Long-Run Demand for Energy Services: Income and Price Elasticities over Two Hundred Years

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Introduction

Is the global economy's appetite for energy insatiable? Will energy demand continue to grow as it has over the last two hundred years? In order to address growing concerns about both energy security and climate stability, it is important to anticipate and analyze future long-run trends in energy consumption. The key to identifying these trends is an understanding of what (and how) factors affect growth rates in energy consumption. The first step in understanding these factors is to study historical experience.

Over the last two hundred years, industrialized societies have been freed from their 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 revolutionized our ability to heat, travel, and illuminate.

The supply side of these spectacular transformations has been examined by Fouquet (2011). However, it is also important to understand how energy service *demand* has evolved over time, at different stages of economic development, or as a result of other economic, technological, political, social, or cultural factors. Economists must begin by addressing a narrower issue: How have the income and price elasticities of demand for energy services changed over time, and what caused these changes?

Some early economic studies appreciated the fact that demand varied and that an elasticity estimate should be an average over a number of years or consumers (Working 1925; Stigler 1954). However, because of limited data sets and the need to find statistically significant results in econometric analyses, many studies have focused instead on producing *single* estimates, often assuming constant elasticities (Marquez 1994).

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In the context of energy demand, some studies have sought to identify changes in elasticities (Hsing 1990; Goodwin, Dargay, and Hanly 2004; Hughes, Knittel, and Sperling 2008). The recent availability of long-run data sets going back hundreds of years (e.g., Mitchell 1988) has allowed economists to explore the evolution of key economic variables—including those relevant for energy markets (Nordhaus 1996; Fouquet 2011). However, to date, only a few attempts have been made to use such long-run data to identify trends in energy demand elasticities (Fouquet 2012a; Fouquet and Pearson 2012).

This article 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.[1] More specifically, by analyzing the evidence in Fouquet and Pearson (2012) and Fouquet (2012a) and providing new estimates, this article seeks to identify how consumers have responded to changes in income and energy prices and to energy efficiency improvements during different stages of the country's economic development (and in relation to other important variables). This effort is a first step toward answering the two questions posed at the beginning of this article. In addition to helping forecast future trends in energy consumption and carbon dioxide emissions, a deeper understanding of long-run trends in energy service demand may be helpful in the formulation of long-term climate policies.

The next section briefly reviews previous efforts to understand the relationship between economic development and energy demand, and between energy efficiency improvements and energy service demand. This is followed by a brief presentation of the data used in the analysis and a discussion of the long-run trends in energy service consumption and the factors most commonly viewed as determining it: income and energy service prices. The subsequent section presents trends in the income and price elasticities of the demand for energy services and discusses the potential forces that appear to have affected them. The final section summarizes the findings, discusses some of the insights they provide concerning future trends in energy use and carbon dioxide emissions, and identifies some topics for future research.

The Demand for Energy Services

This section reviews the theory and empirical evidence on income and price elasticities related to energy service demand.

Income Elasticities

The demand for energy is driven by the desire for energy *services*, such as space and water heating or cooling, powering of appliances, lighting, and transportation (Goldemberg et al. 1985). Consumer theory states that individuals and households consume goods and services in order to maximize 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 increase their consumption more than proportionately for "luxury" goods and less than proportionately for inelastic normal goods, and they reduce their consumption of "inferior" goods. As incomes and consumption of goods rise further, the marginal utility of consuming

[1]Together these sectors accounted for four-tenths, a quarter, and a half of the United Kingdom's final user energy consumption in 1800, 1900, and 2000, respectively.

a good is assumed to decrease. *Saturation effects* imply that with greater income, consumption of goods will eventually increase only moderately.

Beyond these very basic points, economic theory offers little information about either the size of income elasticities or why they are likely to change (Lewbel 2007). Thus the size of and trends in income elasticities is an empirical question.

Early empirical evidence

Engel (1857) provided the classic evidence on how shares of expenditure and consumption change as incomes rise (among Belgian workmen in the 1850s). Interestingly, however, the share of income spent on fuel and light remained constant (5 percent of the total budget) across the income levels studied (see Chai and Moneta 2010). Looking at the budgets of households in Massachusetts in 1870, Carroll Wright (Bureau of Statistics of Labor 1875, p. 441) also found that the share of the household budget spent on fuel and light was virtually constant (6 percent) 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" (Stigler 1954, p. 99).

British studies in the 1790s found that consumers generally spent about 5 percent of their budgets on fuel (Stigler 1954). However, one study showed that the very poorest rural households (those earning less than £20 per year—or £1,500 in 2000 values) consumed a smaller proportion of their incomes (2.6 percent) on fuel (Davies 1795). Another study (Eden 1797) found that urban consumers spent more than their rural counterparts on fuel (i.e., 5.4 versus 4.4 percent) and that there was even more of a difference across income levels, with the urban poor (earning less than £35 per year—or £2,600 in 2000 values) spending almost 8 percent of their budget on fuel and those earning more than £40 per year spending less than 4 percent. Thus this brief review of early empirical studies hints at the possibility of an inverse-U relationship between income and fuel consumption.

Recent empirical evidence

A number of more recent studies have used cross-sectional data to identify changes in income elasticities. For example, Joyeux and Ripple (2011) estimated that between 1973 and 2008, the income elasticity of total energy demand in developing and industrialized countries was 0.85 and 1.08, respectively; however, the income elasticity of residential electricity demand in developing and industrialized countries was estimated to be substantially lower (0.56 and 0.42, respectively). Medlock and Soligo (2001) and van Benthem and Romani (2009) found that at early stages of development, industrial energy demand grew rapidly but then tapered off; meanwhile, although residential and commercial demand grew more slowly, it continued to grow steadily even at higher levels of economic development. Finally, expansion of demand appeared to start later in the transport sector than in the industrial sector, but it increased more rapidly than in the domestic and commercial sector. Nevertheless, Medlock and Soligo (2001) and van Benthem and Romani (2009) found that energy demand growth rates declined in all sectors at higher levels of economic development. Judson, Schmalensee, and Stoker (1999) found that as per capita gross domestic product (GDP) rose, income elasticities in the industrial sector increased toward one, but then (at about $13,000 in 2010 dollars) fell toward zero. Residential sector income elasticity appeared to be constant at about 0.5 until per capita income reached about $13,000, and then it also dropped toward zero or even became negative.

