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Lessons from energy history for climate policy

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Lessons from Energy History for Climate Policy[1]

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September 2015

Abstract

This paper sought to draw lessons from long run trends in energy markets for energy and climate policy. An important lesson is that consumer responses to energy markets change with economic development. In particular, evidence suggests that income elasticities[2] of demand for energy services have tended to follow an inverse-U shape curve. Thus, at low levels of economic development, energy service consumption tends to be quite responsive to per capita income changes; at mid-levels, consumption tends to be very responsive to changes in income per capita; and, at high levels, consumption is less responsive to income changes. The paper also highlights the risks to developing countries of locking-in to carbon intensive infrastructure or behaviours. Without guidance and incentives, rapid economic development is likely to lock consumers into high energy service prices in the long run and bind the economy onto a high energy intensity trajectory with major long run economic and environmental impacts. Thus, effective energy service policies in periods of rapid development, such as in China and India at present, are crucial for the long run prosperity of the economy.

[1] I would like to thank Alex Bowen, Chris Duffy, Paul Ekins, Sam Fankhauser, Mar Rubio, David Stern and Dimitri Zenghelis for valuable comments about this brief. Of course, all errors are my responsibility. Financial support has come from the Global Green Growth Institute, the Grantham Foundation for the Protection of the Environment, as well as the UK Economic and Social Research Council through the Centre for Climate Change Economics and Policy. The views expressed in this paper represent those of the authors and do not necessarily represent those of the host institutions or funders.

[2] The income elasticity of demand for an energy service indicates the percentage change in the consumption of the energy service for a one percent change in income. For example, an income elasticity of 0.5 (or 1.5) implies that, if income rises by 10%, consumption will increase by 5% (or 15%, respectively). Similarly, the price elasticity indicates the percentage change in the consumption of the energy service for a one percent change in the price of the energy service. That is, a price elasticity of -0.5 (or -1.5) implies that, if prices rise by 10%, consumption will fall by 5% (or 15%, respectively).

1. Introduction

The anthropogenic effects on climate change have their roots in the Industrial Revolution and the associated transformation of the energy system. In particular, it set the global economy on a trajectory of rising levels of energy consumption, with great benefits to mankind, and carbon dioxide emissions, with more worrying consequences. More generally, technological, institutional and behavioural lock-ins imply that energy systems have remained unchanged for long periods of time (Aghion et al. 2014, Acemoglu et al. 2015).

As a result, climate strategies and policies, particularly those related to transforming the energy system, need to look decades or even centuries into the future. However, most climate policies are formulated on the basis of short or medium run perspectives – rarely analysing experiences more than a decade or two in the past.

Probably reflecting the growing need to look back, many notable books and journal articles have been published in the past decade on the history and long run nature of energy markets and their environmental effects (e.g., Fouquet 2008, Allen 2009, Ayres and Warr 2009, Wrigley 2010, Smil 2010, Mitchell 2011, Kander et al. 2013, Jones 2014, Grübler and Wilson 2014). These built on earlier generations of studies related to energy history (including Nef 1926, Schurr and Netschert 1960, Cipolla 1962, Landes 1969, von Tunzelmann 1978, Flinn 1984, Wrigley 1988, Smil 1994, Nye 1998, Grübler 1998).

Evidence from these historical and long run analyses offers valuable insights for long run energy and climate policy. In this paper, it would be impossible to summarise the evidence produced by this vast literature. *The objective of this paper is to provide some specific insights from a comprehensive research programme focussing on the United Kingdom's long run energy trends and developments, and their relevance for energy and climate policy.*

In the following section, this paper presents trends in the price and consumption of energy services (i.e., heating, power, transport and lighting) over the past three hundred years, discusses estimates of the related trends in income and price elasticities since the Industrial Revolution, and reviews the environmental impacts of energy consumption over this time period. In Section 3, this paper considers the transferability and relevance of past trends and experiences in the United Kingdom for future patterns of behaviour. Section 4 (based on this evidence) offers policy recommendations for climate policy.

It is worth emphasizing that to provide strong lessons and direct policy recommendations while keeping the text concise, this paper has needed to be efficient with its words. Inevitably, this may have led to simplifications. The reader seeking more depth and detail is encouraged to access the referenced publications, and sources for the insights discussed below.

2. Lessons from Energy History

Insight 1. Energy is Consumed in order to Meet a Demand for Energy Services

Energy consumers are driven by their demand for energy services (such as space and water heating, transportation, appliance uses and lighting), and the costs associated with these services are crucial for understanding energy consumption patterns. The cost of the energy services generally combines the price of energy and the efficiency of the energy technology used.

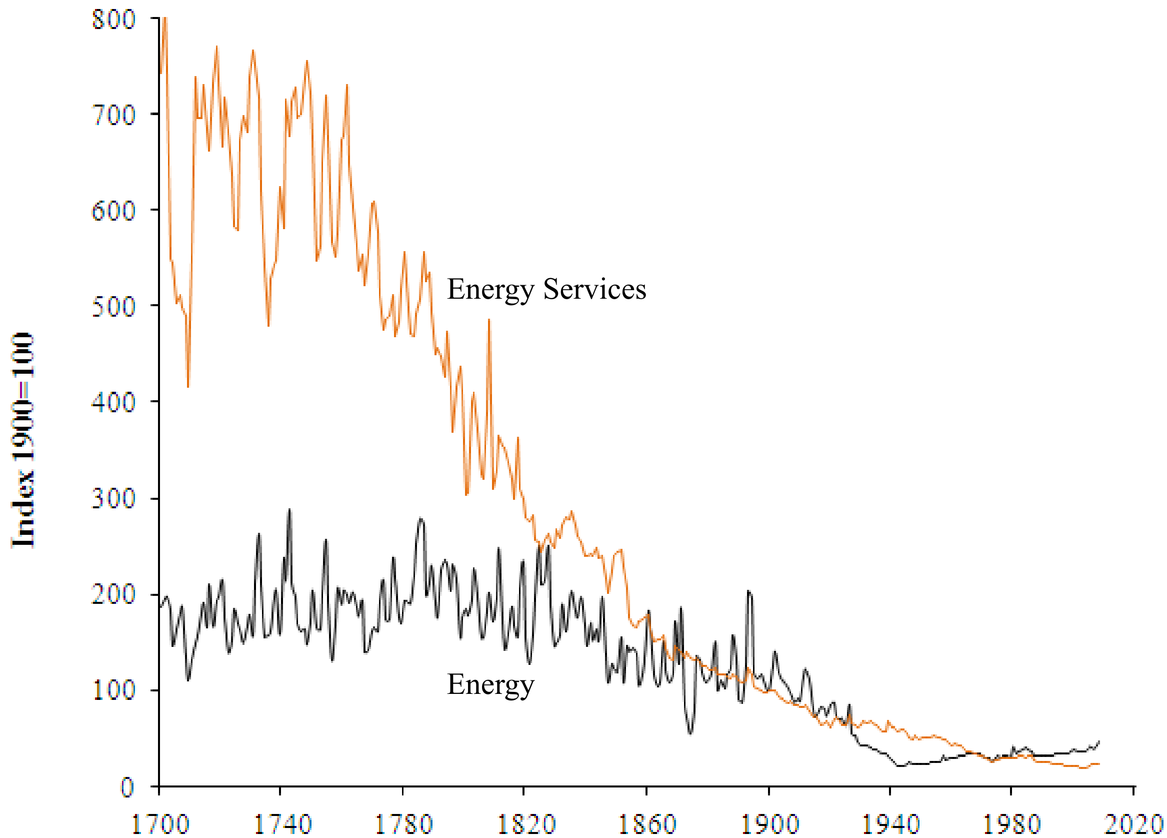
For example, in the nineteenth century, town gas (derived from coal) was the dominant source of lighting (Fouquet and Pearson 2006). A town gas lamp from the late 1820s would have generated 130 lumen-hours per kWh; by 1916, the 'Welsbach Mantle' gas lamp produced more than six times more light, 870 lumen-hours per kWh (Nordhaus 1996). With this information, and data on gas prices, the price of lighting can be estimated – the price of gas lighting in 1830 was £2,700 (in 2000 money) for one million lumen-hours (equivalent to leaving-on a 100-watt incandescent bulb for 30 days) and, in 1920, it was £40. Today, with LED lighting generating 66,000 lumen-hours per kWh, it costs under £1 for the same amount of illumination. In a similar way, consumption of gas and electricity (or other energy sources) can be combined with the efficiency of the technology to estimate lighting use or the consumption of other energy services[3].

As shown in this example, an additional advantage of focussing on energy services (rather than energy) is that the demand for energy services remains comparable with the introduction of new energy sources and technologies. Because of improvements in lighting efficiency between the nineteenth and twenty-first centuries, it would be difficult to properly compare long run behaviour without focusing on the service. Similarly, changes in vehicle efficiency pre- and post-1973 imply that the benefits (or utility) to a car user from consuming one litre of petrol has greatly changed over the last forty years, making it difficult to analyse long run demand using direct analysis of car user energy consumption. Instead, focussing on the energy services provided (e.g., the passenger-kilometres or lumen-hours) helps to identify very long run patterns in consumption that would be hidden by focussing only on the changing uses of different energy sources.

[3] So, while lighting is measured in terms of lumen-hours (where one million lumen-hours is equivalent to leaving-on a 100-watt incandescent bulb for 30 days), passenger transport is measured as passenger-kilometres (km), that is, moving one passenger one km, and freight transport as tonne-km. Residential heating is measured as one tonne of oil equivalent (toe) of effective heating – that is, if a heating system converts one toe (or the calorific equivalent of one toe of firewood, coal, natural gas or electricity) into heating with 100% efficiency, then one toe of 'effective heating' has been consumed. If the heating system is only 10% efficient, as eighteenth century fireplaces were, then the same amount of fuel would only provide one-tenth of one toe of effective heating.

