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An exploration of energy cost, ranges, limits and adjustment process

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Abstract

We have developed a new dataset of national energy expenditures covering more than 30 countries since the early 1970s, complemented by longer-term (65-year) data for the US. From this we explore more robustly the hypothesis of long-term constancy in energy expenditure relative to GDP advanced by Bashmakov (2007) and also implied in research by Newbery (2003). We explore patterns over time and the critical ranges, and consider various interpretations and implications.

We find strong evidence to support a constrained range of long-run energy expenditures relative to GDP ("relative energy expenditures"), across time and countries: an observation which equates to an approximately "-1" relationship between energy price and energy intensity (E/GDP ratio). We demonstrate that timescales of adjustment however are long – in the region of 25-30 years for one cycle of energy prices, with the relationship most stable over periods approaching 50 years which equate to two full cycles. The stable range of energy expenditure we find to be **8±2 percent of GDP.**

We discuss the close relationship of this to long-run elasticity of energy intensity with respect to end-user prices. A constant level of energy expenditure, *ceteris paribus*, would imply an elasticity of (minus)1 – considerably higher than classical time-series measures of energy demand- price elasticity (which point to long-run elasticities of (minus) 0.6-0.7 at most).

Indeed, we find that the cross-country correlation of energy price to energy intensity appears greater than (minus) 1 thus, countries with higher average energy overall prices since the 1970s have actually spent *less* of their income on energy, whilst those which maintained lower prices have spent *more*. Across the full dataset the implied value is almost (minus) 1.5. This includes significant influence from exceptional conditions in a few eastern European countries, which kept prices low for much of the period and developed extremely inefficient economies, but which then faced rapid increases as they joined the EU at a time of rising global energy prices. Even excluding these the cross-country correlation remains greater than (minus) 1.

With the longer US dataset, on a basis of purely territorial energy consumption, there is evidence of a slow decline in energy cost share. We draw on trade statistics to estimate the impact of the US' shift from being a net exporter to net importer of energy intensive goods, and show that by taking account of this – i.e. shifting to a net consumption basis – the slow decline in US energy-related expenditure would reduce and may disappear, implying an even more constant typical expenditure over the 65 year period. We surmise that treating cross-country expenditures on a similar consumption basis would also bring observed relative energy expenditures back towards constancy. Trade effects are far from the dominant cause of higher energy prices being correlated with lower energy expenditures, but rather, accounting for them suggests an even closer '-1' constancy of relative energy expenditures.

We then consider various theories to account for the observed rough constancy of energy expenditure, showing that it is inconsistent with the normal assumption of a fixed (and relatively low) price elasticity of energy demand. Rather, it seems to reflect different 'elastic phases' of response, according to the price levels, affordability thresholds, and price trends, and which appear to have a substantial degree of path-dependence. We show how this can potentially be related to the 'Three Domains' framework advanced by Grubb, Hourcade and Neuhoff (2014, 2015), with shifts of energy price regimes changing the relative importance in different domains of response.

We explore other (potentially related) theories that could explain the observations. These include:

• Theoretical reasons why multi-stage energy systems would ultimately tend towards a price elasticity of demand of "-1", and how - given inertia in some of the intermediate stages – such systems could generate even greater long-run responsiveness to energy price variations, as observed in our cross-country studies;

• The observation that energy prices are regressive, and that lower income groups facing higher energy costs tend to be more price responsive; a general increase in energy prices would then increase the overall national response. Yet simply imposing higher prices can carry a significant welfare cost

particularly on poorer households.

Finally, we touch on potential policy implications, of which we pinpoint three main ones:

• First, the data clearly imply that energy systems have a large capacity to adapt to higher prices and other pressures, given time. There is no particular reason to believe for example that low carbon energy systems will ultimately increase energy expenditures.

• Second, practical policy can only deliver such transformations through the use of multiple policies spanning energy efficiency, environmental pricing, and direct investment in innovation and infrastructure. The energy transformations visible in the data we have covered (notably oil shocks and integration of eastern Europe) were externally driven, and involved large social and economic dislocations; it is doubtful whether any elected political system could drive equivalent transformations using price alone.

• Third, consequently, the normal economic logic that high environmental pricing should be the best instrument to drive transformation may need inverting: rather energy efficiency (in particular) can be viewed as a social policy, of which the environmental co-benefits will be undermined by rebound effects, unless it is accompanied by rising energy prices, so as to keep overall costs within the Bashmakov-Newbery constant of energy expenditure. To combine regulatory certainty with flexibility, it is also possible that price-based instruments (such as fuel duties or environmental pricing) could be designed with escalators that are automatically paused if expenditure thresholds are exceeded, and resume when expenditure falls.

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Introduction

Energy costs are politically sensitive, and resistance to energy price rises is a major impediment to economically efficient energy pricing, including subsidy removal and incorporating the external costs associated with the environmental impacts of energy use. Political debate in most countries has largely equated energy prices and energy bills: if energy prices go up, then, common sense suggests, bills must do too.

In this paper, we critically examine the extent to which this assumption holds true. Noting that energy bills are a product both of energy prices and of levels of energy consumption, we focus on the l*ong-run* and *cross-country* evidence concerning the response of energy intensity and energy demand to energy prices – in economic terms, the elasticity of energy intensity with respect to final energy price. We explore this both through a critical review of the existing econometrics literature, and through development and use of a new international dataset on energy costs.

The divergence in energy prices between different countries is often associated with comparative advantage, not just specifically concerning key sectors, but more generally on the presumption that higher energy prices equate to countries bearing a higher deadweight cost of energy provision. Our analysis also sheds light on this, noting the evidence on the economic impacts of extreme prices, but illustrating also that these periods appear to drive important structural adjustments and innovation, which help to bring bills back down and may contribute to renewed growth.

We examine the issue from a standpoint characterised by:

- a *long-term* and *cross-country* perspective
- a national focus, but with some exploration of sectoral components
- a focus on *energy intensity* – energy demand per unit of GDP – rather than energy demand itself
- *large-scale energy price* changes, rather than estimation of elasticities in response to marginal price changes

Thus, our analysis is focused on the enduring impact of final consumption energy price changes (after taxes and subsidies) on overall energy bills, as a proportion of income, particularly at the national level. Our conclusion is striking: at a sufficient level of aggregation, the proportionate energy bill – the share of income expended on energy – varies within a range far more narrow than the variation of energy prices. Expenditure on energy gravitates back towards similar levels even with extreme energy prices, given time, and to levels that are similar across countries, irrespective of long-run energy prices.

In aggregate we estimate, correspondingly, that this equates to a long-run price elasticity of energy intensity of about “-1”. This suggests that the phenomena observed is in fact more subtle than a constant long-run elasticity of demand, but rather involves different ‘elastic phases’, with differing elasticities, and with the overall pattern being characterised by non-linearities in transitions between such phases. From this observation, finally we also draw theoretical and policy conclusions.

Part I: Concepts and existing literature

There is an extensive literature exploring the elasticity of energy demand, and energy intensity, to energy prices, from which this brief section will identify a selected number of studies to establish the key concerns of this paper.

(a) *Consumer energy demand price elasticities*

Although studies produce a relatively wide range of results (Labandeira, Labeaga & Lopez-Otero, 2015), a common conclusion is that energy demand is relatively price inelastic. Labandeira *et al* (2015) conducted a meta-analysis of 416 papers produced between 1990 and 2014, which provided 951 short-term and 991 long-term estimates of price elasticity for different energy products, sectors and countries. After correction to allow for cross-study comparability, they find average price elasticities of (total) energy demand to be -0.22 in the short-term and -0.6 to -0.66 in the long-term.

Of course there is no definitive standard of what 'short-term' and 'long-term' mean – though typical interpretations point to 'a few years' and 'up to a few decades' respectively. Given the vast range of existing studies of consumer energy price demand elasticities we do not further review these studies, but focus rather on the dynamics, cross-country-evidence, and *long term* – up to about 50 years, for reasons indicated in our data analysis.

The issue of timescales is fundamental to our analysis. Attempts to estimate price elasticities over even longer periods run into increasing data problems (as well as larger exogenous changes), but a few studies have tried:

• At a sector level, studies of UK transport over 150 years by Fouquet & Pearson (2012), and of lighting over 200 years, estimated that price elasticities had declined somewhat over the period but had been relatively stable since 1990, at around -0.6 for transport and -0.7 for lighting, which the authors considered 'very large' compared to previous, shorter-term estimates.

• Stern and Kander (2012) used 200 years of Swedish data to look at whole economy elasticity, and estimate substitution elasticities in a similar range (0.65 – 0.69).

A recent contribution by Saunders (2015) builds on these estimates into a theoretical framework to examine implications for 'rebound'. Our concern in this paper is with the apparent relationship between these varied elasticity estimates and overall national energy expenditures over multi-decadal timescales, and we return to consider these literature estimates after developing our own analysis.

(b) *Income elasticities*

The other factor that would affect energy expenditure as a proportion of income is of course income elasticity. At the level of different income groups it is well established that energy prices are regressive (poorer people spend a higher proportion of income on energy – a well-known fact which turns out to have some significant implications for interpreting our findings in this paper as indicated in Part V).

The literature on income elasticity of energy demand is also well developed, and concludes growth in income is positively, and strongly, correlated to growth in energy consumption.

This includes some very long run studies. Fouquet (2014) summarises the early empirical evidence. He illustrates the case of studies in Britain in the 1790s, which found that households generally spent about 5% of their income on fuel.This result was corroborated first by Engel (1857, cited by Fouquet, 2014) who found, when examining changes in expenditure and consumption as incomes rise among Belgian workmen in the 1850s, that the share of income allocated to fuel and lighting remained at around 5% across the income levels studied, and later (in 1875) by a study of households in Massachusetts, which found that 'the percentage of outlay for…fuel and light, is invariably the same [6%], whatever the income' (see Stigler, 1954, p.99-100). Such early results suggest that the *income* elasticity of energy demand is largely unitary.

This view is broadly supported by more recent, economy-wide, cross-country, studies. Newbery (2003), when examining the evolution of energy use in relation to real GDP (i.e. country-level income) for countries spanning the range of parties to the UN Economic Commission for Europe (UNECE) for the period 1972-1999, found on average near unitary income elasticity of energy demand. Joyeux & Ripple (2011) also conclude long-term unitary income elasticity of energy demand in OECD countries for 1973-2007.

(c) *The relationship between energy prices and the wider economy*

More widely, the relationships between energy consumption, price and economic growth continues to be a subject of substantial and nuanced debate.[1] A huge literature on energy price-GDP relationships emerged since the oil shocks, with relatively little consensus beyond the fact that the 1970s oil shocks unquestionably hurt all the major, energy-importing economies (notably the US). Dispute remains about causality of oil-GDP relationships, as the direct cost impacts are insufficient to explain recessionary effects; but econometric studies have found significant recessionary effects attributable to the oil price impacts of the First (1990) and Second (2002-3) Gulf Wars. The high international oil prices of 2007-8 were again followed by global economic downturn, though attempts to attribute this to oil prices have not surprisingly been far more contested.[2]

More broadly, Fizane and Court (2016) note four different hypotheses concerning the relationship between energy and economic growth: (i) causal running from energy to economic; (ii) causal running the other way round – from economy to energy; (iii) two-way feedback between these two; and (iv) no relationship. Somewhat ruefully they concluded: "Unfortunately, after more than forty years of research and despite the increasing sophistication of econometric studies, this area of study has not so far led to either general methodological agreement or a preference for any of the four positions. More specifically, three independent literature reviews (Chen et al, 2012; Omri, 2014; Kalimeris et al.,2014), covering respectively 39,48, and 158 studies, have shown that no particular consensus has emerged from this empirical literature and that the share of each assumption ranges from 20% to 30% of the total."

They offer various possible reasons for this lack of clarity. We note that interpretation is further confused by the fact that much of this literature does not distinguish between shock (dislocation) and slower changes; or between the impact of international energy price changes (and the consequent international flow of finance), as compared to domestic impacts on energy prices, such as taxation. One would presume the economic impact is very different depending on whether the changes are sudden or gradual, and whether additional consumer expenditure goes abroad or stays within the economy. Indeed, econometric modeling projections have suggested that energy taxes can be associated with enhanced macro-economic performance (though like much else, this remains disputed – not least of course because it depends upon how the money raised is used).

In the context of this report, the interest is potential impact of extremes – exceptional levels of energy expenditures. There seems to be stronger evidence – endorsed in the Fizane and Court paper – that unusually high levels of energy expenditure do have increasingly adverse macro-economic (and social) impacts. An excessive cost share can provoke a recession – particularly if it is sudden, and if the additional expenditure goes abroad, which tend to go together. The long timescale of energy sector adjustment – which are underlined by analysis in this report - can then mean several years of dislocation and adjustment at a time when the economy is already stressed by fiscal outflow.

1 See Huang, Hwang & Yang (2008), Joyeux & Ripple (2011), Chen, Chen & Chen (2012), Omri (2014) and Kalimeris, Richardson & Bithas (2014) for some overviews of the literature.

2 From the early 2000s, the oil price rise was less abrupt and most of the rich economies were more insulated (by many factors including high domestic oil taxation, which provides a buffer, and less dependence on manufacturing), and the recession was driven mainly by the credit crunch of accumulated debt. One view is that the impact of rising oil prices on inflation prompted central banks to raise interest rates, and it is this that slows the economy and amplifies debt problems (see Segal, 2011). The most extensive set of papers analysing oil price variations, financial speculation, and the historical impacts on GDP are collected in a Special Issue of the Energy Journal (M. Manera (ed), 'Financial speculation in the oil markets and the determinants of the price of oil', Energy Journal, Vol 34 no.3, 2013). The associated analysis of GDP impacts is by Morana (2013).

(d) *Long-run & cross-country expenditure estimates*

In the earlier studies cited, examining energy expenditure as a proportion of total income across income groups may be reasonably used to approximate income elasticity of energy demand. These studies focussed on a single sector (i.e. households), in a single country, for a static time period. As such, the energy products consumed, associated prices and conversion processes (e.g. lighting and heating technologies) were likely to be relatively uniform.

For the latter studies however, with economy wide, cross-country examination, such a direct link between income elasticity and energy expenditure as a proportion of income might not be immediately expected. For example, energy intensity - the number of units of primary energy consumed per unit of GDP produced - varies substantially across countries, as we examine more closely in this paper.

Literature examining *long-run energy expenditure across entities* – countries or groups – appears relatively scarce, and recent. Bardazzi et al. (2015) reports that for 3,425 firms and near 19,000 observations in Italy for 2000-2005, energy expenditure as a proportion of gross output falls in the range 3.8-6.2%. Panel data for 6,808 firms, with 54,963 observations for 1992-2012 in India show that the share of energy costs was between 3.3% and 8.7% of the value of total revenue, across the sample (Sadath and Acharya, 2015). For households in Japan, India and the USA, Bashmakov (2007) found that expenditure on housing (i.e. building) energy from 1960 to 2007 has remained stable over time, but also at a similar rate, at between 2% and 5% of total (pre-tax) personal income. Data presented for China, the EU and Russia for the latter years also fall within this range.

At the national, whole-economy level, Bashmakov (2007) also finds that energy expenditure as a proportion of GDP is within the range 6-11% for the USA between 1949 and 2007, and 8-15% for the OECD between 1978-2007 (with ‘sustainable’ ranges of 8-10% and 9-11%, respectively). These results led to the articulation of his first law of energy transitions: *‘in the long-term, energy costs to income ratios are relatively stable with just a very limited sustainable fluctuation range’* (see Annex II for brief reference to Bashmakov’s other two Laws of energy development).

There are two approaches for energy cost accounting: **energy costs for final users** (applied in this paper); or **primary energy** costs applied by King et al (2015) and Fizaine and Court (2016). They calculate not consumer, but primary energy costs multiplying primary energy use for each resource by corresponding energy price. This method ignores additional value of secondary energy resources (enriched coal, petroleum products, heat, fossil fuel electricity, and delivery costs including transmission and distribution of energy) as well as much of taxes collected at the point of secondary energy sale.

On this basis, King, Maxwell & Donovan (2015) estimate energy expenditures as a proportion of GDP for the 44 OECD countries, representing 93-95% of gross world product (GWP), and 73-79% of the IEA’s listed Total Primary Energy Supply (TEPS) (>78% after 1994), for 1978-2010. They estimate average energy expenditure to GDP ratio for all IEA countries of 6.3% over this time period, ranging from a maximum of 10.3% in 1979, to a minimum of 3% in 1998.

Most recently, Fizane and Court (2016) estimate an average expenditure ratio for 1850 to 2012 of approximately 6-7% – however, US values are used as proxies for global data, which as indicated by the authors, is a ‘coarse assumption’, ignoring what are likely substantial differences across the world). Building on data provided by Fouquet (2008, 2011, 2014), they also estimated the energy expenditure to GDP ratio for the UK, for the period 1300-2008.