Income elasticity of energy demand in the transport sector appeared to fall as income levels increased, but only slightly—from 0.75 to 0.50 (Judson et al. 1999).

Implications of the empirical evidence

One interpretation of these empirical results is that, at low levels of economic development, most goods and services are luxuries relative to basic foods. This means that, with the exception of basic foods, as incomes rose, consumption of all goods and services increased more than proportionally. Certain goods and services, such as shelter and cooking, might be seen as urgent needs, and thus as budgets increased, these services were prioritized (Chai and Moneta 2012). With this in mind, one might expect the income elasticities associated with these services to increase first. As mentioned earlier, saturation effects mean that households will demand proportionately less shelter and cooking, as well as fewer basic foods, but more of other goods and services. In principle, even higher income levels would generate new saturation effects, suggesting that consumption of and expenditure on many items previously considered to be "luxury" goods and services would grow less than income (Chai and Moneta 2012). Thus if one examined a period of hundreds of years, one would expect that as an economy developed, there would be a series of waves of income elasticities for different goods and services.

Price Elasticities and the Rebound Effect

Turning to price elasticities, following a decline in prices, energy consumption may increase more than proportionately, less than proportionately, or, in rare cases, even decrease (Deaton and Muellbauer 1980). Price elasticity can be broken down into the income effect, which depends on the service's share of the budget and the income elasticity, and the substitution effect, which depends on the availability of substitutes for the particular good. As with the theory concerning income elasticities, the standard theoretical explanations for the income and substitution effects are limited.

Demand for energy services

Looking more specifically at the demand for energy, Nordhaus (1996) and Fouquet (2011) have shown that, because of efficiency improvements, the cost of consuming one unit of energy service has declined faster than the price of energy in the long run. This implies that energy service consumption and utility rose from a constant level of energy consumption. Thus when examining the long run, during which major energy efficiency improvements are likely, it is important to analyze these relationships in two stages, first the relationship between energy service demands, income, and energy service prices,[2] and then the relationship between delivered energy services, energy efficiencies, and energy consumption. This approach enables us to estimate the price (and income) elasticity of demand for energy services empirically and thus to better understand the trends in energy consumption (Fouquet and Pearson 2012; Toman and Jemelkova 2003).

Moreover, as Fouquet and Pearson (2012) argue, focusing only on energy demand and ignoring efficiency improvements implies an assumption that the price elasticity of demand for energy services is equal to one. This is because a 1 percent efficiency improvement leads to a

[2] If energy prices are mean reverting, consumers may respond less to a price change than to an efficiency change.

1 percent reduction in energy service prices, and, if *energy* consumption remains unchanged following a 1 percent efficiency improvement, then *energy service* consumption must have risen by 1 percent, and this implies that the price elasticity of demand for the energy service must be one. Using the same logic, the assumption that all energy efficiency improvements are translated into equivalent energy savings (i.e., that energy consumption falls by 1 percent, but energy service consumption remains unchanged, as a result of a 1 percent efficiency improvement and 1 percent decline in the energy service price) implies that the price elasticity of demand for energy services is zero.

The rebound effect

There is now a large theoretical literature on the rebound effect that highlights (implicitly or explicitly) the size of the price elasticity of demand for energy services (Howarth 1997; Saunders 1992). The concept (although not the term itself) of the *rebound effect* (i.e., the percentage change in energy consumption in response to a 1 percent improvement in energy efficiency) was first introduced by Jevons (1865) in his classic "The Coal Question": "[I]t 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." However, empirical studies have tended to find rebound effects that are smaller than what Jevons (1865) proposed, with energy consumption declining (all other things held constant), as a result of energy efficiency improvements (Greening, Greene, and Difiglio 2000; Sorrell 2009).

Ayres (2005) proposed that "macro" innovations (i.e., radical innovations like the steam engine) may have led to large rebound effects and thus large increases in energy consumption, whereas more "micro" innovations (i.e., those that improve the efficiency of existing technologies) tended to lead to smaller rebound effects. Fouquet (2008, 277) identified a few historical cases in the United Kingdom where the rebound effects was probably very high,[3] thus providing partial support for Jevons's (1865) hypothesis.

Long-Run Trends in the Consumption of Energy Services

In order to identify trends in the long-run demand for energy services, we need to have data on prices and consumption of heating, transport, and lighting fuels; energy technologies and their efficiencies; and variables such as population and income that help to explain patterns in the consumption of energy services. The main data sources and methods used to assemble the data series are summarized here.[4]

Data Sources

For heating and lighting, consumption (and prices) was calculated by combining energy consumption (and prices) with energy efficiency estimates. For example, in the eighteenth century,

[3]In particular, they focused on freight transport between 1715 and the 1930s, passenger transport from the 1840s to the 1920s, and lighting during the nineteenth century, with Fouquet (2012a) and Fouquet and Pearson (2012) confirming very high rebound effects for the latter two cases.
[4]Details can be found in Fouquet (2008), Fouquet and Pearson (2006), Fouquet (2011, 2012a), and Fouquet and Pearson (2012).

a tonne of coal could be burned in a traditional fireplace, generating around 10 percent of a tonne of coal's useful heat (Fouquet 2008). Using this information and the price of one tonne of coal (£145 in 2000 values), the price of one tonne of coal equivalent of useful heat (or of "effective heating") was estimated (about £1,450). A similar process was used for lighting, which was measured in lumen-hours. Then, using the efficiency estimates in Nordhaus (1996) for lighting and Billington (1982) for heating and simple technological diffusion models (Fouquet 2008), time series for average lighting efficiency were assembled. Next, the implicit price or consumption of the service using a particular technology was calculated and averaged (by taking expenditure weights for individual source-technology mixes). To calculate trends in the consumption of transport, we used data on kilometers traveled and prices per kilometer (see Fouquet 2012a for details).

Throughout the discussion that follows, prices are quoted in *real terms* (i.e., in pounds in year 2000 values). The retail price index is from the data used in Allen (2007) and then updated using Office of National Statistics (ONS 2012) data. This means that the costs of using different fuels and producing services are broadly comparable across time.

Based on these data sources and methods, the remainder of this section presents and discusses general and sector-specific trends in the consumption of energy services between 1700 and 2000, which are used to estimate elasticities in the next section.

