Divergences in Long-Run Trends in the Prices of Energy and Energy Services

Roger Fouquet*

Introduction

Rapidly rising energy prices in the first decade of the twenty-first century have led many economists to examine related long-run trends (Maugeri 2009). After all, the oil shocks of the 1970s left a scar on the global economy by constraining growth for more than a decade and creating major structural changes (Hamilton 2011). Looking further back, the ability to meet the energy needs of a growing population and economy without raising long-run prices has been central to improving human well-being since the Industrial Revolution (Allen 2009).

A long line of economists have tried to understand the interaction between the demand for and the supply of resources and to anticipate their prices in the long run. Malthus's (1798) predictions—which many cite when referring to economics as the "dismal science"—and later, Ricardo's (1817) analysis, suggested that as population grew, diminishing returns would set in, demand would outstrip supply, and renewable resources would become increasingly scarce. Nonrenewable resource theory has offered similarly "dismal" prospects since prices were expected to rise through time (Hotelling 1931). However, ever since the publication of the influential book, *Scarcity and Growth* by Barnett and Morse (1963), economists have generally been able to present a less gloomy message: although energy and resource prices may rise in the future, the empirical evidence does not indicate a long-run trend of increasing prices in the past.

The message from economists became even more upbeat following the publication of Nordhaus' (1996) study on lighting, which took account of technological improvements. He pointed out that using energy prices rather than energy service prices dramatically underestimated the decline in the cost of lighting and the ensuing welfare gains to consumers over the past two hundred years.

The Nordhaus study provided concrete evidence of an issue that had been identified but not properly estimated: that energy consumption was driven by the desire for energy services,

*Basque Centre for Climate Change (BC3), Alameda Urquijo 4 - 4°, 48008 Bilbao, Spain and IKERBASQUE (Basque Foundation for Science), Spain; e-mail: roger.fouquet@bc3research.org.

I am grateful to Charlie Kolstad, Suzy Leonard, Tanya O' Garra, Mikel González-Eguino, and two referees for helpful comments.

Review of Environmental Economics and Policy, volume 5, issue 2, summer 2011, pp. 196–218
doi:10.1093/reep/rer008
Advance Access publication on July 27, 2011

such as space and water heating, powering of appliances and lights, and transportation (Goldemberg *et al.* 1985). To provide these services, it is necessary to combine energy with the appropriate technology, be it a hammer with muscular strength, a harness with horse power, sails with the wind, or a train with steam, diesel, or electricity. When the efficiency of the technology improves, the price of the service falls, even if the price of the energy itself remains unchanged (Howarth 1997; Haas, Nakicenovic, and Ajanovic 2008). While, in the short run, the differences between the prices of energy and energy services may be minor, over several decades, a century, or more, the divergences can be very large.

Fouquet (2008) offered more comprehensive evidence on the importance of energy services by estimating long-run trends in the prices and consumption of heating, power, transport, and lighting. The study did not, however, explicitly discuss whether the problem of focusing on energy prices (rather than energy *service* prices) applies to all energy services. The purpose of this article is to explicitly address this issue by comparing long-run trends in energy prices and energy service prices from the fourteenth century to the present day in what was to become the United Kingdom and examining the tendencies of these prices to diverge. Thus, this article extends the analysis in Nordhaus (1996) to all main energy services in order to determine whether the problem of underestimating the long-run decline in energy prices is a general problem rather than one that is specific to lighting.

This article is a contribution to the literature that values and relies on historical evidence and long-run trends for economic analysis and understanding (see Nunn [2009] for a broad review). In the eyes of many economists, the 1970s oil shocks created a structural break that implied that prior evidence or trends were irrelevant to current energy markets. Yet, past experiences of resource scarcity and abundance, market concentration and competition, or energy transitions are likely to exhibit commonalities that offer lessons for the future. Similarly, studying long-run trends in energy prices (or other economic variables) that reach back before the 1970s can help to identify behavioral patterns over waves of economic and technological development (or over a set of structural breaks), something that is not possible when using shorter run evidence. The point here is that to focus only on the experiences and trends in the last few decades is to ignore a great deal of information that can be helpful to understanding future energy markets, conducting research on climate change, and informing policy advice. For instance, the insights offered by historical evidence lead this article to conclude that when trying to understand and anticipate long-run trends in energy use and forecast carbon dioxide emissions, energy prices and consumption are not the most appropriate variables to use to reflect consumer decisions—the prices of energy services should be used instead.

The next section presents theoretical expectations and empirical findings about trends in energy prices. The following section discusses the sources for the data on the United Kingdom and briefly explains the methodology for estimating energy service prices. The subsequent sections present trends in the prices of heating fuels and heating, other energy services, and "average" energy. These findings provide the context for a brief comment on past and future long-run trends in energy prices. The final section summarizes the findings, reflects on the implications of divergent trends in energy and energy service prices, and provides some suggestions for future theoretical, empirical, and policy analyses.

The Price Signal: Theoretical Expectations and Empirical Findings

Trends in prices generally reflect changing value or scarcity. It is helpful to briefly examine how energy prices might be expected to trend over time, not to delve deeply into the theory of resource extraction but rather to build a bridge between the theory and empirical evidence on price trend determination. Three cases are particularly useful to consider: unlimited resources, renewable resources, and nonrenewable resources.

Unlimited Resources

The first case is the one in which resources are effectively unlimited—either because production is very small relative to the size of the resource base or producers do not perceive their resources to be finite. The individual producer's decision, which does not consider intertemporal extraction problems, is to increase production until marginal costs equal the price—the standard profit maximization decision in a perfectly competitive market. In the long run, the price that the producer faces will tend to stabilize at the lowest long-run average cost, because firms will enter the market if the price rises any further, thus increasing supply (Varian 1992).

In a growing economy, demand will tend to rise over time. The change in price will be a function of the ratio of the change in demand to the change in supply. With effectively unlimited resources, capital, and labor, increases in demand will eventually be met by an expanding supply, and prices would not be expected to rise in the long run.

Improvements in production processes may drive down production costs, causing prices to fall to the new lowest long-run average cost. Consumption may increase in response to the declining pressure on prices, but unless demand is perfectly elastic, prices will fall. A more long-term downward pressure on demand could be driven by improvements in the efficiency of consumption. Working against this pressure would be possible rebound effects and general economic growth, as well as supply adjustments. Nevertheless, in the case of perfectly elastic production and an effectively unlimited supply of resources, prices might be expected to fluctuate around a series of downward steps.

Limited Renewable and Nonrenewable Resources

If resources are limited and renewable, producers will tend to extract resources to ensure that the rate of growth in the production of the resource is equivalent to the discount rate—the opportunity cost of not harvesting and selling resources. In a growing economy, it would be expected that demand would eventually reach the limit at which resources can be renewed and profitably harvested. Then, as demand continues to grow, increases in the resource stock and efficiency improvements in production (as well as on the demand side) would be necessary to avoid demand outstripping supply. Otherwise, prices would be forced upward (Fisher 1981).

For the case in which resources are nonrenewable, Hotelling's (1931) principle proposes that the incentive (for the producer) is to extract more resources as long as the rate of increase in future expected net prices (i.e., price minus costs) is lower than the discount rate.

Expectations of relatively low future net prices will encourage additional extraction today and tend to put upward pressure on current production and supply. Rapid exploitation today means future fuel reserves will be lower, driving up expectations of future prices. If the expected annual rise in net prices becomes greater than the discount rate, managers will have an incentive to invest in fuel reserves by keeping them as stocks. Because these stocks are limited, Hotelling's principle suggests that net real prices will rise through time (Livernois 2009).

The basic model of resource extraction has been extended to incorporate several important variables: the costs of exploration and extraction (the basic model assumes zero costs); the costs of a "back-stop" technology (providing a more expensive yet inelastic fuel substitute); either increasing or decreasing marginal costs of extraction (because of greater difficulty in extracting the next unit and varying resource quality or due to technological improvements); changes in the discount rate; increases in reserves or in demand; market structure such as monopolies or cartels; and uncertainty about demand, reserves, or institutions (Krautkraemer 1998).