However, as highlighted by Bashmakov (2007), determining energy consumption patterns and volumes (along with prices, expenditure and GDP) for such a timeframe is highly speculative - not least due to the radical change in how energy is sourced, transformed and used (e.g. food supplied to labourers and fodder supplied to draft animals used for productive purposes). Combined, these factors render the calculation of consistent, comparable values over such a time frame an extremely difficult task.

D) *Accounting framework*

Four factors determine the evolution of the energy costs to GDP ratio (*Se*):

$$Se = \frac{E * PE}{YR * PY} = \frac{E}{YR} * \frac{PE}{PY} = EI * PER$$

Where *E* is energy consumption; *PE* is energy price; *YR* is GDP in constant prices; *PY* is GDP deflator; *EI* is GDP energy intensity; PER is real price of energy. Energy costs in an economy as a proportion of GDP may thus be reduced to two key factors: energy intensity of real GDP and real energy price.

It is important to note that energy *demand* and energy *intensity* to price elasticities are different concepts. They coincide only when energy demand by income elasticity is unity. Specifically, if energy demand depends on income and energy price in is a log linear forms traditionally assumed, then expressing it in average annual growth rates T we get:

$$T_e = a * T_y + b * T_p$$

where T_e is energy growth rate, T_y is income growth rate and T_p is real energy price growth rate. The elasticity[3] of energy intensity to real energy price (*c*) is:

$$c = \frac{T_{e/y}}{T_p} = \frac{T_e - T_y}{T_p} = \frac{aT_y + bT_p - T_y}{T_p} = (a-1) * T_y / T_p + b$$

The evolution of energy demand and price elasticities along with fluctuating rates of income and price changes (Ty/Tp ratio) can make the apparent elasticity of energy intensity to real energy price for specific years very volatile. We illustrate this with respect to US data in the next section, and show how it seems to smooth and converge towards a long-term (cycle long) stability at around 'minus one', which is perhaps even more surprising in the light of all these fluctuations.

For the energy cost ratio to remain stable in the long run across time and economies, an increase (decrease) in the price of energy or energy intensity of the economy across time and in different economies must be coupled by a proportional decrease (increase) in the other. As such, the derivative of the relationship between these two factors must be around minus 1. This is clearly closely related to the long-run price elasticity of energy intensity, though not identical due to other potential time-related factors such as non-unitary income elasticity and exogenous technology trends. We return to these in Part V, where we also extend the equation above to consider the impact of exogenous drift in intensities, as we observe in the data, as for example caused by autonomous technical change.

Time-related trends should not however directly affect comparisons across countries for the same periods. From cross-country analysis, Newbery (2003), when examining the relationship between time-averaged energy prices and economy-wide energy intensities for OECD countries for 1993-1999, finds a price elasticity of energy intensity of minus 1, with a 0.14 standard error. This relationship remains in the updated analysis presented by Grubb et al (2014), who, recognising Newbery's contribution, rephrased Bashmakov's 'first law of energy transitions' as the 'Bashmakov-Newbery Constant of Energy Expenditure'.

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3 As David Stern has noted, there are many different uses of the term (price) elasticity. In this report, we may use the term not in the strict econometric sense of an econometrically-estimated relationship in a formal model, but we argue that many of the correlations we identify are largely price-driven and thus closely related to the underlying concept of elasticity as a measure of price-related and causally linked response. We do seek to emphasise in particular a distinction between price-elasticity of energy demand, and that of energy intensity.

In the last part of this paper we discuss possible theoretical explanations for these findings. First however, we explore the structure and robustness in more detail, given some apparent discrepancies in the literature. On the one hand several long-run and cross country analyses of the relationship between price and energy intensity / demand find elasticities close to -1, and explorations of expenditure in energy as a proportion of income or GDP tend to find relatively constant shares, also suggesting a -1 elasticity. On the other hand, in studies such as Labandeira et al (2015), much lower elasticities are typically found, especially when looking at shorter time periods. If lower elasticities held, this would imply that higher unit energy costs do translate into higher bills.

In the following sections we examine historical energy expenditures and price data for the US, and then utilise a new dataset covering a range of other (mainly OECD) countries, with the aim of reaching more robust and consistent explanations that may reconcile time series and cross-country, and short and long term, findings.

Part II. Long run trends in US energy prices, consumption and costs

Data for US real GDP from 1949-2014 were downloaded from the Federal Reserve Database, and data for US energy consumption for the same period were downloaded from the US Energy Information Administration (EIA). The EIA also provided data on total energy expenditure, but only from 1970 onwards. To estimate prices, and hence to calculate energy expenditure, for the period 1949 – 1969, the EIA's data on fossil fuel production prices and average electricity retail prices was used to create a harmonised energy price index for this period.

Overview of US data, 1949-2014

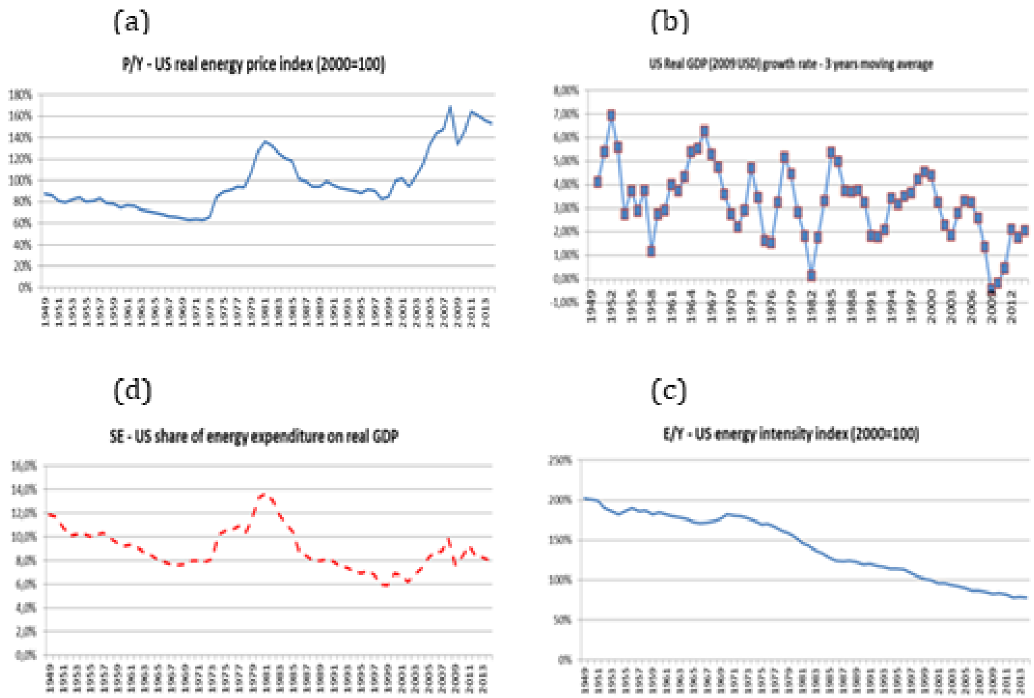

Figure 1: Implicit real price index (a), real GDP growth rate 3 year moving average (b), energy intensity (c) and share of energy expenditure as a percentage of real GDP (d), for the US, 1949-2013.

This continuity of robust data enables us to analyse trends over the past sixty-five years, ie. since shortly after the end of the Second World War. Figure 1 illustrates, across panels a – d, four key indicators arising from this dataset. Panel (a) shows the implicit real energy price index in relation to the year 2000. It shows the effect of the oil price shocks in the 1970s, the steep increase in energy prices from the early 2000s, with the dip in prices from 2008-2009 following the global financial crisis.

Panel (b) shows the three-year moving average growth rate of GDP. The concurrence with the same historical events can be discerned in this panel, with steep falls in GDP growth rates after 1973, 1979 and 2008, with GDP growth briefly going negative in 2009 and 2010. As noted in Part 1, causality is broadly accepted for the 1970s oil shocks – when US energy expenditure first jumped from about 8% to over 10%, and then subsequently (1979) to over 13%, but remains much more contested for the post-2005 price rises (when US expenditure only briefly touched 10%).

Panel (c) shows energy intensity, as the ratio between and energy consumption and real GDP in year 2009 dollars. It shows that energy intensity declined over the period, with a marked acceleration from the 1970s oil shocks.

Finally, panel (d) shows energy expenditure as a share of real GDP. The shape of the energy expenditure curve (d) is reminiscent of the real price index, with clear spikes in energy expenditure corresponding to the price spikes visible in (a). However, whereas the real price index rises from 80 to 140 over the period, the share of energy expenditure declines from 12% to 8%. While short-term price rises do of course increase the share of energy expenditure for a period, the overall long term trend has been for the share of energy expenditure to decrease, even as real prices rise.

The energy costs to GDP ratio shows a cyclic evolution with limited degrees of sustainable variation. After the upper limit is reached or exceeded (1949–1952, 1974–1985, 2008-2014), the ratio drops, and after the lower limit is approached (1965-1973 and 1993–2003), it, on the contrary, grows. Like a pendulum, the ratio driven by some economic 'gravitation' every time gets back to the equilibrium, or to the zone of sustainable dynamics.

For the past 30 years (from c. 1983) the US energy expenditure ratio has fluctuated within a relatively narrow range around a mean of 8% - much of this time within +/- 1 percentage point, and only briefly declining to 6% (1999) and rising to 10% (2007). This is despite a doubling of real energy price over that eight-year period, to levels exceeding even the peaks of the 1970s.

Initially, this apparent corridor of energy expenditure was considered stable (Bashmakov, 2007). With the 65-year timeframe, a general slow decline trend (by about 0.4% for every 10 years) can be observed.

To interpret the data from a historical perspective, it is likely that the 12% share of expenditure on energy at the start of the time period covered by the dataset is atypical for the period as a whole, and is due to the economic structure of the US in the immediate post-war period, still with the high outputs from energy-intensive industry which had been scaled up in part due to the war effort. A subsequent steady decline in the energy share of expenditure, reaching about 8% in the mid-1960s, may then be a part of a broader story of economic restructuring, which we consider at the end of this Part II in looking at trade shifts.

Broad shape of the energy-GDP relationship

As noted in the literature review of Part 1, there is already vast literature exploring the relationship between energy prices and economic growth, with much of it focused on the US economy and the oils shocks. We cannot add to this literature in its general and (as noted) inconclusive debate about energy-GDP relationships. We do however note a strong tendency in the literature – supported by the US data here – to suggest that very high levels of relative energy expenditure become increasingly damaging to economic growth. Fizane and Court (2016) strongly support this view and add to the chorus of argument that energy expenditures above about 10-12% become increasingly stressful and damaging to economic growth. The rationale is that only a portion of economic agents' revenues and attracted financing may be allocated for purchasing energy: apart from energy, they have to purchase other production factors or meet other basic needs. When the energy cost/GDP ratio approaches the upper threshold, purchasing power is increasingly constrained (and so is the growth of real energy suppliers' revenues)[4]. The implication is a non-linear relationship.

The reverse may also be true: as we note in our data, there is not a year within 1949-2014, when the growth rates in the U.S. were below 2%, and the energy cost to GDP ratio was low. This may, of course, reflect causality in the opposite direction: rapid growth in GDP increases the denominator of energy/GDP, and tends to be associated with rapid declines in energy intensity as new stock is introduced. The observation from Figure 1 is that improvements in US energy intensity slowed, but did not reverse, in periods of very low prices.

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4 Bashmakov (2007) estimates that after energy costs share of US GDP exceeds 11%, every 1% of energy costs increment reduces GDP growth by 1%. Fizaine and Court (2016) also suggest that for the US economic growth is severely impacted that after energy cost share reaches 11%. At a high enough cost, elasticity of substitution declines to zero, and the production function is transformed into Leontief's production function with energy shortage limits to growth.

Price cycles, adjustment timescales and expenditure

A key issue for exploration is adjustment timescales. As noted in Part 1 on concepts, both the price and changes in energy intensity can be very volatile. This is illustrated in Figure 2, which shows wide changes in energy intensity changes from year to year fluctuating by serveral percentage points around the long-term mean of -1.43%/yr (the flat orange line) - though it is noteable that after the 1973 oil shock there were very few years of rising intensity.

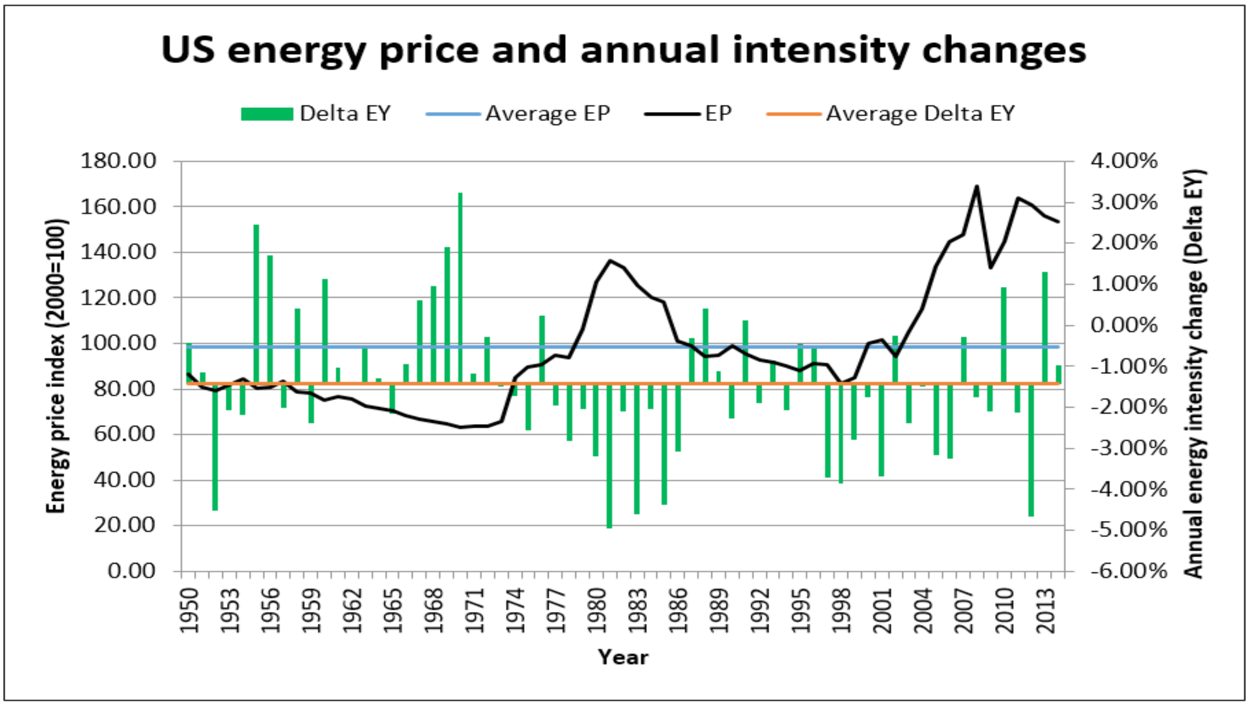


Figure 2: US energy price and annual intensity changes

Adofo et al (2013) amongst other emphasise that energy demand elasticities may be very sensitive to the time period of estimation. Any insights therefore need to look well beyond annual changes. A simple indication of this may be obtained by averaging elasticities over different aggregation periods. This time-aggregated form of elasticity is illustrated for the US data in Figure 3, which depicts the evolution of this ‘aggregate elasticity’ over periods ranging from 10 to 50 years in decadal increments.

Figure 3: Estimated US energy intensity-price elasticities (average of annual correlations) as a function of aggregation period (moving average)

This illustrates substantial instability over time in estimated US elasticities. Over periods even up to a couple of decades, particular economic conditions, or the effects of shocks can create widely varying elasticities, due to a wide range of possible factors.[5] For this US data, however, the results converge towards 'minus one' more consistently over time periods of several decades.

The extreme negative values relative to the immediate post-war years (the early 1950s) deserves particular mention. Comparison with panel (d) shows that the beginning and end years of this period happen to be amongst the highest (12%) and lowest (6%) years for shares of energy expenditure. This difference may be emphasised due to structural factors, as at the start of this period, shortly after the end of the Second World War, the US was at a level of industrialisation unusually high by comparison to most of the rest of the period. This may suggest the importance of economic structure on long-term price elasticities of energy intensity.

Table 1 offers a closer look at the cyclic pattern in terms of main component indices, divided between periods of rising and falling prices. When real energy prices grow, energy intensity declines faster, and the value of energy intensity to real energy prices elasticity is around -0.4 to -0.5 within these periods. When real energy prices decline, reductions in energy intensity do not cease - being driven by the technological progress, which is largely autonomous from the current prices and is largely inspired by delayed reactions to prior price shocks. Given falling prices, the measured elasticity (including the linear trend) becomes positive (falling prices, still falling energy intensity), but the reduction intensity trend does slow down.