General Trends in the Consumption of Energy Services

The consumption of energy services in the United Kingdom has risen dramatically over the last three hundred years (see Figure 1). More specifically, since 1700, there has been a 120-fold increase in power provision for industrial purposes, a 250-fold increase in freight transport (on land and on the sea), a 220-fold increase in household consumption of energy services for effective heating, a 48,000-fold increase in land passenger travel, and a 295,000-fold increase in lighting consumption.

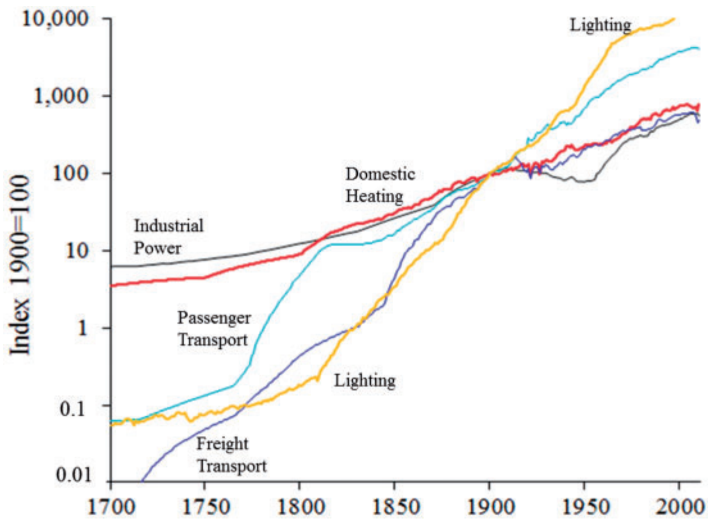

Figure 1 Consumption of energy services in the United Kingdom (Index 1900 = 100), 1700–2010
Source: Fouquet (2008); see online Supplemental material.

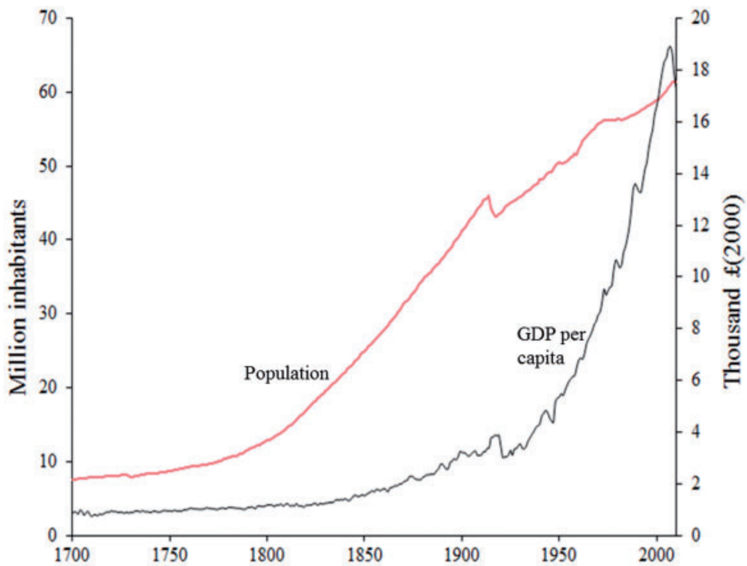

Figure 2 Gross domestic product (GDP) per capita, in real terms (2000 values), and population in the United Kingdom, 1700–2010
Source: Broadberry et al (2011); ONS (2012); see online Supplemental material.

Figure 2 presents trends in GDP per capita and population over the same time period. Both GDP and population grew relatively gradually in the eighteenth century. In the nineteenth century, population grew rapidly and, especially from the 1830s onward, per capita income also increased (nearly tripling in the nineteenth century). Following World War I, the trends were reversed, with slower population growth and spectacular growth in average income (i.e., there was more than a fivefold increase in per capita income during the twentieth century).

Trends in the Growth of Domestic Heating Use

As shown in Figure 3, the price of domestic heating declined from 1700 until the 1920s, due mostly to the transition from wood fuel to coal, which was about half as expensive per unit of energy (Fouquet 2011). Moreover, adoption of the Rumford fireplace doubled the average efficiency of domestic heating during the nineteenth century (Crowley 2004). During the nineteenth century, consumption of effective heating increased eleven-fold.

Beginning in the 1920s, upper-class households (and eventually middle-class households) started to use gas and then, in the 1930s, electricity for cooking and heating (Bowden 1988; Goodall 1999). Although more efficient than coal for cooking and heating, gas and electricity were eight and forty times, respectively, more expensive than coal (per unit of energy) in the 1930s (Fouquet 2011). This suggests that wealthier households were willing to pay for the more expensive but more modern and cleaner cookers and heaters, as consumption of effective heating more than doubled between 1900 and 1950.

However, it was the Clean Air Act of 1956, which followed the 1952 Big Smog (when an estimated twelve thousand additional deaths were caused by air pollution), that required 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, electricity was still five

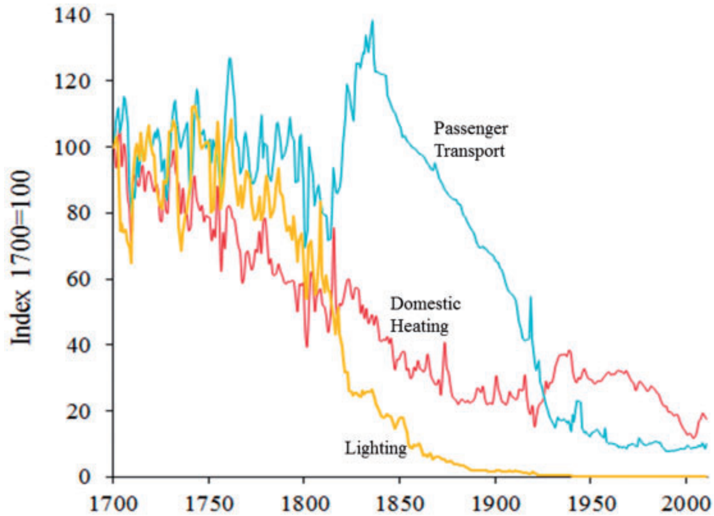

Figure 3 Prices of consumer energy services in the United Kingdom (Index 1700 = 100), in real terms (2000 values), 1700–2010
Source: Fouquet (2011); see online Supplemental material.

times more expensive than coal (per unit of energy), and the price of natural gas was double the price of coal. So this environmental policy did drive up effective heating prices. However, beginning in the 1960s, central heating systems transformed the nature of domestic heating from simply providing a source of warmth to creating a controlled indoor climate (Billington 1982). Thus, as a result of much cheaper effective heating and higher income levels, as well as better heating services, consumption of effective heating more than tripled between 1950 and 2000, and has continued to increase.

