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"Minus 1" and energy costs constants: Empirical evidence, theory and policy implications

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ABSTRACT

This paper demonstrates an apparent long-term constancy of economy-wide energy expenditures relative to income – an inter-decadally-constrained sustainable ("Bashmakov-Newbery") range of 4.2 ± 0.8 % relative to Gross Output, and 7.2 ± 1.5 % relative to GDP, based on data from industrialised countries. Initial evidence suggests the range to be narrower when external trade effects are accounted for. Statistically equivalent to a very-long-term price-to-energy-intensity elasticity of -1 ("Minus 1"), this indicates long-period economic dynamics including induced innovation and structural change, and we probe theories and policy implications. Either higher energy prices are fully offset by reduced energy intensity, or they later decline to match energy intensity improvements. Complementary theoretical approaches help to explain the observations but challenge the conventional economic logic that high environmental pricing should be the principal instrument to drive transformation. Rather, energy efficiency, innovation, deployment, structural change and pricing co-evolve, suggesting need for a diversity of complementary policy strategies implemented over extended periods of time.

1. Introduction

Do higher energy prices increase energy expenditure? The intuitive answer is that they must do, which helps to explain the prevalence of energy subsidies and the political difficulties of introducing policies such as carbon pricing. However, over longer periods the answer also depends upon how the economy reacts to energy prices more widely. Recent decades have accumulated analysis leading to the proposition that in fact, the answer is not so obvious. This paper explores in depth the proposition that economy-wide costs relative to key economic indices, notably GDP – the "energy cost share" (ECS) - typically vary within a constrained range. In conventional economic terms, this equates to a very-long-term integrated-energy-price elasticity (VLTIPE) of "Minus 1″. Due to the data limitations, the analysis below is limited to industrialised economies.

However, across a growing literature, interpretations are constrained and complicated by the use of different and often partial datasets, different metrics, and limited coverage of data across sectors, time, and countries, as detailed in our review of literature (Section 2 and Annex A). This may also help explain low awareness of the issue and its implications for policy.

The topic is important because energy costs are politically sensitive. Resistance to energy price rises impedes the implementation of economically efficient and ecologically sound energy pricing principles,

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including subsidy removal and incorporating the external costs associated with the environmental impacts of energy use. Political debates in most countries have largely focused on energy prices, and to a lesser degree on energy affordability thresholds. The divergence in energy prices between different countries is often associated with comparative advantage on the presumption that higher energy prices equate to countries bearing a higher deadweight cost of energy provision – but this depends upon how energy use itself responds to energy prices. Energy bills are a product of energy prices, energy service and of levels of energy efficiency in delivering this service. These are not independent, especially in the long-run: this paper uses both historical and cross-country analysis which shows just how *interdependent* these are.

Bashmakov (2007a) suggested three general laws of energy transitions, with the first one being that "*in the long-term, energy costs to income ratios are relatively stable with just a very limited sustainable fluctuation range*" (Bashmakov 2007a:3585). Based on the data available he postulated that, averaged over decades, energy cost to income proportions are relatively stable, and very similar across regions and large countries. Grubb et al. (2014), updating Newbery (2003), showed that across OECD countries, averaged over 1990–2005, energy prices were inversely related to the energy used to produce a unit of wealth: US, Japan, and the largest EU countries lay close to a line of constant energy expenditure despite large price variations: Japanese energy prices are, for example, typically more than twice those in the US, but with half the energy intensity.

This paper reviews subsequent literature and offers several new contributions, including with a new dataset with reconstructed *ECS* time series for a number of OECD countries and Russia (reliable data for other countries are limited) extended to 2019, to combine a wider range of perspectives with updated analysis and theoretical perspectives. We bring together a diverse range of literature and perspectives from different schools, helping to reconcile different datasets, and utilise the new and updated data to explore the robustness of the finding of energy cost constancy. We extend timescales and geographical coverage to allow closer study of patterns and mechanisms of adjustment. We introduce theoretical frameworks to help explain the observations, and also aim to introduce a more consistent nomenclature into the field. Our analysis is not focused upon measuring energy elasticities on the classically-inbuilt assumption that elasticities represent a fixed relationship between percentage changes in demand *vis-à-vis* prices; rather we examine patterns of energy expenditure over different time scales and price levels. From this, we argue that elasticities depend not only on time horizons and on scope (for structural changes), but also vary with different regimes of energy expenditure; "minus 1″ is the result of aggregation across a range of induced responses. These findings relate to the complementary theoretical explanations of the phenomenon observed, from which we also draw policy conclusions which differ significantly from the norm.