Table 1 - Relationship between US real energy prices and energy intensity in different periods

Period	Characteristic	Ratio of Energy intensity change to real energy price change	Average annual growth rates		
			Energy intensity (E/YR)	Real energy price (PE/PY)	GDP AAGR (Ty)
1949-1972	Declining / low price	0,35	-0,51%	-1,44%	4,16%
1972-1985	Rising / high price	-0,53	-2,60%	4,87%	3,06%
1985-2003	Declining / low price	2,56	-1,71%	-0,67%	3,15%
2003-2014	Rising / high price	-0,46	-2,01%	4,33%	1,63%
	full cycles				
1963-1986	Full cycle 1	**-1,14**	-1,58%	1,39%	3,54%
1986-2014	Full cycle 2	**-0,98**	-1,76%	1,80%	2,61%
	two cycles				
1963-2014	Past 50 years	**-1,04**	-1,67%	1,61%	3,05%

Sources: same as for Figure 1.

If a-quarter-to-third-of-a-century long cycles of energy costs/GDP ratio are considered (see Table 1), then US energy intensity declined about as much as real energy prices grow, with the correlation nearly equal to -1: **the 'minus one' phenomenon.** Complete adjustment to energy price shocks takes at least quarter of a century. And overall over the fifty-year period, real energy prices doubled whilst intensity more than halved.

5 A period in which the elasticity is greater than minus one implies that energy's share of expenditure is growing. This could be because energy consumers are insensitive to rising prices (as a result of which their bills are going up); because the structure of the economy is rebalancing in favour of energy intensive industries; or because of a contraction in GDP that is not immediately transferred to reduced energy consumption. A period in which elasticity is less than minus one implies that energy's share of expenditure is falling; this could be because of structural changes away from energy intensive industries; "ratcheting" effects - energy efficiency improvements undertaken as a result of price rises in a previous phase, which are continuing to have an effect in reducing energy intensity even while prices rise less steeply, stagnate or fall; or boosts to GDP that are not immediately transferred to increased energy consumption.

Finally with this dataset, Figure 4 shows the density plot of normalised energy expenditure compared against that of the price range. The most striking features are the very rapid drop-off of observations outside of a core range - including the extent to which the high US prices during the two oil shocks, reflected in the right-hand peak of the cost distribution, is pulled back considerably in terms of the actual energy expenditure/GDP ratio.

The mean over the full dataset was 8.8%, influenced as indicated not just by the period of high prices, but by the exceptional intensity in the immediate post-war years (we report specific range statistics in Annex II) . Since the mid 1950s, almost 80% of the observations lie within ±2 percentage points of the mean. The narrow range is reflected in the statistics, with the variance of the expenditure distribution (0.04) being less than half that of the price distribution (0.094).

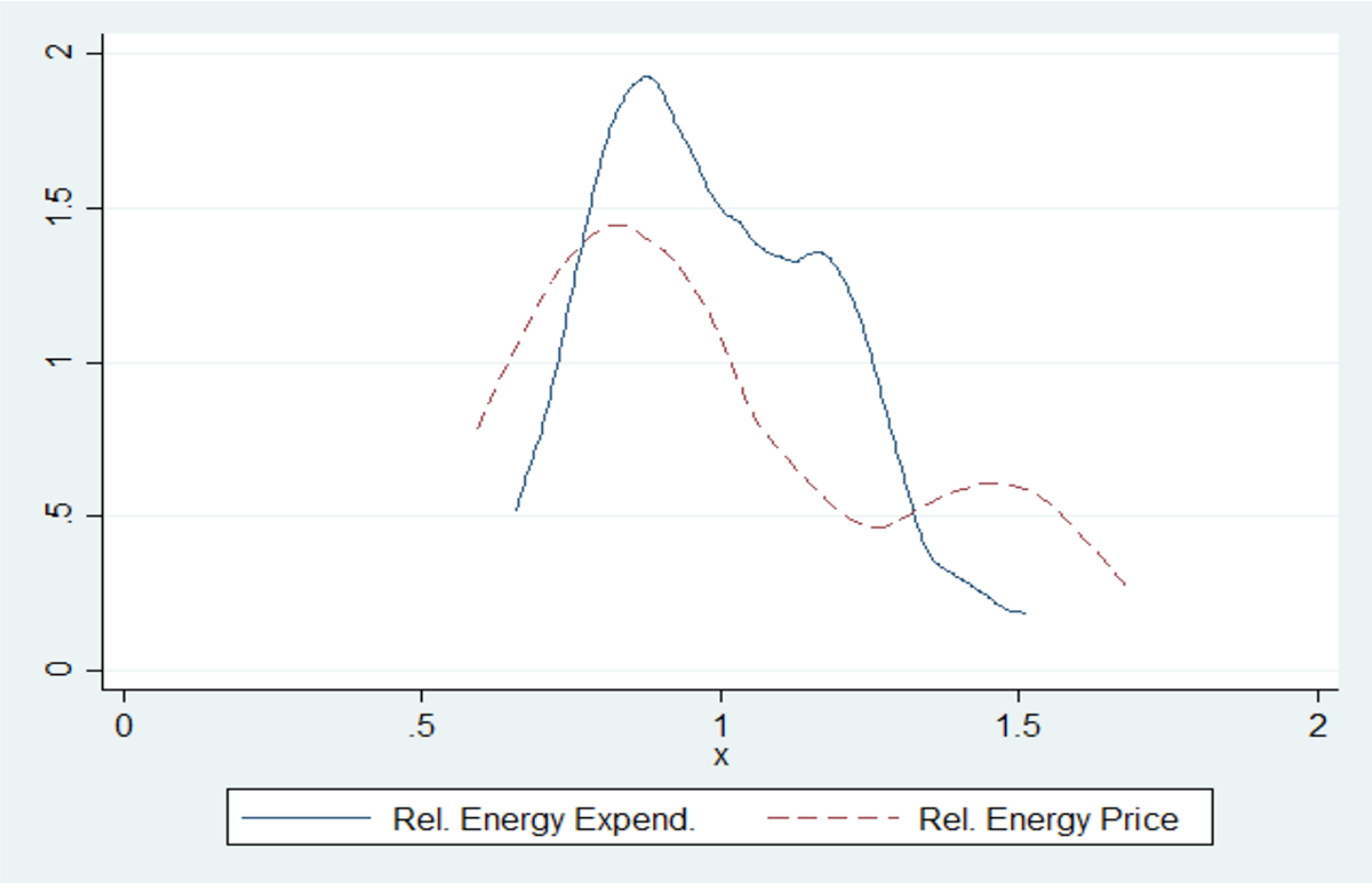


Figure 4: Distribution of US energy expenditure/GDP ratio and real energy price (relative to mean) over 1950-2014

To conclude: the various forces have led to overall expenditure on energy being within a range significantly narrower than price fluctuations, but with a slow downward drift (averaging around 0.04 percentage points a year over the period) which we analyse next, punctuated by the oil shocks. Excepting the immediate post-war period, energy expenditure has remained mostly in the range 7-10% of US GDP - despite energy prices fluctuating by over 100% during the two decadal periods of energy price shocks.

In addition to behavioural and technological adaptations to energy price growth, other factors, such as economy slow down, structural shifts, production factors substitution, and inflation, get to work to bring *long-term price-intensity correlation* close to 'minus one'. Whilst price shocks have undoubtedly had macro-economic impacts (in part because the oil shocks resulted in both dislocation and a flood of petrodollars' outside the US), higher prices have not ultimately resulted in higher proportionate US energy expenditure – which has indeed declined.

The impact of trade

Almost all data on energy use, including the EIA data used above, are published on a territorial basis – the energy used in a given country. This is also the basis for almost all emissions inventory accounting.

However, this neglects the effects of shifting trade patterns – not of energy itself, but of other goods and in particular commodities and manufactured products which have consumed energy in their production. A natural challenge to the findings above is to enquire to what extent some of the changes may be due to shifting trade patterns.

To explore this, we used the database of the Carbon-CAP project, which compared and evaluated a number of different multi-region input-output databases of international trade, with a focus on energy and related carbon issues (www.carboncap.eu). In particular, it examined how much of the apparent reduction in CO_2 emissions in industrialised countries has actually been due to 'offshoring' of energy-intensive manufacturing to developing countries (Wood et al., 2017).

The main results are reported for per-capita CO_2 emissions in terms of the difference between 'production' (i.e. territorial) and 'consumption' (i.e. including emission transfers 'embodied' in the trade of goods), with results for the US shown in Figure 5. Given the complexity of trade data, the latter **could only be estimated from 1970**. At this time the US was (still) a net exporter – with energy-intensive exports exceeding imports. The 1970s oil shocks led – with significant time lags - to some restructuring, and over 1985-1995 the US moved to being approximately neutral in terms of 'embodied' carbon transfers.

After the mid 1990s however, with the scale of globalisation and the rise of China, the US became a net importer of energy-intensive goods and associated embodied carbon. This peaked in 2005, just touching 10% net imports; it declined thereafter, more sharply as the financial crisis and global recession hit trade more heavily than domestic consumption.

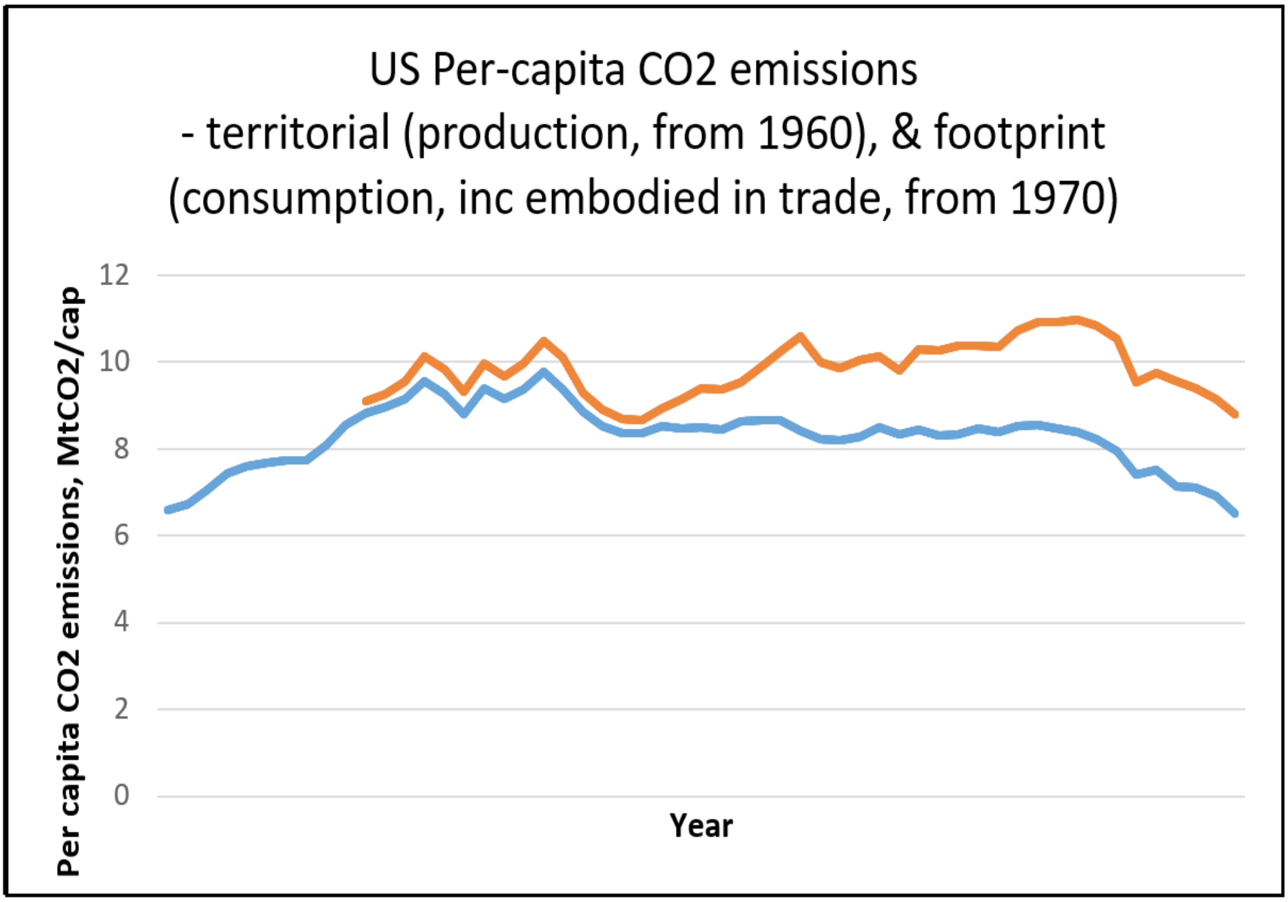


Figure 5: The impact of international trade on US CO_2 emissions, 1960/70 - 2014

Source: Carbon-CAP data, www.carboncap.eu

In Figure 6 we show a rough estimate of how this might affect energy expenditures on a consumption basis – i.e. attributing energy costs to the energy used in manufacturing imports and exports. To do this fully would require detailing the structure of trade, which was beyond the scope of this study. However, we make an approximation by attributing the CO_2 trade to a basket of coal, oil and electricity production associated with the traded goods, and applying the domestic prices of each fuel.

For simplicity we assume an equal basket of these three energy sources (neglecting natural gas, which tends to be used predominantly for household uses so less relevant to embodied trade), and attribute US energy prices by fuel, as a proxy for how much the US would have spent, had the traded goods been manufactured in the US.

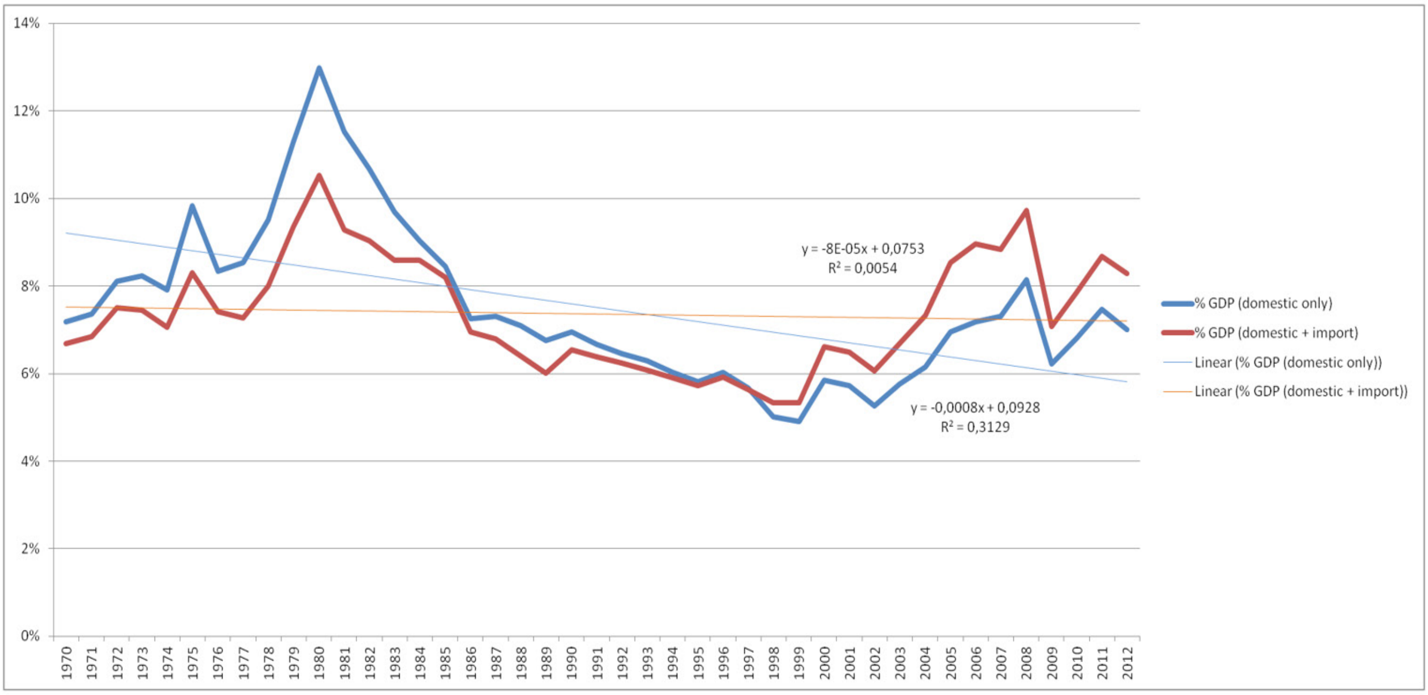


Figure 6: US energy expenditure per unit GDP – proximate impact of including net imports

Interestingly, the results in Figure 6 appear to indicate that including trade effects on this basis removes the structural decline in US energy expenditure intensity, which is clearly centered on 8%, with no discernible trend. The exceptional peak of 1979 (over 12% on production basis) reflected in part the impact of high oil prices on an oil-intensive export sector; on a net consumption basis, energy expenditure since the 1970s has been almost entirely in the range 6-10% of GDP.

