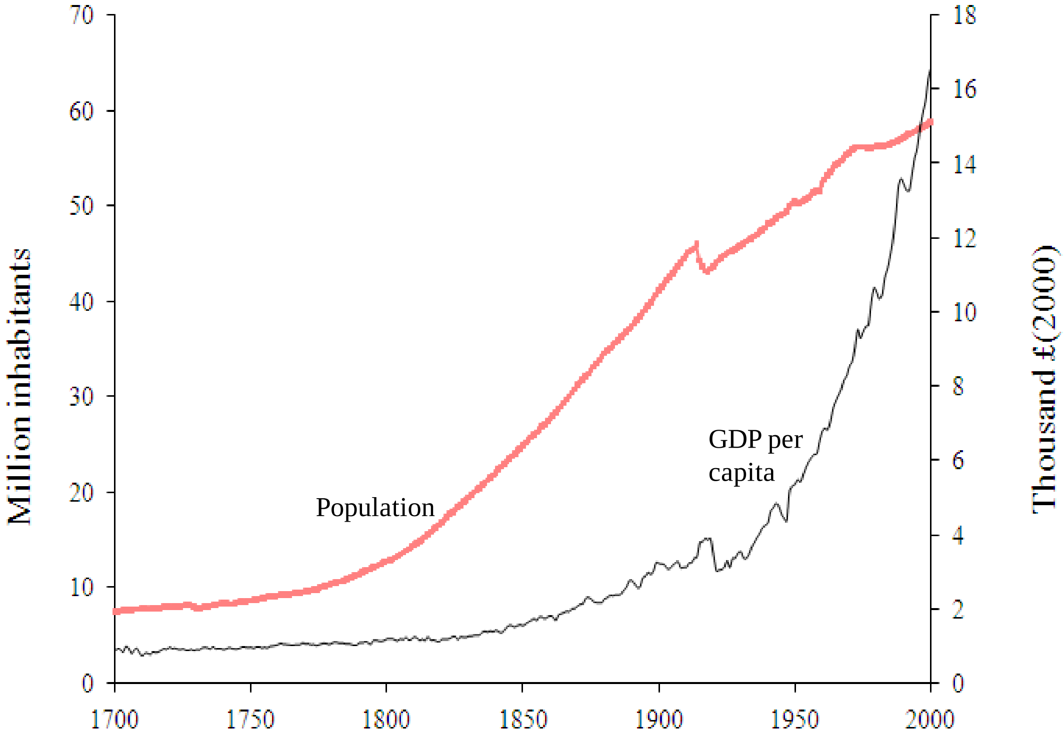
Over the last three hundred years, consumption of energy services in the United Kingdom has risen dramatically (see Figure 1). Looking at the use of energy services for production activities, power provision for industrial purposes increased more than 120-fold since 1700. Carriage of goods (on land and on the sea) rose nearly 250 times in three hundred years. Turning to energy services for consumption purposes, household use of effective heating increased 220-fold since 1700. Land passenger travel rose more than 48,000 times since 1700. In that time, lighting consumption soared 295,000 times.



Source: Fouquet (2008)

Figure 1. Consumption of Energy Services in the United Kingdom, Index 1900=100, 1700-2000

Figure 2 shows how GDP per capita and population have increased over the last three hundred years. Economic growth was relatively gradual in the eighteenth century. In the nineteenth century, population grew rapidly and, especially from the 1830s, per capita income increased (nearly tripling in the nineteenth century). After the First World War, the trends were reversed, with slower population growth and spectacular improvements in average income (more than a five-fold increase during the twentieth century).



Source: Broadberry (2011a, 2011b), ONS (2012)

Figure 2. GDP per capita, in real terms (2000 values), and Population in the United Kingdom, 1700-2000

Comparing the growth rates in Figure 1 with those in Figure 2, it is clear that, although greater population and wealth is a key driver for the rising consumption of energy services, other forces are also important in directing specific energy service usage. Figure 3 shows the evolution of prices for consumer energy services (domestic heating, passenger transport and lighting).

The price of domestic heating declined from 1700 until the 1920s (see also Table 1). For two hundred years, this decline was mostly due to the transition from woodfuel to coal, which was about half as expensive per unit of energy (Fouquet 2011). From the early nineteenth century, the adoption of the more efficient Rumford fireplace, which, by 1900, had doubled the efficiency compared with the traditional fireplace (Crowley 2004). During the nineteenth century, consumption of effective heating increased eleven-fold (3.5 times to 1850, and then 3.2 times from 1850 to 1900).