The paper is organized as follows. *First,* it examines data sources and their indications of cross-country aggregate energy costs.[1] Following a review (Section 2) of the core literature relating to the Energy Cost Share (*ECS*), from which our new contributions are clarified, Section 3 presents new cross-country energy cost data for IEA countries relative to GDP. This indicates that the share of GDP that market economies have spent on final energy consumption (including energy taxes) has gravitated around a range 7.2 %±1.5 % (or up to 1 % point higher if non-energy uses of fossil fuels are included). Reflecting the earliest studies on energy cost constancy, we refer to this as the Bashmakov-Newbery range of long-run energy expenditures, and find evidence suggesting an even narrower range of energy costs as a share of gross output (Section 3) or when trade effects are considered (Section 5).

Second, having established the basic cross-country empirics, we then analyse the dynamics in the largest country with the longest dataset available (the US). Section 4 probes more fully the various component trends and timescales supplemented by brief estimates from literature for other countries. Analysis of the *ECS*s over these long-time scales indicates that adjustments to past energy price shocks have taken some decades, and combine both demand and supply-side adjustments.

Third, Section 5 combines this with tentative estimates of the impact of shifting trade patterns for US, concluding that taking account of trade effects likely strengthens, not weakens, the core finding of energy cost constancy.

Fourth, based on these combined empirical cross-sectional and longitudinal findings, the paper then considers the economic processes and theoretical rationales that can explain these observations, including relationships to established literature on energy elasticities. Section 6 discusses how energy expenditures may relate to economic growth, in ways suggestive of a non-linear 'wing function', at least concerning the major historical impacts of oil-led energy international price rises on OECD countries.

Fifth, Section 7 then explores the theoretical grounds for the energy costs constants and the 'minus one' phenomenon, arguing that the findings can best be explained in terms of the different domains of economic behaviour that occur under different price conditions, and by understanding the energy economy in terms of multi-stage energy systems. Hence, the paper presents theoretical reasons why "Minus 1″ might be expected and compares this to the literature, noting that the underlying theory predicts the possibility of dynamic response in which elasticities are non-constant, or asymmetric (response to price rises not reversing with price declines), and highlights the role of broader policy responses. These create the long-term cycles within which only limited deviation of *ECSs* from the sustainable range is possible.

From this, our concluding sections (8 and 9) discuss policy implications, as well as potential applications of the sustainable energy cost range for the long-term energy modelling and reflection of energy costs in national and international statistics. It is not just the existence of apparent 'affordability thresholds' that is important, but also their quantification and the interaction mechanism of thresholds with economic growth and distributional impacts. Specifically, the paper concludes that the impact of rapidly increasing carbon prices to the levels suggested by some models, to be implied by the Paris climate targets, could be untenable.[2] Rather, policy may need multiple instruments to simultaneously accelerate energy efficiency improvements and innovation consistent with limiting climate change, coupled with a schedule of energy/carbon price rises to shape future expectations, support structural change and constrain rebound, to ensure that economies stay broadly within the range of energy expenditures identified.

2. Literature review

Study of the relationship between energy price and demand – generally codified as the energy price elasticity - is a key feature of energy economics. Labandeira et al. (2015) identified almost 1000 estimates of energy price elasticities for different energy products, sectors

[1] Energy costs accounting and different data sets are discussed in Annex A.

[2] Understanding of this is growing, see Chiu and Lowe (2022).

and countries, finding an average long term price elasticity (LTPE) of typically in the range -0.6 to -0.66, but with quite wide ranges (see Section 7). At first sight, a constant *ECS* simply implies an energy-price elasticity of minus 1, which appears to differ substantially from such findings in the standard energy elasticity literature.

In this paper, some ambiguity of terms is noted, and focus is clarified: related to long-run energy intensity or energy productivity to energy price elasticities, but with the focus on *national energy cost share* (*ECS*). Section 7 discusses the relationship of elasticity estimates to our analysis. Specifically, we focus on the ***very-long-run*** *ratio of* ***integrated energy-intensity*** *to* ***consumption-averaged end-use energy price,*** which is indeed implied as around −1.[3] This means that in the long run, either higher energy prices are fully offset by reduced energy intensity, or they later decline to match energy intensity improvements (Bashmakov, 2017). Conversely, keeping energy prices low, e.g. with intent to improve competitiveness, in the long-term actually conserves inefficiencies and technological backwardness.

This paper identifies four specific streams of literature on *ECS*, each significantly more limited than the scope of this paper: (1) energy costs share (*ECS*) accounting methodologies and data; (2) similarities across countries and historical evolution of *ECS*, including timescales and cycles of adjustment processes and the impact of structural changes and in particular international trade; (3) limits of energy affordability and economic growth; (4) scope and timing of policies to adjust energy prices, and put a price on carbon or other environmental damage.