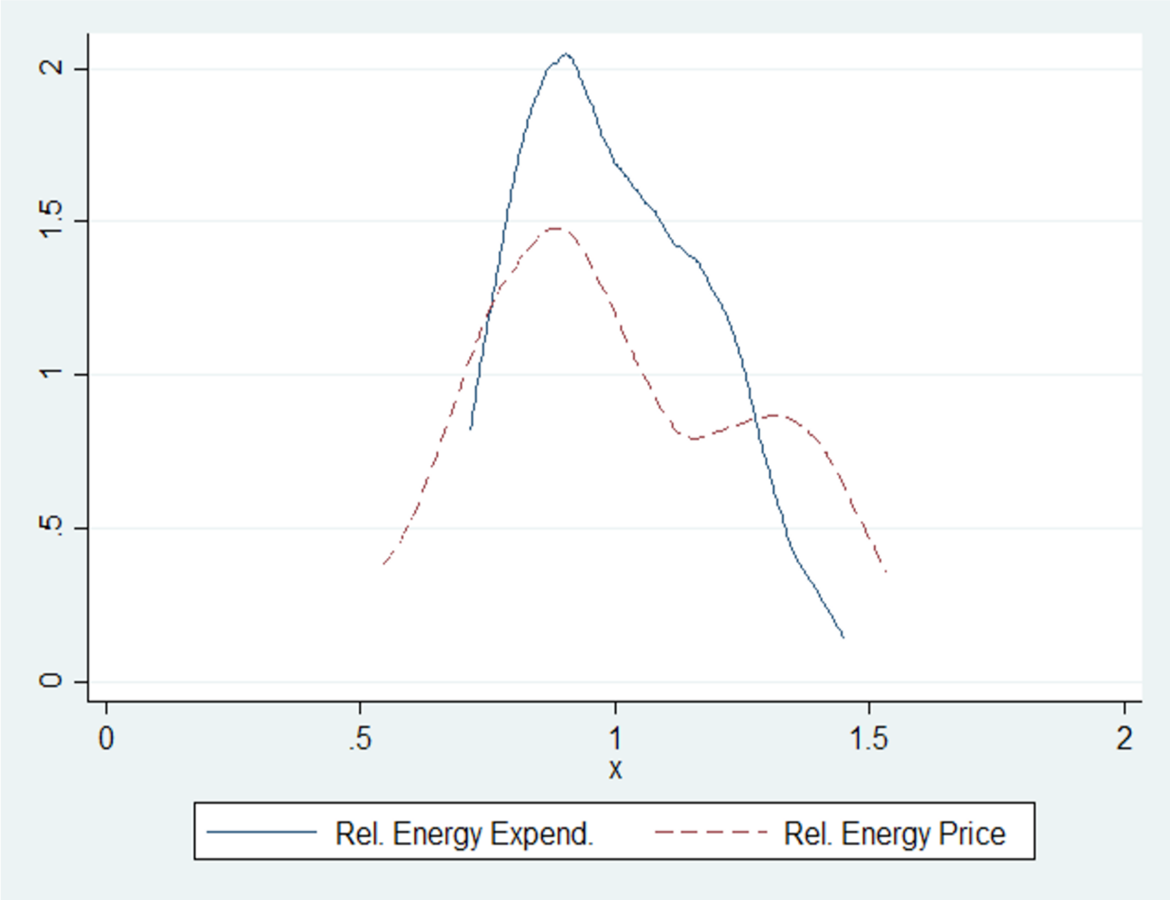


Figure 7: Distribution of US energy expenditure/GDP ratio and real energy price (relative to mean) over 1970-2014, including attributed to internationally traded goods

As before, in Figure 7 we show the distribution of energy expenditure/GDP ratio compared to the price range. This shows even more strikingly a sharp drop-off of relative energy expenditures at both ends of what is an even narrower range: the mean is 7.4%, with 80% of the years between 6 and 9%. Again, this is reflected in the distributional statistics, with the variance of expenditure intensity (0.032) being less than half that of the price variance (0.71).

Obviously, the above analysis does not amount to a formal econometric test of price-intensity elasticities that takes into account other potential factors. We return to discuss the interpretations later in the paper. First, having presented the empirical fact that the range of US energy expenditures has apparently been strongly curtailed at both ends compared to the range of energy prices, we turn to consider the international evidence.

Part III: Cross-country analysis of time-averaged energy expenditures

Interpretation of a single country time series is inevitably complicated by a multitude of factors which change over time – rising income, exogenous technical changes, structural changes, etc. In this section, therefore, we turn to consider cross-country evidence, comparing energy price and energy intensity of a range of different countries.

Methodology and data

Cross-country studies have been far sparser than time-series analyses, partly because of the difficult of assembling the required data – particularly on energy prices and expenditure.

Aside from the US starting from 1850 (Fizaine and Court, 2016), there have been detailed studies published with long-time-series energy expenditure estimates for the UK (Fouquet, 2008 from 1500, Csereklyei et. al 2014 (from 1800), and Sweden from 1800 (Kander, 2002)).

Beyond this, the global conclusions of Fizane and Court (2016) for example are actually derived from the heroic assumption of extrapolating global from US prices. For his first study, Bashmakov (2007) focused initially on US data and then on IEA data on energy prices and final energy use by sectors, as well as on national data for estimating the share of housing energy costs in personal income before tax. Newbery (2003) similarly assembled estimates that also gave useful insights but had significant limitations in data scope and time coverage.

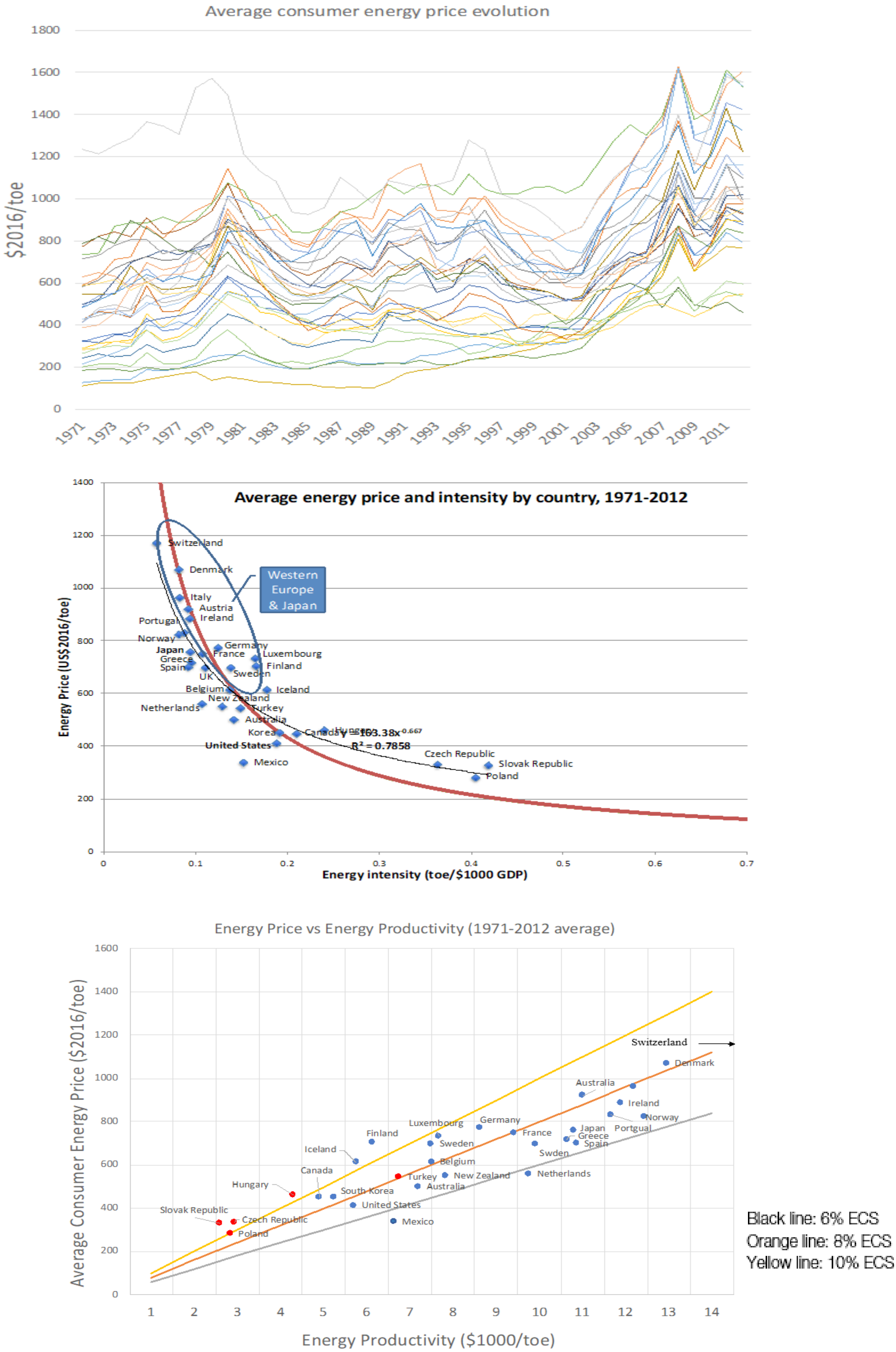
To explore the issues more robustly, we developed a new dataset on energy-related expenditure, for 32 OECD countries, for the period 1971 – 2012. The dataset was built principally using data from IEA Extended Energy Balances and Energy Prices and Taxes datasets, supplemented by estimates on energy prices from proxies and external sources. Approximately 89% of total final energy consumption across the countries and period examined are covered by this approach, with assumptions made to correct for the remaining 11% for which data is not presently available. See Annex I for more information.

This dataset encompasses the oil shocks and the period of low international energy (particularly oil and gas) prices, but with wider variation of domestic energy prices due in particular to high gasoline taxes introduced in Europe and Japan during this period, alongside the legacy of extensive energy subsidies in some other parts of the world. Resulting prices by country are shown in Figure 8 (a).

For national insights we present results in the form used by Newbery (2003) and subsequently somewhat updated as presented in Grubb, Hourcade and Neuhoff (2014) – a plot of primary energy intensity (toe/GDP) vs end-user energy prices per unit of primary consumption (calculated using data on end user prices and total final consumption per energy product and sector). Results aggregated over the full period 1971 – 2014 are presented in Figure 8 (b). This shows the average consumer energy prices (y-axis) and how these related to the average energy intensity (x-axis), illustrating the extent to which the data embodies a wide range of both price (vertical scatter) and intensity (horizontal scatter, and the relationship between them.

Energy expenditure is of course the product of energy intensity x price, and the thick (red) line shows the line of constant energy expenditure at the overall mean – the ‘minus 1’ line in terms of intensity price correlation (based on the average expenditure as a share of GDP across all countries for the period), which averaged around 8.2%. Countries to the right / above that line spent more of the GDP than the average, those to the left / below spent less. Firgure 8 (c) presents the x-axis as energy productivity - the inverse of energy intensity presented in Figure 8 (b) - with lines to represent ECS values of 6%, 8% and 10%.

Figure 8: Cross-country price analysis: (a) Average energy price evolution by country, (b) Average energy price and intensity by country, 1971-2012, (c) Energy Price vs Energy productivity, 1971-2012



The overall pattern

As expected, countries with higher average energy prices have lower energy intensity, but the extent of the relationship between price and energy intensity is striking. Most countries appear surprisingly close to the line of average energy expenditure.

From an analytic perspective this is an important complement to the US data examined in Part 1, because – along with the obvious acceleration of energy intensity improvements after the oil shocks – it strongly suggests that the "-1" observation cannot be explained in terms of exogenous, time-related technology improvements that happen to correlate with the transition to higher energy prices of the past 40 years; nor is it explicable (much) in terms of income elasticity. It does suggest price as a key determinant, not just a chance correlation (examined further and more formally with reference to econometric findings in Part V).

In fact, the findings are even more striking. The thinner (black) line shows the OLS regression line, in Figure 8 (b), for an exponential fit to the data. Over these 42 years and for this group of countries, there seems to be a clear tendency for those with higher energy prices to spend less on energy, per unit GDP. The best-fit line has an exponent of -0.67, with a good degree of statistical significance ($R^2 = 0.79$). The implied elasticity is the inverse of the exponent: -1.5. Correspondingly, ***those with the lowest energy prices actually spent more of their income on energy***: taken at face value this seems to imply that energy prices twice as high were associated with, on aggregate, one-third of the energy intensity - consequently spending 30% less of their GDP on energy.

These combined factors influence the global statistics of this dataset, which as with US are summarised in the form of the density plots shown in Figure 9. The data overall show a wide range of price, and the spread of relative energy expenditure is much less, whilst still bigger than for the US-only data; and for this international dataset, are is clearly skewed to higher ends.

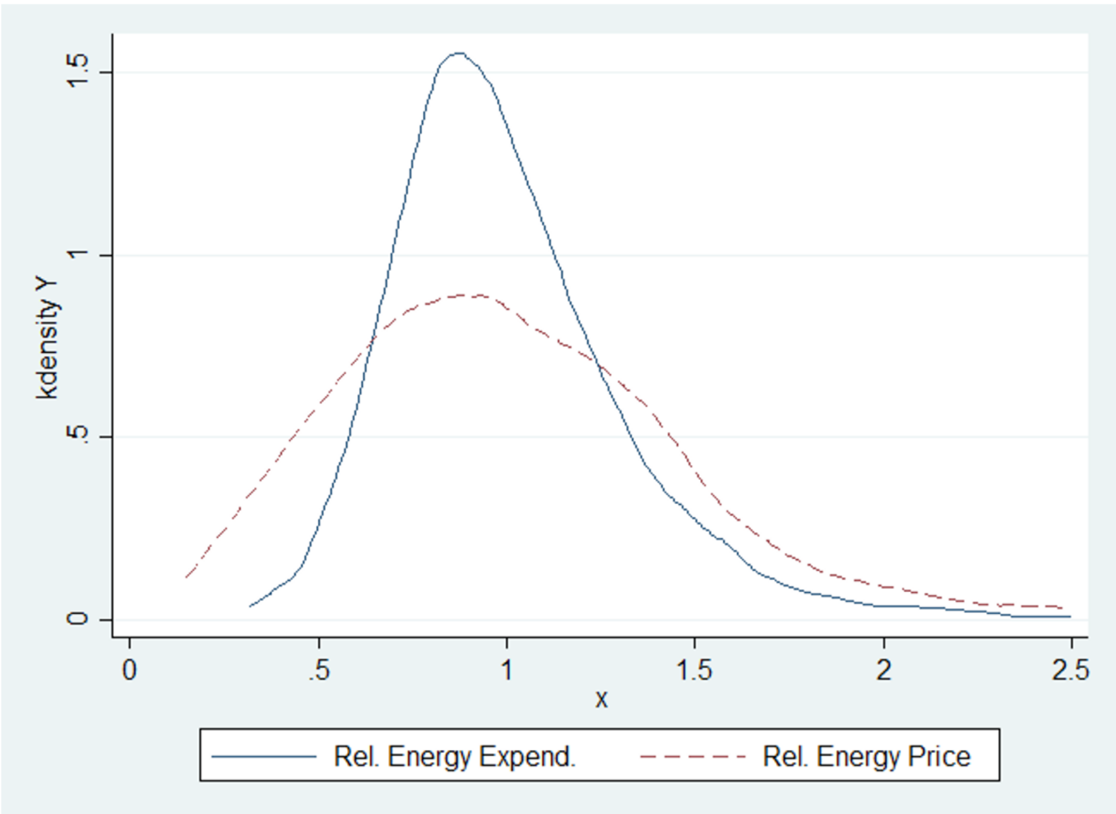


Figure 9: Global distribution of energy expenditure / GDP and real energy price (relative to mean) across 30 IEA countries, 1971-2012

Note: See Annex I for detail on data sources and country coverage

The global mean expenditure across the countries is 8.2% of GDP, with a wider 90%-ile range of 5.5 – 11% - which as we now show is largely due to particular (and telling) anomalies on the high side, and to Mexico and the Netherlands on the low side. Again, these are all reflected in the statistics of the distribution, with the variance of relative energy expenditure (0.096) being just under half that of the price (0.198).

National characteristics

In fact of course there is considerable variation between countries; the nature of the positions, and the deviations from the “-1” line, are telling.

Most of the western European countries appear very close to the line of constant expenditure (12 of the EU-15, along with Japan, are within the lozenge indicated in Figure 8 (b) – as is the US. Though energy prices in Switzerland, Denmark, Italy, Austria and Ireland averaged more than twice those of the US during the period, they used less than half as much energy per unit of GDP.