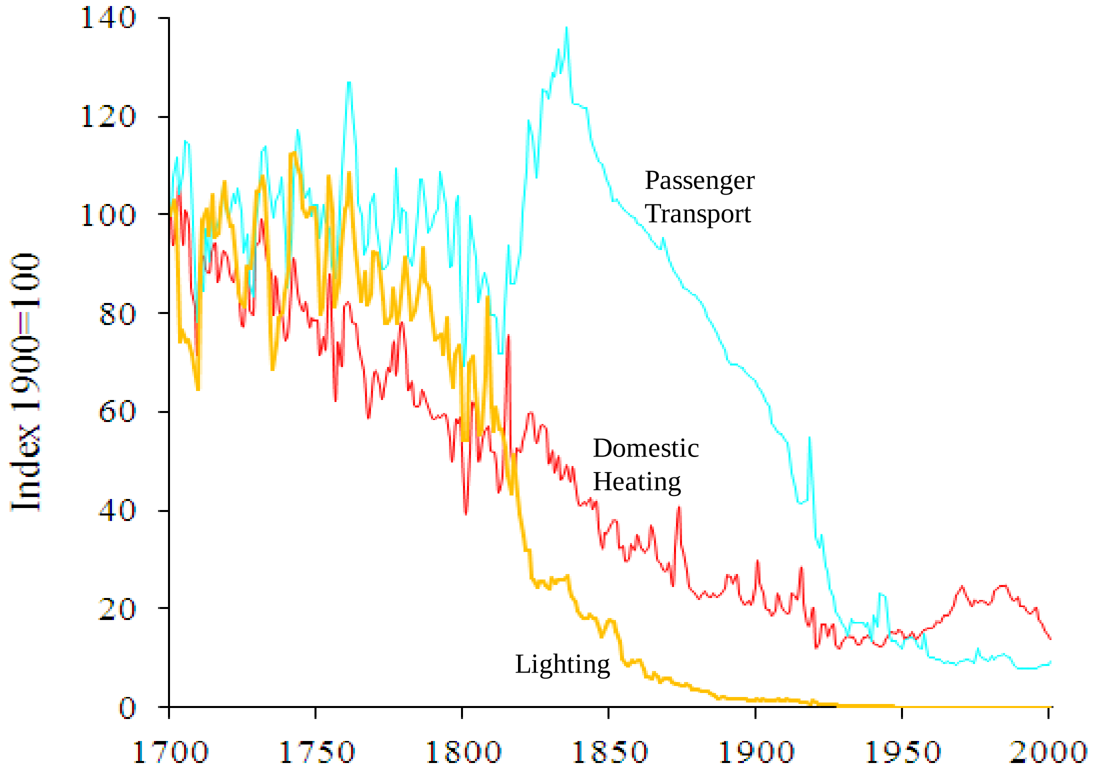


Figure 3. Price of Consumer Energy Services in the United Kingdom (Index 1900=100), in real terms (2000 values), 1700-2000

From the 1920s, upper and eventually middle class households started using gas and then electricity for cooking and heating (Bowden 1988, Goodall 1999). Although more efficient than coal for cooking and heating, per unit of energy, gas and electricity were, respectively, eight and forty times more expensive than coal in the 1930s (Fouquet 2011). This implies that wealthier households were willing to pay for more expensive but also more modern and cleaner cookers and heaters. Between 1900 and 1950, consumption of effective heating more than doubled. Yet, it was the Clean Air Act of 1956, following the tragedy of the 1952 Big Smog (when an estimated 12,000 additional deaths were caused by air pollution) that imposed a switch to smokeless fuels, forcing poorer households to adopt gas and electricity (Fouquet 2012b). Despite falling gas and electricity prices between 1950 and 1970, per unit of energy, electricity was still five times more expensive than coal, and natural gas double the coal price. Then, from the 1960s, central heating systems transformed the nature of domestic heating from a source of warmth to creating a controlled indoor climate (Billington 1982). Consumption of effective heating more than tripled between 1950 and 2000, and has continued to increase.

Table 1. The Price and Consumption of Domestic Heating, Land Passenger Transport and Lighting in the United Kingdom, Index 1900=100, 1700-2000*

	1700	1750	1800	1850	1900	1950	2000	2010
Prices:								
Heating	325	255	145	120	100	95	42	58
Transport (Land)	153	156	106	161	100	20.7	14.6	15.4
Lighting	5,400	5,325	2,950	950	100	6.3	0.79	0.69
GDP (per capita)	27	30	37	48	100	166	515	540
Consumption:								
Heating	3.5	4.5	9.0	31.2	100	229	736	772
Transport (Land)	0.06	0.13	4.7	16.7	100	683	2,715	2,890
Transport (Total)	0.06	0.13	4.7	16.7	100	683	3,530	3,840
Lighting	0.06	0.08	0.17	3.5	100	1,390	11,650	17,700

Source: Author´s own estimates

The price of passenger transport declined in the eighteenth century, following improvements in the quality of roads (associated with the expansion of turnpikes) and the consolidation of the stage coach network (Pawson 1977). Then, from the 1770s, stage coach journeys became better managed and faster – by 1830, average trips were five times faster than in the 1770s (Bagwell 1974). Between 1775 and 1815, passenger travel increased from 0.05 billion passenger-km (bpk) to 3 bpk – a sixty-fold increase (Chartres and Turnbull 1983). In the 1820s and 1830s, travel use stagnated, at a time of considerable economic growth and increasing prosperity, but rising prices of transport services. Stage coach prices soared as the coach companies tried to make back their investment once they were unable to compete with the railways (Hart 1960).

Railways radically transformed transport services in the nineteenth century. Although initially inefficient, locomotives improved dramatically in the 1850s and 1860s, and transport prices fell rapidly. The railway network offered faster and cheaper travel. By 1860, railways dominated passenger services. However, from the 1880s consumption soared, as government pressured railway owners into providing cheap services for third-class customers. Access to railways dramatically enhanced mobility of the poor and saved huge amounts of time (Leunig 2006). Passenger transport rose six-fold between 1850 and 1900, reaching 27 billion passenger-kilometres.

Then, the development of the internal combustion engine radically changed transport services in the twentieth century. The bus was especially valuable at providing public transport in rural areas not connected to the railway network. In 1911, the Model-T Ford became the first `affordable´ car for the

British private vehicle market. As the price of vehicles fell, the market share of smaller motors increased and the fuel efficiency of engines improved, car use soared, becoming the dominant mode of transport by 1950 (Bagwell 1974) At the end of the twentieth century, cars were responsible for around 600 billion passenger-kilometres per year; 50 billion associated with buses and coaches. Land passenger travel had increased more than 350 times in the last two hundred years and 35 times in the last one hundred years.