Compared to the huge literature on energy price elasticities, relatively few theoretical and empirical analyses of energy costs-to-income ratios have been reported, due mainly to the lack of attention to *ECS* indicator and limited aggregated country- or region-level energy cost data – only a few countries regularly report consumers' energy spending, and energy costs to GDP ratios (ECS_{gdp}). Among a few statistical periodicals, direct energy costs are reported by the EIA SEDS starting from 1970. In the US such data are published at the national and provincial levels. Russia has been collecting information on energy costs across the whole economy, by sectors and provinces, but only since 2010. In general, data from official statistical sources are only available from the late 20th century onwards, and with limited geographical coverage. Bashmakov (2016) pointed out that even for recent history, and even for countries with good statistical systems, there remains disagreement around assessment of *ECSs* and with respect to energy cost accounting methodologies (see Annex A for details).

ECS_{gdp} estimates across countries. A growing range of studies have started to produce estimates for different regions. IEA (2011) estimates ECS_{gdp} evolving from 6 to 7 % in 2000 to over 10 % in 2011 for the EU, China and Russia. For China, IEA estimates ECS_{gdp} for 2011 at 11.6 %. For Russia, Bashmakov (2014) estimated ECS_{gdp} at 10–11 %. According to Desbrosses (2011), in 2010 it reached globally 10 % and for many regions, ECS_{gdp} varied between 6 % and 13.5 % (for CIS, Other Asia & Pacific it was 10 %, for Japan 9 %, for Europe 8 %, for China and India it is estimated at 13.5 % and 11.5 % respectively). The lowest ratio is shown for Africa (6 %), but Desbrosses' estimates do not account for non-commercial fuels, which are significant there.

A few other papers consider more recent estimates and comparisons of energy costs to GDP ratios for the global economy and separate regions; (NrCan, 2011; Bashmakov, 2016; Grubb et al., 2018a; Bashmakov, 2019; IEA 2021a) assessed global direct spending on energy by all end users, at USD 6.3 trillion in 2020. For the European Union, EC (2018) estimated energy services costs to GDP ratio, which besides energy costs includes annualized investment in energy supply and incremental investments in energy efficiency, at 11.7 % in 2010, 10.5 %, in 2015, and 9.7 % in 2020. Deducting the investments component (as provided in (European Comission, 2021)) gives ECS_{gdp} for 2015 at 8.3 % and for 2020 – at 7.1 %.

Time trend of ECS. There is little agreement in the literature on whether there is a long-term ECS_{gdp} trend. Long-term historical data on *ECSs* have been reconstructed for Sweden (Kander, 2002); for England and Wales (Fouquet, 2008; Csereklyei et al., 2014), and for the US (King, 2015; Fizaine and Court, 2016; Court and Fizaine, 2017) covering periods from 1800, and with limited data, from 1300, onwards. Based on historical analysis, Csereklyei et al. (2014), Stern and Kander (2012), Kander et al. (2014) conclude that a 'typical feature of economic development' is the decline of the energy costs to GDP ratio.[4] Fizaine and Court (2016) concluded that Bashmakov's 'first energy transition law' works for the post-Second World War era, yet not for earlier periods. However, Bashmakov (2016, 2017), based on an extended dataset argues that the first law of energy transition, holds over periods of a century or more. These findings challenge the 'stylized fact' of *ECS* reduction. Moreover, Lowe (2003) had presented a proof that for energy conversion systems with multiple stages, price elasticity would converge towards (minus) 1 as the number of sub-systems increased, which as explained in Section 7 provides a theoretical explanation for the empirical phenomena.

Sectoral Energy Cost Shares. The literature on sectoral *ECS* ranges and evolution is, with the exception of the domestic sector, even more limited. For the industrial sector, Astrov et al. (2015) and Horne and Reynolds (2016) use aggregated *ECS* as a metric for industrial competitiveness and a driver for industrial structure composition. Astrov et al. (2015) report *ECS* in manufacturing gross output growing from 3.8 to 7.5 % for EU-27 in 1995–2011, from 3.4 to 9 % for Japan, from 4.8 to 11.3 % for the US, and from 6.2 to 8.1 % for China. These ranges fit the panel data well. Welsch and Ochsen (2005) concluded that for German companies, *ECS* is stable in the long-term (4.2–6.4 % in gross output), and all changes induced by production factor substitution cancel out in the long-run. Bardazzi et al. (2015) report that for Italian companies, *ECS* of gross output was in the range 3.8–6.2 %, and Sadath and Acharya (2015) show a broader *ECS* range of 3.3–8.7 % for Indian firms. Bashmakov and Myshak (2018) conclude that not only for industry, but for other sectors as well, historical *ECSs* are similar across different countries at different stages of economic development, while also reflecting legacies of long-standing national energy pricing policies, and that the aggregated country-wide energy cost range is a weighted linear combination of those for individual sectors.