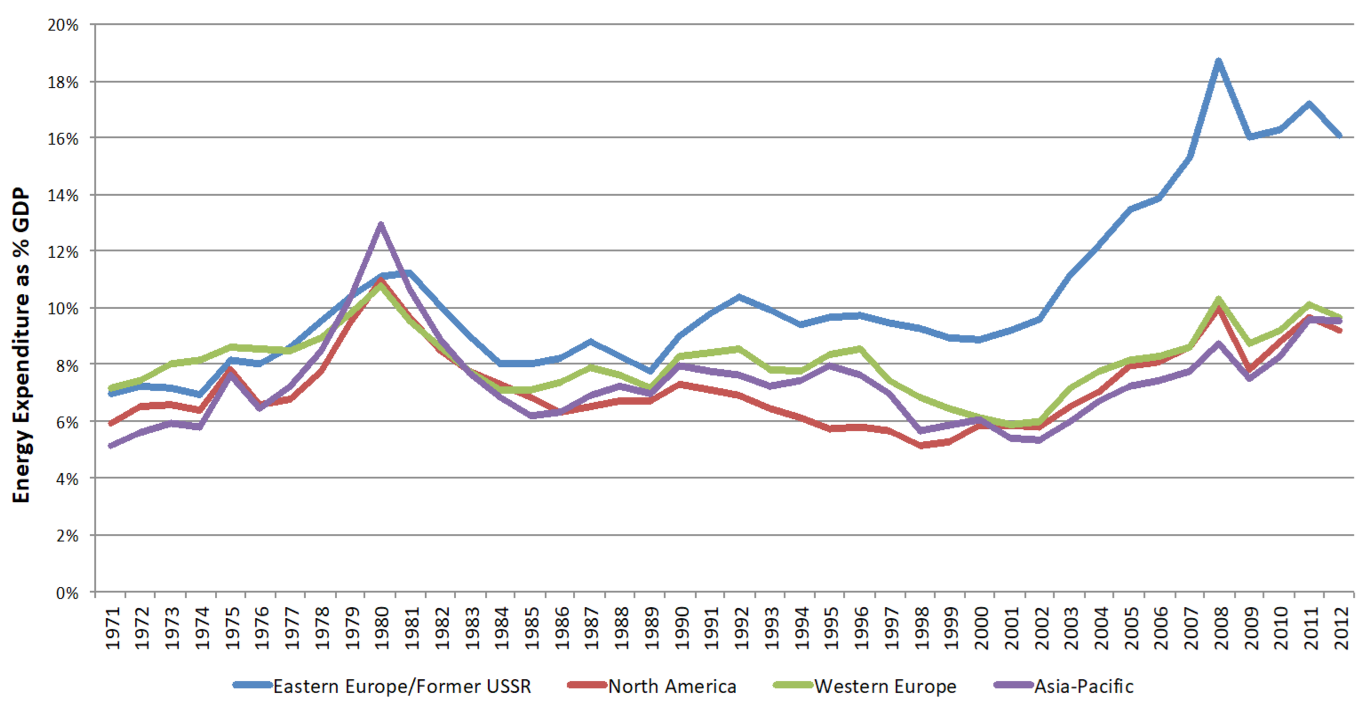
As noted, there are some outliers. The hydro-dominated countries with traditionally strong environmental concerns (notably Norway and Switzerland) spent less than the average; so did the Netherlands, Spain, and most of all Mexico, which is striking for its apparent combination of low prices and low energy intensity.

National trends and the exceptionality of Eastern Europe.

In contrast, the countries of Eastern Europe were for the first half of this period largely centrally planned as part of the Soviet sphere, with artificially low energy prices as a result of energy subsidies during the period. However these did not deliver significant savings in energy expenditure, due to much higher energy intensity, at least as measured with these market exchange rates.

The IEA data available only covered the four indicated, of which three (Czech and Slovak Republic, and Poland – the other being Hungary) are striking for having had, on average, twice the energy intensity of the US (and four times their western European counterparts). Figure 10 illustrates the evolution of % GDP energy expenditures since 1971 for the countries divided into four groups - North America, Western Europe, Asia-Pacific and these four countries of Eastern Europe (Turkey is excluded).

Figure 10: Energy Expenditure as a Proportion of GDP for Country Groupings



The *Asia Pacific* region started with the lowest expenditure but peaked the highest in 1980, but overall is close to the *North American* and *European* levels of energy expenditure which remained remarkably similar – within 1 percentage point - throughout the period. Until around 1990, the *Eastern Europe* group followed a similar though flatter trajectory until around 1990: all four groups rose from around 5-7% GDP in 1971 to a 1-year peak of 11-13% in 1980, before falling to around 7-8% in 1989.

Overall, except for very brief interludes all the three groups of market economies stayed in the range 8±2 %GDP energy expenditure throughout the 42 years, mostly in the lower half (6-8%), except for the few years of oil shocks of late 1970s – 1982 and after 2005. From the late 1980s however, the trend in Eastern Europe was radically different.

The phases of the various countries can be seen more closely by looking at how patterns and positions evolved over time, divided into three periods:

- 1971-1984 (high international energy prices)
- 1985-1999 (falling/low international energy prices)
- 2000-2012 (rising/high international energy prices)

Figure 11 (a-c) uses the cross-sectional scatter plots to show more about the evolution of price and intensities at the national level. The east European group in this dataset (Czech and Slovak republics and Poland) started with very low energy prices, largely shielded from the oil price shocks. Their energy efficiency slowly evolved up to the end of the 1990s, as global energy remained cheap, but still averaged expenditure around 8-10% of GDP to around 2002.

Joining the EU in the mid 2000s, requiring a move to market-based energy systems at a time of sharply rising energy prices, provoked a major shock – energy expenditures increased dramatically, hitting over 16% from 2006-12. Their energy intensity did improve substantially, but not nearly fast enough to keep pace. Again, this underlines the high degree of inertia in energy systems, so that countries with relatively large energy intensities suffer much more from energy price shocks.

The opposite extremes are also striking. In the first period, Switzerland was an outlier with exceptionally high energy prices; by the last period, it was spending less of its GDP on energy than almost any other country. Table 2 presents the actual expenditures over these periods by countries, which are in turn presented graphically by Figure 12.

Figure 11: Average energy price and intensity by country (a) 1971-1984 (b) 1985-99 (c) 200-2012

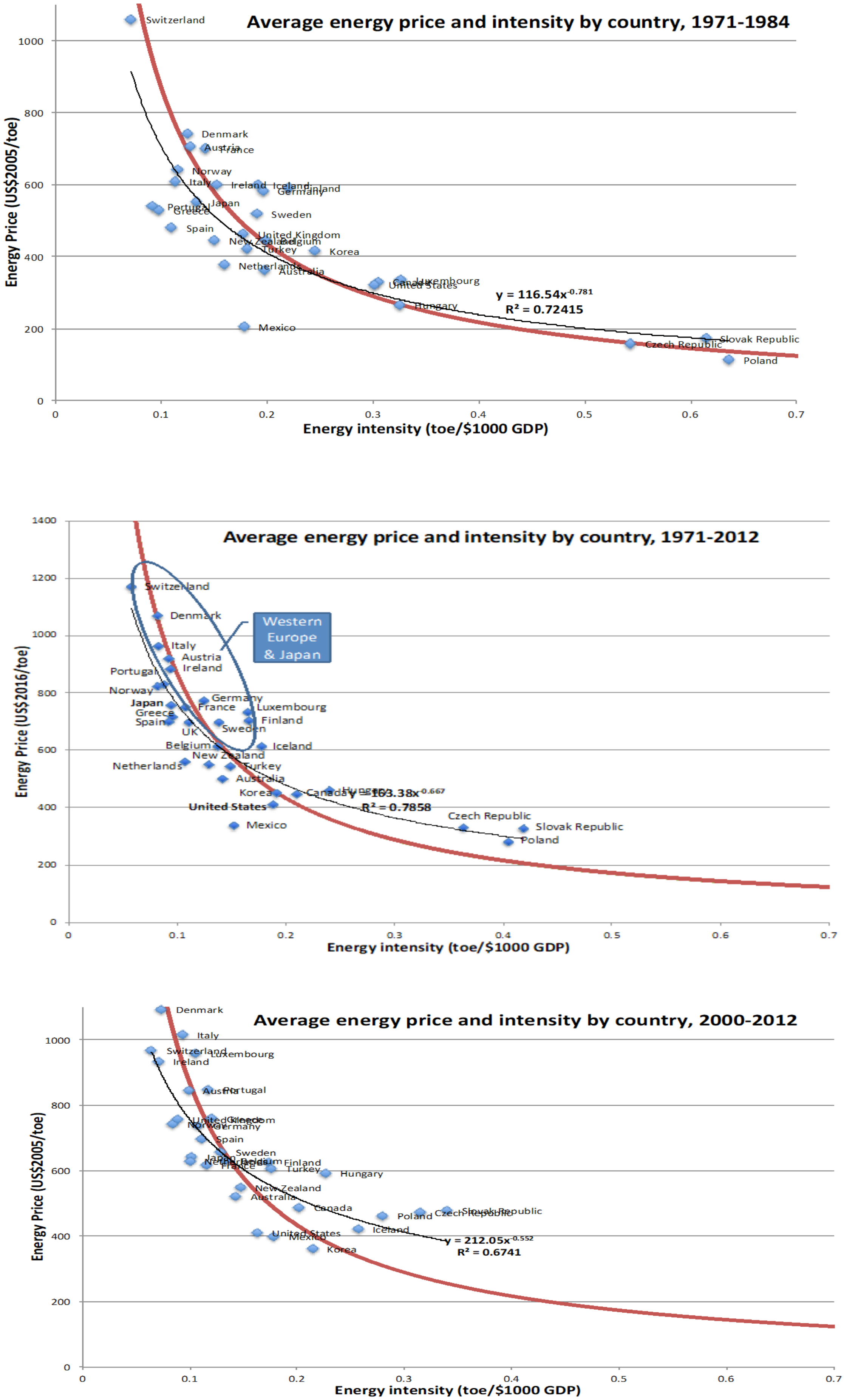
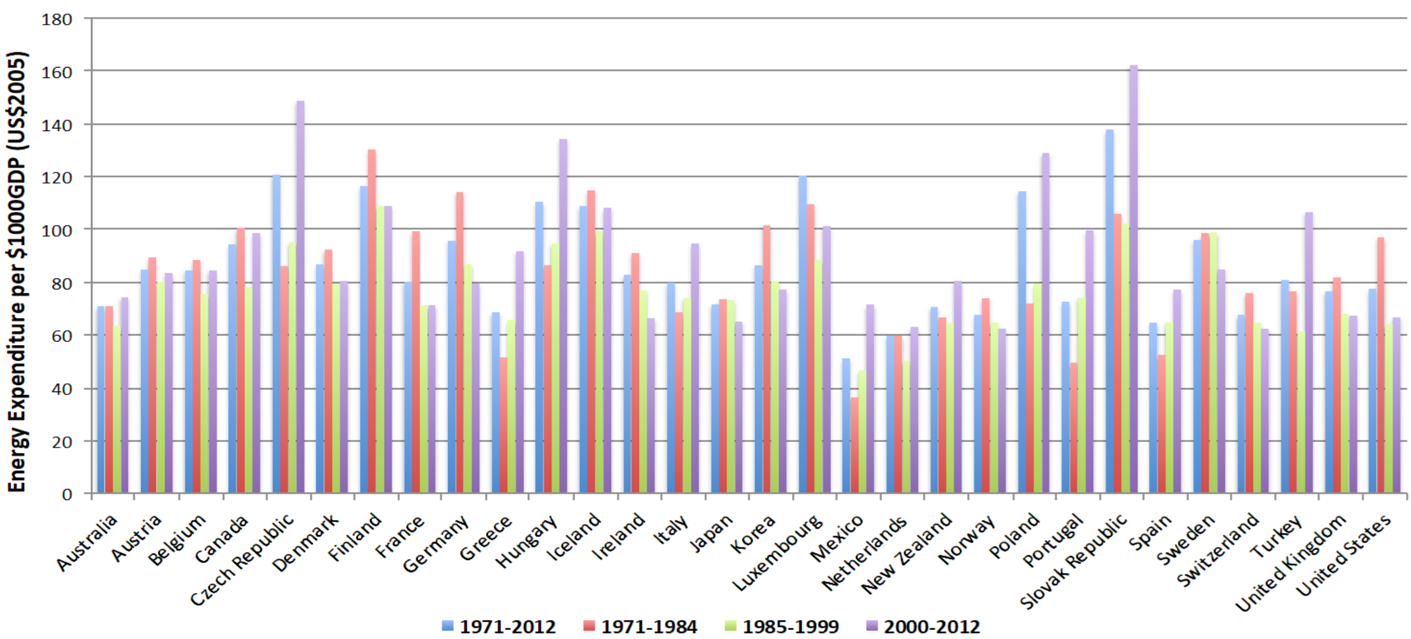


Table 2 – Energy Expenditure per $1000 GDP

	Energy Expenditure per $1000 GDP			
	1971-2012	1971-1984	1985-1999	2000-2012
Australia	70.8	71.1	63.5	74.4
Austria	84.8	89.4	80.1	83.5
Belgium	84.5	88.5	75.5	84.6
Canada	94.4	100.5	78.1	98.6
Czech Republic	120.7	86.2	95.1	148.8
Denmark	86.8	92.3	79.5	80.4
Finland	116.4	130.4	108.7	109.0
France	80.4	99.2	71.4	71.3
Germany	95.8	114.2	86.9	79.6
Greece	68.7	51.6	65.5	91.6
Hungary	110.4	86.4	94.8	134.3
Iceland	109.0	114.9	99.4	108.1
Ireland	82.7	91.2	76.9	66.3
Italy	79.9	68.6	74.1	94.7
Japan	71.7	73.5	73.3	65.2
Korea	86.4	101.8	80.5	77.3
Luxembourg	120.4	109.4	88.5	101.2
Mexico	51.1	36.5	46.6	71.4
Netherlands	59.7	59.8	50.3	63.0
New Zealand	70.7	66.6	64.3	80.6
Norway	67.5	73.9	64.8	62.3
Poland	114.4	72.0	79.5	129.1
Portugal	72.6	49.5	74.3	99.6
Slovak Republic	137.8	106.0	102.3	162.4
Spain	64.6	52.6	64.8	77.4
Sweden	95.9	98.6	98.9	84.8
Switzerland	67.8	75.9	64.6	62.5
Turkey	80.7	76.5	61.3	106.6
United Kingdom	76.6	82.0	68.2	67.3
United States	77.6	96.9	64.2	66.8
Average (not GDP-weighted)	**86.7**	**83.9**	**76.5**	**90.1**

Figure 12: Energy Expenditure per $1000 GDP



Aggregate characteristics with and without Eastern Europe

Table 2 summarises the results in terms of the OLS exponents and corresponding elasticities in these different periods. Table 3 repeats these results, excluding Central and Eastern European Countries.

Table 3 – OLS exponent and Elasticities

Period	Exponent of OLS	Cross-country Elasticity
1971-2012	***-0.667***	***-1.50***
1971-1984	-0.781	-1.28
1985-1999	-0.832	-1.20
2000-2012	-0.552	-1.81

Table 4 – OLS exponent and Elasticities – Excluding CEE Countries (Poland, Czech Rep. and Slovak Rep.)

Period	Exponent of OLS	Cross-country Elasticity
1971-2012	**-0.705**	***-1.42***
1971-1984	-0.609	-1.64
1985-1999	-0.845	-1.18
2000-2012	-0.675	-1.48

It appears that the cross-country elasticity was higher during periods of high prices, and in the first price shock this may have been masked by the central planning of the east European which insulated them from international prices. Nevertheless, the cross-country elasticity remains substantially bigger than (minus) one: even amongst the long-term OECD countries, those with more expensive energy do appear to end up spending less of their income on it.

Indeed, the east European countries significantly distort the overall distribution of Figure 9. Across all 30 countries over these 42 years, the mean expenditure/GDP ratio is 8.2%, with variance 9.6% and statistical skewness of 1.09. If just these four east European countries are removed, the mean drops to 7.9%, the variance falls to 8.1%, and skewness to 0.79.

The trade effect

As with the US analysis of the previous section, one potential important complicating factor here is international trade. The period covered by the analysis – and particularly the second half of the overall period – was as noted characterised by growing globalisation and the rise of manufacturing in China. Many of the OECD countries became far greater importers of energy intensive goods (and associated embodied carbon) than the US.

The simple expedient used to examine the impact of trade in the US analysis of Part 1 – making a crude assumption on the basket of fuels used to make manufacture these (net) imports, and prices at domestic energy prices, is likely to lead to much exaggerated estimates. This is not only because of the greater imports, but because higher energy prices in these countries means that attributing these prices to imports would result in far greater exaggeration of the actual energy costs imputed. After all, importing energy intensive goods from regions where energy is intrinsically cheaper is entirely appropriate, reflecting standard economics of comparative trade.

Detailed analysis would need to break down imports by commodity, and make a reasonable proxy for the actual energy cost used in making those products. This is beyond the scope of this study. All that we can reasonably say is that looking at energy costs from such a consumption perspective, including imported goods, would presumably pull the line back towards “-1”, rather than the substantially greater numbers observed here, and further narrow the range of energy/GDP ratios amongst the market economies.

Part IV: Theoretical explanations

Econometric evidence and the consistency of elasticity estimates

We started this report with a brief review of literature on energy elasticities. We noted that the literature on the price elasticity of consumer energy demand underlines the increase of elasticity with time horizons, but the huge meta-analysis of Labandeira et al (2015) nevertheless suggests (from almost 1000 estimates) long-term elasticities of energy demand of 0.6-0.66 in the 'long run'.