After the Second World War, the market for long-distance air travel began to develop. The introduction of the jet engine enabled faster, larger and more comfortable planes, at declining prices. Rising income, more annual vacations and tour operators selling the virtues of exotic destinations created a mass demand for leisure travel. In 1950, air travel accounted for 1.2 billion passenger-kilometres; it grew rapidly, especially in the early 1970s, reaching 60 billion passenger-kilometres in 1975 and 250 billion passenger-kilometres in 2000 – increasing two hundred-fold in 50 years.

In the market for lighting, tallow candles (made from animal fats) had been the main source of illumination to supplement the domestic fire. From the 1810s, gas lighting offered consumers another energy service revolution. Before, when a great deal of light was required, the concentration of candles generated intolerable amounts of heat. Also, candles and lanterns frequently generated fires (Schivelbusch 1988) – the great fire of London in 1666 supposedly started by a spilt lantern caused an estimated £(2000)900 million of damage or around 15% of national GDP (Fouquet 2008 p.201). Finally, in the 1820s, town gas was more 50% more expensive (per unit of energy) than tallow candles. Yet, town gas lighting technology was twice as efficient at illuminating. By 1850, town gas was half the price of tallow candles (per unit of energy) and far more efficient (Fouquet 2011). Gas lighting became the dominant source of lighting before 1850, increasing total lighting consumption. Yet, the high installation costs of pipes prohibited many households. In the 1890s, companies began installing the pipes and prepayment meters, enabling poorer households to benefit from gas lighting. At the same time, the Welsbach gas mantle was introduced, providing further efficiency improvements (Falkus 1967). Lighting consumption increased 570-fold during the nineteenth century.

When electricity began to replace town gas (and kerosene) for lighting, around 1900, it was twenty-five times more expensive per unit of energy than gas (Fouquet 2011)). At the time, electric lighting was seven times more efficient. So, at first, electric lighting was more expensive than gas lighting. Nevertheless, it was still used in luxury homes, restaurants and theatres, where the novelty of the new technology was highly valued (Schivelbusch 1988). By 1930, when a rapid switch was occurring, electricity was five times as expensive as gas, but electric lighting was ten times more efficient (Fouquet 2011). Lighting consumption increased from 10 trillion lumen hours in 1900 (80% of which was provided by gas) to 150 trillion lumen hours in 1950 (more than 95% of it was generated from electricity). From 1950, the growth rate in consumption started to decline, until the introduction of more efficient lighting technologies in the 1990s, which drove down the price of lighting further. In 2000, 1,200 trillion lumen hours were consumed, which increased to over 1,800 trillion by 2010.

Table 2. Actual and Expected (given Unit Income and Price Elasticities) Growth Rates in the Consumption of Domestic Heating, Land Passenger Transport and Lighting in the United Kingdom, 1700-2000

	1700-1750	**1750-1800**	**1800-1850**	**1850-1900**	**1900-1950**	**1950-2000**	**2000-2010**
Heating (Actual)	1.3	2.0	**3.5**	3.2	2.3	3.2	1.0
Heating (Expected)	2.4	3.0	2.5	3.3	2.7	5.4	1.8
Transport (Actual)	2.2	**36.2**	**3.5**	**6.0**	6.8	4.0	1.1
Transport (Expected)	2.1	2.7	2.0	3.7	6.5	4.5	2.0
Lighting (Actual)	1.3	2.1	**20.6**	**28.6**	13.9	8.4	1.5
Lighting (Expected)	2.1	3.0	4.4	11.6	17.5	11.1	2.2

Source: Based on Table 1.

To summarise, Table 2 offers some basic evidence on growth rates for heating, land transport and lighting consumption. For each energy service, the actual growth rate over 50 year periods is presented. Also, the growth rate expected if the demand for each energy service was both income and price unit-elastic (i.e., elasticity equal to one). The actual growth rates that are substantially greater than the expected value are presented in bold, and indicate high income and/or price elasticity. This indentifies crudely that heating demand was elastic between 1800 and 1850, transport demand between 1750 and 1900, and lighting demand between 1800 and 1900. To explore these variations in elasticities in more detail, and to distinguish the roles of income and prices are consumption, it is necessary to use econometric methods.

5. The Changing Demand for Energy Services

This section presents evidence on the changing relationships between the demand for energy services, economic activity and the prices of energy services over the last two hundred years[2].

5.1. Estimating the Relationships

As discussed in Section 2 and 4, it is proposed that, based on the economic model of demand, consumers use energy services to maximise their utility subject to budget constraints and the existing prices of energy services. To estimate the changing relationships in more detail, it is necessary to

[2]. Although, in the previous section, trends over the last three hundred years were discussed, only annual (i.e., non-interpolated) data is used for the analysis in this section.

analyse the data using econometric methods. Here, the discussion focuses on the results rather than the methods and data, which have already been presented in Fouquet and Pearson (2012)[3] and Fouquet (2012a). Although there are limitations associated with the method used to analyse the data[4], it offers estimates that are consistent with a basic review of trends and, so, the results are worthy of discussion.

Having observed that variables of interest tend to rise or decline in the long run and, so, may well be non-stationary (see Figures 1, 2 and 3) and since long run energy consumption, GDP per capita and energy prices are often cointegrated (Hunt and Manning 1989, Fouquet 1997, Stern 2000), the possibility of using vector error-correcting models (VECM) was explored and, from a statistical perspective, was found to be appropriate, as will be explained.