All of these extensions to the basic model alter the optimal rate of extraction. For example, a "back-stop" technology provides the upper limit for the cheaper fuel's price; lower costs of extraction will lower the initial price but raise the rate of growth in future prices; higher discount rates will have a similar effect; new discoveries will reduce the price range, as well as the rate; new demand will have the opposite effect; and monopolies are likely to reduce the rate of extraction, creating a higher initial price with a lower eventual price. Thus, all of these factors will play a role in determining the price path, which may be rising, downward sloping, or U-shaped (Farzin 1992).

Empirical Evidence

Numerous studies have examined the long-run trends in commodity, resource, and energy prices to identify whether, over time, resources within a growing economy have become increasingly scarce. Potter and Christy (1962) and then Barnett and Morse (1963) undertook the first systematic studies of long-run price trends by analyzing the real average costs for a number of mineral, agricultural, and renewable resources in the United States between 1870 and 1957. They found that all but three of the prices had remained constant or had fallen. The findings of these initial surveys were corroborated by Nordhaus (1974). Smith (1979), Slade (1982), and Berck and Roberts (1996) studied nonrenewable resource price trends over periods of more than one hundred years. More detailed statistical analyses have found that the trends tend to vary according to the samples. For example, Pindyck (1999) investigated U.S. oil, coal, and natural gas prices over 127 years and found that, while a U-shaped regression could explain trends up until the 1980s, it overestimated the prices in the last fifteen years of the twentieth century. Adelman (1995) analyzed consumer oil prices over eighty years and crude prices over more than one hundred and thirty years and concluded that it was difficult to reconcile the evidence with the theory that oil is a limited resource. Reviews of the literature have argued that the discoveries of new deposits, shorter-term market volatility, technological progress in exploration and in use, and the development of substitutes imply that the finiteness of resources does not directly influence the economic scarcity of the commodity (Krautkraemer 1998; Livernois 2009).

One could argue, however, that one hundred years is too short a period to test the theory of scarce resources and identify whether energy prices increase over time. Despite the difficulties of creating a long time series and the consistency of values within the series, longer series have been built. Hausman (1995) spliced consumer and producer price series to create a very long-run series from 1450 to 1988. He found no support for the view that fuel prices were rising over the very long run and that when individual fuel prices have risen, consumers have switched away from the more expensive fuel.

Fouquet and Pearson (2003) examined trends in individual fuel and average energy prices from 1500. They found that there was little evidence of systematic or substantial rises in individual fuel prices. However, the twentieth century was characterized by an increase in the real average price of energy. During this period, energy systems were dramatically altered, with large-scale substitution toward more expensive fuels. This transformation was reflected in the growing share of petroleum, gas, and ultimately electricity in final user expenditure on energy over the period. Fouquet and Pearson (2003) proposed that, rather than being associated with rising scarcity, this price increase may have been due to the rising value placed on these higher quality energy sources by consumers. To test this proposition and help identify the influence of energy transitions as well as technological developments on energy costs to the consumer, this article builds on Nordhaus' (1996) study of improvements in lighting over hundreds of years in order to estimate the long-run trends in the prices of energy services and compare them with their respective energy prices.

Data and Methodology

Identifying trends in the evolution of the cost of energy services requires statistical information on fuel prices and efficiencies. Schools, colleges, hospitals, and government departments around the United Kingdom offer remarkable records of the history of the country's agricultural and energy prices, going back almost one thousand years (Rogers 1886; Beveridge 1894; Mitchell 1988). The data set used for Clark (2007) fills in the gaps and improves the data on the prices of coal and firewood back to the year 1300. The volumes of the *History of the British Coal Industry* (particularly Hatcher 1993; Flinn 1984; Church 1987) pull together most statistics on coal prices over the past five hundred years. The statistical abstracts of the *British Parliamentary Papers* and the Ministry of Fuel and Power provide data beginning in the mid-nineteenth century and were forerunners of the current DECC's *Digest of United Kingdom Energy Statistics*, which provides annual data on all energy sources.

In order to convert the prices (and consumption) of fuels into their equivalents in energy services, they must be combined with the energy efficiency of the equipment used. For example, in the eighteenth century, a tonne of coal could be placed in a traditional fireplace and burned, generating around 10 percent of a tonne of coal in useful heat. With these data, and knowing that the price of 1 tonne of coal (in year 2000 values) was equal to £145, one can estimate the price of 1 tonne of coal equivalent of useful heat to be about £1,450. By the 1950s, coal fireplaces were reaching efficiencies of nearly 30 percent. Thus, at £100 (in 2000 values) per tonne of coal, the price of the "useful" heating from 1 tonne of coal was £300—nearly five times cheaper. The efficiency of the main heating technologies in Britain over the past five centuries can be found in Billington (1982) and Crowley (2004). This approach also applies to lighting, and the efficiency estimates of key technologies presented in Nordhaus (1996) are used.

Thus, the cost of heating or lighting using any particular technology can be calculated by multiplying the energy price by the efficiency. Next, for each of the principal technologies, a model of the growth in its adoption and its share of the energy service market was developed based on evidence about energy consumption (Fouquet 2008). Thus, by combining the share of the market with the cost for each technology, a relatively reliable average heating or lighting price can be estimated, comparable across various waves of technological development.

For power, considerable information about energy equipment (e.g., horses, mills, steam engines) was available (Thompson 1976; Crafts 2004; Langdon 2005). The price (in pence per kWh) was calculated by combining the energy requirements to generate 1 kWh (found in Smil 1994) with the energy prices (in £ [2000] per tonne of oil equivalent). For most of the twentieth century, the power (e.g., electricity) price was already available (from the standard energy statistics sources mentioned above) and thus did not need to be calculated.

Early transport prices were estimated directly by breaking down journeys into pence per kilometer (Jackman 1960; Masschaele 1993). Mitchell (1988) and DoT (2002) provide data on freight and passenger transport in the second half of the nineteenth and twentieth centuries. For power and transport, some prices are based on the energy costs of using equipment (e.g., horse or steam power and cars), while others are based on the price charged to the customer (e.g., horse drawn, railways, and electricity), including network and capital investments and reflecting supplier market power. This means that power and transport price trends may be biased downward during the transition to new technologies whose estimates are based on energy costs.

Thanks to the data set in Allen (2007), the costs of using different fuels and producing services are broadly comparable across time, and prices are quoted in real terms for the year 2000. Further details about the principal sources and methods used to assemble the data series associated with fuel prices and technologies can be found in Fouquet (2008).

Despite the relative richness of the data, they should be interpreted with caution. Especially for the early centuries, the data have often been drawn from the records of institutions that bought fuel in the South of England and so are not representative of Britain as a whole. In addition, data do not exist in cases where woodfuel was collected rather than bought (such as in rural areas). Where woodfuel was bought, price trends reflect freight distances and local resource availability.[1] As markets became more integrated due to improvements in freight transport, and as consumers switched from wood to coal (a commercial product initially sold from the northeast), prices became more nationally representative.

In some cases, a war (such as the Civil War of 1642–1646 or the two world wars) affects price estimates. For a few exceptional years (a total of four over the seven hundred years in the time series), there are no coal price data.[2] For these four years, the data are interpolations based on information for previous and later years. However, these estimates do not alter the long-run trends in prices.

There are valid concerns about the representativeness of the data, about their comparability over time and across technologies, and about major disruptive events. Nonetheless, the data

[1]Indeed, evidence of high woodfuel prices, in towns and villages in particular, caused much debate about the existence of a national energy crisis in the seventeenth century—now it is interpreted more as a reflection of the high cost of transporting nonlocal woodfuel (Nef 1926; Hatcher 1993).

[2]One such year is 1926, when there was a miners' strike.

do provide a clear indication of the costs of different energy services over the centuries, which can be compared with present day costs. These trends identify differences in orders of magnitude over several decades or from one technological revolution to the next, which reflect genuine changes in the prices of energy services. Thus, the reader is advised to focus on these broader trends rather than on individual year-to-year changes.