This seems to contrast with the price - energy-intensity correlations of the previous sections, particularly the simple cross-country results with implied cross-country elasticities apparently significantly greater than (minus) 1.

The vast majority of formal energy elasticity studies are limited to data since 1970. Econometric studies of much longer periods include Fouquet (2012) and Fouquet and Pearson (2012) for UK lighting and transport, and Stern and Kander (2012) for the Swedish economy. As reviewed by Saunders (2016), even these seem to generate similar numbers: "for lighting, price elasticities have remained relatively stable since 1900, averaging about –0.6; for transport, they remained highly stable since 1950 at about –0.7" - results which "reinforce the substitution elasticities measured by Stern and Kander (2012) for the Swedish economy as a whole (0.645 to 0.686)."

We can go some way towards reconciling the estimates from our introductory observation in Part 2 that several other potential factors contribute to observed price – intensity correlations:

Income elasticity of energy demand. As noted, an income elasticity less than one would also lead to declining energy intensity over time. The literature on income elasticity is not conclusive. Many studies suggest it remains close to one. However there is some evidence that income elasticity declines as countries develop. Mir and Storm (2016) present evidence for this 'decoupling' – potentially leading to a 'Kuznet's curve' relationship - though they go on to argue that this more hopeful outlook disappears if one takes account of trade. *i.e.* they argue that apparent declining income elasticity in fact can be ascribed to the outsourcing of manufacturing from OECD countries in recent decades (see also the response by Grubb *et al* (2016) on the trade effects in terms of embodied CO_2).[6]

This could contribute to the observed US declining energy intensity. But it is clearly at best only a modest part of the observed trend, given the clear impact of 1970s oil shocks and the fact that intensity improved more rapidly alongside the subsequently lower GDP growth rates. It is also notable that many of the countries with higher energy prices as reviewed in the previous section are amongst the richer countries (certainly, compared to the CEE countries), so income elasticity effects could also plausibly influence the cross-country analysis. But even if the income elasticity were as low as 0.7, thus accounting for a decline of 0.3 in intensity as income doubles, it would still be insufficient to bring the observed cross-country elasticity below 1 even if countries at the extremes of high efficiency receive double the income.

Overall, income elasticity itself is thus appears to be at most a marginal contribution.

Exogenous technology trends. Exogenous technology improvements also could contribute to declining intensity over time (a relationship however complicated by energy-efficiency rebound effects), and hence apparent correlation when measured over time, given the broadly rising energy prices over the period considered in the US data. One might also postulate that the countries with higher energy prices tend to be not only richer, but more advanced in their adoption of more efficient technologies, though this somewhat tenuous by way of explanation.

6 Michael Grubb, Annela Anger-Kraavi, Igor Bashmakov, and Richard Wood (2016), 'Carbon decoupling? Carbon emissions and economic growth - production vs consumption-based evidence', Institute for New Economic Thinking, https://www.ineteconomics.org/perspectives/blog/carbon-decoupling

Neither of these factors offer strong explanations of the price – intensity relationships observed - particularly when it is acknowledged that technological change is itself influenced by price – and the associated limited range of energy expenditure.

The Bashmakov-Newbery constant, particularly when adjusted for trade effects, appears to consistently gravitate around 8% of GDP with a range exceeding ±2 percentage points only in exceptional circumstance, for brief periods or in countries with exceptionally distorted (and transitional) conditions.

Overall, the data cannot be primarily explained through factors of income elasticity or exogenous trends: there is good evidence that the collective impact of forces in the energy system drive long term adjustments that keep total bills within the ranges indicated, through *price-related* responses.

In this section we explore two other dimensions, from this perspective:

- Theoretical rationales to expect price elasticities close to "-1"
- The limitations to this and complementary models that need to be explored in any more complete theory

Theoretical rationales for "Minus 1"

A price elasticity of (minus) 1 is familiar in high-level economic theory, as it is implicit in the popular, simple, Cobb-Douglas production function. If energy were specified as a separate input to economies, therefore, such a production function would indeed imply a price elasticity of -1. Saunders (2015) notes that increasing literature pointing towards an energy intensity-price elasticity of -1 is very appealing from this perspective.

In terms of theoretical explanation however, "-1" from this perspective is a tautology - a product of assuming a Cobb-Douglas form - and not a theory of why it should be so.

From a physical/engineering perspective, a more fundamental argument is offered in a little-known paper by Lowe (2003). He demonstrates that for an energy conversion system with multiple stages of energy transformation, the *overall system* elasticity should tend asymptotically to unity as the number of sub-systems increases, even if the component subsystems are inelastic ($0 < e_i < 1$, for each step i in the chain).

The rationale is simple (though his mathematical formulation isn't): each step in the system offers another element of flexibility to respond to price changes in its inputs. The final output is the sum of these flexibilities. If the cost of primary input changes, how much of that price impact is transmitted depends on the flexibility of each step:

- The more a given step of process energy efficiency can increase its efficiency or otherwise reduce dependence on the input in response to higher energy prices (the physical) – or the higher its elasticity (the economic perspective) - then the more it will mitigate the price transmitted along the chain; conversely
- The less that any physical step in the chain can change in response to higher price (the physical) – or the lower its elasticity (the economic perspective) - then the more the price will be passed on to the next step.

So a long enough chain of steps i with $e_i > 0$ will gradually attenuate the price signal until it has been absorbed by multiple efficiency improvements (or substitutions) in components along the way. So for a long enough chain, the full system should tend to a price elasticity of (minus) one.

Many energy conversion systems do in fact comprise multiple conversion stages.

The rationale is not however confined to purely energy systems. If the concept of embodied energy (see Hammond and Jones, 2008) is applied to the wider economy, then it can be considered as a multi-stage energy conversion system. When embodied energy analysis is applied, it means that changes in material efficiency improvements also contribute to the process. Lowe's conclusion becomes relevant to whole sectors of the economy, as becomes clear from applying the material balance method used to assess embodied energy.[7]

The "minus one" effect thus has a logical foundation. It is the result of the assumption that sub-systems efficiencies depend on input energy prices, linked in long supply or energy conversion chains. This mitigates price impacts at following stages.

One apparent puzzle is that from this logic it appears impossible to generate elasticities greater than (minus) 1. If a component (or cumulative response up to and including a component) has elasticity exceeding unity, it actually would reduce the price passed on, so the system would tend back to (minus) 1.

However, considering dynamics of the system makes such an outcome quite plausible, because few responses are likely to be instantaneous. If later stages in the chain can respond faster than earlier stages, they may 'overshoot' their response; when the upstream stages finally adjust, the result is indeed an overall reduction in the final cost.

If the downstream gains are reversible, the higher system wide response starts declining asymptotically from that new level back to a response of "-1". However, if the downstream improvements are sticky (e.g. due to innovation) and do not then reverse, this offers a physical context for a strong form of 'Porter's Hypothesis' in which an increase in raw input costs leads to an overall long term improvement.

One might cautiously interpret the Swiss example noted above – having apparently endured in the 1970s with amongst the highest energy costs, and now spending substantially less than the norm on energy – as such an example.

Limitations and complementary models

This of course is a theoretical construct, and the data we have shown are more complex, in particular in suggesting not a full constancy of energy expenditures, but rather a range, and very long timescales of overall response.

The corresponding implications are (a) that responses are much stronger at extremes of prices: that high prices provoke a disproportionate degree of efficiency improvement, whilst the cost of energy inputs may be virtually ignored if the price is low enough, slowing and even reversing gains in energy; and that (b) more attention is needed to the dynamics of responses. Lowe's approach hints at some of these issues, but this just emphasizes the need to look at more sophisticated model structures.

We conclude that the explanatory power of the normal economic assumptions are constrained by the attempt to impose fixed parameters – fixed elasticities of price or income, or exogenous technology change – on what is actually a more complex and non-linear set of responses. This reflects our suggestion in the US study that the evidence points towards different "elastic phases".

In particular, there are three kinds of approaches – not exclusive of each other – which could more fully explain the observations:

7

$$Eemb = (1-m)*(\sum_i X_i * a_i + Pe) + Te$$

where m – is share of production process loss; Xi – masses of input materials; ai – specific embodied energy use per unit of input materials; Pe – energy directly used in given production process; Pe – the transport energy of the final product. This insight on the wider application of Lowe's idea is from Igor Bashmakov.

Asymmetric (1-way) elasticities

Asymmetric elasticities were first formalised by Dargay and Gately (1995). They reflected on the apparent observation that the rapid decline in energy intensity in response to the oil shocks was not in any way matched by an equivalent increase when the price fell. They argued that many of the responses were essentially irreversible – embodied in more efficient equipment and capital stock (including closure of antiquated inefficient stock), and econometrically tested a model that involved 3 terms: different elasticities in response to rising or falling prices, plus a 1-way additional response when price rose above previous levels.

Box 1: Bashmakov (2016) approach to asymmetric price change

If energy demand is a log linear function of income and energy price, then by expressing it in average annual growth rates (T_e) we get: $T_e = a * T_y + b * T_p$, where:

T_y is income growth rate, and

T_p is real energy price growth rate.

Elasticity of energy intensity to real energy price (c) is:

$$c = \frac{T_{e/y}}{T_p} = \frac{T_e - T_y}{T_p} = \frac{aT_y + bT_p - T_y}{T_p} = (a-1) * {T_y}/{T_p} \quad (8)$$

If there is some autonomous technological progress driving energy demand down $(\gamma<0)$, then:

$$c = (a-1) * {T_y}/{T_p} + b + {\gamma}/{T_p}$$

. Energy intensity to real energy price elasticity is a function of energy demand price elasticity corrected for income elasticity and for the ratio of average annual income growth rates to average annual real energy prices growth rates. Assuming (γ = 0), these two elasticities are equal only when either *Ty*=0, or *a*=1. According to the theory, *b* is negative. T_y and T_p can be either positive or negative.

- If $a<1$, and both T_y and T_p are positive, then $c<b$.
- When energy prices decline, or T_p is negative, then $c>b$.
- During price shocks, when T_p is very large and T_y is relatively small, and so T_y/T_p is very low, c $\longrightarrow$ b.

So mostly the sign of T_p defines the sign of the first component, when a is given, and therefore the relationship between *c* and *b*. Due to the instability of the T_y/T_p, elasticity c is not constant and evolves as both energy prices and rates of economic growth or income cyclically fluctuate.

In the general case, both a and b are not constant across time so that evolution of energy demand elasticities along with the T_y/T_p ratio influence the dynamics of the real energy price elasticity of energy intensity therefore making its long-term (cycle-long) stability at 'minus one' even more striking.

Only whole cycle-long real energy price elasticity of energy intensity (very-long-term elasticity) is equal to -1. For time series that start and end in different cycle phases, *c* can vary a lot with given *b*, depending on combinations of the parameters of equation (8).

For the 'minus one' phenomenon, c=-1, or $\frac{a-1}{b+1} = -\frac{T_p}{T_y}$, and therefore $b = (1-a) * {T_y}/{T_p} - 1$.

If the whole cycle-long time frame is taken, then for the U.S. the ratio of GDP growth rates to real energy prices growth rates was 2.7 in 1963-1986, 1.5 in 1963-2014, and 1.9 in 1963-2014 (Table 1). So in the long-term in the U.S. b≈1-2a, but the coefficient preceding *a* was different for the two cycles. For OECD-Europe, this ratio for 1981-2013 was 2 as well (based on the data from IEA, 2014a; and IEA, 2014b).

A modest literature continued (not to be confused with other literature on different aspects of asymmetric price responses).[8] Recent empirical and modeling literature on asymmetric price reactions explains the asymmetry effect through *an uneven technological and behavioral change* under different energy price changes (Huntington, 2003; Gately and Huntington, 2002; Griffin and Shulman, 2005; Jimenez-Rodriguez and Sanchez, 2005) through *different consumers' reaction to the 3 energy price components* with live memories of previous price maximums while making investment and management decisions, *different perception of, and reaction to, price declines and price recoveries* after declines (Adeyemi and Hunt, 2014), *risk aversion* of human nature (van de Ven and Fouquet, 2014), as well as through *purchasing power thresholds*, which drive the uneven technological and behavioral change and impact economic activity (Bashmakov, 2007). All those factors may be important.

Much of this literature has been focused around the specific 3-term formulation of Dargay and Gately (1995). Bashmakov (2016) considers another approach to asymmetric energy intensity response to price changes, as summarised in Box 1.

Stochastic Structural Time Series Models (STSMs)

STSMs which were introduced by Harvey (1989) involve stochastic changes in two trend components, i.e. the level and slope of the variable in question, in ways that reflect path-dependence since they always refer to changes at time t relative to t-1. This can be interpreted as representing for example enduring structural and technological changes in the system.

Agnolucci (2010) adopted the principle of *General to Specific* econometric modelling – to start with a very general unconstrained model form which could describe observed data, and reduce it in complexity by eliminating statistically non-significant variables and trend components. He applied this to data on UK energy demand in both domestic and industrial sectors. He found that 'Stochastic trends are rather important, whilst the hypothesis of symmetric price effects could not be necessarily *rejected* when using the price decomposition of Dargay and Gately (1995). However, the stochastic trend was itself found to be quite correlated with price changes.

Moreover, both the asymmetric elasticity and the STSM formulations involve path-dependence – the energy demand in one period being contingent upon the prior trajectory. There was no reasonable fit of the data without drawing on one of these – so a degree of path dependence is intrinsic to Agnolucci's findings. Moreover he found that the two specifications can act as substitutes at least in the industrial sector - where response was found to be strongly influenced by price.

This finding would create an equilibrium correction mechanism for the energy expenditure share, implying an upper and lower bound for the ratio. In the presence of exceptionally high prices, for example, an increase in energy expenditure would be tempered and eventually reversed by permanent improvements in energy intensity, represented by the stochastic trend, contributing to push the ratio back towards its long-run equilibrium. In the industrial sector these adjustments could, of course, include structural changes that result in growing imports from regions with lower energy costs – which itself a way of containing energy costs grounded in standard principles of trade economics, that regions with intrinsically higher energy costs do well to specialise in activities other than energy-intensive manufacturing.

In the domestic sector, Agnolucci found that 'the effect of price in domestic energy use is markedly smaller' – and that 'the stochastic trend in the domestic sector is mainly shaped by factors other

8 Notably, literature on corporate responses in passing through rising input costs but failing to pass declining input costs on to customers, more commonly known as final prices 'rising like a rocket but falling like a feather'.

than energy price.' And, that 'after 1995 … the diffusion of efficiency standards caught up with the increased number of appliances, hence a decreasing trend of energy intensity in the latter half of 1990s despite still declining energy prices.

Non-linear price elasticities and inequality

The actual shape of the data observed in this study – a range of energy expenditures (estimated to be stable only in the range 8±2 %GDP after accounting for trade effects) with relatively sharp cutoffs on either side - suggests a non-linear response. Long-term elasticities closer to those cited in the literature (e.g. 0.5-0.7) may be applicable within this "normal" range, but they need to be accompanied by acknowledging several other factors:

- When energy costs rise above this range, the economic impacts provoke much stronger responses, that act over time to bring energy costs back towards the B-N constant.
- Conversely, when energy costs are very low – particularly, below the low end – it may be that energy costs cease to become a factor in decision-making and the elasticity becomes very low.

Of course, the former response also reduces pressure on the energy supply markets, whilst the latter increases demand – thus, this pattern, combined with corresponding responses on the supply side of the energy industries, leads to the long-term cyclical nature of energy prices.

These two factors imply that energy elasticities are non-linear: the elasticity rises as prices and expenditures rise. This in fact is not a new suggestion; literature over decades has raised this proposition[9]. It has to a large degree been ignored in the wider modelling literature, however, presumably because of the added complexity – which is not a good reason to ignore a potentially crucial issue in long-run energy dynamics.

In addition, an important third factor complicating assessments may be the role of energy-environmental policy, which may also reduce energy consumption during periods of 'normal' energy expenditure ranges, mimicking elasticities closer to "-1" – but then facing risk of growing rebound if and as they reduce energy expenditure to below the lower threshold.