First, the time series properties of the data series were examined. For the GDP per capita, and for the prices and consumption of individual energy services, non-stationarity[5] could not be rejected, following a number of standard and more advanced tests (Elliott, Rothenberg and Stock 1996), thus, unit roots (i.e. non-stationarity) were likely. Second, there is an extensive literature on the direction of causality between energy and GDP (Kraft and Kraft 1978, Stern 2000, Joyeux and Ripple 2011). Toman and Jemelkova (2005) formalised the potential causal effect of energy service use upon GDP, as well as from GDP to energy services consumption. Energy service use for productive activities might be expected to affect GDP – for instance, increases in industrial heating or power might be expected to feed through into higher levels of GDP. In the current paper, however, the focus is specifically on energy service use for consumption activities, such as domestic heating, passenger transport and lighting, which are less likely to affect GDP. Also, individually, their share of total consumer expenditure was rarely more than 8% and often closer to 2%. In the tests run, the causal relationship was examined and the results indicated that, for the whole period under analysis, unidirectional causality ran from per capita GDP to energy service consumption.

Third, the next set of tests was to identify the number of cointegrated relationships. Once the appropriate number of lags from a series of different tests (Nielson 2001) was selected, the null

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[3]. The estimates of lighting demand elasticities in Fouquet and Pearson (2012) were slightly affected by inaccuracies (between 1850 and 1930) in the GDP per capita time series used (and I am grateful to Paul Warde for having highlighted this problem). So, the estimates were re-run for this article and, benefitting from this correction, also offer additional evidence on the trends.

[4]. Lutz Killian, Bill Nordhaus, David Stern and Lester Hunt encouraged me to pursue this line of research, although offered caution about the methods (see, for instance, Hunt et al. 2003, or Killian and Murphy 2009).

[5]. Non-stationary series do not tend to revert to an average value, and instead they tend to drift through time, as a result of shocks with a long-run effect. It is important to identify whether they are co-integrated with other series (that is, the series drift together) or their apparently joint drifts are merely a statistical coincidence (Bannerjee et al. 1993).

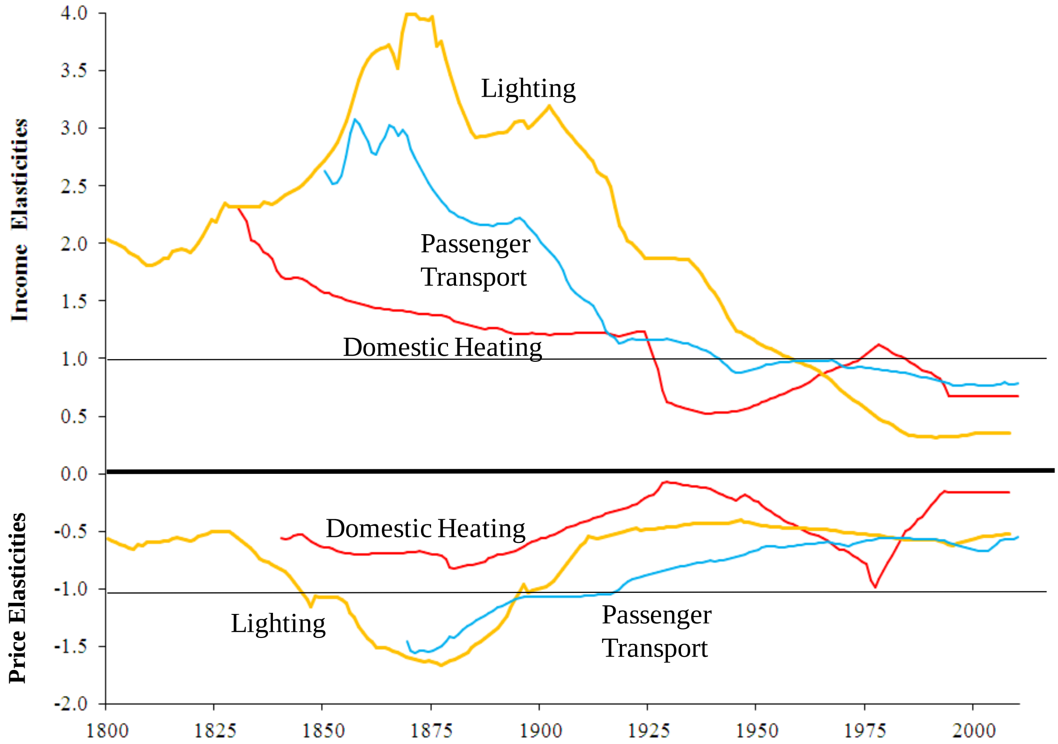
hypothesis of one cointegrated relationship consistently could not be rejected (Johansen 1995). Having been satisfied with the statistical properties of the time series, VECM were, therefore, used to estimate the changing relationship between consumption, income and prices.

A simple method was developed in Fouquet and Pearson (2012) to estimate the trends in income and price elasticities, estimating the average value for fifty year periods moving through time. For example, the income and price elasticities of heating demand were estimated for the period 1830-1879, then 1831-1880, and so on until 1961-2010. Then, the elasticity for any particular year would be the moving average (i.e., the average of all elasticities estimated where that year was included). So, for the moving average around the year 1950, fifty income elasticity of demand for domestic heating estimates were produced (for the periods 1900-1950, 1901-1951, and so on until 1950-2000) and the average of all these estimates was equal to 0.60. Estimated in the same way, the average price elasticity of heating demand around 1950 was -0.25.

Inevitably, for some periods, the results were either not as expected (e.g., very large and positive price elasticities). In particular, the period broadly between 1880 and 1920 produced unexpected price elasticities for domestic heating. For transport demand, only the price elasticities before 1870 were inconsistent with expectations. Similarly, for lighting demand, a few income elasticity estimates around 1860 were not as expected. These results were not used. This implied that, for some years (such as the 1850s and 1860s for lighting demand), the average value was based on fewer than 50 estimates (but never less than 8 estimates). In general, however, the estimates from one year to the next were remarkably stable, with modest annual changes. Over nearly two hundred years, the majority of estimates produced standard signs and sizes – income elasticity estimates were used for 80%, 97% and 84% of the moving averages related to heating, transport and lighting, respectively, and price elasticity estimates were used 63%, 93% and 99% of the moving averages.