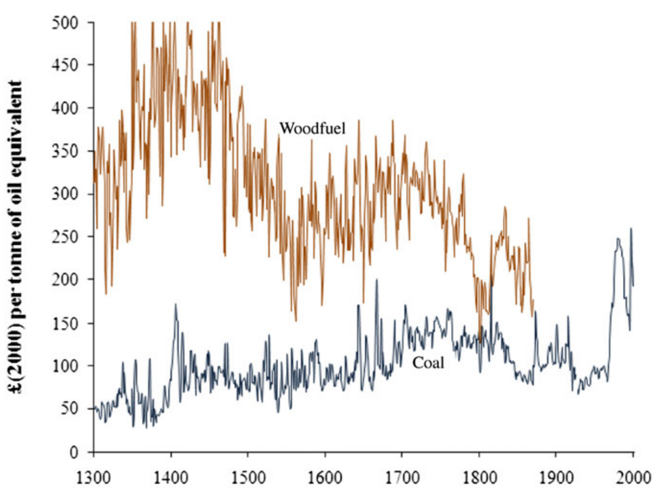
Trends in the Prices of Fuels and Heating

This section presents evidence concerning long-run trends in the prices of both heating fuels and the heating services they provide.

Woodfuel and Coal Prices

Figure 1 offers some evidence on long-run trends in the prices of woodfuel and coal, the fuels that historically provided the heat in homes and for industries. Woodfuel prices reflected market pressures. For example, in the fourteenth century, the rising population put major pressures on woodfuel supplies. After the Black Death and the dramatic decline in population, woodfuel prices fell. Prices started rising as the population grew again in the sixteenth century. The experience of the 1300s suggests that woodfuel prices would have risen much higher in the sixteenth century (above £300 in real terms) if there had not also been a shift toward coal during this time period.

The evidence on average coal prices suggests a rising trend in coal prices between 1600 and 1800. However, this hides the fact that the price series is an aggregate of prices in different regions of England. Thus, it is helpful to investigate what lies beneath this rising trend in order to understand whether it reflects rising scarcity or other forces. Beginning in 1500, coal prices in the North of England stayed close to £40 (in 2000 values) per tonne for three hundred years



Source: Fouquet (2008), Clark (2007), Allen (2007)

Figure 1 Woodfuel and coal prices in England (1300–2000)[3]

[3]All figures contained in this article can be produced using the data presented in the online supplementary materials. See http://www.reep.oxfordjournals.org.

(Clark 2007). This series follows the pithead price, providing an indicator of the long-run marginal cost of production. Thus, there is no evidence of rising marginal costs of production over hundreds of years.[4]

The rising trend in the national average price of coal between 1600 and 1800 (Figure 1) does not appear to be due to scarcity. Instead, it results, first, from the growth in coal consumption in London (which increases the weighting of the London price series where prices were highest), and second, from the increase in consumer prices (i.e., for London and the rest of England), not pithead prices. The main reason for this rise in consumer prices was the imposition of taxes on coal beginning in the late seventeenth century. By the mid-eighteenth century, taxes accounted for a third of the consumer price (Hausman 1987). Thus, consumer coal prices increased as consumption grew, reflecting the government's ability to capture some of the consumer surplus associated with a relatively inelastic demand.

At times, there was upward pressure on coal prices, but supply adjusted to accommodate demand. In fact, after 1800, coal prices tended to fall, as new regions began to exploit coal resources, helped by the invention of the steam engine, which could pump out the water mechanically from ever-deeper coal mines. Thus, the evidence here suggests that it is unwise to accept a simple theory of long-run coal prices that proposes an upward rising trend.

Heating Fuel Prices and Household Heating Prices

Figure 2 presents trends in the average price of fuels used for heating as well as trends in the average price of household heating (i.e., the service provided by the fuels). Average heating fuel prices are weighted by consumer expenditures (i.e., price multiplied by consumption) on the fuels. For the fourteenth and fifteenth centuries, the weightings for 1500 were used because no consumption data were available. Estimates suggest that, at the time, woodfuel was responsible for 98 percent of heating expenditure (Fouquet 2008). Thus, between 1300 and 1550, woodfuel prices dominated, while afterward, coal prices increasingly dominated.

The next two centuries were associated with the transition to coal. Since the price of coal was roughly half the price of woodfuel, the switch implies a declining trend in average prices, despite a rising average coal price. Woodfuel and coal consumption were believed to be similar at the beginning of the seventeenth century—each roughly equivalent to 0.5 million tonnes of oil equivalent (mtoe) (Hatcher 1993; Warde 2007; Fouquet 2008). But coal consumption had increased to more than 2 mtoe by 1700 and to around 13 mtoe by 1800 (providing over 90 percent of heating energy). By 1900, coal use for domestic and industrial heating was about 70 mtoe. In 2000, natural gas met 80 percent of domestic heating requirements and 60 percent of industrial needs, and total heating energy consumption was roughly 80 mtoe (Fouquet 2008).

The trend in average household heating prices is indicated on the right-hand axis in Figure 2. These prices are estimated by combining the prices of individual fuels with the efficiency of the relevant technologies. The average price is calculated by weighting the individual heating prices by household expenditures on the different methods of heating. The

[4]In addition to regional variability in prices, coal quality differed greatly. Unfortunately, there is little information on the long-run trends for different varieties of coal. If such data existed, a hedonic price model could be used to estimate, for instance, changes in consumer willingness to pay for low-smoke coal, such as anthracite, which could then be used as an indicator of past demand for environmental quality.

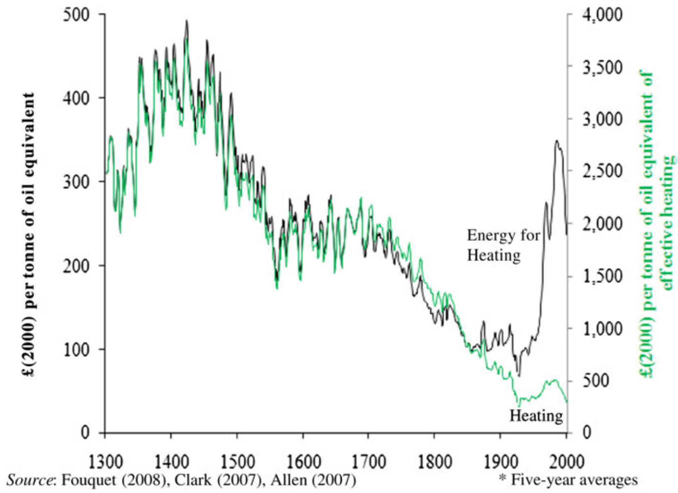


Figure 2 Prices of energy (for heating) and price of household heating in England (1300–2000)*

unit of measurement is an effective tonne of oil equivalent—that is, the heat produced from 1 tonne of oil, using equipment that has an efficiency of 100 percent. Thus, the lower the efficiency, the higher is the price of household heating (for a given fuel price).

The trends in the price of heating followed the peaks and troughs in the price of heating fuels between 1300 and 1800. However, in order to shift to coal, the far cheaper fuel, consumers also had to switch to a less efficient technology—from the hearth to the fireplace, which could expel the noxious coal smoke more effectively. This implies that over this five–hundred-year period, the price of fuels fell more than the price of heating. Nevertheless, this shift in fuels and technology still enabled heating prices to fall, which would not have been possible if consumers had continued to use woodfuels.[5]

In the nineteenth century, the efficiency of heating equipment started to improve greatly, thanks to the widespread adoption of the Rumford fireplace (Crowley 2004). In the twentieth century, the improvement in efficiency intensified and ultimately led to the cleaner and highly efficient natural gas and electricity central heating boilers (Billington 1982). After the introduction of the Clean Air Act in 1956, (town and natural) gas and electricity consumption grew rapidly, and coal declined swiftly. 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 was double the coal price. So, over the period, average heating fuel prices tripled and heating

[5]The switch in domestic heating technology, coupled with the regional differences in coal prices mentioned earlier, were key catalysts for the Industrial Revolution (Allen 2009, 80–105). The dearth of local woodfuel near London created a demand for coal from the northeast of England. The London market, as an international center of trade with higher incomes, was willing to pay a higher price for heating fuels and drove the expansion of the coal industry in the northeast. London also drove the associated technological development of chimneys, fireplaces, and grates to burn coal in homes. Once the coal-burning home was refined, households across Britain could switch to coal, driving the expansion of coal mining in the west of England, Wales, and Scotland. Closer to the pits, however, the price of coal as a source of energy was very low (by international standards). Thus, in the eighteenth century, after the invention and development of the coke-iron furnace, western England had access to cheap coal for smelting local iron, as well as for driving steam engines to spin cotton, and became the cradle of the Industrial Revolution.

prices increased by an estimated 50 percent, reflecting the cost associated with meeting environmental standards. Nevertheless, despite the rapid shift toward more expensive energy sources, household heating prices were nearly three times lower in 2000 than in 1900, the quality of heating improved, and local environmental standards were being met.