Insight 2. Energy Service Prices tend to Decline in the Long Run

Evidence indicates that, since the First Industrial Revolution, there has been an acceleration in the tendency of households and firms to find ways of consuming energy more efficiently, producing cheaper energy services (Fouquet 2008). A crucial role was played by knowledge production and its declining cost in driving the transformations in the energy system (stimulated initially by the creation of the patent system in the sixteenth century and the Scientific Revolution in the late sixteenth and seventeenth centuries (Mokyr 2002)) and of the diffusion of new energy technologies. This was facilitated by the introduction of new energy sources, such as coal/town gas, petroleum products, electricity and natural gas.



Source: Fouquet (2011)

Figure 1. Average Price of Energy and of Energy Services[4] in the United Kingdom (1700-2008)

[4] The energy service price series only exists as an indexed average price series (1900 = 100) – there is no other unit of measurement, because each energy service price has its own unit of measurement, so, the only way to combine them is by converting them into an index. Thus, each individual energy service (passenger transport, lighting, etc..) price series was

Nordhaus (1996) and Fouquet (2011a) showed that there has been a divergence between the price of energy and of energy services (see Figure 1). While average energy prices may have increased (as they did in the second-halves of the eighteenth and twentieth centuries), decreased (e.g., in the first-halves of the nineteenth and twentieth centuries) or stayed stable (e.g., in the first-halves of the nineteenth and twentieth centuries), the price of energy services has tended to fall in the long run. The divergence implies that focussing exclusively on energy prices and consumption and failing to consider energy services will lead to misleading conclusions about energy consumption behaviour.

An example of this divergence was associated with the beginning of the transition away from town gas towards electricity for lighting. While individual fuel prices (i.e., for town gas and electricity) were declining at the beginning of the twentieth century, average energy prices for lighting remained stable. Over that period, the price of lighting fell dramatically (Fouquet 2011). The reason for the divergence was that the consumers, interested in cheaper energy services, increasingly bought more expensive energy sources (i.e., electricity rather than town gas) but which were used in conjunction with much more efficient energy technologies. At the beginning of the twentieth century, town gas was cheaper than electricity per unit of energy, but electric lighting technology was six times more efficient at converting the energy into lumens (Nordhaus 1996). As electricity prices fell (and particularly once they were less than six times the price of town gas), consumers made the transition to electric lighting – but, this also implied that the average price of energy for lighting had gone up, though the average price of lighting had fallen. By the mid-twentieth century, electricity had taken-over the majority of the lighting market (Fouquet and Pearson 2006).

Insight 3. Energy Service Consumption Rises in the Long Run

These declining prices of energy services, along with rising incomes, have driven-up energy service consumption and, as a consequence, energy consumption – with the former far out-pacing the latter. Indeed, income growth played a crucial role in driving-up demand in the United Kingdom. Thus, with probable continuation of declining energy service prices (as consumers invest in more efficient technologies) and likely rising incomes, one might expect future trends in the consumption of energy services to continue upwards. However, the size of the increases depends crucially on income and price elasticities, which, in turn, may depend on the phase of economic development.

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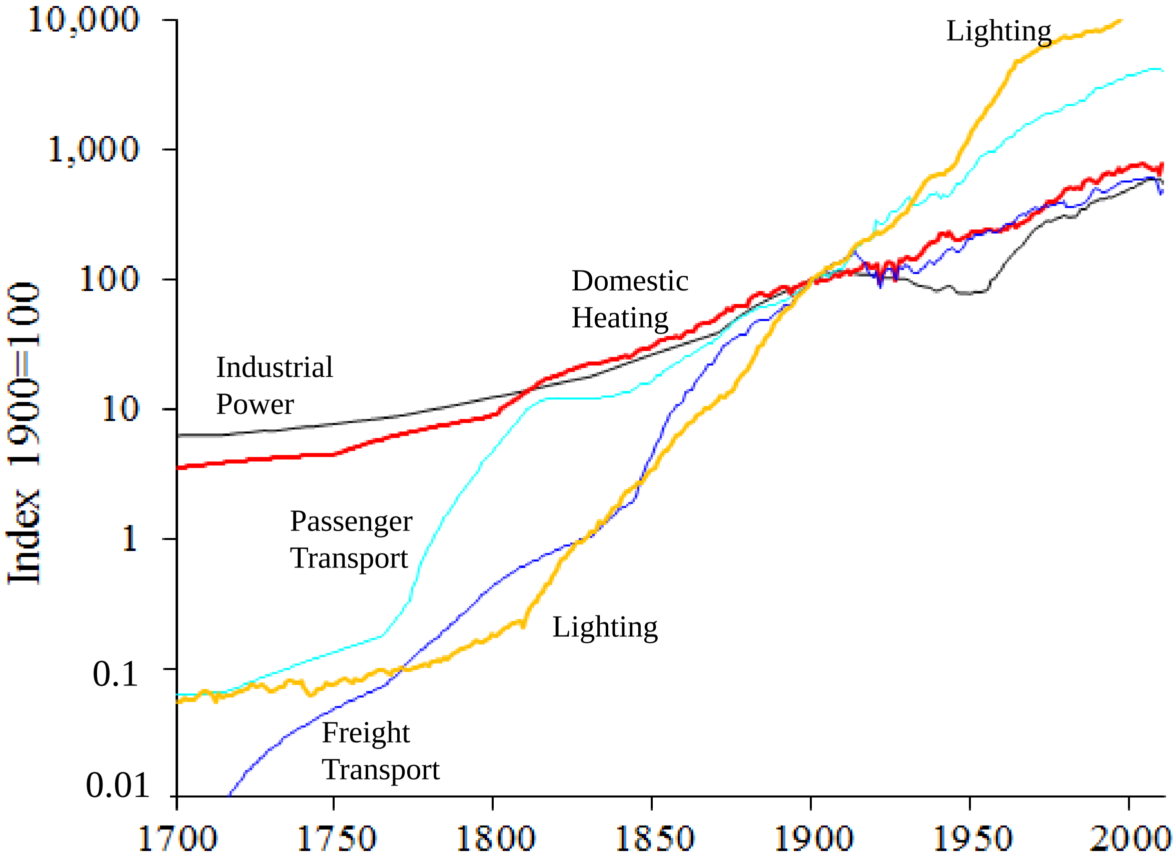
converted from its specific units (e.g., passenger-kms, lumen-hours, etc.. – see footnote 3 for details) into an index where 1900 = 100 and combined by weighting them by the consumer expenditures associated with each energy service.



Source: Fouquet (2014)

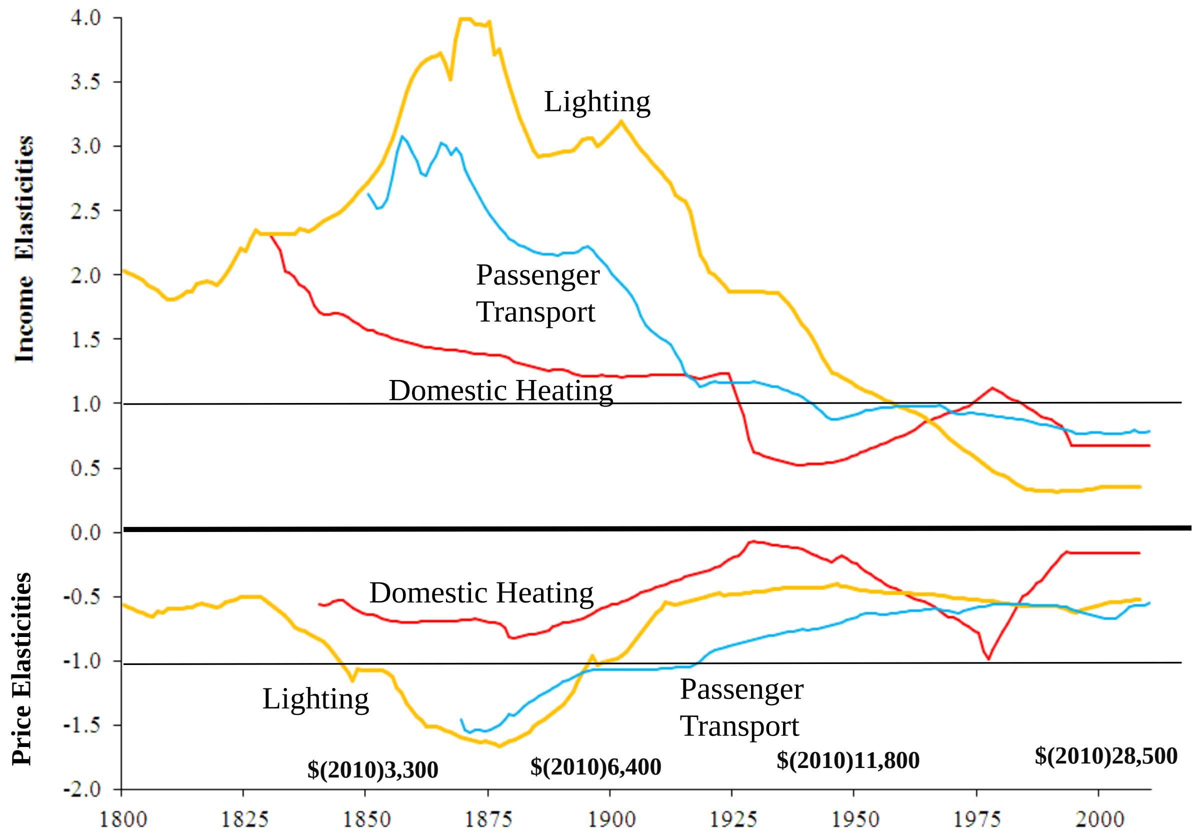
Figure 2. Consumption of Energy Services in the United Kingdom, Index 1900=100, 1700-2010

Insight 4. Income and Price Elasticities Change with Economic Development

The responsiveness of energy consumption to changes in income and prices (i.e., the income and price elasticities) have changed through time. The main finding from Fouquet (2014) is that, as the United Kingdom economy developed over the last two hundred years, trends in income elasticities followed an inverse U-shape curve[5] (see Figure 3, top-half). For instance, they reached a peak (about 2.3, 3.0 and 4.0 for income elasticities of demand for heating, transport and lighting, respectively) in the nineteenth century (at levels of GDP per capita below $(2010) 6,000. For example, when GDP per capita was around $(2010) 4,000, in the second half of the nineteenth century, a 10% increase in per capita income would

[5] For a discussion of the methods used to estimate income and price elasticities, please see the appendix.

lead to a 30% rise in transport use. Similarly, a 10% increase in per capita income would lead to a 40% rise in lighting consumption.