5.2. The Relationship with Economic Development

The results confirm the expectations proposed by basic theory. That is, despite the data limitations, income elasticities for energy services appear to rise, at early phases of economic development, reach a peak, then decline (see Figure 4). The peaks (occurring in the nineteenth century) were substantially above unit elasticity and, following declining trends (for almost 100 years), unit elasticity was eventually reached (well into the twentieth century). Also, income elasticities at high levels of per capita income (i.e., in the twenty-first century) are significantly different from zero.



Source: Fouquet (2012); Author s own estimates

Figure 4. Income Elasticities (Top) and Price Elasticities (Bottom) of Demand for Energy Services, 1800-2010

Comparing different energy services, the peak was earliest for heating[6], then for transport and then lighting. This could be due to priorities of wants, as income increases, implying that basic energy services, such as cooking and heating take precedence in a poor household´s basket of goods and services over transport and lighting. When transport income elasticity was peaking, the heating income elasticity was approaching unity. Similarly, unit income elasticity was reached in the same order: heating, transport and lighting – supporting this prioritisation. Also, the peak was substantially higher for lighting than for transport, which was higher than for heating – suggesting that the smaller the budget share required for an energy service, the higher will be the peak.

Figure 4 also shows the decline in income and price elasticities over time and, by implication, at higher levels of income. As mentioned before, saturation effects suggest that, beyond a certain level of consumption, as income rose, a declining share of the budget was dedicated to the energy service – and income elasticities fell. Lighting demand shows this trend most clearly, with income elasticities

6. For heating, although the timing of the peak cannot be identified, because annual data on domestic coal consumption is not available before 1830, it was clearly before 1830, but probably not much earlier. In the eighteenth century, elasticities were lower (see Table 2).

continuing to fall below unity to between 0.2 and 0.3. Heating demand in the second-quarter of the twentieth century, as income elasticities fell to about 0.5. However, related income elasticities rose again from the mid-century, requiring another explanation. Similarly, land transport demand showed signs of saturation in the second quarter of the twentieth century, but was forced upwards by the use of cars amongst poorer people. Thus, saturation effects are clearly visible, but other factors appear to affect demand (and these will be discussed later, in section 5.4).

Another important point to note is the close relationship between income and price elasticities for particular energy services (shown in Figure 4). The declining trends and the peaks in income elasticities, such as in the 1870s for lighting elasticities and in the third-quarter of the twentieth century for heating, are mirrored by price elasticities. This is not entirely surprising since price elasticities are determined by income effects, as well as substitution effects. Therefore, higher income elasticities feed through into price elasticities.

Yet, income effects are muted by the fact that energy services were not a large proportion of consumer expenditure. At its peak, around 1910, the three services together amounted to just over 10% of average income. Consumer expenditure on heating was 2-3% of average income from 1850 to 2010; transport expenditure was closer to 6%, dropping after the 1950s towards 2%; and, lighting expenditure was around 1-2% of expenditure between 1800 and 1950, and fell towards zero afterwards. Meanwhile, the substitution effect is relatively small, because there are few alternatives for heating, transport and lighting other than using energy services. Having said this, price elasticities were still relatively large during the second-half of the nineteenth century, reaching unity (for transport and lighting) around 1900 and falling (in absolute terms) to -0.5 around 1950.

The peaks in income elasticities were more pronounced, however. And, in general, the magnitude of the income elasticity was greater than the magnitude of the equivalent price elasticity. In other words, consumers were more sensitive to equivalent income increases than to price decreases. It is indeed possible that rising incomes push consumers to raise their standards of energy service use more than equivalent price declines.

5.3. The Role of Declining Service Prices

Section 4 explained how energy efficiency improvements drove down the price of services, increasing consumption. A topical question is: by how much did energy consumption fall? As mentioned earlier, Jevons (1865) argued that energy consumption actually increased. More recent studies (Sorrell 2009) find modest rebound effects, implying that energy consumption fell, but by not as much as the proportional efficiency improvement.

In this study, the evidence (i.e. price elasticities below -1.0 in Figure 4)) suggests that, between 1850 and 1900 (when Jevons´ was writing), the rebound effects did increase energy consumption related to transport and lighting. Outside this period, and for heating, however, efficiency improvements appear to have lead to net energy savings, all other things being constant. Yet, because the price elasticity has consistently been (estimated to be) significantly different from zero, rebound effects are a pervasive feature of energy behaviour, and should never be ignored.

Despite the discussion above, the question remains: what drove the changes in income and price elasticities? Figure 5 shows the three-dimensional relationship between income elasticities, income per capita and service prices. From the early nineteenth century to the early twentieth century, energy service prices fell dramatically and, then, from the mid-twentieth century, per capita income grew rapidly. This suggests that income elasticities fell first with falling prices, and then, from the 1930s, with rising income levels.