Trends in the Growth of Passenger Transport Services

As shown in Figure 3, passenger transport prices declined in the eighteenth century, following improvements in road quality, associated with the expansion of turnpikes (Pawson 1977). Beginning in the 1770s, stagecoach journeys became better managed and faster, and, by 1830 average trips were five times faster than in the 1770s (Bagwell 1974). Thus 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). There was a sharp increase in transport prices in the 1820s and 1830s. This was probably because stagecoach companies on routes not yet served by trains raised their prices in order to recover as much of their investments as possible before the railways arrived (Hart 1960).

Railways transformed transport services in the nineteenth century. Although initially inefficient, locomotives improved dramatically in the 1850s and 1860s, and as a result, transport prices fell rapidly (see Figure 3). The railway network offered faster and cheaper travel, and, by 1860, railways dominated passenger transport services. Transportation consumption soared in the 1880s as the government pressured railway companies to provide cheap services for third-class customers (Leunig 2006). Thus passenger transport rose sixfold between 1850 and 1900 when it reached 27 bpk.

The internal combustion engine radically changed transport services in the twentieth century. First, the bus provided public transport to rural areas not connected to the railway network. Then, 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, fuel efficiency improved, and car use soared, becoming the dominant mode of transport by 1950 (Bagwell 1974). By 2000 cars accounted for approximately 600 bpk per year, and land passenger travel had increased thirty-five times during the twentieth century.

The introduction of the jet engine enabled faster, larger, and more comfortable plane travel at declining prices. Rising incomes, more annual vacations, and tour operators promoting exotic destinations created a new mass demand for leisure travel. In 1950 air travel accounted for 1.2 bpk, but it grew rapidly, reaching 60 bpk in 1975 and 250 bpk in 2000, a 200-fold increase in fifty years. Thus driven by declining prices and rising income, as well as the changing nature of transport services, each person in 2000 traveled on average 17,200 km per year, compared with only 110 km (excluding walking) in 1800—a 165-fold increase

Trends in the Growth of Lighting

Historically, tallow candles (made from animal fats) and the domestic fire were the main sources of illumination, but beginning in the 1810s, gas lamps revolutionized lighting. In the 1820s, town gas (made from coal) was 50 percent more expensive (per unit of energy) than tallow candles, but gas lighting technology was twice as efficient. By 1850 the price of town gas was half the price of tallow candles (per unit of energy) (Fouquet 2011) and had become the dominant source of lighting. However, the high costs of pipe installation prohibited many households from adopting gas lighting. In the 1890s, gas companies began installing pipes and prepayment meters, which enabled poorer households to adopt gas lighting. At about the same time, the Welsbach gas mantle was introduced that provided major efficiency improvements (Falkus 1967). Overall, there was a 570-fold increase in lighting consumption during the nineteenth century.

Around 1900 electricity began to replace town gas (and kerosene). At first, electric lighting was more expensive overall, as it was twenty-five times more expensive per unit of energy than gas, but only seven times more efficient (Fouquet 2011). Nevertheless, electric lighting was used in luxury homes, restaurants, and theaters, where its novelty was highly valued (Schivelbusch 1988). By 1930 electricity was five times as expensive as gas, but electric lighting had become ten times more efficient, so many consumers had begun to switch to electricity. Total lighting consumption increased from 10 trillion lumen-hours in 1900 (80 percent provided by gas) to 150 trillion lumen-hours in 1950 (more than 95 percent generated from electricity). Beginning in 1950, lighting consumption grew more moderately, until the introduction of compact fluorescent technology in the 1990s, which drove down the price of lighting further. In 2000, 1,200 trillion lumen-hours were consumed, increasing to more than 1,800 trillion by 2010—nearly a 20,000-fold increase in consumption per person since 1800.

Summary of Trends

To summarize the trends in the consumption of energy services, Table 1 presents fifty-year growth rates for actual and expected heating, land transport, and lighting consumption, where

Table 1 Actual and "Expected"* Growth Rates in the Consumption of Domestic Heating, Land Passenger Transport, and Lighting Services 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

*"Expected" growth rates are based on unit income and price elasticities.
Source: See online supplemental material.

expected growth rates are based on the assumption that income and price elasticities were equal to one (in absolute terms). Actual growth rates that are greater than the expected value indicate a high income and/or price elasticity, and they are presented in bold. Table 1 suggests that heating demand was elastic between 1800 and 1850, transport demand was elastic between 1750 and 1900, and lighting demand was elastic between 1800 and 1900. To investigate these elasticities in more detail and to identify the specific impacts of income and prices on consumption requires the use econometric methods.

Analyzing the Changing Demand for Energy Services

As discussed earlier, consumers use energy services to maximize their utility subject to budget constraints and the existing prices of energy services. To examine in more detail how the relationships between the demand for energy services, economic activity, and the prices of energy services have changed over time, we need to use econometric methods. While the discussion in this article focuses on the results of the analysis rather than the details of the data and the methodology, which are presented in detail in Fouquet and Pearson (2012) and Fouquet (2012a), this section briefly outlines the method used to estimate trends in elasticities.

Identification of the Demand Curves

One challenge to econometric estimation of the demand for energy services is the identification problem.[5] That is, when using combinations of annual price and quantity data that represent the equilibrium of demand and supply, it is often difficult to determine whether fluctuations in the equilibria are due exclusively to shifts in the supply curve (in which case the demand curve can be identified) or are also due to shifts in the demand curve (in which case, the demand curve cannot be identified directly).