Source: Fouquet (2014)

Figure 3. Income and Price Elasticities of Demand for Energy Services, 1800-2010

After the peaks, there were, at first, rapid declines, then more gradual declines. Income elasticities took almost 100 years to reach unity (that is, a 10% increase in income led to a 10% rise in energy service consumption), in the mid-twentieth century, at between $(2010) 9,000-12,000 per capita. The results also indicate that income elasticities were significantly different from zero at high levels of per capita income in the twenty-first century, implying that current increases in income generate rises in energy service consumption (roughly, around 5% rises for a 10% increase in income). These rises feed through directly into greater energy consumption.

In other words, consumers at lower levels of income were much more responsive to income changes than wealthier consumers. One could expect developing country energy service (and energy) consumption to rise much more with income than in developed economies. For instance, if China, currently with a per capita income of $6,000 (in 2010 dollars), were to follow a similar trend in income elasticities (as the United Kingdom did historically), then they would have recently peaked and started to decline. Based on the same assumption, however, India's income elasticities might be starting to peak. After the peak, however, income elasticities would remain above unit elasticity for many decades, implying further sizable increases in energy consumption.[6]

That developing economies follow inverse U-shaped income elasticities is very possible, even probable, given saturation effects – that is, an additional unit of energy service generates less benefit or utility to the consumer. However, that they peak and reach unit elasticity at similar levels of per capita GDP as the United Kingdom is highly uncertain. 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 (Fouquet 2014).

Insight 5. Rebound Effects[7] Change with Economic Development

Similarly, price elasticities also change as per capita income rises. The price elasticity of demand for energy services also peaked (at values of about -1.5) at levels of per capita income of between $(2010) 4,000 and $(2010) 5,000 (See Figure 3, bottom-half). That is, in the United Kingdom in the 1870s and 1880s, a 10% reduction in energy prices or a 10% improvement in energy efficiency (both reducing the price of energy services) increased transport and lighting use by around 15% (Fouquet 2014). Any price elasticity less than -1 (that is, more than 1 in absolute terms) leads to a greater increase in energy service use than the efficiency improvement, and increases in energy consumption. This implies that, in the 1870s, energy efficiency improvements associated with transport and lighting led to rises in energy

[6] It is not proposed that China or India will follow the same trend (although, they might). Instead, this cross-country comparison is made to provide a concrete example of applying directly the United Kingdom's experience to present-day industrialising economies. The transferability of these lessons to present-day experiences is discussed in Section 3.

[7] Rebound effects refer to consumer, producer and market responses to energy efficiency improvements. They include a direct effect on the consumption of energy services and, thus, energy in response to a higher efficiency improvement and lower energy service price. There are also indirect effects on consumption behaviour related to complements and substitutes of the cheaper energy service (and associated energy source) and related to a probable increase in purchasing power (after taking account of the expenditure on the new efficient technology) and, therefore, increase in the consumption of other goods and services. Finally, macroeconomic rebound effects occur because the reduction in the price of energy services tends to boost the economy, stimulating further energy service and energy consumption. Thus, for instance, a 10% improvement in energy efficiency is unlikely to lead to a 10% saving in energy use. Instead, the sizes of the different and combined rebound effects are empirical questions (see, for instance, Sorrell 2009, Gillingham 2014).

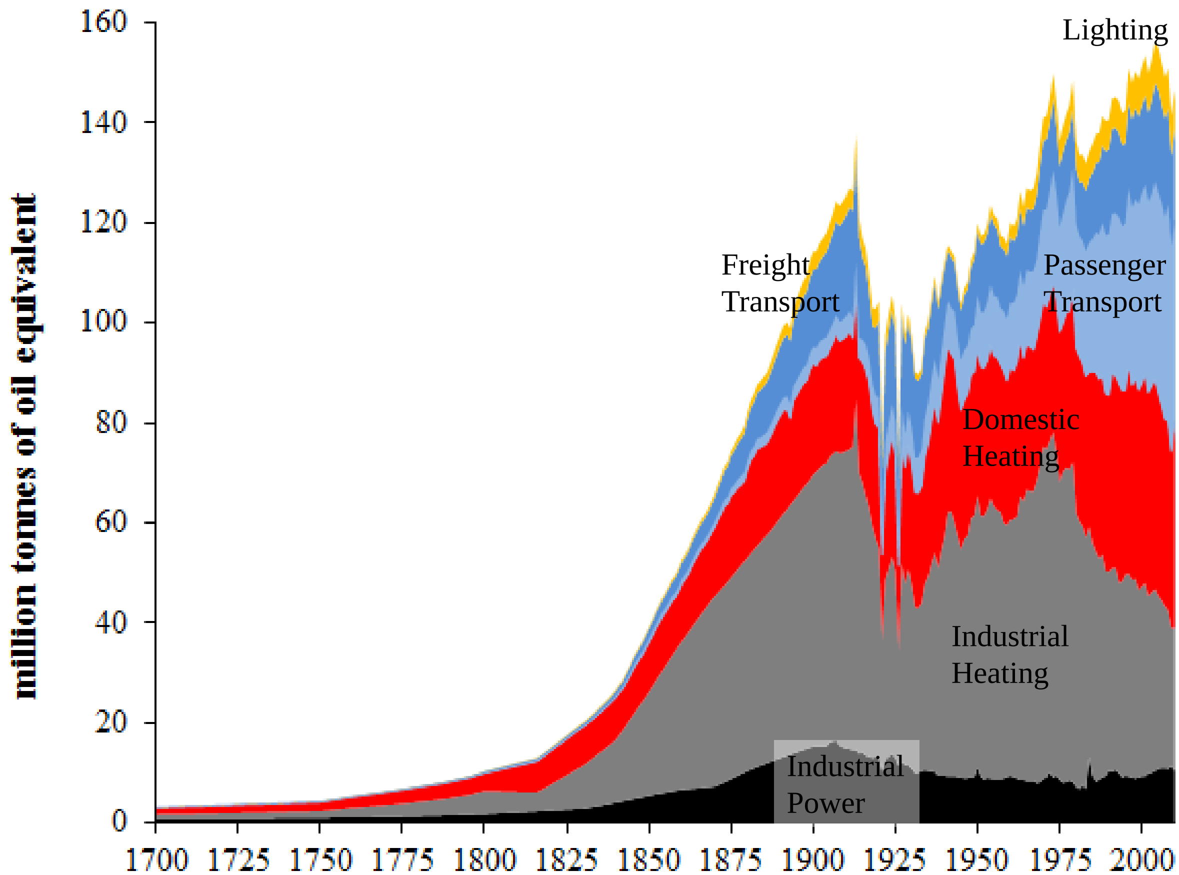
consumption. One might suspect that developing economies today (e.g., around $(2010) 5,000 income per capita) may have high price elasticities of demand for energy services and, therefore, experience large rebound effects.

Just like income elasticities, price elasticities tend to fall (in absolute terms) as income increases. This means that the direct (i.e., excluding indirect and macroeconomic) rebound effects have tended to fall with economic development. Price elasticities of demand for energy services tend to be between -0.1 and -0.5, implying between 90% and 50%, respectively, of the efficiency improvements are fed into energy savings and from 10% to 50%, respectively, lead to increases in energy service consumption.

These results offer the beginnings of a stylised fact about the relationship between elasticities of demand and economic development. That is, at very low levels of economic development, consumers focus on meeting basic needs, particularly food and cooking. As income grows, shelter and indoor climate become important – such as space and water heating, in temperate climates. As income rises further, these demands start to grow less proportionately than income (e.g., income and price elasticities for heating fall). In turn, other demands are met, for instance, mobility, lighting and entertainment (implying rising income and price elasticities for transport and lighting demand). As income increases further, these income and price elasticities start to fall. Thus, following confirmation from further studies, these general patterns could help to guide forecasts of energy service and, therefore, energy consumption. For example, while the IEA (2014) does incorporate saturation into its models (thus, implying declining elasticity through time), they do not take account of the likelihood of peaking elasticities in developing economies.