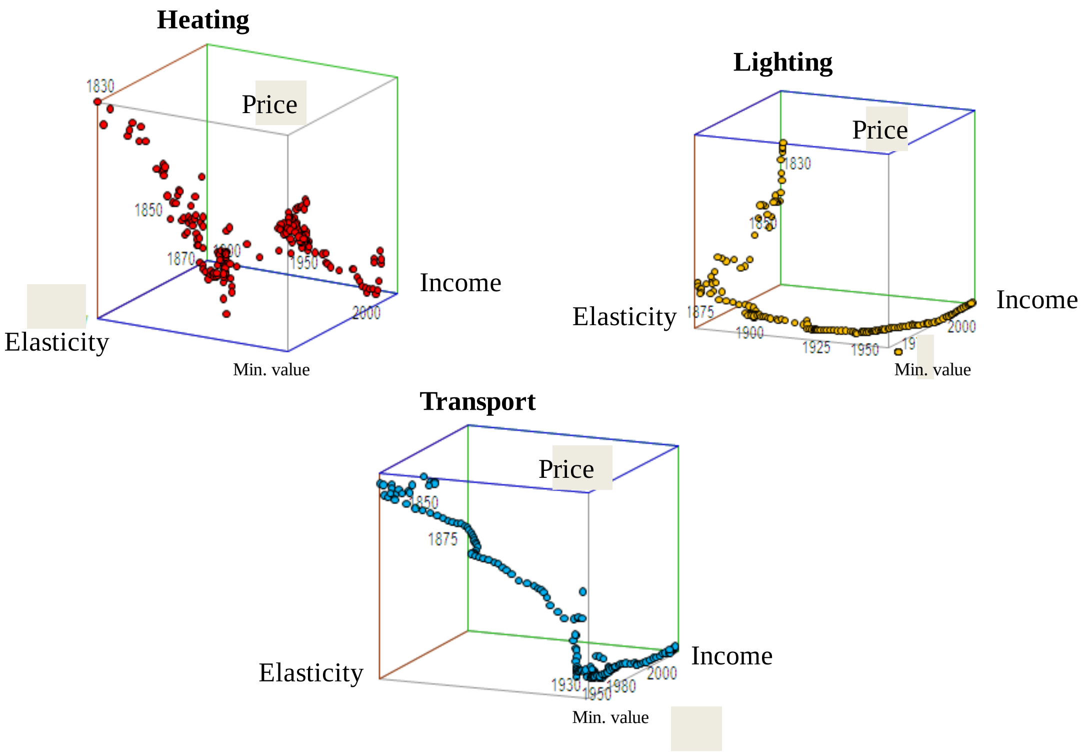


Figure 5. Income Elasticities of Heating, Transport and Lighting Demand relative to Per Capita Income and Prices, 1830-2010

The improvements in energy efficiency and the resulting reductions in energy service prices during the nineteenth century met a growing latent demand for energy services. From the 1650s, wealthy consumers had been gradually seeking refinements in the quality of their food and household goods, and improving their domestic levels of comfort (Shammas 1990, Crowley 2004, Trentmann 2012). Over the centuries, as income levels gradually increased, more households were able to join in this consumer revolution (McKendrick et al. 1982). From 1750, the lower classes were willing to spend more time working to acquire these goods, creating the 'industrious revolution' (De Vries 1994). Thus, in the nineteenth century, when many of the technological innovations were occurring, consumers had met a number of other wants (particularly related to food and fabrics) and were open to greatly increasing their demands for heating, transport and lighting.

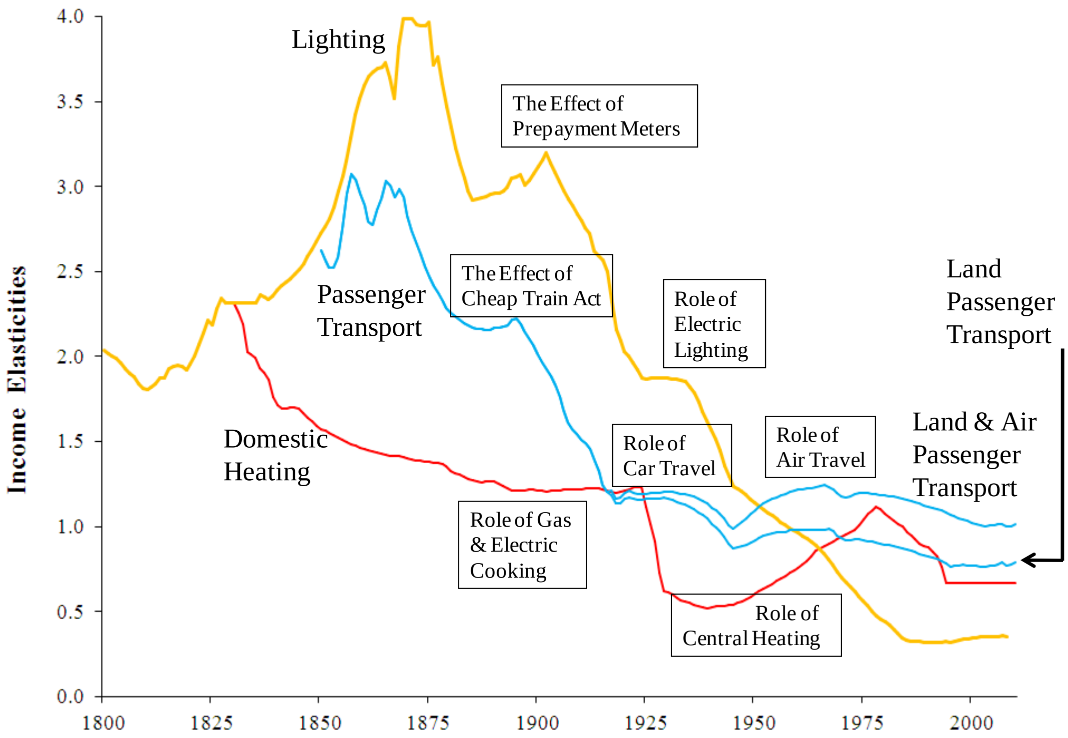
Based on Figures 4 and 5, one can interpret consumer behaviour towards energy services in the following way: when consumers had low incomes and energy services were very expensive, they could only dedicate a small amount of their budget to these services; when radically more efficient technologies were introduced, some consumers (particularly wealthier ones) were willing to adopt the new technologies and increase their consumption; less wealthy households observed the early adopters´ behaviour and desired these new levels of consumption; modest increases in income implied they were willing to greatly increase their demand and consumption.