Just as Nordhaus (1996) found for lighting, in the long run, the price of the heating service fell far more than the price of the energy source. In fact, in the case of heating, the average energy price actually rose substantially, while heating prices only increased briefly following the introduction of environmental legislation. Thus, together, the evidence makes a strong case for focusing on the service rather than on the fuels.

Trends in the Prices of Energy and Energy Services

In this section, the prices of energy services other than heating (i.e., power, transport, and lighting) are examined and their long-run price trends are compared with those for their related energy sources.

Power

Until the Industrial Revolution, animals, particularly horses, provided around 70 percent of all the power needs in Britain (Fouquet 2008). The supply of energy (i.e., provender) for horses depended on agriculture. During the sixteenth century, the prices of horse provender (a combination of hay, oats, and peas) rose rapidly. Figure 3 (left-hand axis) reflects this rising trend in the prices of energy for power, which was caused by the increased crops required to feed the growing populations of humans and animals.[6]

The price of power (i.e., the energy service, shown on the right-hand axis) rose rapidly in the sixteenth century, as the economy grew. From the mid-seventeenth century, the price of power (i.e., the cost of using animals) started declining as better horse breeding led to more efficient animals working the land and in industry (Edwards 1988).

The cost of using energy to generate power fell during the nineteenth century as the dominant source of energy for power shifted from fodder to coal, which was roughly twenty times cheaper. Until the mid-nineteenth century, steam engines were less efficient than horses at converting energy into power. Yet, they were still cheaper at generating power. In addition, the steam engine offered a concentrated method of production, which the horse could not provide. This enabled cost reductions in other aspects of production of the final product, especially for cotton. However, widespread use of steam power only took place in the second half of the nineteenth century, as the steam engine's efficiency tripled between 1850 and 1900. The price of steam power fell fourfold in that period, and the average power price was cut in half (Figure 3).

[6]Here, human power and its related food requirements have been removed from the energy and power price series. This is because humans, although providing around one-fifth of the power needs before the Industrial Revolution, also supplied human capital, which was reflected in the wages and heavily distorted an average price of energy and power. The costs of wind and water power, which provided around one-tenth of the power, are also not included because of the difficulty in measuring them (see Fouquet 2008).

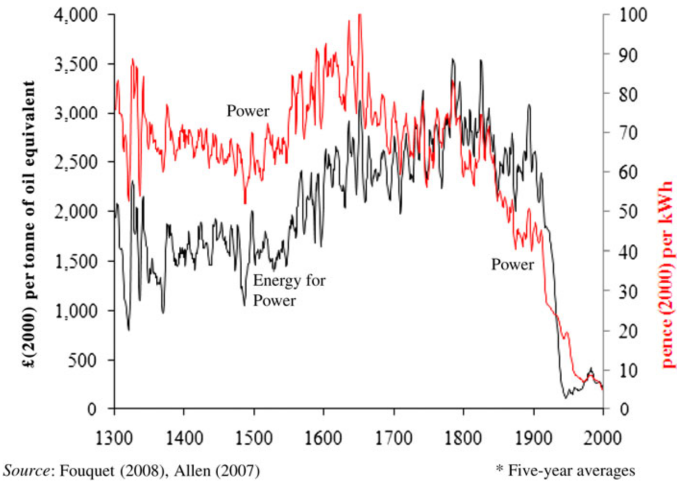


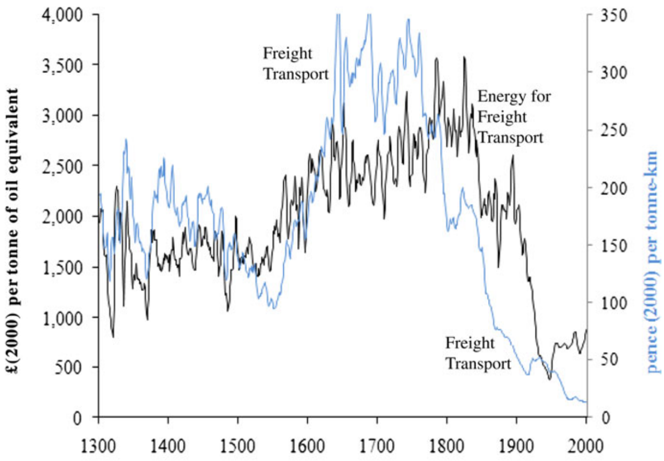
Figure 3 Prices of energy (for power) and power in the United Kingdom (1300–2000)*

Surprisingly, during the first half of the twentieth century, the average price of energy fell faster than the price of the service. The principal explanation for this phenomenon is a technical one. Animals still played a role in generating power at the beginning of the twentieth century. However, given their inefficiency at converting energy into power, expenditure on provender was great (relative to animals' share of power provision), which heavily weights the fuel price series but not the power series— horses in agriculture accounted for 60 percent of all expenditure on energy for power and 35 percent of all expenditure on power in 1900.[7] Following the First World War, the role of animals in power provision declined significantly and had effectively disappeared by the mid-twentieth century. However, in the second half of the twentieth century, this trend was reversed, with rising dependence on more expensive energy sources (i.e., petroleum, then natural gas) for power generation, but cheaper electricity.

When examined over the period from 1700 (before the diffusion of the steam engine) to 2000, the price of power fell more (a sixteenfold decrease) than the price of the fuel (a thirteenfold decrease).[8] Both the shorter and longer trends support Nordhaus' (1996) view that it is necessary to focus on the services the commodity provides rather than on the commodity itself. From the seventeenth century onward, the trends in the price of energy used for power and the price of power have been distinct. Moreover, in the long run, using the former when it is the latter that drives the demand for power and the associated energy is likely to lead to a misunderstanding of consumer responses.

[7]Kander and Warde (2011) provide confirmation of these high energy needs.

[8]When examining these trends, it is important to recall the procedure used here for estimating prices of energy services. The prices of power from horses were measured by the costs of using them. This was the annualized cost of using a horse (mostly provender and maintenance) divided by an estimate of the power generated in one year. For steam engines, which dominated at the end of nineteenth century, similar annualized costs were estimated. For both horses and steam engines, the exclusion of capital costs underestimates the full cost of generating power—but, only by about 10 percent to 20 percent. For electricity, however, the price faced by the consumer was used. This price includes the profits to the electricity producer and supplier, the taxes imposed, the costs of maintaining reserve capacity and a complex supply network, and inefficiencies in distribution.



Source: Fouquet (2008), Allen (2007) * Five-year averages

Figure 4 Prices of energy (for freight transport) and freight transport in the United Kingdom (1300–2000)*

Freight and Passenger Transport

For transport, the long-run trends in the prices of energy and freight services (Figure 4) diverge even more than they do for energy (for power) and power. Looking at the left axis, we can see that the price of energy for transport (fodder until the mid-nineteenth century, coal until the mid-twentieth century, and then oil) followed a trend that is similar to the trend in the price of energy for power. However, turning to the right axis, the price of transport services was dependent not only on the costs of the fuel but also on the quality of the transport infrastructure and network, whose declining quality explains much of the rise in the prices of transport services in the sixteenth and seventeenth centuries. This decline in quality resulted from the growing use of heavier and more damaging four-wheeled wagons and the fact that, after King Henry VIII's religious reformation and his dissolution of Catholic churches, there was an institutional vacuum associated with maintaining roads (Jackman 1960). Once turnpikes (i.e., privately provided public goods) were introduced more than a century later, quality improved and prices fell. Prices fell further after the introduction of railways, and they have continued to fall in the twentieth century.

Even though there was not a downward trend in energy prices (increasingly associated with oil) in the second half of the twentieth century, improvements in vehicle efficiency implied cheaper freight transport services. Just as for heating and power, consumers experienced declining trends in the cost of the service, despite rising or flat trends in energy prices. Once again, it would be misleading to use the latter to study long-run transport demand and its related fuel consumption.

Data for passenger transport prices are only available starting at the beginning of the eighteenth century and follow a course that is similar to the trends for freight transport—a divergence in energy and service prices appears, implying the same risk of using the wrong variables for analyzing passenger transport services.