Insight 6. The Impact of an Energy Transition on Energy Use Depends on Price Elasticities

Grübler (1998) noted that a characteristic of historical energy transitions is that they led to dramatic increases in energy consumption. This was certainly true of energy transitions in the nineteenth century (see Figure 4). The resulting increase in energy consumption depends, first, on the decline in the price of energy services associated with the transition and, second, on the price elasticities of demand for energy services. At the end of the eighteenth century and during the nineteenth century, energy service prices fell rapidly (see Figure 1) and the elasticities were very high (see Figure 3). In the twentieth century, the energy transitions to oil, gas and electricity also drove down the prices of energy services (see Figure 1). However, the price elasticities of demand for energy services were lower (see Figure 3). As a consequence, the increases in consumption of energy services and of energy were less dramatic (see Figure 4).



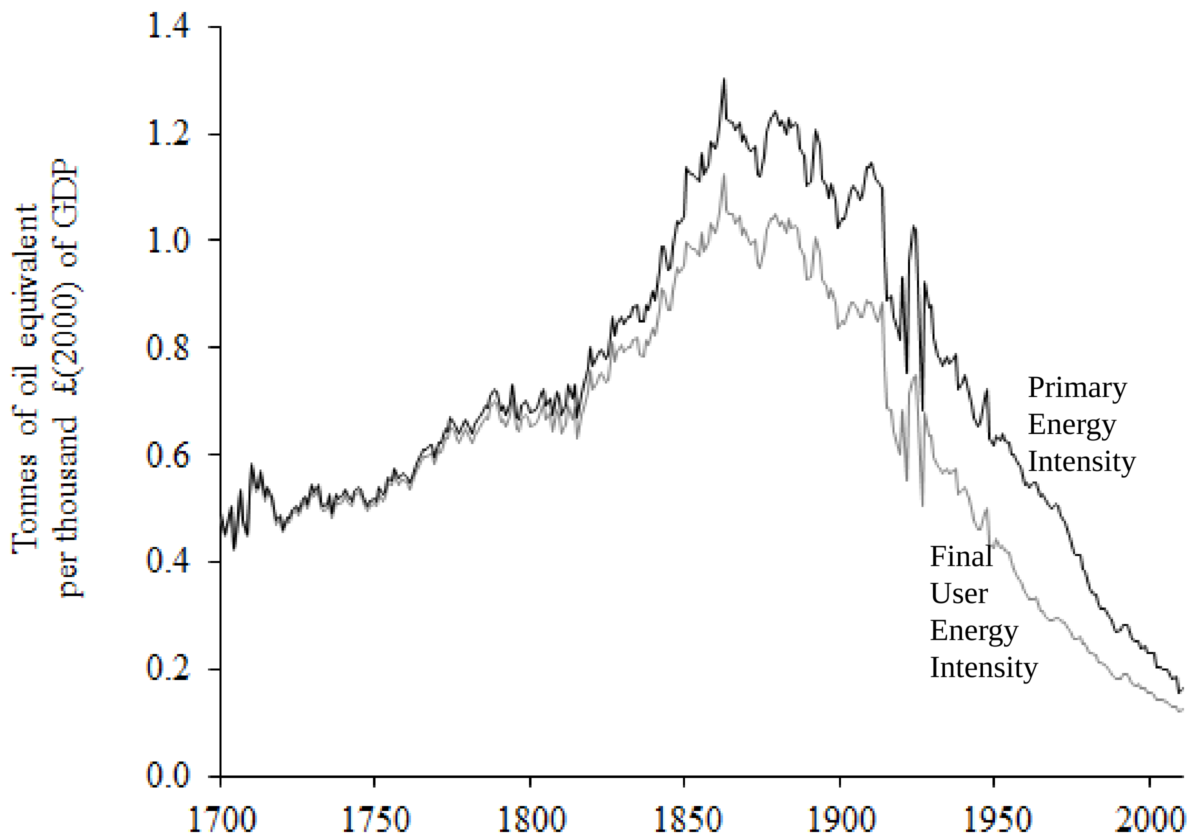
Source: updated from Fouquet (2008)

Figure 4. Energy Consumption by Energy Service in the United Kingdom (mtoe), 1700-2010

Insight 7. The Energy Intensity of the Economy depends on (i) the Demand for Energy Services and (ii) the Energy Efficiency with which these Services are Provided

The demand for particular energy services changes at different stages of economic development. In Britain, income and price elasticities of demand for energy services (i.e., consumer responsiveness to changes) peaked between 1825 and 1875 (see Figure 3). Similarly, Figure 4 displays Britain's dramatic increase in energy consumption related to industrial heating and power during the nineteenth century, which probably also reflect peaking income and price elasticities (though, they are harder to estimate because of the circular causality between energy services use for productive (rather than consumptive) activities and GDP). Thus, the Industrial Revolution (and particularly the technological innovations coupled with the cheap, abundant energy reserves driving down prices of energy services) enabled the British economy to become more heat-intensive, power-intensive and transport-intensive.

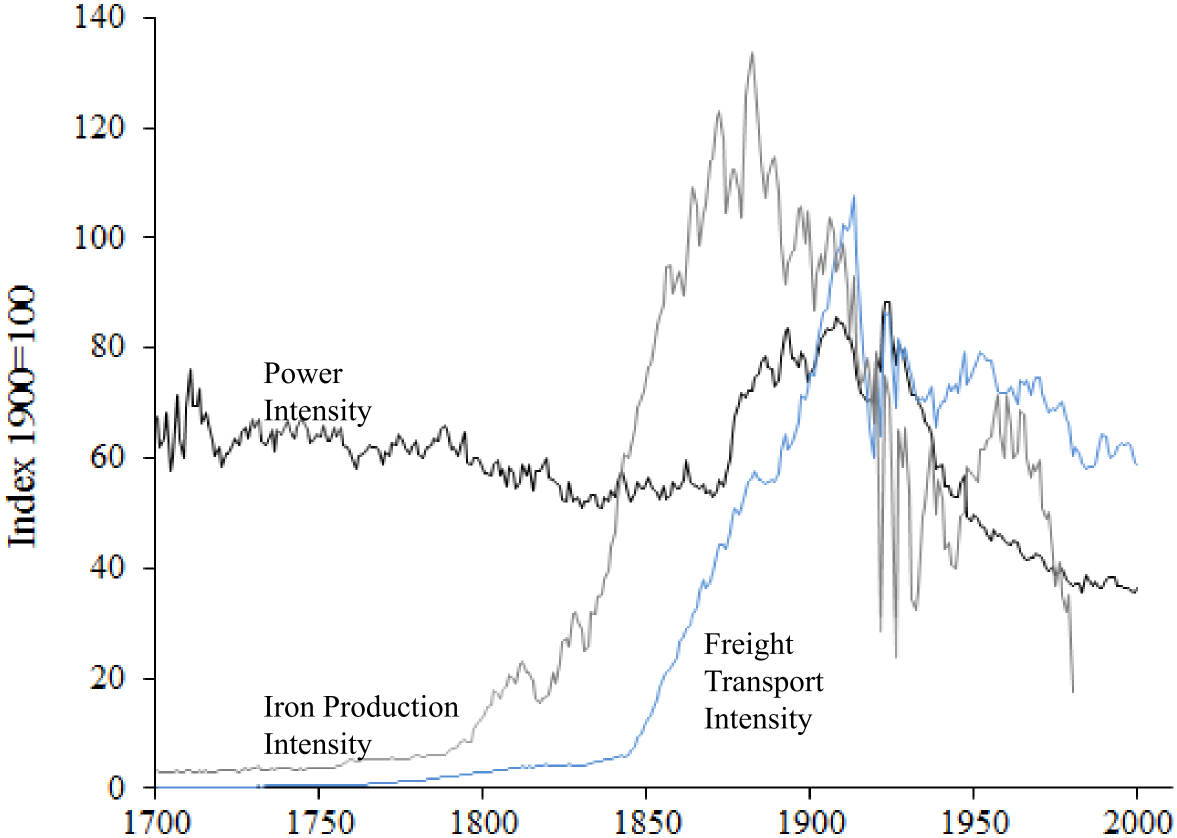
This is reflected in the rise in energy intensity during the eighteenth and especially the first half of the nineteenth century (see Figure 5). This trend can be seen in two ways: first, because energy services were becoming cheaper, firms found ways to produce (e.g., per one pound sterling of GDP) using more heat, power and transport, which implied consuming more energy; and, second, the amount of energy required to produce energy services remained high until the second half of the nineteenth century.