Such behavior is entirely consistent with the 'Three Domains' framework advanced in Grubb, Hourcade and Neuhoff (2014), which argues that the development of energy systems can only be understood by recognizing different domains of economic decision-processes:

- The satisficing domain corresponds to low prices, strong dominance of behavioral effects etc., There is little change in industrial dynamics. Improvements in energy intensity are due either to lagged technology effects or direct government policy on energy efficiency – once the technologies borne in previous eras have diffused, or the political impetus for enhanced energy efficiency dissipates, costs drift back up again despite low prices; hence the lower bound on energy costs.
- The markets domain reflects a zone of relatively constant elasticities, particularly in industrial energy use, but with limited structural change or radical innovation; consequently, the elasticities are also substantially reversible, and from the perspective of a particular fuel may be dominated by fuel substitution effects as relative fuel prices vary.
- The transforming domain occurs when energy prices rise sharply and/or peak at levels not

9 Drifts of elasticity coefficients for energy demand functions have been observed by modelers since the early 1980's (Kouris, 1981) and were initially (while the share of energy costs was on the rise) addressed through simple trend models (Girod, 1983). After energy price elasticity coefficients declined driven by the declining share of energy costs in the late 1980's, it became clear that time was not a driver behind such evolution. Bashmakov (1988) developed an energy demand model with a dynamic price elasticity coefficient as a function of 3 years' moving average real energy prices. So as energy prices grow, price elasticity coefficient escalates. Haas and Shipper (1998) showed that for many countries energy price elasticities are higher, when prices are growing. Ghalwash (2007) demonstrated that price elasticity for the tax portion of the energy price in Sweden is higher, than for its base part.

experienced for many years. The Dargay and Gately (1995) – inspired literature on asymmetric effects of peak prices points to strong technological, structural and behavioural impacts of such extreme prices – which are of course, themselves a reflection of the strong impetus to avoid economically-damaging levels of overall energy costs. Or in the common phrase – necessity becomes the mother of invention (or of structural adjustment).

Following on from Bashmakov's treatment of asymmetric price elasticities (see box above), depending on the model specification used to assess the parameters of the energy demand function, energy price asymmetries may reflect an 'affordability threshold. In the extreme, the assumption that income and prices can vary independently in one-equation energy demand functions is no longer valid.' [10]

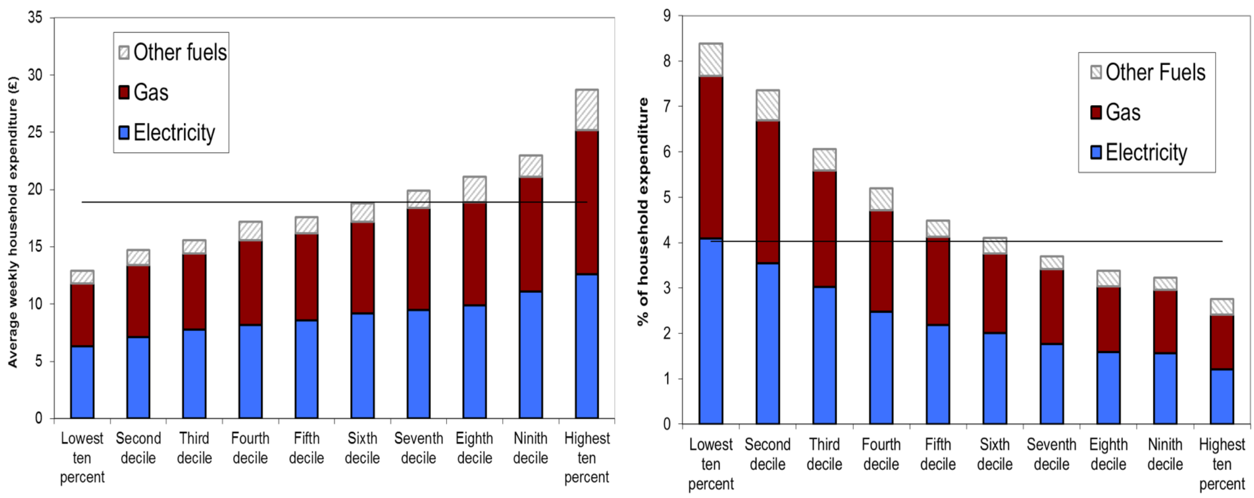
Energy demand functions turn out to be functions with price-dependent elasticity factors. Particularly as upper bounds of the normal range of energy expenditure intensity are approached and exceeded, energy price growth is accompanied by price elasticity growth[11].

The Inequality Dimension

Finally, we pinpoint a crucial dimension of some of the above explanations, relevant both to understanding energy expenditure characteristics and the policy implications – namely inequality.

Numerous data and studies have demonstrated that energy prices are regressive. For example, Figure 14 shows how although (a) energy expenditure increased across successively richer household deciles in the UK, the (b) relative expenditure, as a proportion of income, declined sharply.

Figure 13: Energy expenditure and inequality: distribution of energy expenditure across UK households



Source: UK Office of National Statistics, Average Weekly Household Expenditure 2009

The scale of the regressive pattern in UK household expenditure was relatively modest compared to some countries, and even poorest decile spent "only" about 8% of income on energy in 2008. Nevertheless, the energy price rises of the subsequent years made both environmental policy, and energy poverty, a political hot potato: the UK government defined "energy poverty" as spending more than 10% of income on energy, and soon found that several million households were breaching this.

10 When the energy expenditure to GDP ratio is above the affordability threshold, $T_y = T_{yp} - mT_p$. In other words, price elasticity grows absolutely by am. Parameter le may be also reflected in energy price elasticity, when the share of energy costs is high.

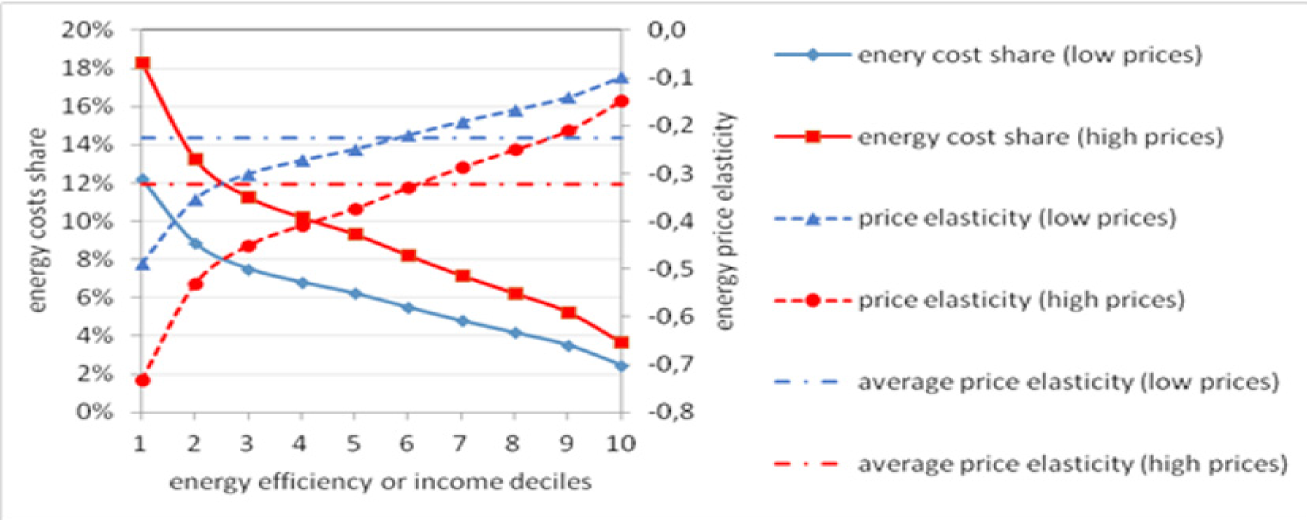
11 The relation of tax collection to the tax rate and the function of housing and utility payments collection from residents (Bashmakov, 2004a) are functions of the same class

This also sheds light on the nature of aggregate elasticities. Energy consumers may be grouped in deciles, based on the share of energy costs either in income or in gross output. The whole sector energy demand function may be presented as $E = AY^a P^b$, but every decile i may have a different response: Energy price elasticities can be different for each group and by absolute value positively $E_i = A_i Y_i^{ai} P_i^{bi}$ depend on the share of energy costs: *bi =f(Sei)*, and negatively depend on income. The overall energy price elasticity is a weighted sum of price elasticities specific for each group: .[12]

The greater the share of personal income (or indeed, corporate cost) devoted to energy, the stronger is the likely response to price rises. Thus for example the numerous tales of the poor suffering (and sometimes dying) because they could not afford to heat their homes when energy prices rise – a response that the rich would never even consider.

One might therefore expect groups with higher shares of energy costs to have higher energy price elasticity. If this is true, then when energy prices grow faster than income, the share of energy costs in income grows for all income groups. So each group may become more sensitive to energy prices, making each *bi* and thus total aggregated *b* higher, and vice-versa. This effect is illustrated in Figure 14.

Figure 14: Evolution of shares of specific energy costs by deciles and energy price elasticities



Source: authors.

If the energy price escalates by 50%, the share of energy costs grows by more percentage points for the decile with the highest energy costs, than for the one with the lowest energy costs (6.1% and 1.2% respectively, for the data in Figure 14)[13]. Overall, distributional issues – in business as well as domestic sectors - may thus be important contributors to the asymmetry and drifting of energy price elasticity – and an important factor for policy consideration.

12 Strictly, the groups may differ in their use of different fuels, so average prices may different systematically from the overall average economy price. If the ratios of average energy price to the one specific for a given group is (ρ_i): then $b = \sum_i b_i * d_i^e * \rho_i$.

13 This makes energy price elasticities higher for each group. The growth by absolute value is proportional to the increase in the share of energy costs and therefore uneven. Average price elasticity gets higher as well, but the weights of each group in the energy use change. Groups with high shares of energy costs and therefore high energy price elasticities reduce their consumption by a larger value compared to groups with lower shares of energy costs, and so the weight of the last ones increases. To a certain degree this effect mitigates the increase in average energy price elasticity. So might the behavioral characteristics of poverty sometimes cited as a reason why poor people don't always respond actively to opportunities to save money – but this hardly mitigates the need to pay attention to the equity dimensions of energy prices.Some similar effects may arise with industrial energy use. Some of the least energy efficient companies may lose profit margin entirely, so reducing the load of the most energy intensive equipment or stop operation of the whole facility. Should this happen, energy demand will be cut further, increasing the price elasticity. The reverse is also true: if energy prices are 1.5-fold reduced, every income (or energy efficiency) decile faces declining price elasticity, profit margins grow, previously unloaded facilities may get back to work (rebound effect), and average price elasticity declines.

Part V: Policy implications

Subsidies and taxes: evidence and narratives

This is not a policy paper, but we offer some outline policy conclusions from our analysis of the apparent relative constancy of energy expenditures – of which we suggest there may be many.

Subsidies. Perhaps the most obvious is that it strengthens further the macro-economic arguments against consumer energy subsidies. Our dataset only included a limited number of east European countries, but the evidence from these is striking: the philosophy that subsidising energy was good for social welfare and economic in fact achieved the precise opposite. It led to deep structural inefficiencies in energy use, and as the cost of the subsidies could no longer be supported – and the countries moved to market economics as part of EU Accession – the countries ended up spending *more* than the Bashmakov-Newbery constant of energy expenditure. Particularly as global energy prices rose, this involved crippling social and economic costs.

Taxes/environmental pricing. The flipside of this is that, at least on the surface, the B-N constant offers a new angle on energy taxation and environmental pricing. Governments in Europe and Japan managed to introduce excise taxes, but only during the 1980s in the wake of OPEC-induced prices rises which had enhanced energy efficiency, reduced oil dependence, and conditioned publics to higher price regimes. Their acceptance was also enhanced by positioning these taxes in terms of improving energy security and reducing road congestion (directly through incentive effects, but more often, linked through using the revenues to improve road infrastructure).

Even then, excise duties have remained sporadically controversial, particularly in the US, and more widely as global oil prices reached high levels again from around 2005. History has also shown more emphatically the political difficulties faced by carbon pricing almost everywhere – people do not like paying more for their energy, particularly for components that were previously free.

The observation of the B-N constant provides a new political angle on this because it suggests a focus on energy bills, not prices. The narrative implied is not that prices must rise to reflect external costs and to force people to be less polluting; it is that prices can rise without people ultimately paying more for their energy. The historical evidence is that *systems* can adjust to higher prices so that people do not end up paying more.

Not just prices

There is however a very important qualification to this argument. The adjustment processes which explain the B-N constant in the face of high prices are painful, and mostly slow – we have shown that the full cycle can take at least 2-3 decades. And, it is precisely *because* high energy prices are economically painful that such a degree of adjustment does take place.

From a political perspective, any government that tried to impose anything like the oil shocks of the 1970s or late 2000s would not last long. As indicated, time and again, energy prices have proven to be politically sensitive, and even removing subsidies has been politically contentious and slow, whilst efforts at energy taxation have generally been even more so. However hard politicians try to explain the evidence that *in the long run* the country and bills can adjust., "suffer now, it will be OK a couple of decades" is not an appealing political message. Moreover, it remains the fact that energy prices are economically regressive.

Consequently, changing the narrative to focus on long run constancy of bills may be a necessary, but not sufficient, condition. The policy message of the B-N constant is not that governments can just impose carbon pricing and tell a better story about it. Rather, to accompany carbon pricing, governments need to directly mimic the adjustment processes that lead to improved energy/carbon intensity.

On policy packages

This perspective is consistent with (and implicit in) the “3 domains” framework and its explanatory power in relation to the data. The essence of the framework is that the energy system overall comprises multiple domains of decision-making, given the shorthand terms of *satisficing, optimising*, and *transforming*. It follows that policy aiming to fundamentally change energy systems needs to engage with the corresponding pillars of policy, as summarised in Figure 15, because different policies are most relevant to different domains of decision-processes.

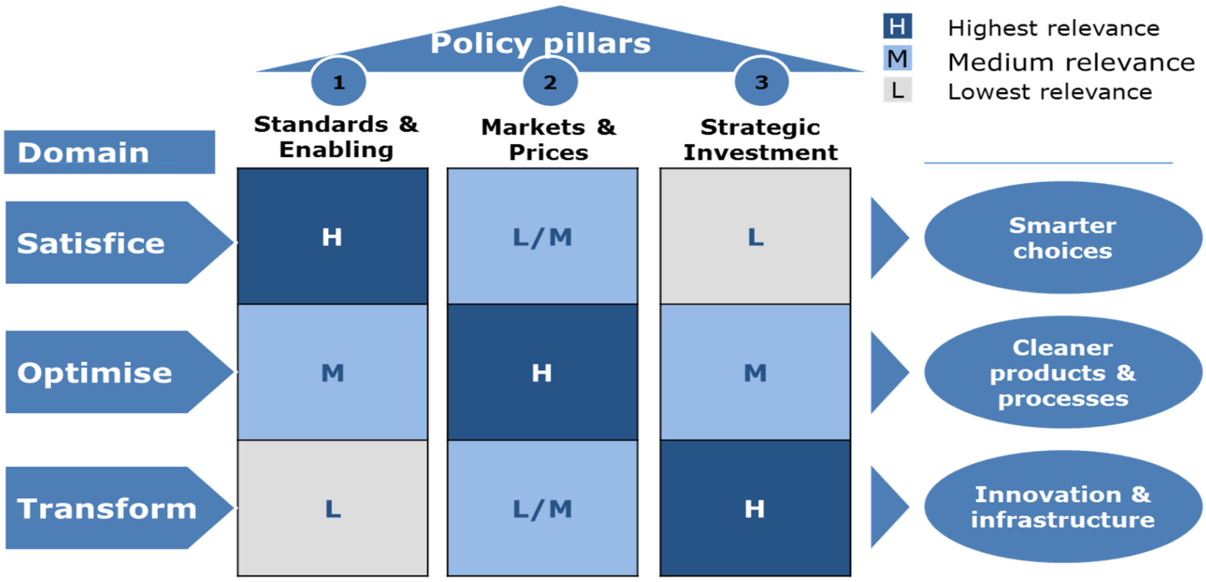


Figure 15: The Three Pillars of policy in relation to Three Domains of decision-processes

As a simple example; many of the cost-efficient opportunities for energy efficiency, typified in terms of the ‘energy efficiency gap’, reflect First Domain ‘satisficing’ behaviours in the broadest sense of the term. If energy prices rise steeply, this may kick many actors to start paying attention to energy bills which had hitherto been ignored – an attention impact, leading them to stop wasting so much energy. But if those price rises are imposed by the actions of their own government, their other response would be to try and get rid of the government.

To an important degree also, energy intensity could be reduced at lower cost by energy efficiency standards and/or well-targeted investment programmes (e.g. in buildings efficiency) and/or engagement programmes using ‘nudging’ & other messaging techniques. Given the prevalence of satisficing behaviours in energy consumption, this would be likely to be both more efficient and more effective – *at least in the short run.*

But in the longer term of course, the effectiveness of such policies would be undermined if nothing is done about energy prices, as the effect of reducing energy intensity alone would be to drive energy bills further and further below the B-N constant, amplifying satisficing effects and hence ‘rebound’. It is correct to note that an elasticity of around “minus 1” implies constancy of energy bills. As stressed by Saunders (2016) it also potentially implies a high degree of rebound.

Moreover, the costs of energy efficiency programmes would rise with the level of ambition, whilst their economic viability (in terms of the value of energy saved) would decline.

Whilst the issues around “rebound” are somewhat more complex than all this implies, a high elasticity does imply that energy efficiency may be more effective as a social policy than a policy purely to save energy.