Fortunately for the analysis here, it is unlikely that the prices of heating, passenger transport, and lighting services were affected by shifts in their respective demand curves because the price of the individual energy services was a function of the price of energy and the efficiency of the relevant technology. The energy price (whether for coal, oil, or natural gas) was determined by

[5]I am grateful to Lutz Kilian and an anonymous referee for highlighting this potential problem, and appreciate comments from David Stern and Lester Hunt on the exogeneity of variables.

the interaction of the national (and, in some cases, the international) demand for and supply of these energy sources. In any case, the impact of the individual demands for heating, transport, and lighting on GDP are likely to have been very modest. To illustrate, in 1900 the coal consumption associated with domestic heating, passenger transport, and lighting was only a tenth, a fortieth, and a fiftieth, respectively, of national coal production, and at no point in the period under study did any of these services account for more than a third of the consumption of the relevant aggregate primary energy production (Fouquet 2008). In other words, energy prices were unlikely to be the result of separate shifts in the demands for domestic heating, passenger transport, and lighting.

Similarly, it is unlikely that the efficiency of the individual heating, transport, and lighting technologies was directly determined by the demand for these services. Therefore, it can be assumed that fluctuations in the prices of the energy services were exogenous to the individual demand curves and the result of shifts in the supply curve, thus enabling us to identify the demand curves for heating, passenger transport, and lighting.

Estimating the Relationships

The first step in the econometric analysis was to examine the time series properties of the data and whether they are nonstationary.[6] Using a number of standard and more advanced tests, we could not reject nonstationarity[7] for GDP per capita and the prices and consumption of individual energy services (Stata 2007, 365). Thus we concluded that the variables were nonstationary. Because the variables of interest were nonstationary and because long-run energy consumption, GDP per capita, and energy prices are often cointegrated (and, therefore, their movement is closely related through time [Fouquet et al. 1997; Stern 2000]), we used a model (in particular, a vector error-correcting model) that provides an estimate of their long-run relationship.

Second, the direction of causality in their relationship was analyzed (Kraft and Kraft 1978; Joyeux and Ripple 2011; Stern 2000). Toman and Jemelkova (2003) formalized the potential causal effects of energy service use on GDP, and GDP on 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 translate into higher levels of GDP. However, the focus here is specifically on energy service use for consumption activities, such as domestic heating, passenger transport, and lighting that (as mentioned earlier) are less likely to affect GDP. In addition, each energy service's share of total consumer expenditure was rarely more than 8 percent and often closer to 2 percent. The causal relationship was examined for the tests run (Stata 2007, 367), and the results confirmed that for the entire study period, the causality was only running from per capita GDP to energy service consumption. Thus the analysis supports the use of a model that estimates the unidirectional influence of GDP (and prices) on energy service consumption.

[6]Nonstationary series do not tend to revert to an average value. Rather they tend to drift through time as a result of shocks with a long-run effect. It is important to identify whether nonstationary series are cointegrated with other series (i.e., the series drift together) or their apparently joint drifts are merely a statistical coincidence (Bannerjee et al. 1993).

[7]Each statistical test was performed about 180 times for heating, 160 times for transport, and 210 times for lighting (roughly, once for each year used). Readers who would like details of the thousand-plus tables generated to produce these tests and estimates are encouraged to contact the author directly.

To estimate the trends in income and price elasticities, we followed the method developed by Fouquet and Pearson (2012) that estimated 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, 1831–1880, and so on, until 1961–2010. This means that the elasticity for any particular year would be the moving average (i.e., the average of all elasticities estimated that included that year). Thus for the moving average around the year 1950, fifty estimated income elasticities of demand for domestic heating were produced (for the periods 1901–1950, 1902–1951, and so on, until 1950–2000). The average of all of these estimates was 0.60. The average price elasticity of heating demand was estimated in the same way, and around 1950 it was −0.25.

Inevitably, the results for some periods were not what was expected (e.g., some elasticity estimates were very large or positive). For example, for regressions starting between 1880 and 1920, the results generally produced positive price elasticities for domestic heating. For transport demand, the only price elasticities that were inconsistent with expectations (i.e., positive) were those before 1870. Similarly, for lighting demand, a few income elasticity estimates around 1860 were very large. These inconsistent results were dropped from the analysis.[8] This means 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 only modest annual changes. In fact, for the nearly two hundred year period, the majority of estimates produced standard signs and sizes (statistically significant at the 99 percent level)—and we were able to use the income elasticity estimates for 80, 97, and 84 percent of the moving averages for heating, transport, and lighting, respectively, and 63, 93, and 99 percent of the moving averages (respectively) for the price elasticity estimates.

Trends in Elasticities

Based on the data and methods discussed in the previous two sections, this section presents estimates of the income and price elasticities of demand for energy services in the United Kingdom over the last two hundred years.[9]

Trends in Income Elasticities

The estimated elasticities resulting from the analysis are generally consistent with the expectations based on basic theory. For instance, income elasticities for energy services appear to have generally followed an inverse U-shape curve, rising at early phases of economic development, reaching a peak, and then declining (see Figure 4). 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, at first, a rapid decline, then a more gradual decline. Income elasticities took almost

[8] The large majority of these dropped values were statistically insignificant. Although dropping these results was not ideal, including them was likely to alter the estimates and detract from the general trends.
[9] Note that although the previous section discussed trends over the last three hundred years, the analysis in this section covers the last two hundred years because the necessary annual data (i.e., noninterpolated) are available only from the early nineteenth century forward.