Source: Fouquet (2014)

Figure 5. Energy Intensity in the United Kingdom, 1700-2010

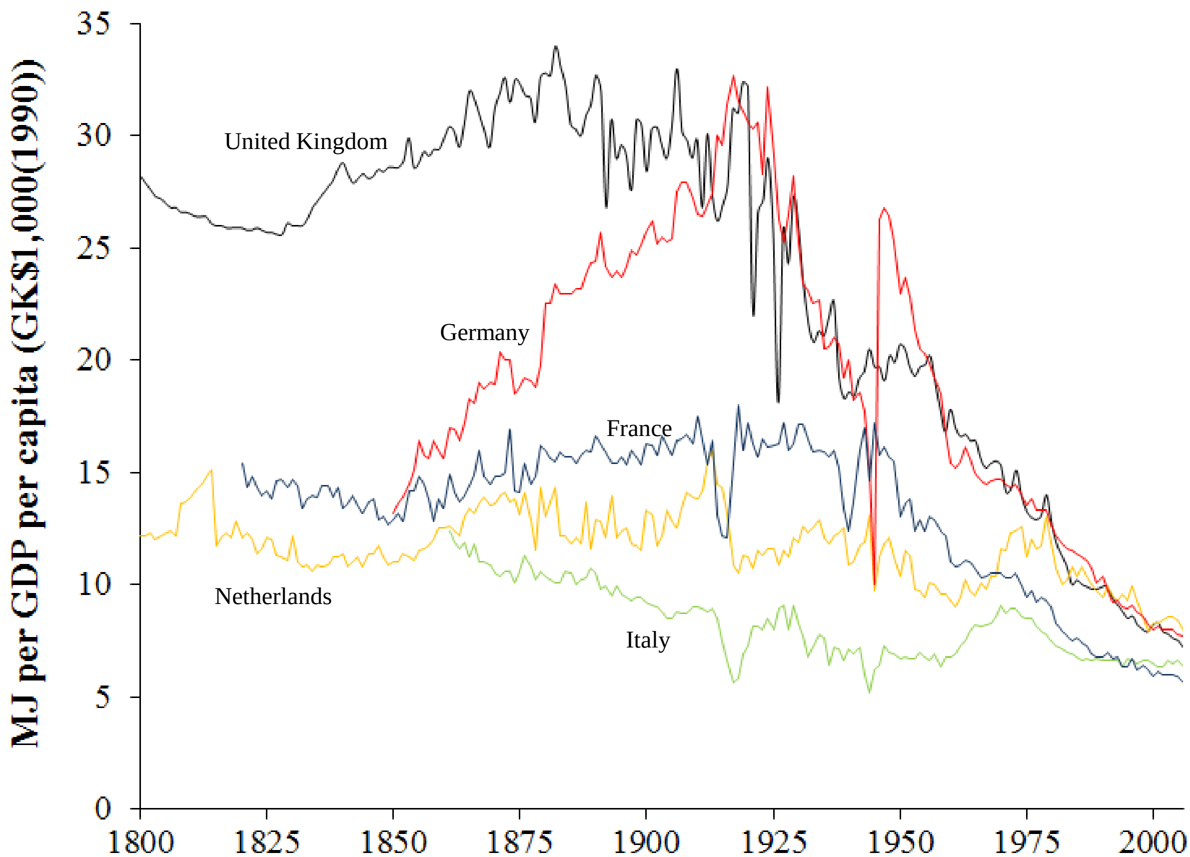
However, from the mid-nineteenth century, the energy intensity declined consistently. That is, the economy no longer needed as much energy to produce one pound sterling of GDP. This could occur for two reasons, either, because the economy became less heat-intensive, power-intensive and transport-intensive or it produced each unit of heat, power and transport more efficiently. Figure 6 indicates that, certainly until the 1920s (i.e., about £(2000) 3,500 or $(2010) 6,500 per capita GDP), this was, in great part, due to improving efficiency. For instance, the economy became more power-intensive and freight transport-intensive during the second half of the nineteenth century. Iron production intensity, which was a great consumer of heating and energy, did decline from the 1870s, indicating a possible decline in the need for heating to produce one pound sterling (or dollar) of GDP. This indicates that, as an economy industrialises, the demand for energy services for production evolves: first, the economy becomes heat-intensive to produce iron and steel to build the infrastructure and the foundation of the economy; then, it needs power to produce (producer and consumer) goods and it needs freight services to distribute those goods around the economy. While the reality is much more complex, it offers a crude model of energy requirements as economies industrialise.



Source: Updated from Fouquet (2008)

Figure 6. Energy Service Intensity per GDP in the United Kingdom, 1700-2000

In other words, the energy intensity of the economy is likely to experience upwards pressures as it industrialises. However, the efficiencies with which these services are provided are crucial for determining the peak energy intensity. Figure 7 shows the energy intensity in a number of European economies. United Kingdom[8] and Germany experienced major increases in energy intensity. The energy intensity in France and the Netherlands increased modestly with industrialisation at the end of the nineteenth century. Meanwhile, Italy's industrialisation process was achieved without increasing its energy intensity. Interestingly, Britain and Germany were both the first economies to industrialise, using inefficient technology (by today's standards) and exporting an important share of their production. They also had access to the large and cheap coal reserves. France, the Netherlands and Italy followed later, using more efficient technology, exporting less and not having access to such large and cheap coal reserves.



Source: Kander et al. (2013)

Figure 7. Energy Intensity in European Countries (Megajoules per GDP per capita), 1800-2008

[8] Note that the United Kingdom's energy intensity differs slightly in the earlier period in Figure 5 and 7 because of different data sources.

This historical experience indicates that developing economies are likely to experience substantial increases in the demand for energy services as they develop – first for industrial heating, then industrial power and freight transport, as the production side of the economy expands. As per capita income levels rise, economies are likely to increase their demand for consumption energy services, such as indoor comfort (whether heating or air-conditioning depending on the climate), passenger transport, and power residential appliances, including lighting, computing, information and communication. These are likely to feed through into greater energy consumption. However, European historical experiences also highlight how economies can develop and increase energy service consumption, while reducing their energy intensity and therefore limiting their rise in energy consumption. Thus, these trends highlight that the experiences in one country need to be applied with care to generate lessons for other countries.

Insight 8. The External Costs of Energy Consumption Can Increase Dramatically

After a period of declining coal prices and soaring consumption of energy services and, thus, of coal, which fuelled the First and part of the Second Industrial Revolution, the nineteenth century British firms and households were externalising the social costs of energy production and consumption on a massive scale. In the 1880s, nearly £(2000) 20 billion (around 20% of GDP) of estimated damage was being caused by air pollution resulting from coal combustion (see Figure 8[9]). Interestingly, air pollution in China in 1995 was estimated to have caused damage equivalent to 9% of GDP (Matus et al. 2012).

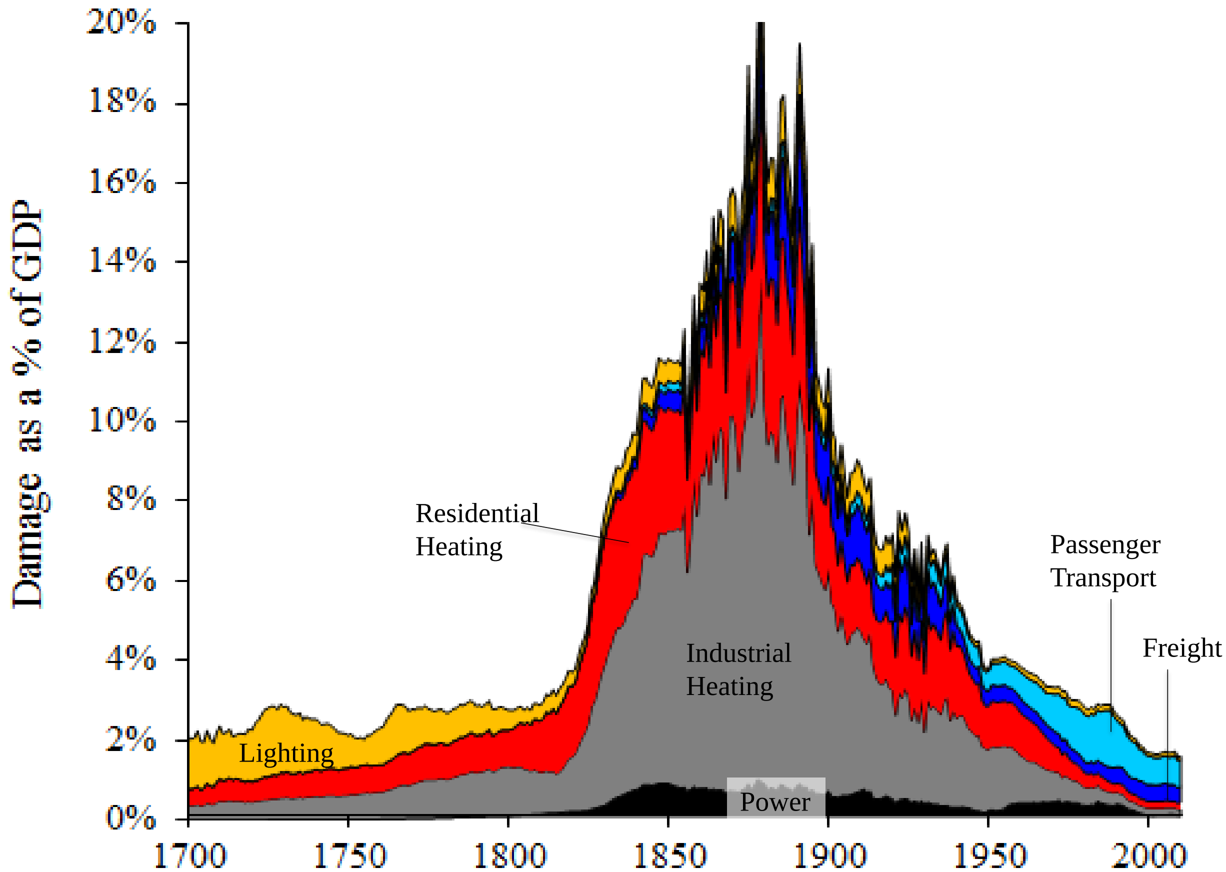
The British economy in the second half of the nineteenth century was highly dependent on coal, particularly for industrial and space heating and industrial power. At the time, improvements in energy efficiency were leading to greater energy consumption because of high price elasticities of demand for energy services. An important factor was that the damage associated with air pollution appears to have been non-linear in the second half of the nineteenth century. For instance, while average air pollution concentrations in London increased by an estimated 30% between 1840 and 1890, deaths attributed to bronchitis in London increased from 20 to 300 deaths per 100,000 inhabitants (Fouquet 2011b).