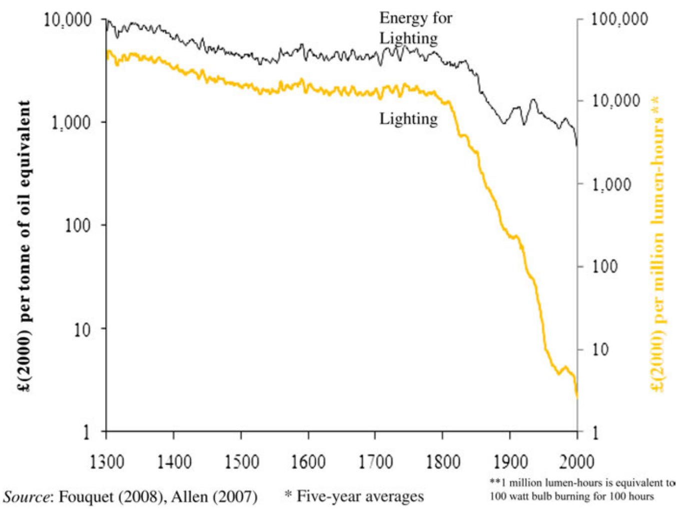


Figure 5 Prices of energy (for lighting) and lighting in the United Kingdom (1300–2000)*

Lighting

Looking at lighting, the price of energy declined from the fourteenth to the sixteenth century, as the main source (tallow or animal fat) was relatively abundant (Figure 5, left axis). The price then stabilized and rose a little, as the growth in demand for lighting was greater than the increase in supply. By the nineteenth century, new fuels (town gas, kerosene, and then electricity) were being used. At the beginning of the transition, in the 1820s, town gas was more expensive per unit of energy than tallow candles (averaging more than £3,000 [in 2000 values] and about £2,000 [in 2000 values] per tonne of oil equivalent, respectively). Yet, town gas lighting technology was twice as efficient at converting the fuel into lighting as tallow candles. By 1850, town gas was half the price of tallow candles, per unit of energy, and far more efficient.

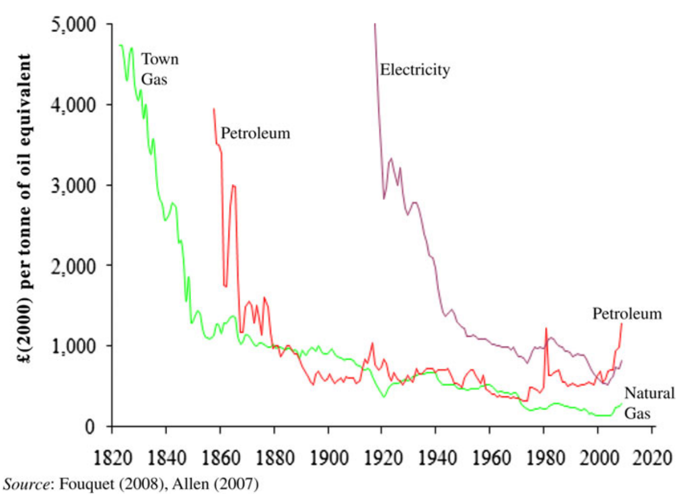


Figure 6 Prices of new energy sources in the United Kingdom (1820–2008)

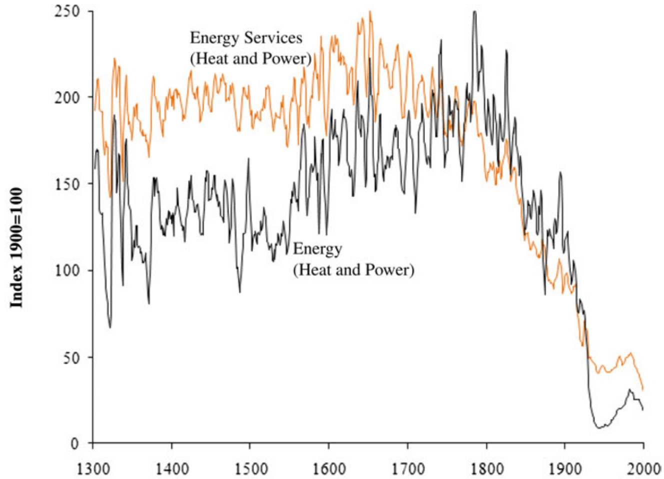
The growth of these other new energy sources was also associated with rapid declines in their prices (Figure 6). In the second half of the nineteenth century, kerosene, produced by refining crude petroleum, was used for lighting, especially in poorer households, because of the low capital costs of investing in oil lamps (compared with installing gas pipes and lamps). There was great volatility in the beginning, but by 1900, the price of oil had fallen sixfold and remained comparatively stable for more than fifty years (Hamilton 2011). Like coal for heating in the seventeenth and eighteenth century, the strong dependence on oil for transportation has led the British government to rapidly increase the tax rate over the past twenty years—in 2000, three-quarters of the price of gasoline was revenue for the government (Sterner 2007)—and the trend in prices reflects this process, rather than providing clear evidence of growing long-run resource scarcity. So, while many have focused on the volatility in petroleum prices in the last few decades and the signs of short-run supply shortages associated mostly with political disturbances, the history of petroleum has been (to a great extent) one of declining and then stable prices with occasional peaks.

In 1900, when electricity began to replace town gas (and kerosene) for lighting, it cost twenty-five times more per unit of energy (electricity cost £10,000 [in 2000 values] per tonne of oil equivalent and gas cost £390 [in 2000 values] per tonne of oil equivalent). At the time, electric lighting was seven times more efficient. This means that at first, electric lighting was more expensive than gas lighting. Nevertheless, it was still used in luxury homes, restaurants, and theaters, where the novelty of the new technology was highly valued (Schivelbusch 1988). By 1930, when a rapid switch was occurring, electricity was still five times as expensive as gas, but electric lighting was ten times more efficient. Thus, in the nineteenth and twentieth centuries, there was a shift to costlier fuels but cheaper lighting (Figure 5, right-hand axis). The average price of energy for lighting hardly fell in the twentieth century, despite rapid declines in the price of lighting (from £250 [in 2000 values] per million lumen-hours in 1900 to £15 [in 2000 values] in 1950 to £2 [in 2000 values] in 2000). Moreover, the increases in energy consumption were far greater than the efficiency improvements (Fouquet and Pearson 2006). Thus, again, it would be misleading to use energy prices rather than the price of energy services as a guide to understanding energy demand and consumption.

Trends in the Average Prices of Energy and Energy Services

Given that energy is often discussed in its broadest terms, it is useful to examine and compare an average price of energy and an average price of energy services. There are insufficient data on expenditure to complete full average price series back to 1300. Instead, the average prices of energy and energy services associated with heat and power are presented (Figure 7). The full average price of energy and its related services can be examined beginning in 1700, when data on transport and lighting expenditure became available (Figure 8).

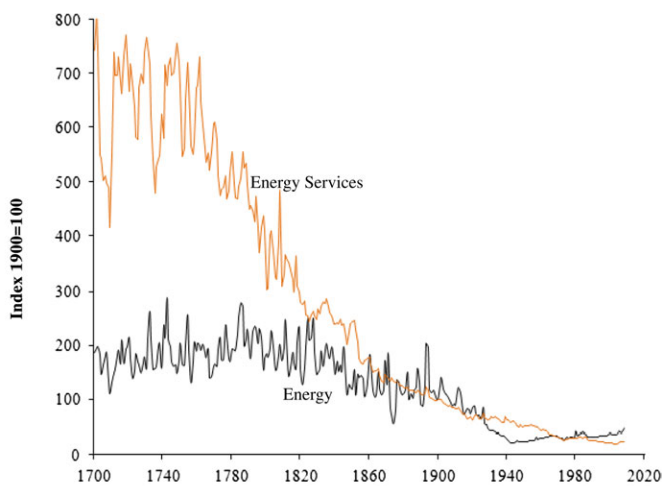
Over the very long run (Figure 7), the broad trends for energy and service prices are similar: a rising price for both energy and its services and then a declining price. This reflects the growing pressure on land as the population and the economy were growing in the early modern era and then, in large part, the transition from renewable sources of energy to fossil fuels—woodfuels to coal for heating and especially provender to coal for power.