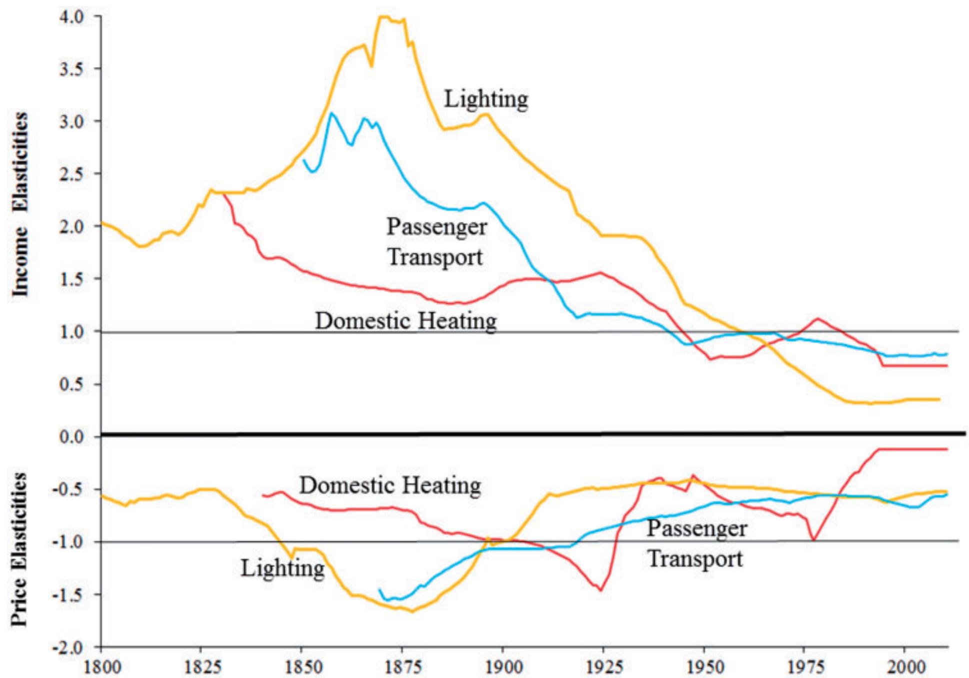

Figure 4 Income and price elasticities of demand for energy services, 1800–2010*
*The estimates of lighting demand elasticities in Fouquet and Pearson (2012) were slightly affected by inaccuracies in the GDP per capita time series between 1850 and 1930. Thus new estimates were produced for this article. I am grateful to Paul Warde for identifying this problem.
Note: See Supplemental data for 95% confidence intervals around trends.
Source: Fouquet (2012a); author's own estimate; see online Supplemental material.

100 years to reach unity (in the mid-twentieth century). The results also indicate that income elasticities are significantly different from zero at high levels of per capita income in the twenty-first century.[10,11]

Examining the trends in income elasticities for individual energy services, the peak was earliest for heating,[12] followed by transport and then lighting. This could imply that basic energy services, such as cooking and heating, were prioritized over transport and lighting in a poor household's basket of goods and services. In fact, when income elasticity for transport was peaking in the 1860s and 1870s, the income elasticity for heating was heading toward unity. Moreover, unit income elasticity was broadly reached in the same order (i.e., heating, transport,

[10]The estimates for the twenty-first century are similar to cross-sectional evidence (Joyeux and Ripple 2011; Judson et al. 1999).
[11]The estimates of lighting demand elasticities in Fouquet and Pearson (2012) were slightly affected by inaccuracies in the GDP per capita time series between 1850 and 1930. Thus new estimates were produced for this article. I am grateful to Paul Warde for identifying this problem.
[12]Although the exact timing of the peak for heating cannot be determined because the annual data on domestic coal consumption are interpolated for certain years before 1830, it was probably not much before 1830. Elasticities seem to have been lower in the eighteenth century (see Table 1).

lighting),[13] lending further support to the idea that a form of "prioritization of needs" was present.

Finally, the peak for lighting was substantially higher than for transport (which was higher than for heating). This may reflect the fact that the costs to the consumer (e.g., the budget share required for a particular energy service) were lowest for lighting. However, more research is needed to confirm this hypothesis.

Saturation Effects

Figure 4 also indicates a decline (in absolute terms) in income and price elasticities over time and, by implication, at higher levels of income. As mentioned earlier, saturation effects imply that beyond a certain level of consumption, as incomes rose, a declining share of the budget was dedicated to certain energy services—and thus income elasticities for those energy services fell. Lighting demand most clearly follows this trend, with income elasticities continuing to fall below unity (to between 0.2 and 0.3) in the last quarter of the twentieth century. Income elasticities for heating demand fell to about 0.5 in the second quarter of the twentieth century. However, they rose again from the midcentury, suggesting another explanation (discussed later). Similarly, passenger transport demand showed signs of saturation in the second quarter of the twentieth century as income elasticities fell close to unity, but they were then forced upward as car use increased. Thus the results indicate saturation effects, although as discussed later, other factors also appear to have affected the demand for energy services.

Relationship between Income and Price Elasticities

Another important result is the evidence of a close relationship between income and price elasticities for particular energy services (see Figure 4). The declines and peaks in income elasticities, such as in the 1870s for lighting and in 1925 and 1975 for heating, are mirrored by the price elasticities for these services. This should not be surprising since price elasticities are partially determined by income effects, and thus higher income elasticities feed through into price elasticities.

However, the role of income effects in determining price elasticities is muted because energy services accounted for only a small share of consumer expenditure. In fact, around 1910, when they accounted for the largest share of total consumer expenditure, the three services together accounted for slightly more than 10 percent of average income.

The substitution effect has likely been relatively small because there have been few alternatives for heating, transport, and lighting services. Nevertheless, price elasticities were still relatively high (in absolute terms) during the second half of the nineteenth century, reaching unity (for transport[14] and lighting) around 1900 and then falling (in absolute terms) to −0.5 around 1950. Domestic heating price elasticities were generally lower than transport and lighting elasticities, apart from a couple of peaks (in absolute terms), but generally followed the same pattern. Thus price elasticities followed a U-shape curve as the economy developed (see Figure 4).

[13]However, as discussed later, heating income elasticities rose again in the 1890s.
[14]The estimates for transport elasticities are a little higher than recent estimates, such as Small and van Dender (2007), which focused only on car travel rather than total aggregate transport (which includes substitution between modes).

Rebound Effects

The trends in price elasticities also provide insights concerning rebound effects. As mentioned earlier, Jevons (1865) argued that energy consumption actually increased following efficiency improvements. The evidence here (i.e., price elasticities below −1.0 in Figure 4) suggests that between 1850 and 1900 (the time period during which Jevons was writing), the rebound effects did cause energy consumption related to transport and lighting to increase. For a brief period around 1925, heating also demonstrated a "Jevons paradox." With these exceptions, the results here suggest that efficiency improvements have led to net energy savings (all other things being equal). However, because the price elasticity of energy service demand has been estimated to be significantly different from zero over the last two centuries, rebound effects appear to be a pervasive feature of energy behavior and should be incorporated into forecasts of energy consumption.

Some Key Factors Affecting Trends in Elasticities

Although the prioritization of needs and saturation effects appear to be responsible for the general trends in the demand for energy services, what drove the specific changes in income and price elasticities? As shown in Figure 3, from the early nineteenth century to the early twentieth century, energy service prices fell dramatically, and then starting in the mid-twentieth century, per capita income grew rapidly (see Figure 2). This suggests that income elasticities first fell with falling energy service prices and then (from the 1930s onward) fell with rising income levels. However, there is clearly a need to further investigate the factors affecting trends in elasticities. Thus this section discusses the factors pushing income elasticities upward, such as latent demand, as well as changes in lifestyles and in the characteristics of energy sources and technologies.