In the second half of the twentieth century, transport became the source of new air pollution problems. Until the 1980s, and the rapid uptake of unleaded petrol, lead was a major source of air pollution-related health damage; as unleaded petrol was phased-out, associated pollution declined. Particulate matter, however, continues to be a hazard today, responsible for around 70% of energy-related external costs from the transport sector.

Yet, the estimated damage from carbon dioxide emissions continues to increase. Because of the rising damage placed on a tonne of carbon dioxide emitted as carbon concentrations have accumulated (Kunnas et al 2014), the estimated damage from the United Kingdom economy doubled between 1980 and 2000 to £(2000) 12 billion – equivalent to 1% of GDP. Similarly, the share of climate change impacts in total external costs (shown in Figure 8) was estimated to have increased from 27% in 1980 to 46% in 2000.

[9] For a discussion of the methods used to estimate external costs, please see the appendix.

This trend is likely to continue. Thus, while the reductions in coal use led to a decline in total energy-related external costs during the twentieth century, these external costs have risen again, close to £30bn (or 2.4% of GDP) in 2000, due to transport-related air pollution and carbon dioxide emissions. The evidence (see Figure 8) shows that energy service consumption has gone through three phases of external costs, where a particular problem dominated. In the seventeenth and eighteenth century, fires were a major social threat (the property damage associated with the Great Fire of London in 1666 was equivalent to 16% of England's GDP at the time (Fouquet 2008 p.201)); in the nineteenth century, it was air pollution from coal consumption; and in the twentieth and twenty-first century, climate change is the new problem, and could increase dramatically, outweighing the benefits from consuming energy services.



Source: Fouquet (2015)

Figure 8. Energy-Related External Costs from Air Pollution and Climate Change in the United Kingdom, 1700-2000

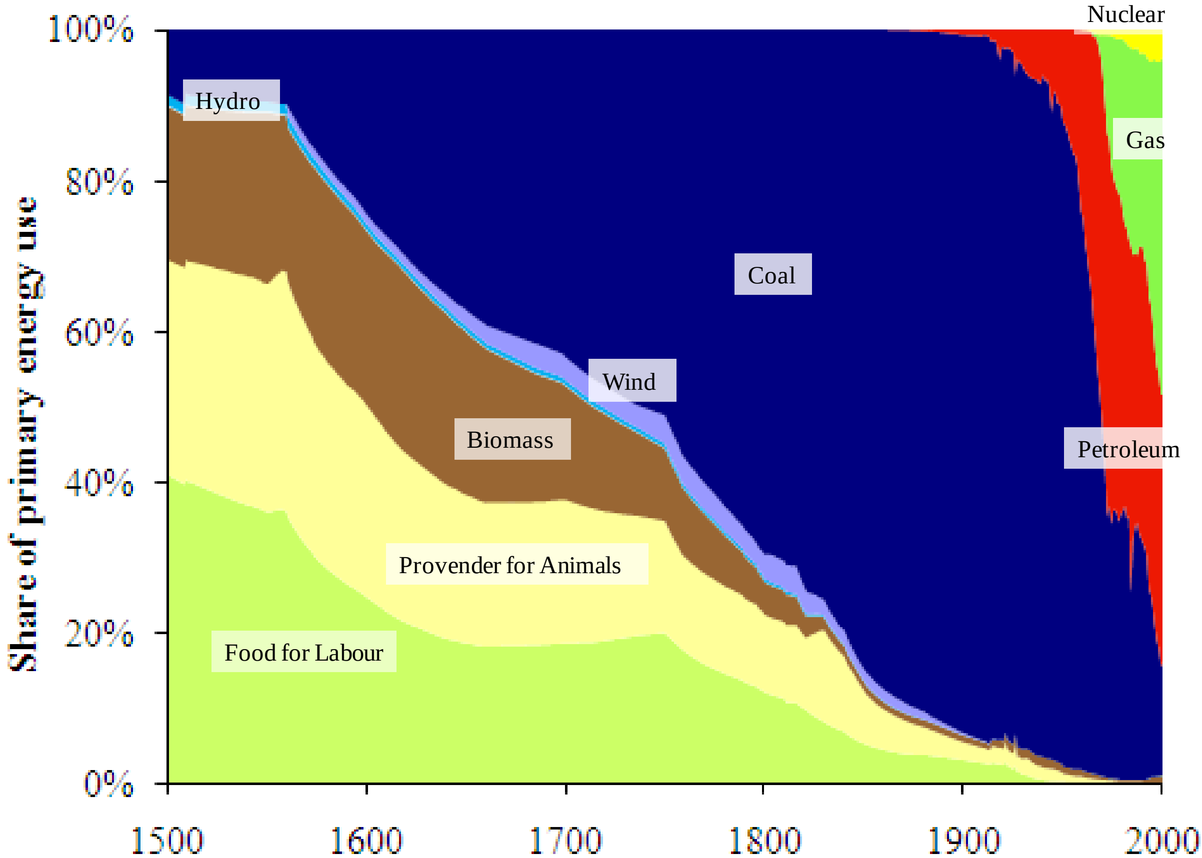
Insight 9. Energy Transitions depend on the Price of Energy Services

Historically, the important drivers for the energy transitions were the opportunity to produce cheaper and/or better energy services (Fouquet 2010). In a majority of cases, a successful new energy source or technology provided the same service (i.e. heating, power, transport or light) with superior or additional characteristics (e.g. easier, cleaner or more flexible to use). Often, after their introduction, the price of the service they provided was higher than from the incumbent energy source. This implied that their adoption was limited to niche markets. However, because some consumers were willing to pay a premium for those better or additional characteristics, these technologies could be refined and costs could fall gradually. Once the price of the service fell sufficiently (either because the energy efficiency improved or the price of energy declined), full transitions could occur. Nevertheless, since the Industrial Revolution, it has taken, on average, nearly fifty years for sector-specific energy transitions (i.e. the diffusion of energy sources and technologies) to unfold[10] (see Figure 9).

The British economy in the second half of the nineteenth century was highly dependent on coal, particularly for industrial and space heating and industrial power. At the time, improvements in energy efficiency were leading to greater energy consumption because of high price elasticities of demand for energy services. An important factor was that the damage associated with air pollution appears to have been non-linear in the second half of the nineteenth century. For instance, while average air pollution concentrations in London increased by an estimated 30% between 1840 and 1890, deaths attributed to bronchitis in London increased from 20 to 300 deaths per 100,000 inhabitants (Fouquet 2011b).

In the second half of the twentieth century, transport became the source of new air pollution problems. Until the 1980s, and the rapid uptake of unleaded petrol, lead was a major source of air pollution-related health damage; as unleaded petrol was phased-out, associated pollution declined. Particulate matter, however, continues to be a hazard today, responsible for around 70% of energy-related external costs from the transport sector.

[10] Rubio and Folchi (2012) show that countries in Latin America with smaller markets for energy tended to be faster to make the transition out of coal and into oil.



Source: Fouquet (2008)

Figure 9. Share of Primary Energy Consumption in the United Kingdom (1500-2000)

Insight 10. Climate Policy is likely to be Weak until Low Carbon Energy Sources and Technologies are Competitive

Throughout history, citizens, observing damages related to air pollution, have demanded improvements in environmental quality, generally through legislation. Past attempts to instigate environmentally benign energy transitions can offer insights for climate mitigation strategies and efforts to direct the economy along a low carbon pathway (Fouquet 2012). In particular, the public reaction following the Big Smog of 1952, when around 12,000 people died from coal-emitted air pollution, led to the introduction of the Clean Air Act and smoke-free zones, and the accelerated uptake of gas for cooking and heating. However, examples of environmental demands in nineteenth and early twentieth century Britain show that while environmental campaigners may manage to get draft legislation introduced, industrialists often managed to weaken the Parliamentary bill´s effectiveness and its enforcement. Nevertheless, each time demands for environmental improvements were made, they sent signals both to government (to introduce effective legislation) and to polluters (that they should seek low pollution solutions and, if they find sufficiently cheap alternatives, to introduce them rather than lobby against the bill and its enforcement). Thus, the development of effective and sustained environmental legislation was not a one-off ´game´, but rather an iterative series of demands (and opposition) that could take decades or centuries to unfold, eventually leading to a sufficiently low-cost solution for polluters to stop opposing the demands (or possibly the disappearance of the problem, because of the decline of the polluting industries). Thus, in the meantime, to achieve a transition towards environmentally-benign energy technologies and sources is likely to need persistent and consistent global collective action.

However, even in this situation, vested interests associated with incumbent energy sources and technologies (e.g., the fossil fuel industry) might hinder the diffusion of low carbon energy sources and technologies (Barbier 2013), keeping the global economy on a socially inferior pathway. The influence of vested interests, as well as other technological, institutional and behavioural lock-ins, implies path dependencies in the energy system (Aghion et al 2014). In other words, the demand for climate stabilisation and the development of successful climate policies are likely to follow a similarly protracted course.

3. Transferability of Historical Lessons to Future Patterns of Behaviour

A key issue for this paper is the relevance and transferability of the historical evidence to present-day industrialised and developing economies. Theory acts as the conduit between past experiences and lessons for understanding future behaviour and formulating policies. However, at present, no formal economic theory of how income and price elasticities vary at different phases of economic development exists (Lewbel 2007). Instead, an inverse-U relationship between income elasticities and economic development is explained informally as due to structural change (Medlock 2009), as discussed in Insight 4 and 5.