Source: Fouquet (2008), Allen (2007) * Five-year averages

Figure 7 Average prices of energy and energy services (heating and power) in the United Kingdom (1300–2000)*

However, the declines in the prices of energy and energy services began at different times. For energy prices, the decline occurred at the beginning of the nineteenth century with the increased use of the steam engine. The average series for energy in Figure 7 is heavily dominated by the price of power fuels until the second half of the nineteenth century, as provender (as well as food and water power, which are not included here) was replaced by cheaper coal. For heating and power services, there have also been considerable improvements in energy efficiency since the Industrial Revolution, possibly triggered by rising trends in energy prices. Yet, Figure 7 shows that the decline in the price of energy services began in the mid-seventeenth century—when more efficient horses were being used. At the same time (but not shown in Figure 7), transport services were also improving. Thus, within the



Source: Fouquet (2008), Allen (2007)

Figure 8 Average prices of energy and energy services in the United Kingdom (1700–2008)

Table 1 Divergences in prices of energy and energy services (1700–2000)

	X-fold decline in price of energy	X-fold decline in price of service
Heating	1.1	5.1
Power	12.5	16.1
Transport (freight)	3.0	20.1
Transport (pass.)	2.9	11.7
Lighting	9.0	5,830
Average	3.7	37.4

Source: Adapted from Fouquet (2008).

confines of the renewable energy system, there were attempts to resolve the problems posed by growing demands for resources.

However, differences in the trends in the prices of energy and energy services are particularly apparent since the Industrial Revolution and when the transport and lighting series are included (Figure 8, Table 1). From 1760 to 1913, the average price of energy services fell much faster than the price of energy. Between 1913 and 1950, the trends were reversed and the price of energy fell faster. Then, from the 1950s, the trend in the prices of energy services dropped considerably, while average energy prices increased (as consumers shifted to more expensive energy sources and faced the oil shocks).

A Comment about Past and Future Trends

Energy prices have risen considerably since the beginning of the twenty-first century (Figures 6 and 8). Clearly, global demand for energy services, and thus for energy, has soared, especially as the Chinese economy has expanded. Yet, placed in a historical context, it is also clear that many peaks preceded the price hike of 2008.

Between the seventeenth century and the nineteenth century, commentators expected coal prices to soar, with grave impacts on the economy (see e.g., Jevons 1865). Although there were temporary hikes, long-run price trends remained remarkably stable. Suppliers continued to deliver fuels—finding new and deeper reserves and hiring more workers and capital to meet the demand. In the 1910s, the new energy sources, petroleum and electricity, temporarily struggled to meet the rapidly increasing demand for personal transport, power, and lighting. Prices peaked, and in response, suppliers expanded petroleum and electricity capacity to meet the new needs. Similarly, in the 1970s, observers feared permanently higher energy prices (see e.g., Hamilton 2011). Yet, starting in the mid-1980s, nearly twenty years of low energy prices followed—even for oil, the prices were equivalent to the average over the previous one hundred years, despite having been heavily taxed. Thus, despite the many peaks in the past, markets adjusted. Suppliers found new reserves and built greater infrastructure, and consumers, where possible, reduced waste, increased efficiency, and shifted to cheaper sources. As a result, long-run trends in individual prices continued a relatively stable and slightly downward trend.

Based on this historical context, it is tempting to conclude that the future trend in individual prices will be generally downward, although peaks can be expected. The global recession is allowing energy producers and suppliers time to expand reserves and infrastructure.

Iraqi and Brazilian oil fields may help (Maugeri 2009), and greater expansion of Russian and North African natural gas reserves will, no doubt, also assist. In addition, the development of technologies aimed at tapping unconventional natural gas reserves at low cost implies very large fossil fuel reserves (Stevens 2010).

In 2009, the current global primary modern (i.e., fossil fuel and primary electricity) energy consumption was a little more than 11,000 mtoe (BP 2010). One estimate of global fossil fuel reserves is close to 30 million mtoe (Rogner 2000, p. 168). This is nearly 2,500 times the current annual global primary energy consumption. Unconventional natural gas reserves are particularly important—roughly 80 percent of the total. But, even for oil reserves alone, the estimate is more than 450 times current annual global oil consumption. Thus, even allowing for economic and population growth, fossil fuels are clearly abundant, making the specter of dwindling fossil fuel reserves unlikely (at least for a very long time).

Another phase of scarcity passed in 2010, as the global economy began to recover from the recession, and a new period of relative abundance probably lies ahead—at least for a few years. This will help boost growth around the world, which will generate greater demand for energy services and energy, causing another phase of scarcity to ensue. Thus, it is tempting to expect, in the long run, cycles of scarcity and abundance along a slightly downward trend (Fouquet 2008).

Might the current process of internalizing the external costs of carbon alter this expected trend? The process of internalizing these costs will probably be a once-and-for-all shift, unless marginal damage continues to increase. Thus, it seems appropriate to expect an upward rise in individual prices of energy, especially sources with higher carbon contents. Both suppliers and consumers will respond and adjust by favoring low-carbon energy sources. This will in turn put downward pressure on high-carbon energy prices and upward pressure on low-carbon energy prices. Finally, it is tempting to conclude that these shifts and responses concerning carbon sources will occur within the context of long-run prices of energy declining gradually and long-run prices of energy services declining faster.

Conclusions

The purpose of this paper has been to present evidence on trends in the prices of energy and energy services from the fourteenth century to the present day in what is now the United Kingdom and to examine the divergences in these two types of prices. This evidence has helped assess whether the problem of incorrectly using long-run price variables was related only to lighting or, more generally, to all energy services.

There are inevitably questions about the reliability and accuracy of historical data. Some might question the validity of creating a single price series for fuels, energy, and associated services over such a long period because of the inevitable geographical and measurement inconsistencies across data sources (Hatcher 1993). Nevertheless, such price series clearly do provide an indication of the costs of heating a home in the sixteenth century, lifting a tonne of grain in the seventeenth century, traveling to London in the eighteenth century, or illuminating a room in the nineteenth century and enable us to compare them with the equivalent costs at the beginning of the twenty-first century. Furthermore, given the nature of the data and the findings, it is important for the reader to identify and examine trends and changes in orders of magnitude rather than focus on prices in individual years.

Diverging Trends

The broad trend in British energy prices and their energy services over the last seven hundred years was first upward, as the expanding economy faced increasing pressures from its consumption of mostly limited renewable energy resources, and then downward, especially as fossil fuels replaced them (Figure 7).

Woodfuel prices in the 1300s and in the 1600s suggest rising population pressures led to higher prices (Figure 1). Similarly, the prices of fuels for power and transport (i.e., the provender for horses) had been rising up to 1800, reflecting the growing pressure on land, and thus agricultural products, and the lack of large-scale substitutes (Figures 3 and 4). It appears that economic growth that was driven by renewable energy sources resulted in higher energy prices—although it did not become an economy-wide energy crisis as suggested by Nef (1926).[9] In fact, it appears that there were attempts to find solutions (e.g., better horse management and turnpikes) within the confines of the renewable energy system, and these appear to have lowered certain energy service prices from the seventeenth century onward. Yet, it is likely that without the switch to fossil fuels, economic growth in the United Kingdom (and possibly many other economies) would have been severely constrained, the country would have faced further increases in average energy and service prices, and the Industrial Revolution might not have occurred (Allen 2009).

A key aspect of the transformations that took place during the nineteenth century was the innovation, development, or expansion of markets for a whole series of new energy sources and technologies, enabling substitution and improved efficiency—possibly driven by rising agricultural and renewable energy prices. The price of those new energy sources fell dramatically (Figure 6) and have continued to fall or have been stable, until recently. In the case of oil, just like coal in the seventeenth and eighteenth century, the rising trend after the oil shocks in the 1970s was mostly due to increasing taxation. Thus, the trends (and the explanations underlying them) in the United Kingdom over the last five hundred years corroborate earlier studies (Adelman 1995; Livernois 2009), suggesting that, at least in the eyes of the market, fossil fuel resources have so far been perceived to be "unlimited."

The tendency to substitute energy sources toward cheaper or more valued energy services has also had a strong influence on average energy prices (Fouquet 2010). In many cases, this has encouraged substitution toward cheaper energy sources (such as the transition to coal). This implies that, even if individual fuel prices may rise in the long run (and there is little evidence to support this for fossil fuels), average energy prices will tend to fall. However, as in the case of the transition away from coal toward gas, oil, and electricity, this implies switching to more expensive energy sources and a rise in average energy prices. Thus, energy transitions can either lower or raise average energy prices (depending on the nature of the energy sources and technologies involved), but this occurs within the context of mostly declining or stable individual energy prices.