Meeting a Latent Demand

First, 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. Beginning in the 1650s, wealthy consumers gradually sought improvements in the quality of their food and household goods and in their domestic levels of comfort (Crowley 2004). As income levels gradually rose, more households were able to join in this "consumer revolution" (Trentmann 2012). From the mid-eighteenth century onward, the lower classes were willing to spend more time working to acquire these goods, leading to the "industrious revolution" (De Vries 1994). Thus by the nineteenth century, when many of the technological innovations were occurring, consumers had already met a number of those other domestic wants and were ready to greatly increase their demands for heating, transport, and lighting.

The trends in Figures 2, 3, and 4 suggest the following hypothesis about consumer attitudes and behavior regarding energy services: When incomes were low and energy services were very expensive, consumers could dedicate only a small share of their budgets to these services; when radically more efficient technologies were introduced, some consumers (particularly the wealthy) were willing to adopt the new technologies and increase their consumption; less wealthy households observed the early adopters' behavior and desired these new levels of

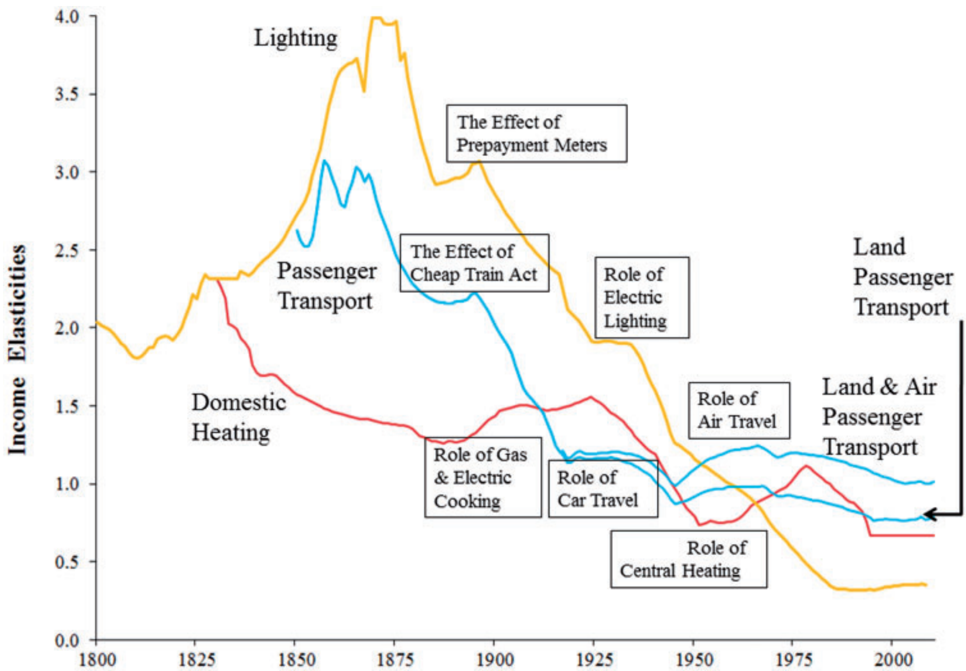

Figure 5 The impact of energy and technology transitions on income elasticities of demand for energy services, 1800–2010
Source: Fouquet (2012a); author's own estimate; see online Supplemental material.

consumption, and with modest increases in income, they were willing to greatly increase their demand and consumption.

Transforming Lives

Once this latent demand was met during the nineteenth century, greater consumption of energy services transformed people's lives. Figure 5 tries to identify these transformative phases through the trajectory of trends in income elasticities of demand for energy services. For example, prior to the nineteenth century, most households used the heat generated from cooking to provide space heating (Crowley 2004). The lower heating costs of the Rumford fireplace meant that even poorer households could separate their cooking and space heating services (Davidson 1986), which caused dramatic changes in the design of houses (i.e., with more, smaller rooms) and how families and friends interacted (Crowley 2004).

In addition, starting in the 1840s, many upper- and upper middle-class households sought to move away from the crime, sewage, and smoke of the cities. The expansion of urban railway networks made it possible for them to move to the suburbs, with the wealthy moving away first, followed by the upper middle class, and then the lower middle class. Income was the key to escaping the disamenities of the city, and as more people reached higher income levels, they moved to the suburbs and traveled more. 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 to the city (Jackson 2003). Figure 5 shows a second peak in income elasticities around 1900, which may well be associated with the rising demand for energy services from this lower income population.

As shown in Figure 5, income elasticities for lighting also experienced a second peak (around 1910); this was likely due to the introduction of prepayment meters, which allowed poorer consumers to use gas lighting, as well as the much more efficient Welsbach mantle. These lighting improvements transformed people's lives. As discussed in Fouquet and Pearson (2012), cheaper gas and kerosene lighting was an "enabler" of or complement to other goods and services. Activities such as working, socializing, and education all became much easier to undertake (or cheaper to "produce") at night. The expansion of street lighting also promoted urbanization and reduced urban crime. Interestingly, lighting improvements also changed sleeping behavior. Prior to the growth in lighting use, the long nights were often broken up into two periods of sleep; however, as the day was lengthened, at it were, work, socializing, or education replaced sleeping, which became more concentrated (Koslofsky 2011).

The Demand for New Attributes of Energy Sources and Technologies

The previous discussion focused on explaining variations in the peaks in income elasticity trends. This subsection discusses how the introduction of new attributes affected the demand for energy services. This is particularly relevant for explaining certain second (and subsequent) peaks or plateaus displayed in Figure 5.

Attributes are characteristics or features of a product (including energy sources and technologies) that consumers might value. For example, wood fuel is far less dense than coal or kerosene (which affects the costs of transportation and storage of the fuel); dung is not hygienic; coal is far dirtier than gas; and electricity is the easiest to use (and quite flexible) but cannot be stored easily, which restricts its mobility. This suggests that household energy and energy service consumption patterns may, in part, be a reflection of their *preferences* for certain attributes or characteristics of energy sources or technologies, such as energy density, ease of storage and use, health effects, cleanliness, and flexibility and mobility of the energy source. These different preferences help to explain the "energy ladder" whereby, as consumers' incomes rise, they shift from using biomass fuels to coal and then from coal to oil, gas, and electricity (Barnes and Floor 1986; Sovacool 2011). More generally, transitions to new energy sources and technologies are often associated with new attributes (Fouquet 2010).