In the absence of a theory, a rich empirical literature supports the view that income elasticities of energy demand (i.e., not energy service demand) fall as economies reach high per capita income levels (Galli 1998, Judson 1999, Medlock and Soligo 2001, van Bentham and Romani 2009, van Bentham 2015). The trends in elasticities for the three separate energy service demands (heating, transport and lighting) in the United Kingdom over two hundred years (shown in Figure 3) are consistent with the evidence for energy demand, though with higher peaks for energy services and upward trends in income elasticities at very low levels of economic development. Given that studies of energy demand and energy service demand have found that income elasticities are high (i.e., greater than one) at mid-income per capita levels, the evidence presented in this brief appears to be highly transferrable to present-day situations – for instance, it is probable that developing economies will broadly follow inverse U-shaped income elasticity trends and U-shaped price elasticity trends.

Clearly, many factors will be different between these experiences and future ones, and it would be important to identify how changing knowledge, technologies, infrastructure and institutions, amongst other variables, alter these patterns of behaviour. In particular, thought needs to be given to how the peaks and the steepness of curves might differ as current developing economies have access to energy sources and technologies at earlier levels of economic development. In the context of energy demand, it has been proposed that economies that develop later will have access to more efficient technologies at a lower level of economic development and, therefore, will have lower energy intensities than leading economies (Medlock 2009). Certainly, Britain, as the first economy to experience the Industrial Revolution, may well be an extreme case. As discussed in Insight 8, a comparison of the histories of Britain and Germany with other European economies supports this view - though other factors, such as exports of manufacturing productions and average price of energy (and, of course, energy services), were also very different - so, this does not directly tell us about income elasticities. Using a larger historical database, Csereklyei et al (2015) find that, although they tend to broadly converge at high levels of per capita income, some (but certainly not all) economies did exhibit flat energy intensity trends in the long run. Interestingly, this evidence partially contrasts with a recent study which finds that present-day developing economies are experiencing higher energy intensities at the same per capita income levels (i.e., within the $3,500-$10,000 range) as present-day OECD countries did historically (van Bentham 2015). The author states that this finding is consistent with the argument developed in Fouquet (2014) and Insight 4 that, because of access to more modern energy sources and technologies, present-day developing economies may experience earlier and smaller elasticity peaks. Thus, with no theory to be guided by nor other energy service demand studies to be compared with, but strong support from energy demand literature, it seems appropriate to conclude that earlier and lower peaks are likely to characterise trends in income (and price) elasticities of demand for energy services.

Regarding lessons about energy transitions, the free rider problem of low carbon energy makes the applicability of past lessons more problematic and needs greater caution. Nevertheless, some of the basic points - about how the incentives will influence consumers' likelihood of adopting new energy technologies and sources, and about the process through which the demand for environmental quality gradually leads to policies – are generally transferable to present and future situations.

4. Policy Recommendations for Climate Policy

Policy Recommendation 1: Formulate Integrated Energy Service Policies

The focus of most climate mitigation analysis on energy (rather than energy services) risks producing misleading advice when considering long run issues. It is based on a failure to consider consumer motives in energy-related behaviour and a lack of data on energy services (such as space and water heating, cooking, transportation, lighting, communication and computing). Today, policy-makers should be focussing on what drives consumer behaviour and improves wellbeing. As discussed in Insight 1, if a consumer's energy consumption falls, it does not necessarily imply that this person is worse-off. For example, if energy consumption fall by 5%, but energy efficiency improves by 5%, then energy service consumption has remained constant, and consumer wellbeing has not changed. On the other hand, if energy service consumption falls then the consumer is likely to be worse off. So, policy-makers should be seeking to increase more affordable and available energy services, not necessarily energy consumption.

As a consequence, it is important to develop policies that focus explicitly on energy services. Government policies related to energy markets (such as market liberalisation or regulation, and the promotion of competition) are unlikely to be based on a consideration of, for instance, their impact on investments in energy-using equipment and how efficiency might be affected by lower energy prices. Indeed, although this is not a forum for questioning the merits of promoting competition, one might expect that a phase of declining prices associated with market liberalisation will stimulate consumers to invest in energy-using equipment that is less energy efficient and incorporates characteristics that are more energy-intense (Newell, Jaffe, and Stavins 1999, Popp 2002) – after all, the period of low energy prices in the 1990s stimulated investment in heavier vehicles, such as SUVs (Knittel 2011). In fact, Ito and Sallee (2014) show the inefficiencies in policies that have allowed lower efficiency standards for these heavier vehicles. Thus, despite the undoubted benefits these characteristics provide, there is a long run trade-off between lower energy prices and higher investment in energy efficiency. Here, it is proposed that governments should take account of the trade-offs between energy prices and efficiency investment in the long run and ideally find the optimal trade-off between them. As will be discussed in the third recommendation, the trade-off between prices and efficiency improvements might differ at different phases of economic development, and the optimal policy should reflect this difference.

However, energy service policies should go beyond, simply looking at balancing energy prices and technical efficiency. They should try to integrate policies related to the pricing and provision of energy sources with those focussing on promoting energy efficiency improvements, including research, development and demonstration (R,D&D)) and considerations about behavioural features to address the energy efficiency gap (Gillingham and Palmer 2014) – and not exclusively through efficiency standards, which have received considerable criticism (Anderson et al 2011). In other words, they should actively develop energy service policies.

They should develop a broader and more strategic approach to thermal comfort, mobility, illumination and computing. Yet, once they are thought of in those terms, the interconnections between energy services (particularly related to energy markets) risk being lost. Identifying which ministry is responsible for thermal comfort, mobility, illumination and computing is unclear. In fact, many would feel uncomfortable with the idea that a ministry is needed to achieve such objectives – would it fit within the remit of a "ministry of physical/material well-being"? This goes beyond (or more precisely offers a more concrete example of) the recommendations of Stiglitz et al (2010) on alternatives to GDP measurement. So, more thought is needed about how to achieve a cheaper provision of these services in a sustainable way without directly interfering with households' individual decisions and lives.

An important first step is to encourage ministries responsible for energy to collect annual statistics on the consumption and price of providing energy used for end-uses and energy services (which incorporates the efficiency of the related technologies). DECC had been collecting data on end-use energy consumption irregularly since the late 1990s, and these have, since the late 2000s, become a fundamental part of its Digest of United Kingdom Energy Statistics (DUKES). Since 2005, DECC has undertaken a more concerted effort to collect data on the efficiency of energy technologies, as reflected in the Household Energy Efficiency Database (HEED), which is particularly focussed on the quality of the heating systems and housing stock, although this process is challenging and remains far from comprehensive (Foulds and Powell 2014). This is a new development and, in general, ministries around the world have tended to ignore the efficiency of energy technologies. They should seek to measure energy efficiency improvements and incorporate the data into their digests (Hamilton et al 2013). Furthermore, ministries need to combine energy and efficiency data to generate valuable energy service data. *These will enable stakeholders to observe the success of policies aiming at providing cheaper energy services while reducing energy use.*

Policy Recommendation 2: Prices Matter, especially in the Long Run

One of the major challenges associated with climate policy is that, in the long run, rising income and high income elasticities drive-up energy service and, therefore, energy consumption. However, there are no obvious climate policy instruments related to income or income elasticities. Thus, the main source of leverage for climate policy-makers is influencing the price of energy services (either the price of energy[11] or the efficiency of energy technologies).

After all, consumers (and producers) react to incentives. Especially in the long run, consumers respond to relative prices which can push them either towards environmentally damaging or towards environmentally benign decisions. If there are, for instance, taxes on carbon emissions, consumers can put up with additional costs of environmentally unfriendly behaviour in the short run perhaps because they are locked in to technologies and processes that are expensive to substitute in the short run. However, in the long run, the burden of environmentally damaging behaviour being taxed is likely to push consumers towards environmentally friendly decisions, if competitive substitutes are available.

Especially for durable goods, such as plant and equipment embodying energy technologies, expectations of long run additional costs associated with environmentally damaging behaviour may well be decisive in swaying investment decision-making. The prospect of locking oneself into an expensive pattern of energy service consumption by selecting a particular technology is likely to be unattractive to consumers, if it polluting and the polluters has to pay for the emissions (see Insight 9). Thus, clear long run price signals are important for directing the momentum of an economy towards a low carbon economy.

Changing policies (particularly market-based instruments) in the short run is not constructive. This is often the result of political intervention driven by vested interests, either succumbing to the influences of powerful energy companies or appealing to voters. However, if the policies are clear, and unambiguously designed to discourage broadly agreed upon undesirable outcomes, and unquestionably encouraging broadly-agreed-upon objectives, they are likely to be harder to overturn than highly specific policies with

[11] In the short run, the market conditions under which energy is delivered (e.g., competition, monopoly or oligopoly) also heavily influence the final price to consumers for energy services. However, higher energy prices tend to feed through into more improvements in energy efficiency (Newell, Jaffe, and Stavins 1999, Popp 2002), which, in the long run, are likely to reduce energy service prices more than the upward pressure due to the imperfectly-competitive market structure.

ambiguous virtues. Thus, the government should clearly identify the direction sought and allow the momentum of market forces to work, while being aware of and redressing negative social impacts.

As discussed in Insight 10, following the Big Smog and the ensuing Clean Air Act, the British government banned the use of smoke-emitting fuels in certain zones in the 1960s. This radical environmental measure imposed temporary increases in the price of residential heating, as consumers were generally forced to switch to cleaner, but more expensive, fuels. Within a decade, the price of heating had fallen below its pre-Clean Air Act level, as consumers adopted more efficient technologies.