Especially since Potter and Christy (1962) and Barnett and Morse (1963), economists have sought to understand long-run energy price trends and the forces driving them. Most studies

[9]Of course, these experiences in Britain—a small, densely populated island—do not imply that all economic growth that depends on renewable resources is destined to suffer increasingly higher prices (Allen 2009; Fouquet 2011b).

of long-run price trends have been able to construct series of around one hundred years, which should capture the impact of one or two major technological developments. However, the ability to study longer run series raises the issue of what variable should be of interest. For lighting, it was shown that, due to major innovation in the efficiency of the consumption technology, the price of energy and of the service diverged considerably (Nordhaus 1996). While the very broad trends in the prices of energy services are similar to their respective energy prices (upward then downward), especially since the Industrial Revolution, this analysis has found that their trends have diverged (Figure 8). In other words, although lighting was the most dramatic example (Figure 5), the divergence is general rather than specific to lighting.

The last two hundred and fifty years have been a period of historically exceptional technological innovation. The cost of generating services has changed greatly, not only as a result of changes in the price of the resources but also from the ability to use those resources more efficiently. In fact, in the case of heating, power, and transport in the second half of the twentieth century, the average energy price was rising, while the price of the service was rising only briefly, was stable, or was falling due to the substitution of new fuels that used more efficient technology—here the rising average energy price indicated not so much that resources were increasingly scarce, but rather that consumers placed a higher value on the new fuels.

As discussed below, the tendency for economists to focus exclusively on long-run trends in energy prices could be responsible for misleading conclusions concerning consumer price indices, energy markets, and climate policy and reveals the need to improve our understanding of the long-run forces that drive energy service prices.

Theoretical Implications

Given the importance of long-run trends in energy service prices and their divergence from long-run trends in their respective energy prices, it would be useful to develop a richer theoretical understanding of why the long-run price of energy services might be expected to decline. The current study is not the place for such an analysis. It can only offer the following basic and simplified arguments and implications. First, markets behave as if fossil fuel resources are unlimited, implying stable or even declining long-run individual energy prices (Adelman 1995; Livernois 2009). Second, markets for energy-using equipment seek to improve efficiency, especially when spurred by short-run energy price increases (Fouquet 2008). Third, generally, the price of the service is the price of the fuel multiplied by the amount of energy required to produce one unit of the service (Nordhaus 1996), with the former being stable or declining and the latter declining. So, for any particular source and equipment combination, the medium-run trend in the price of energy services is downward and is especially pronounced shortly (perhaps a decade) after a temporary individual energy price rise.

Fourth, a full energy transition only tends to occur when the new source and technology combination result in a lower price for the service (Fouquet 2010). At the beginning of a transition, early adopters may be willing to pay more for the additional attributes associated with the new source and equipment combination, but the majority of consumers are likely to adopt and make the transition only with lower service prices. Consequently, the average price of the energy service may be flat or even slightly rising at the beginning of the transition (such as during the introduction of fireplaces, central heating, and steam engines). However, both because equipment manufacturers will seek to improve efficiency (i.e., the second argument) and because a full transition will take place only if service prices fall (i.e., the fourth argument), the long-run price trend in energy services can be expected to decline.

Empirical Implications

Although in the long run, the price of energy and the price of energy services have diverged significantly and can be expected to diverge in the future, economists still use commodity price series rather than those for services, even when considering long-run issues, mostly because of a lack of data. This reliance on commodity prices may also be due to a lack of appreciation of the implication of not using energy service prices.

Divergences between trends in the prices of energy and their related services have major implications for the process of studying long-run trends in energy markets and climate change. First, as Nordhaus (1996) pointed out, focusing on energy prices in the long run dramatically underestimates the welfare gains to the consumer and should affect traditional measures of the overall consumer price index. The data examined here indicate that, in the long run, people have also been able to heat their homes, push and pull objects, move people and goods, and light their homes far more cheaply than a simple examination of the consumer price index would suggest. These services have radically altered people's lives. This evidence further supports the argument that we need to alter the way consumer price indices are measured.

Second, there are important implications if the correct consumer price index in the past is lower than originally thought and if it is also likely to be lower in the future than previously expected. One implication is the interesting debate about the values of future environmental resources for assessing the scale of damages that will be caused by climate change (Sterner and Persson 2008). The values will depend, in part, on the relative (shadow) prices of those resources. Given that energy service prices and thus, to some extent, overall consumer price indices are likely to be lower in the future than might be expected, the prices of environmental resources will probably be relatively higher. Thus, a better understanding of long-run prices is important for this debate.

Third, as a result of the radical price decreases, the incentive has been for the economy and society to become more heat, transport, and light intensive in particular (Table 1). Looking forward, while more research is needed to ascertain whether heating and power prices will fall, we can anticipate substantial further improvements in transport and lighting efficiency. Thus, the global economy is likely to become even more mobile and dependent on lighting. This obviously has major implications for both energy markets and climate change.

Fourth, building on this last point, modelers need to try to estimate the income and price elasticity of the demand for heat, power, transport, and light, as these drive the behavior associated with energy consumption and greenhouse gas emissions.[10] After all, focusing only on energy rather than energy services will produce misleading estimates of consumer responses to long-run income, price, and efficiency changes.

[10]Until now, transport is the only service for which elasticities have been estimated (Small and Van Dender 2007).

Models of energy use and forecasts of greenhouse gas emissions have often been based on the relationship between energy use, gross domestic product (GDP) growth, and fuel prices. Because of the lack of data and possibly the lack of awareness about the implications, energy service demand has been ignored. However, better insights into future fuel use and emissions might come from understanding the two-stage relationship between (1) energy consumption, energy technologies, and delivered energy services and (2) energy service consumption, GDP growth, and the prices of energy services. Inclusion of energy services in models should improve our understanding of energy markets in both industrialized and developing economies (Howarth 1997; Haas, Nakicenovic, and Ajanovic 2008).

Policy Implications

Historically, government decisions have, at times, considerably influenced the evolution of energy markets (such as coal taxes in the eighteenth century) or their associated services (such as the Reformation and its impact on roads). In addition to being aware of the long-run impacts of their decisions, it is important for governments to appreciate the difference between markets for energy and markets for related services and to consider how to decouple energy from its services. This would ensure more carefully directed policies and, even though short-term fears about energy price hikes often have to be appeased, help governments to develop long-run strategies that meet the need for "sustainable" services.

Furthermore, while the figures in this article identify long-run trends in private marginal costs, they ignore the external costs. For example, in the sixteenth century, the adoption of chimneys in buildings allowed residents to externalize smoke and thus make the transition to cheaper, but more polluting, coal. By the end of the nineteenth century, the accumulation of smoke emissions on cold, windless days in British cities was responsible for externalizing an estimated 70 percent of the social costs of coal production and consumption and imposing damages equivalent to 17.5 percent of GDP (Brimblecombe 1987; Fouquet 2011a). Thus, price evidence tells us little about trends in full social costs.

Similarly, persistently declining energy service prices (along with growing populations and economies) have dramatically increased greenhouse gas emissions over the past two centuries, which are now imposing costs associated with climate change (Tol 2002; Aroonruengsawat and Auffhammer 2010). Governments need to appreciate that markets will be encouraged to consume more services, possibly imposing very high external costs in the future.

Some might suggest that the current global economy is facing pressures on the atmosphere similar to those experienced by the United Kingdom's eighteenth-century economy with respect to land. The Industrial Revolution may have been triggered, in part, by rising long-run energy and energy service prices. The difference now, however, is that energy and energy service prices fail to signal *atmospheric* scarcity. Instead, the economy is depending on governments to provide the correct signal to trigger a low-carbon industrial revolution.

References

Adelman, M. A. 1995. Trends in the price and supply of oil. In *The state of humanity*, ed. J. L. Simon, Oxford: Basil Blackwell p. 287–93.

Allen, R. C. 2007. Pessimism preserved: Real wages in the British Industrial Revolution. Economics Series Working Papers 314. Oxford: University of

Oxford, Department of Economics. http://www.nuffield.ox.ac.uk/General/Members/allen.aspx. (accessed July 10, 2011).