When this latent demand was met, during the nineteenth century, greater consumption of energy services then transformed people´s lives. Prior to the nineteenth century, most households used the heat generated from the cooking to provide space heating (Crowley 2004). The lower heating costs of the Rumford fireplace implied that even poorer households could separate their cooking and space heating services (Davidson 1986). This changed the layout of houses (with more, smaller rooms) and how families and friends interacted (Crowley 2004).

Similarly, from the 1840s, upper and upper-middle class households had sought to move away from the crime, sewage and smoke of the cities, and the expansion of urban railway networks enabled them to move to the suburbs. The introduction of the Cheap Trains Act of 1883 and a rapid expansion of suburban housing in the 1890s offered an opportunity for lower-middle class families to live in the suburbs and commute into the city (Jackson 2003). In Figure 6, a second peak in income elasticities (around 1900) is associated with the rising demand for this poorer population.

Similarly, for lighting, income elasticities experienced a second peak (around 1910) due to the introduction of pre-payment meters, which allowed the poorer consumers to use gas lighting, as well as the much more efficient Welsbach mantle (Figure 6). Lighting also transformed people´s lives. As discussed in Fouquet and Pearson (2012), cheaper gas and kerosene lighting was an "enabler" or complement of other goods and services. For instance, numerous activities, such as working, socialising and education, become much easier to undertake at night (or cheaper to produce, in the eyes of Stigler and Becker (1977)). Interestingly, this changed sleeping behaviour. Prior to the growth in light use, the long nights were often broken-up into two periods of sleep; as the 'day was lengthened', work, socialising or education replaced sleeping, which became more concentrated

(Ekirch 2001, Koslofsky 2011). Also, the expansion of street lighting aided the development of urbanisation and reducing related crime.



Source: Fouquet (2012); Author s own estimates.

Figure 6. The Role of Transitions on Income Elasticities of Demand for Energy Services, 1800-2010

5.4. The Demand for New Attributes

Along with economic development and changes in service prices, energy and technological transitions might have affected the trends in elasticities. In section 2.2, it was proposed that an analysis of energy services rather energy means that the relationship between consumption and utility is more stable (Stigler and Becker 1977). Even after a transition to a more efficient technology, households are still seeking to consume energy services – heating, transport and lighting.

However, new energy sources and technologies can change many other attributes (Lancaster 1971). This explains to a large extent the existence of an energy 'ladder' (Barnes and Floor 1986). Woodfuel is far less dense than coal or kerosene; dung is hardly hygienic; coal is far dirtier than gas; and electricity is the easiest to use, and quite flexible, but cannot be stored easily, limiting its mobility. Thus, household consumption patterns associated with energy technologies and their fuels may be reflecting their preferences for energetic density, storage, health effects, cleanliness, ease of use, flexibility and mobility of energy source. Similarly, technologies embody many different attributes beyond their ability to produce heat, transportation or illumination. Inevitably, though, these characteristics are hard to identify, measure and analyse.

Nevertheless, the role of energy and technological transitions can be discerned over the last one hundred years. The introduction and diffusion of new energy sources and technologies coincide with rises in income elasticities. For example, between the 1890s and the 1930s, there was a rapid growth in the uptake of more expensive to use, but cleaner gas cookers (Goodall 1999) – this can be seen in the trend in income elasticity for domestic heating in Figure 6. From the 1950s, the rise in domestic heating income elasticities is very clear. This is due to the growth in gas heating and then in the 1970s the growth of central heating, which transformed households´ abilities to control their indoor climates (Billington 1982).

An earlier example of how consumers value characteristics was related to the stove. During the eighteenth and nineteenth century, the stove was used for heating in dwellings on the continent and was far more efficient than the fireplace. However, Britons refused to adopt it because they found the heat it produced suffocating and it hid the flames, which were a source of great entertainment (Crowley 2004).

Although there is a lack of annual data to estimate elasticities, it is probable that, during the late eighteenth century, transport demand had already been growing. As mentioned before, travel between 1775 and 1815 increased a spectacular 60-fold, despite only modest income growth and price declines (see Table 1 and 2). This suggests income and price elasticities for transportation were very high in the late 1700s. Crucially, during the last quarter of the eighteenth century, journey speeds increased up to 80%, driving-up the demand for energy services.

Nevertheless, stage coach journeys were generally uncomfortable experiences. Passengers were squeezed together, and arrivals were dependent on weather conditions. Trains made journeys even faster and more reliable (Leunig 2006). Rising wages and cheaper, more efficient cars meant the democratisation of private travel, enabling individuals to select and control their journeys (O´Connell 1998) – from 1920, the decline in income elasticities related to land transport demand was halted for twenty years (see Figure 6). More recently, the speed of air travel has enabled intercontinental travel to be a short journey – the effect on demand can be seen in Figure 6 by the divergence in the trends related to land transport and total (i.e., land and air) transport.

In the lighting market, tallow candles were made from foul-smelling animal fat (mutton fat was preferred), that were prone to generate excessive heat (when over concentrated) and cause fires. Although not odourless, the introduction of gas lighting was a great improvement for producing more concentrated lighting and for safety (Schivelbusch 1988). Electricity made lighting far easier and cleaner. However, many today complain that energy efficient light bulbs produce a ‘colder’ light than do incandescent bulbs.