Indeed, Figure 5 indicates a number of increases or plateaus in income elasticity trends that coincide with energy and technological transitions that provided new attributes to the consumer. For example, between the 1890s and the 1930s, there was a rapid growth in the adoption of more expensive to use but cleaner gas cookers (Goodall 1999). This might be the cause of the rise in income (and price) elasticities for domestic heating over that period (see Figure 5). Similarly, starting in the 1960s, there was a clear rise in domestic heating income elasticities that coincides with the growth in gas heating and then the growth of central heating in the 1970s, which transformed households' abilities to control their indoor climates (Billington 1982).

Another example of consumers valuing attributes concerns passenger transport. Stagecoach journeys were generally uncomfortable experiences. Passengers were squeezed together, and arrivals depended on weather conditions. Trains made journeys faster and more reliable (Leunig 2006). Similarly, the introduction of cars offered passengers greater travel flexibility and privacy (O'Connell 1998). In the 1920s and 1930s, the decline in income elasticities related to the demand for land transport halted (see Figure 5), suggesting that passengers placed a high value on flexibility and privacy. More recently, the high speed of air travel means that intercontinental travel takes only a few hours, and its effect on demand is illustrated by the divergence in the trends for land transport and total (i.e., land and air) transport shown in Figure 5.

In the lighting market, tallow candles were made from foul-smelling animal fat (the smell of mutton fat was preferred), prone to generate excessive heat (when overconcentrated), and caused fires. Although not odorless, gas lighting was a great improvement, providing more concentrated lighting safely (Schivelbusch 1988). Electricity made lighting far easier and cleaner, and it probably explains the plateau in income elasticities during the 1920s and 1930s (see Figure 5).

Most recently, the environmental effects of fuels are viewed as an important attribute of energy services. In particular, the climate impact is seen as a negative attribute. If a sufficiently large demand to avoid this attribute develops, there may be a reverse effect on elasticities—that is, an energy and technological transition may push the income elasticity of demand for energy services downward.

Summary and Conclusions

This article has presented evidence on trends in the income and price elasticities of demand for energy services in the United Kingdom between the early nineteenth and early twenty-first centuries. The evidence indicates that as the economy developed and energy service prices fell, income elasticities followed an inverse U-shaped curve and price elasticities followed a U-shaped curve (see Figure 4).

This generalized pattern of a rise, a peak, and, in particular, a decline (first rapid, then gradual) in income elasticities is consistent with the theory concerning declining marginal utility and saturation effects associated with consumption. However, numerous factors appear to have affected the trajectory of price and income elasticities. The first factor is the transformative effect of consuming higher levels of energy services, which likely influenced the size of the peaks in elasticities. This is especially true for transport and lighting. Another important factor (particularly for the second peaks in elasticities) was the entry into the energy services market of another (generally, poorer) segment of the population (see Figure 5).

Third, some energy and technological transitions provided new or additional attributes valued by consumers (e.g., ease of use, flexibility, cleanliness, speed of service, privacy, health and environmental effects) that affected the quality of the energy services and appear to have altered the trend in elasticity estimates and delayed their decline.

One limitation of this study is the inevitable difficulty of controlling for changing omitted variables over such long periods of time. One could also question the reliability of historical data or the validity of the econometric procedures. Nevertheless, the econometric estimates (and their associated confidence intervals) presented here are broadly consistent with theoretical expectations, prior empirical evidence, and the data itself. It is hoped that the reader will find that the benefits gained from this historical perspective outweigh the limitations of the data and analysis.

The analysis and evidence presented here offers some useful lessons concerning likely future trends in energy use and carbon dioxide emissions, particularly in developing countries.

This information may also be helpful for designing long-term climate policies. The first lesson concerns the timing of the peak for income elasticities of demand for energy services. If developing countries such as China and India were to follow a trend similar to the United Kingdom, then their elasticities of demand would peak between \$4,000 and \$7,000, and fall below unity around \$12,000.[15] In this case, energy service and energy consumption in these countries would continue to increase at a faster rate than GDP per capita for many more years (see, e.g., Wolfram, Shelef, and Gertler 2012).

A second lesson is that, if any future energy or technological transitions unfold, they may delay the decline in income elasticities. Any delay will probably be stronger the more valuable the additional attributes provided—and, historically, markets have been remarkably effective at delivering new attributes (see Figure 5). 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.

Another lesson (from the trends in price elasticities) is that efficiency improvements have, over the last two hundred years, been associated with rebound effects. In particular, the large rebound effects in the United Kingdom prior to 1900 (until per capita GDP reached \$9,000 [in 2010 US dollars]), imply that energy efficiency improvements led to increases in energy consumption. This suggests a limited potential for using energy efficiency measures to reduce carbon dioxide emissions, especially if price elasticities of demand for energy services in developing countries follow a trajectory similar to the trajectory in the United Kingdom.

However, because today's developing economies have access to cheaper energy services (relative to what the United Kingdom faced when it had a similar income level), they may experience smoother trends in elasticities (i.e., smaller and earlier peaks). This means that compared to the historical experience in the United Kingdom, these economies may (at their elasticity peaks) experience smaller increases in energy consumption due to rising incomes and declining energy service prices; however, the period during which consumption increases at a faster rate than GDP per capita may be longer.

Given the uncertainty about the extent to which today's developing economies will follow the path of current developed economies, future research in this area should focus on advancing a more theoretical analysis of how elasticities change through time. This would help provide a bridge between past and future trends in elasticities. Another area for future research, building on Nordhaus (1996) and Gordon and Griliches (1997), would be to estimate the impact of different attributes on consumption patterns, and to control for these changes to improve the elasticity estimates.

In conclusion, while the global economy's appetite for energy may not be insatiable, it is probably still far from being satiated. The evidence presented here suggests that at least for the next few decades, market forces and the long-run trends associated with population and economic growth, price and income elasticities, and energy transitions are likely to push global energy service demand and energy consumption upward, especially in developing economies. Given the slow speed at which a full low-carbon energy transition is likely to unfold (Fouquet 2012b), this also implies rising carbon dioxide emissions, and hence rising greenhouse gas concentrations and an acceleration of the process of climate change.

[15]These values are expressed in 2010 U.S. dollars.

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