———. 2009. *The British Industrial Revolution in global perspective*. Cambridge: Cambridge University Press.

Aroonruengsawat, A., and M. Auffhammer. 2010. Impacts of climate change on residential electricity consumption: Evidence from billing data. In *Climate change past and present: Uncertainty and adaptation,* ed. G. Libecap, and R. H. Steckel. Chicago: University of Chicago Press p. 311–42.

Barnett, H. J., and C. Morse. 1963. *Scarcity and growth: The economics of natural resource scarcity*. Washington, DC: Resources for the Future.

Berck, P., and M. Roberts. 1996. Natural resource prices: Will they ever turn up? *Journal of Environmental Economics and Management.* 31 (1): 65–78.

Beveridge, W. 1894. *Prices and wages in England: From the twelfth to the nineteenth century*. London: Longmans, Green and Co.

Billington, N. S. 1982. *Building services engineering: A review of its development.* London: Pergamon.

BP. 2010. *BP statistical review of world energy*. London: BP.

Brimblecombe, P. 1987. *The big smoke: A history of air pollution in London since medieval times*. London: Methuen.

Church, R. 1987. *The history of the British coal industry, Vol. 3, 1830–1913*. Oxford: Clarendon Press.

Clark, G. 2007. The long march of history: Farm wages, population, and economic growth, England 1209–1869. *Economic History Review* 60 (1): 97–135.

Crafts, N. F. R. 2004. Steam as a general purpose technology: A growth accounting perspective. *Economic Journal,* 114 (3): 338–51.

Crowley, J. E. 2004. *The invention of comfort: Sensibilities and design in early modern Britain and early America*. London: John Hopkins University Press.

DoT. 2002. *GB transport statistics*. London: HMSO.

Edwards, P. R. 1988. *The horse trade in Tudor and Stuart England*. Cambridge: Cambridge University Press.

Farzin, Y. H. 1992. The time path of scarcity rent in the theory of exhaustible resource. *Economic Journal* 102 (4): 812–30.

Fisher, A. C. 1981. *Resource and environmental economics*. Cambridge: Cambridge University Press.

Flinn, M. W. 1984. *The history of the British coal industry, Vol. 2, 1700–1830*. Oxford: Clarendon Press.

Fouquet, R. 2008. *Heat power and light: Revolutions in energy services*. Cheltenham: Edward Elgar Publications.

———. 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy* 38 (10): 6586–96.

———. 2011a. Long run trends of energy-related external costs. BC3 Working Paper Series 2011-01. Bilbao, Spain. Basque Centre for Climate Change (BC3).

———. 2011b. The sustainability of 'sustainable' energy use: Historical evidence on the relationship between economic growth and renewable energy. In *Handbook of Sustainable Energy,* ed. I. Galarraga, M. González-Eguino, and A. Markandya. Cheltenham: Edward Elgar Publications. p. 8–29.

Fouquet, R., and P. J. G. Pearson. 2003. Five centuries of energy prices. *World Economics.* 4 (3): 93–119.

———. 2006. Long run trends in energy services: The price and use of lighting in the United Kingdom, 1300–2000. *Energy Journal.* 25 (1): 139–77.

Goldemberg, J., T. B. Johansson, A. K. N. Reddy, and R. H. Williams. 1985. An end use oriented energy strategy. *Annual Review of Energy and the Environment* 10: 613–88.

Haas, R., N. Nakicenovic, and A. Ajanovic. 2008. Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. *Energy Policy* 36 (11): 4012–21.

Hamilton, J. D. 2011. Historical oil shocks. NBER Working Paper 16790. Cambridge, MA: MA National Bureau of Economic Research.

Hatcher, J. 1993. *The history of the British coal industry, Vol. I*. Oxford: Clarendon Press.

Hausman, W. J. 1987. The English coastal coal trade, 1691–1910: How rapid was productivity growth? *Economic History Review* 40: 588–96.

———. 1995. Long-term trends in energy prices. In *The state of humanity*, ed. J. L. Simon. Oxford: Basil Blackwell p. 280–6.

Hotelling, H. 1931. The economics of exhaustible resources. *Journal of Political Economy* 39: 137–75.

Howarth, R. B. 1997. Energy efficiency and economic growth. *Contemporary Economic Policy* 15 (4): 1–9.

Jackman, W. T. 1960. *The development of transportation in modern England*. London: Frank Cass.

Jevons, W. S. 1865. *The coal question: An inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*. London: Macmillan.

Kander, A., and P. Warde. 2011. Energy availability from livestock and agricultural productivity in Europe, 1815–1913: A new comparison. *Economic History Review* 64 (1): 1–29.

Krautkraemer, J. A. 1998. Nonrenewable resource scarcity. *Journal of Economic Literature* 36 (3): 2065–107.

Langdon, J. 2005. *Mills in the medieval economy: England 1300–1540*. Oxford: Oxford University Press.

Livernois, J. 2009. On the empirical significance of the Hotelling Rule. *Review of Environmental Economics and Policy* 3 (1): 22–41.

Malthus, T. R. 1798. *An essay on the principle of population as it affects the future improvement of society*. London: Ward Lock.

Masschaele, J. 1993. Transport costs in medieval England. *Economic History Review* 46 (2): 266–79.

Maugeri, L. 2009. Understanding oil price behaviour through an analysis of a crisis. *Review of Environmental Economics and Policy* 3 (2): 147–66.

Mitchell, B. R. 1988. *British historical statistics*. Cambridge: Cambridge University Press.

Nef, J. U. 1926. *The rise of the British coal industry, Vol. I–II*. London: Routledge and Sons.

Nordhaus, W. D. 1974. Resources as a constraint on growth. *American Economic Review* 64: 22–26.

———. 1996. Do real output and real wage measures capture reality? The history of lighting suggests not. In *The Economics of New Goods*, ed. T. F. Breshnahan, and R. Gordon. Chicago: Chicago University Press p. 29–66.

Nunn, N. 2009. The importance of history for economic development. *Annual Review of Economics* 1 (1): 65–92.

Pindyck, R. S. 1999. The long-run evolution of energy prices. *Energy Journal* 20 (2): 64–78.

Potter, N., and F. T. Christy. 1962. *Trends in natural resource commodities*. Baltimore: Johns Hopkins University Press for Resources for the Future.

Ricardo, D. 1817. *On the principles of political economy and taxation*. London: John Murray.

Rogers, J. E. T. 1865, 1882, 1886. *A history of agriculture and prices in England, Vol. I–VI*. Oxford: Clarendon Press.

Rogner, H. H. 2000. Energy resources and technology options. In *World Energy Assessment (WEA)*, ed. J. Goldemberg, and T. B. Johansson. New York: UNDP p. 135-71.

Schivelbusch, W. 1988. *Disenchanted night: The industrialization of light in the nineteenth century*. Oxford: Berg.

Slade, M. E. 1982. Trends in natural resource commodity prices: An analysis of the time domain. *Journal of Environmental Economics and Management* 9 (2): 122–37.

Small, K. A., and K. Van Dender. 2007. Fuel efficiency and motor vehicle travel: The declining rebound effect. *Energy Journal* 28 (1): 25–52.

Smil, V. 1994. *Energy in world history*. Boulder, CO: Westview Press.

Smith, V. K. 1979. Natural resource scarcity: A statistical analysis. *Review of Economics and Statistics* 61: 423–7.

Sterner, T. 2007. Fuel taxes: An important instrument for climate policy. *Energy Policy* 35 (6): 3194–202.

Sterner, T., and U. M. Persson. 2008. An even Sterner Review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy* 2 (1): 61–76.

Stevens, P. 2010. *The 'Shale Gas Revolution': Hype and reality*. Chatham House Report. London: Chatham House.

Thompson, F. M. L. 1976. Nineteenth century horse-sense. *Economic History Review* 39 (1): 60–81.

Tol, R. S. J. 2002. Estimates of the damage costs of climate change: Part II. Dynamic estimates. *Environmental and Resource Economics* 21: 135–60.

Varian, H. R. 1992. *Microeconomic analysis*. New York: W. W. Norton.

Warde, P. 2007. *Energy consumption in England & Wales 1560–2000*. Napoli: Consiglio nazionale delle ricerche.