Most recently, the environmental effects of fuels have been considered an important characteristic of energy services. In particular, the climatic impact is seen as a negative attribute. If a sufficiently large demand develops to avoid this attribute, then, a reverse effect on elasticities may be observed – that is, an energy and technological transition might push downwards the income elasticity of demand for energy services. However, as in the past, transitions are often associated with the introduction of valuable additional attributes, which push upwards income elasticities. Thus, the outcome of a future (low carbon) transition upon income elasticities of demand for energy services will depend on the relative strength of the demand for climate stability and for the other potential attributes.

6. Conclusion

Over the last two hundred years, energy service consumption increased dramatically as a result of declines in energy service prices (especially due to improvements in energy efficiency) and rising per capita income. Within this period, the rates of change of these three variables differed greatly. The purpose of this paper was to present evidence on the trends in the income and price elasticity of demand for energy services - in particular, for domestic heating, passenger transport and lighting in the United Kingdom between the early nineteenth and the early twenty-first century.

The evidence (see Figure 4) indicated that, during the nineteenth century, income elasticities for energy services rose, at early phases of economic development and upon dramatic declines in the price of energy services. When they reached a peak (about 2.3, 3.0 and 4.0 for income elasticities of demand for heating, transport and lighting, respectively), there was a rapid decline, though it took almost 100 years for the income elasticities to reach unity. At the end of the twentieth and during the early twenty-first century, the elasticities were generally below unity but well above zero.

Price elasticity followed a similar course – for transport and lighting, they peaked around the 1870s and dropped (in absolute terms) to unity between 1900 and 1920, and fell gradually during the twentieth century. Domestic heating price elasticities were lower, but generally followed the same pattern. This generalised pattern of a rise, a peak and a decline (first rapid, then gradual) fitted the theory surrounding declining marginal utility associated with consumption. That is, as they consumed more, households´ hunger for energy services declined.

However, the evidence also indicated that these general trends were disrupted by energy and technological transitions. These transitions were often associated with an increase in income or price elasticities (in absolute terms). That is, consumers became more sensitive to changes in income and prices, again. An explanation for second peaks in trends was that another (generally, poorer) segment of the population entered the market – the Cheap Train Act in the 1880s, the prepayment meter in the 1890s and the use of cars amongst poorer households from the 1950s created surges in the demand for energy services (shown in Figure 6).

The other changes in responsiveness to income and prices often occurred after energy and technological transitions that provided additional valuable attributes to the consumer. These new attributes or characteristics related to new energy sources or technologies (such as ease of use, flexibility, cleanliness, speed of service, privacy, and effects upon health and the environment) appear to have altered the trend and delayed its decline (by several decades). Thus, although income elasticity may have followed an inverse U-shape curve (and a U-shape curve for price elasticity) as an economy develops and energy service prices fell, numerous factors (including the entrance of a new segment of the population or new attributes) associated with energy and technological transitions can alter the trends.

Having analysed the trends, this study can offer certain insights for understanding future trends in the demand for energy services, energy consumption and carbon dioxide emissions. The first insight, based on price elasticities, is that efficiency improvements have always been associated with rebound effects, sometimes (such as in the nineteenth century, as Jevons had predicted) leading to greater energy consumption. In the case of the United Kingdom, the price elasticities fell below unity around $(2010)7,000-9,000. In the twentieth century, the rebound effect fell, but still, at the beginning of the twenty-first century (in the United Kingdom, as in other developed economies (Greening et al. 2000, Small and van Dender 2007)), it is far from zero – limiting the power of energy efficiency measures to reduce carbon dioxide emissions.

This has important implications for the future. Given recent R&D investments in energy technologies, it is likely that, over the next 30 or 50 years, the efficiency of energy technologies will improve substantially. So, even if future trends in individual energy prices do not follow the same patterns as past ones (Hamilton 2012), consumers´ tendency to seek more efficient technologies and cheaper energy sources (Fouquet 2011) implies that energy service prices are likely to continue their long run downward trend. Price elasticities of demand for energy services imply that these trends will feed through into higher energy service consumption – and probably, in developing economies, into increases in energy consumption.

Another insight from this historical and long run analysis is that, in the case of the United Kingdom, the turning-point for income elasticities of demand for energy services was around $(2010)4,000-7,000. If present-day developing countries follow a similar trend, then the elasticities of countries, such as China, will be peaking. This implies (in a similar vein as, say, Wolfram (2012)) that its energy service and energy consumption are and will continue (for many years) to increase at a faster rate than its GDP per capita. For the United Kingdom, income elasticities of energy service demand fell below unity around $(2010)12,000.

It was suggested that the prices of energy services at particular levels of economic development may have influenced the trend in income elasticities. It is likely that, compared with the United Kingdom at equivalent levels of GDP per capita, today´s developing economies have cheaper energy services. If that is the case, probably, present-day developing economies will have smoother trends (that is, a smaller peak) and possibly an earlier peak for income elasticities.

Eventually, though, it is proposed that all countries experience a decline in elasticities, associated with saturation effects, implying a slower growth in energy service and energy consumption. However, if any future energy or technological transitions unfold, they are likely to delay the decline in income elasticities. This delay will be stronger the more valuable the additional attributes these energy sources and technologies provide – and, historically, markets have been remarkably effective at delivering new attributes (see Figure 6). The extent to which these transitions will be low carbon in nature will determine whether this rising energy consumption translates into further increases in carbon dioxide emissions.

So, while the global economy´s appetite for energy may not be insatiable, it is far from satiated. In other words, the evidence suggests that, certainly for many decades into the future, market forces and long run trends (associated with population and economic growth, price and income elasticities, and energy transitions) are likely to push upwards energy service demand and energy consumption. Given the slow speed at which a full low carbon energy transition is likely to unfold (Fouquet 2012b), this also implies increasing carbon dioxide emissions, raising greenhouse gas concentrations and intensifying the process of climate change.

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