Introducing taxes or permits on carbon emissions are unlikely to be popular with polluters. However, for the average consumer, the increase in costs is likely to be short-lived. The long run trend in the price of energy services is generally downward (see Insight 2). Furthermore, after introducing taxes, say, there will be a heightened incentive to adopt more efficient ways of providing the energy services, which will enable the price of providing those energy services to fall. Thus, especially if energy efficient technologies are available, but not always invested-in, imposing a cost on environmentally unfriendly behaviour might accelerate the reduction in the price of energy services.

So, government should explain to the public that these temporarily higher prices are part of a package of measures, including targeted energy efficiency investments, seeking to encourage cheaper services, and less energy use and carbon emissions.

Furthermore, care should be taken about the distributive effects of carbon taxes or prices. When introduced, they risk being regressive, in that poorer households spend more of their budget on energy or energy service than wealthy homes. Furthermore, these measures can be ‘dynamically regressive’. That is, poorer households will suffer the most over time. This is because poorer households are frequently the last to invest in new energy efficient technologies, which enable the price of energy services to fall. So, especially following the imposition of new taxes or permits, a possible strategy would be to encourage them to invest in energy efficient technology, through subsidies.

Policy Recommendation 3: Energy Service Policies in Periods of Rapid Development are Crucial

As mentioned in Insights 4 and 5, consumer responses to rising income, energy price changes and energy efficiency improvements will differ as an economy develops. Industrialising economies are likely to need relatively large increases in heating and power. As they develop, they might also be seeking far more transportation, and probably a lot more lighting, entertainment, communication and computing, as well powering of other residential appliances. Thus, policies that work against these market forces are likely to be counter-productive.

Indeed, the process of industrialisation is likely to be a period of high investment in energy-using equipment, such as personal vehicles and residential appliances - based on the peaks in income elasticities in Figure 3 as indicators, rapid investment might occur when per capita incomes are between $(2010) 3,000-6,000. Households (with generally high discount rates) are likely to invest in inefficient technologies. Thus, *without guidance and incentives, private decisions at that time can lock consumers* *into experiencing high energy services prices in the long run and the economy onto a high energy intensity trajectory with major long run impacts – related to environmental pollution, trade balances, inflation, vulnerability to energy price shocks, and political pressures from energy companies* (see, for instance, van der Ven and Fouquet 2014).

One could argue that, in time, if energy prices increase, consumers will adapt by investing in more efficient technologies. After all, much of the improvements in efficiency in Britain occurred without government intervention. While the British experience has shown that markets do adjust, they also showed that markets adjust slowly (as Figure 7 shows). Furthermore, it is proposed that industrialisation is a phase of high adjustments and substitutability (as represented by the high elasticities at mid-level incomes in Figure 3). However, once this major phase of transition and transformation is completed, lifestyles and production processes, as well as technologies, infrastructure, institutions and behaviour, become more fixed and less flexible (as represented by the declining elasticities as the economy develops from mid-income to high-income levels in Figure 3). Thus, it is suggested that the rate of adjustment to higher prices is dependent on the phase of economic development, and this implies that, after the initial phase of industrialisation, households and firms will be slower to invest in efficient technology as a result of higher energy prices. Using Acemoglu and Robinson's (2012) terminology, the process of industrialisation is a critical juncture in an economy's history, and the outcome of this process will determine the economy's energy intensity path for many decades in the future.

So, periods of strong industrialisation and rapid development are crucial times for governments to develop policies that promote energy efficient technology investment and ensure lower long run energy service prices to consumers. Yet, reductions in energy price subsidies and taxes on energy consumption are likely to be unpopular. Furthermore, energy service policies may not be seen as a government priority at early phases of economic development. Nevertheless, if they are combined with strong support for the subsidy of energy efficient technologies and information campaigns explaining the package of measures and their long run benefits, a government could encourage a large share of consumers to invest in energy efficient technologies. In other words, despite the fact that much of the initial improvements in energy efficiency are likely to lead to large rebound effects, the government has an opportunity to place its economy on a lower energy intensity trajectory (as seen in Insight 7), with huge benefits associated with environmental pollution, trade balances, inflation stabilisation, and reduced vulnerability to energy price shocks and to political pressures from large energy companies.

5. Conclusion

This paper presented trends in the prices and consumption of energy services and in income and price elasticities of demand for energy services over the last three hundred years for the United Kingdom. Given the need to develop climate policies over decades or even centuries, this longer run perspective offered energy-related empirical evidence on a more appropriate timescale than is traditionally available and used. This evidence provided insights about how energy service use and energy consumption behaviour changed as an economy developed (i.e. the inverse-U trend in income elasticities as the economy developed). This understanding could provide a 'backbone' for long run energy consumption and carbon dioxide projections.

At low levels of economic development, energy service consumption tended to be quite responsive to per capita income changes; at mid-levels, consumption tended to be very responsive to changes in income per capita; and, at high levels, consumption was less responsive to income changes. Just to provide a concrete example, if China were to follow a similar pattern of demand for energy services (e.g., space and water heating, cooling, cooking, transport, lighting and communication) as it develops as the United Kingdom did historically, its income elasticities would now be starting to decline – a mildly positive message for global carbon dioxide emissions. However, its income elasticities would not fall below unity (i.e., a 10% increase in income would not lead to a less than 10% increase in consumption) for many decades into the future – a rather pessimistic message for global carbon dioxide emissions. Although the inverse U-shaped trend in income elasticities is expected to hold for present-day developing economies, there might be reasons to anticipate that their trends will peak earlier and be less pronounced than the United Kingdom historically. This new understanding of how long run trends in income and price elasticities changed with economic development will be useful for improving projections of energy consumption and carbon dioxide emissions in both industrialised and developing economies, such as those produced by the IEA and the IPCC.

Based on the ideas presented in this paper, several lessons for policy emerge. For instance, governments should seek to formulate integrated energy service policies. Governments rarely make decisions about energy markets and technologies related to the provision of energy services as part of an integrated strategy. For instance, policies should be aiming to encourage the cheaper provision of energy services while reducing high-carbon energy use. It is proposed that, for instance, governments should take account of the trade-offs between lower energy prices and lower efficiency improvements in the long run and ideally find the optimal trade-off between them. Furthermore, this trade-off might vary at different phases of economic development, and the optimal trade-offs through time should reflect this difference. Finally, energy service policies should go beyond simply looking at balancing energy prices and technical efficiency, and should develop a broader and more strategic approach to energy services, focussing directly on thermal comfort, mobility, illumination and computing.

A final point is that energy service policies in phases of industrialisation are crucial for the long run prosperity of the economy. The process of industrialisation is a critical juncture in an economy's history, in which the choices of technologies, infrastructure, institutions and behaviour are more flexible than once the economy has become industrialised. Without guidance and incentives, private decisions in periods of rapid economic development can lock consumers into experiencing high energy service prices in the long run and, similarly, bind the economy onto a high energy intensity trajectory with major long run impacts – related to environmental pollution, trade balances, inflation, vulnerability to energy price shocks, and political pressures from energy companies.

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Appendix

Summary of Method Used for Estimating Income and Price Elasticities

The elasticity estimates were generated using annual time series data on energy service consumption, prices and GDP per capita from 1700 to 2010 (see Fouquet 2014). Because of the non-stationarity of the data (i.e., they do not revert to a mean value), vector error correction (VEC) models offered a method to identify the long run relationship between energy service consumption, energy service prices and income. An important assumption (confirmed through statistical tests) was that the causality ran from income and prices to consumption, and not from consumption to income and price – implying that any changes in income and prices were exogenous and, therefore, they could identify the demand curve. A simple method was then employed to estimate the trends in income and price elasticities, by estimating the average value for fifty year periods moving through time (Fouquet and trends in income and price elasticities, by estimating the average value for fifty year periods moving through time (Fouquet and Pearson 2012). For example, the income and price elasticities of heating demand were estimated for the period 1830-1879, then 1831-1880, and so on until 1961-2010. Then, the elasticity for any particular year would be the moving average (i.e., the average of all elasticities estimated where that year was included). So, for the moving average around the year 1950, fifty income elasticity of demand for residential heating estimates were produced (for the periods 1900-1950, 1901-1951, and so on until 1950-2000) and the average of all these estimates was equal to 0.60. Estimated in the same way, the average price elasticity of heating demand around 1950 was -0.25.

Summary of Method Used for Estimating External Costs of Energy Services

Figure 8 represents the value of the external damage caused by energy services (as a share of GDP) over the last 300 years. A value of a life year lost - the UK's Department of Health places the value in 2005 at £29,000 per year lost from air pollution – was calculated for each year, by reducing the value in the past to take account of the lower income (and, thus, willingness or ability to pay for reductions in the risk of dying) and an income elasticity of 0.8, which reflected estimates based on empirical studies in industrialising economies (see Fouquet 2011b). So, for instance, in 1800 and 1900, the values of a life year lost were estimated to be £(2000)7,500 and £(2000) 10,000 respectively. While to many these methods are controversial, individuals, firms and policy-makers make trade-offs between money and mortality risks. Equally, values were placed on lives in the past – life insurance has existed in England since the sixteenth century, and became a major industry from the eighteenth century, even if at first only as a source of gambling or to replace the loss of slaves, but later to compensate relatives (Clark 1999). The method presented offers a crude measure of the value of the damage associated with accidental fires (hence, the high value for lighting in the eighteenth century), air pollution, coal mining and climate change – for details of the methodology for each problem, see Fouquet (2011b, 2015). While the deaths from fires, air pollution and coal mining are quite different from climate change damage, by placing them on the same graph, they help us to identify the scale of the external damage caused by energy or energy service use.