The need for integrated policy packages

Indeed, when we step back from the data analysis of Parts II and III of this report to compare against actual national policies, it is clear that governments have in practice always drawn upon multi-pillar policies and this in itself is part of the explanation of the B-N constant. The low energy intensity of Japan and most EU-15 countries, for example, is not just because higher energy prices forced stronger consumer / investor responses, but because energy efficiency became a national goal:

- Japan is well known as a global leader in industrial energy efficiency, with closely co-ordinated programmes between METI and industry, and its "top-runner" approach to self-ratcheting energy efficiency standards in vehicles, household appliances, and more, is widely acknowledged as amongst the most effective instruments for energy efficiency in the world.
- The EU-15 countries similarly strengthened and expanded energy efficiency policies throughout the period covered by the data – particularly from the mid 1980s, as prices declined but environmental concerns started to drive energy policy. These programmes spanned energy appliance labelling, rapid strengthening of building energy standards and later vehicle efficiency standards, and utility-based programmes for rolling out energy efficiency investments.

Both these regions also invested heavily in more energy efficiency infrastructure, notably urban and intercity rail transport. In both Japan and the EU, some of the funding for these 'other pillars' came from the energy sector – as with excise duties used to fund transport infrastructure, and utility-led energy efficiency programmes funded by levies on energy bills (also, increasingly, renewable energy programmes with tariffs again funded through charges on energy bills).

Such observations in turn probably help to explain the econometric evidence of Agnolucci (2010), that whilst the 'standard' model of asymmetric price response cannot be statistically proven, trends in UK energy demand seem to embody a stochastic, path-dependent element which has driven enhanced energy efficiency in both domestic and industrial sectors, the latter with a stronger price-based element (as one would expect).

Of course, some of the policies in Japan and western Europe were matched in some of the US, but more sporadically: in particular, after initial push in the Carter years of the late 1970s, US vehicle efficiency standards were effectively frozen for thirty years, whilst building efficiency standards remained weak or non-existent in many US states. Low US energy prices weakened the incentive for government action on the other pillars; it has been the lower prices combined with weaker action across the other pillars that lie behind the high US energy intensity, and the paradox that the US energy expenditure is amongst the highest in the OECD despite it having amongst the lowest prices.

The conclusion that the 'Three Domains' framework implies three distinct but interdependent pillars of policy is thus just as much a description of reality as an economic theory. Overall, Grubb, Hourcade and Neuhofff (2014) conclude that none of the three pillars of policy is sufficient or stable on its own:[14]

"*Since the characteristics of energy systems and climate change span all three domains, changing course towards a low-carbon economy will involve working across all three pillars of policy simultaneously. Indeed, relying on a single domain or process is ultimately self-defeating:*

- *A focus purely on increased efficiency is clearly inadequate: success makes it cheaper to do things that consume energy or emit carbon, with the consequence of 'rebound' as people consume or do more in response. There are also likely to be diminishing benefits from efforts to bring us ever closer to the 'best practice frontier'. Only progress in the Second and Third Domains will then expand the scope for new cost-effective energy efficiency options.*
- *Relying on price alone is the favoured tool from the classical perspective, it maximises the*

14 *The Planetary Economics* book (Grubb,, Hourcade and Neuhoff 2014), in which the framework is developed and this excerpt written in the concluding chapter, focused particularly on the challenges of decarbonisation. But the framework is general, and the conclusions apply equally to countries seeking to manage the other legs of the 'energy trilemma', concerning energy bills and energy security.

efficiency of market transactions. Yet it assumes conditions that are not satisfied in the first or third Domains, and political obstacles have hugely constrained the pace of introducing price measures. In the short run, the extent to which energy demand falls in response to price increases is limited (at least without complementary Pillar I policies) and the timescale of energy supply system responses to price changes can be decadal. Moreover, the failures in the innovation chain blunt any innovation response ("if the innovation chain is broken, energy/carbon pricing will not fix it."). The result is that rising prices hit consumers – who are voters as well – with rising costs, when they have very limited options to respond, and cannot readily identify or relate to the potential benefits, which are more distant and nebulous. Prices have the biggest distributional impact of almost any instrument, provoking strong opposition. Relying on price alone risks generating more resistance than positive action.

- *Purely technology-driven approaches, applied without complementary measures, are also self-defeating. Successful innovation requires a mix of push and pull forces, and that both are weak in the energy sector. If there is no market-based pull, technology programmes will have to be entirely driven by the government. The products of such innovation will compete with well-established incumbents, which will be in a strong position to keep out new entrants. Without pricing, regulation, or actively engaged consumers, it is all push and no pull. Without pull there is little market; without a market, innovation will either wither, remain confined to the laboratory, or totally dependent on subsidy. Successful Pillar I and II policies are required to generate demand for low carbon products and processes."*

Conclusions: implications for strategy, instruments and timing

The data covered in this report adds additional empirical evidence and insights to the idea of a relatively stable range of energy expenditure, which tends to gravitate back towards a range of 8±2 per cent of GDP. This goes along with the implication that long-run energy elasticities are not constant, but are rather non-linear and/or asymmetric, with a collective impact tending towards "minus 1". This, as indicated, is all consistent with theoretical reasoning from multiple perspectives of energy chain interactions (Lowe 2013), the Three Domains framework (Grubb et al 2014), and distributional considerations.

Overall, this suggests that energy systems have considerable capacity to adapt to pressures – as most obviously expressed through energy prices - through combinations of several factors. Notably, in an environment of high price or supply risks, as characterised most obviously by the 1970s oil shocks and the policy aftermath, notably energy efficiency and structural changes which affect intensity, innovation, and supply-side changes, act to bring the overall energy cost back to within the range indicated. Conversely, exceptionally low prices induce waste, a slowdown of energy productivity and innovation, which leads costs back up again.

However, we have also shown that the timescales of adjustment are long – to be measured in decades.

Strategic implications and climate policy

In principle, this is a positive message which points to a large capacity of energy systems to adapt to prices and constraints given time, though it also points to the risks of high costs if either prices rise suddenly, or rapid changes are otherwise forced in to the system: the timescale of adjustment is just as important.

In a separate analysis (Grubb, Mercure, Salas et al 2018), we present a formal terminology and mathematical approach to estimating some of the causal forces and evaluating systems with these characteristics, which we term pliable – capable of making enduring adaptions of technology, resource needs and structures, but requiring pressure to do so.

One insight is that whilst the long-run costs of moving to a low carbon economy may be much lower for such systems, the initial effort justified in cost-benefit terms may be considerably higher. Moreover, the optimal trajectory may be completely different from that with systems with a more traditional cost structure, tending towards a linear path of emission reductions as adjustments accumulate.

Policy instruments and timing

The policy conclusions also go beyond suggesting a different pathway and narrative behind energy pricing (including carbon pricing) policies and a need to involve multiple policy instruments. The analysis also points towards crucial issues of timing, and the relationship between the different instruments. The traditional conception is that prices should drive improvements in efficiency and innovation through market mechanisms.

Our logic throws serious doubt upon this. Notwithstanding the important caveats about interpreting economic impacts (see Part 1), energy costs above the range we have identified appear to involve increasingly high economic and welfare costs – and certainly, political obstacles.

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Annex I – Cross-Country Data Methodology

Energy Consumption Data

Final energy consumption data is sourced from the International Energy Agency's (IEA) Extended Energy Balances of OECD Countries Database. Data were retrieved for all end-use sectors (agriculture & forestry, fishing, commercial and public services, industry, residential and transport, plus 'non-specified (other)'), for each of the energy products presented in Table 6, below. Energy products used for non-energy purposes are excluded. Data were retrieved in tonnes of oil equivalent (toe), and for the period 1971-2012. Although some data for 1970 and 2013 are available for the countries, energy products and sectors of interest, they are uncommon, and thus excluded from the analysis. Data for some OECD countries, including Israel, Turkey, Slovenia and Estonia were not available, and were also excluded. Non-OECD countries are also excluded to do the lack of comprehensive data.

For some coal products, for some countries for the period 1971-1977, data were unavailable. In these instances, values were assumed to be the average value of the proceeding eight years (1978-1985). In many cases, these values are zero.

Table 5 presents the proportion of total final energy consumption covered by the sectors and energy products above for each country, as an average over the period 1971-2012.

Table 5 – Proportion of total final energy consumption covered by energy products with price data

Australia	Austria	Belgium	Canada	Czech Rep.	Denmark
90%	77%	96%	92%	96%	93%
Finland	**France**	**Germany**	**Greece**	**Hungary**	**Iceland**
80%	89%	96%	92%	93%	70%
Ireland	**Italy**	**Japan**	**Korea**	**Luxembourg**	**Mexico**
93%	93%	84%	90%	98%	78%
Netherlands	**New Zealand**	**Norway**	**Poland**	**Portugal**	**Slovak Rep.**
94%	91%	91%	94%	78%	95%
Spain	**Sweden**	**Switzerland**	**Turkey**	**UK**	**USA**
90%	84%	95%	74%	95%	94%

The average of these values is 89%. The proportion of energy consumption not covered by these products is accounted for by those for which prices (or reasonable proxies) are not available, or which do not have not direct costs. This includes direct biomass (either purchased or directly sourced), biofuels, geothermal and solar thermal energy, and waste products used for direct energy. Such energy resources are are significant in some countries considered in this analysis, particularly in later years.

Energy Price Data

End user energy product prices were principally provided by the consultancy Cambridge Econometrics. This data is originally sourced from the IEA Energy Prices and Taxes database, and consists of the final price paid by the end user per unit of final energy product consumed, including taxes (but excluding any post-tax subsidies), for each country listed in Table 5. Data points not present in the IEA database are 'gap filled' by Cambridge Econometrics, mainly using price growth rates contained in the E3ME model, and those of proxy countries. Data were provided in US$/toe, current prices. Table 6, below, illustrates how different price categories were mapped to the energy product categories as defined by the IEA Extended Energy Balances. Sector abbreviations are as follows: Agriculture & Forestry (A&F), Commercial & Public Services (C&P), Fishing (F), Industry (I), Residential (R), Transport (T), Other (O).

Table 6 – Energy products and associated price categories

Energy Product Group	Energy Product	Product Price Used
Electricity		Electricity: Industry (A&F, C&P, F, I, T, O) Electricity: Household (R)
Natural Gas		Natural Gas: Industry (A&F, C&P, F, I, T, O) Natural Gas: Household (R)
Oil Products	Fuel Oil	Light Fuel Oil: Industry (A&F, C&P, F, I, T, O) Light Fuel Oil: Household (A&F, C&P, F, I, T, O)
	Gas/Diesel Oil	Diesel (*All*)
	Motor Gasoline	Unleaded (*All*)
	Aviation Gasoline	*US Energy Information Administration**
	Gasoline Type Jet Fuel	
	Kerosene Type Jet Fuel	
Coal & Related Products	Anthracite	Steam coal: Industry (A&F, C&P, F, I, T, O) Steam coal: Household (R)
	BKB	
	Blast Furnace Gas	
	Coal Tar	
	Coke Oven Coke	
	Coke Oven Gas	
	Coking Coal	Coking Coal (*All*)
	Gas Coke	Steam coal: Industry (A&F, C&P, F, I, T, O) Steam coal: Household (R)
	Gas Works Gas	
	Lignite	
	Oil Shale and Oil Sands	
	Other Bituminous Coal	
	Other Recovered Gases	
	Patent Fuel	
	Peat	
	Peat Products	
	Sub-bituminous Coal	
Heat		Werner (2016)**

*The US EIA[15] provides annual average prices from sales by refiners for U.S kerosene type jet fuel, for 1978 onward (in current prices). For 1971-1977, it is assumed that the annual value is equal to the average of the proceeding 8 years. For this analysis, it is assumed that these prices are applicable globally, for all jet fuel.

**Wener (2016) [16]provides data on district heating prices for a range of countries from 1980 onwards (with varied temporal coverage for each country), in Euros (constant prices). For countries with data but without full temporal coverage, the average rate of change in absolute Euros across time for the data present is continued until a negative value is produced. The final non-negative value is then assumed to hold. For countries with no data, it is assumed annual prices are equal to the average of the price in countries for which data is available (or has been estimated using the method described above). Euros are then translated to US$ values using market exchange rates provided by Cambridge Econometrics, and as used in the E3ME model.

As illustrated in Table 6, proxy prices are used for a number of sub-products (particularly for coal products), due to the lack of available product-specific prices. However, in most instances, the price categories map directly to the energy product group or sub-categories that account for the greatest proportion of final energy consumption.

15 US EIA (2017) *U.S. Kerosene-Type Jet Fuel Retail Sales by Refiners*, [Online] Available at: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMA_EPJK_PTG_NUS_DPG&f=M

16 Werner, S. (2016) *European District Heating Price Series*, Energiforsk, Sweden

Subsequent Calculations

The final consumption of each energy product (in toe) listed in Table 6 was multiplied by its associated price (in US$, current prices), with the product summed to produce total expenditure per country, per year. However, as illustrated by Table 5, this falls short of the total expenditure on all final energy consumption. To correct for this, the total expenditure value for each country and year was inflated under the assumption that the average price paid for the energy products not accounted for, for each year and each country, is 50% that of the average for products for which prices (or proxies) are available.

Annual values for each country were then converted to US$2005 values, using US GDP deflator values from the World Bank World Development Indicators Database (rebased from 2010 to 2016). Values for each year were then divided by the corresponding total primary energy consumption for each country (excluding non-energy use), to produce the average end user price per unit of primary energy consumption in the economy.

Energy intensity of the economy is calculated using primary energy consumption (excluding non-energy use) for each year and country, and corresponding GDP values (in US$2005, market exchange rates), also provided by the IEA's Energy Balances of OECD Countries Database.

Annex II: Distributional statistics of Energy Cost Shares of GDP (ECSgdp)

Table 7 - US data analysis

Summarises statistical results from US data analysis, indicating the exceptional impact of the immediate post-war years, and the nature and importance of trade effects in the (shorter) period for which consistent trade data are available.

	US ECS_{gdp} - Long run territorial from US EIA data		US ECS_{gdp} 1971-2012 *** from OECD-IEA data **	
	1950 – 2012	1955 – 2012*	Territorial	Consumption (trade corrected)
Mean	8.8%	8.6%	7.5%	7.4%
Standard deviation	1.7%	1.7%	1.8%	1.3%
Skewness	0.49	0.72	1.06	0.43
10-90% percentile range	6.9%-12.7%	6.7%--10.5%	5.7 - 10.7%	5.6-9.5%
25-75% percentile range	7.6%-10.1%	7.4%-10.0%	6.1% - 8.3%	6.4% - 8.5%

*See discussion: US after WWII was worlds manufacturing centre with large export supporting reconstruction in Europe and Japan
** Based on IEA data, described in Annex I
*** Trade data only available from 1971; authors approximations on imputed energy costs of imported/exported goods, also some additional data estimation 1971-1978

Key points: the reduction in upper end of ECS ranges from column 1 to 2 reflects the exceptional cost intensity of the post-war decade in which the US manufacturing was underpinning post-war reconstruction in Europe and Japan, with ECS values which were exceeded only for brief periods after the 1970s oil shocks. The lower average in columns 3 & 4 reflects the observed downward long-term trend in ECS, due partly to trade shifts. The higher standard deviation and skewness of the territorial relative to consumption data (columns 3 vs 4) reflects in part that 1971-2012 covers the period of US shift from being a major net exporter to a net importer of energy intensive goods, and the consumption data appears to remove the declining ECSgdp trend. For fuller analysis, see Part II, and Figures 1 – 7.

Table 8 - Panel analysis from IEA data

	All 30 industrialised countries in dataset, 1971-2012 [1260 data points]	All 30 industrialised countries in dataset, 1971-2012, as OECD Members only [1100 data points]*	Excluding central and east European countries (Poland, Czech and Slovak Republics)** [1134 points]
Mean	8.2%	8.2%	8%
Standard deviation	2.6%	2.5%	2.3%
Skewness	1.09	1.19	0.88
10-90% percentile range	2.9% – 19%	5.5% - 11.6%	5.4% - 11.2%
25-75% percentile range	3% - 18.6%	6.5% - 9.5%	6.4% - 9.2%

*Excludes data for years pre-OECD membership for each country
**See Part III, notably Figure 10 and discussion of eastern Europe

Key points: Comparison of the first and second and third columns illustrate the extreme ECSgdp numbers associated with some countries reporting of estimates from before they joined the OECD, and were at earlier stages of economic development. In particular, some of these data points imply an exceptionally low ECS which we suspect may reflect inadequate or incomplete data. Rather than examine country specifics, column 2 addresses this concern by only including data points from countries after joining the OECD, with its associated formalised statistical procedures.

Comparison of the first and third columns illustrate the exceptional situation of the east European countries that had highly subsidised energy and resulting inefficiencies, but then in the 2000s faced pressures of market prices at a time of rising energy prices, both occurring on timescales much faster than the characteristic timescales of adjustment we indicate. This radically reduces the upper end of ECSgdp ranges as compared with the full dataset. For fuller analysis, see Part III, and Figures 8 – 12.

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