ECS and economic growth. Starting from Bashmakov (2007a), a growing stream of literature has considered the role of *ECS* in economic growth (King, 2015; Fizaine and Court, 2016; Murphy and Hall, 2011a, b; Lambert et al., 2014; Kopits, 2015, Stern and Kadner, 2012 and others). This literature tends to find that when *ECS* exceeds thresholds of energy affordability, it adversely impacts economic growth (in Section 7 we indicate an important distinction between energy importing and energy exporting countries). Bashmakov and Myshak (2018) show how this manifests across sectors, including the energy poverty threshold for the domestic sector. Bashmakov (2019) shows that while *ECS* is much below the labour cost share or materials cost share, the volatility of *ECS* is higher, as is economic vulnerability to such volatility.

[3] In the rest of this paper, this will be referred to as "the minus one phenomenon".

[4] Interestingly, a paper on 'Stylised facts' by Csereklyei et al. (2016) states one as being ".. The cost share of energy declines over time. However, we only have empirical evidence for three countries—Sweden, the UK, and the US… If the elasticity of substitution between energy and capital-labor is less than unity and effective energy per effective worker increases over time then the cost share will go down (Stern and Kander, 2012). This characterisation of the growth process appears likely to be qualitatively correct, over a period of more than two centuries during which costs of primary energy fell, and conversion efficiencies rose. But this stylised fact is still more of a prediction than a proven regularity."

Our analysis. To explore the robustness of results in the literature and to expand the analysis, a new dataset (built on Grubb et al., 2018a[5] and subsequently extended to 2019) of national *ECSs* was utilised covering 32 OECD countries and Russia, for most of which, 50 years of data were available. This was complemented by an even longer (72 year) dataset for the US, including not just GDP but also gross output. This longer US data has been used to more extensively explore adjustment processes (including trade) and to support analysis over longer timescales (Section 5).

The implication is that ultimately the energy system is highly adaptive - and a key aspect of these adaptive processes is that they act to restore overall energy costs burden to within the sustainable *ECS* range, on which this paper provides new and additional evidence. Based on this standpoint, combining both the empirical data and our theoretical analyses, policy conclusions are drawn which go substantially beyond the standard economic recommendation for energy/carbon pricing.

Thus, more than fifteen years on from Bashmakov's original proposition, and two decades after the cross-country observations of Newbery (2003) and the theoretical contribution of Lowe (2003), this paper builds upon what has been learned to advance our understanding of 'energy cost constancy'. By utilising different datasets, we examine different dimensions, and critical ranges, and explore patterns over time.

Formal tests are valuable, but inevitably require some narrowing down – whether on particular countries, sectors, and/or model specifications including functional forms. This involves potential restrictions, sometimes insufficiently acknowledged, when the phenomena may be substantially non-linear, asymmetric, time-dependent over years to decades, with a wide mix of adjustment processes including those within sectors, structural changes, innovations (exogenous, induced, and embodied), and macroeconomic impacts. In addition, our core hypothesis concerns the impact of extremes – outside the 'sustainable range' - for which data points are naturally sparse.

Consequently, rather than estimating energy demand price elasticities with limited scope (in terms of time, country or sector), we offer complementarity in taking a long-term and cross-country perspective, and a focus on energy intensity (productivity) rather than energy demand *per se*. We focus on adjustments to large-scale energy price shocks, rather than estimation of elasticities in response to marginal price changes, so as to explore the enduring impact of energy price on overall energy bills, as a proportion of wealth, particularly at the national level. By then considering theoretical interpretations and practical implications, we go beyond parameter estimation to consider the deeper processes at play, and their policy implications. The US data of Section 4 is already publicly available, and together with this paper we publish our core new dataset (used for Section 3), to enable other researchers to pursue further econometric interrogation and elaboration of our conclusions. Most fundamentally, we conclude that the traditional focus of energy economics on energy prices needs to be complemented by equal attention to overall energy cost - which is not at all the same – and to the forces that drive its evolution. The implication is that the combination of *ECS* and price is more fundamental than price alone to the problem of designing energy and environmental pricing and taxation policies.

3. Energy cost constants in the cross-country analysis

We define ECS_{gdp} as the ratio of total final energy-use consumer expenditure (accounted for all taxes and subsidies) on energy (non-fuel use excluded), to national GDP in a given year. For comparison with results using data from the IEA and the US Energy Information Administration (EIA), used in much of the literature reviewed above, for energy cost accounting we also utilise four widely-available datasets: EU KLEMS Database (Timmer et al., 2011) and the three releases of World Input-Output Database (WIOD) (Timmer et al., 2015; Woltjer et al., 2021). See Annex A for additional information and for our treatment of the data, which focuses upon estimation of *final consumer expenditure* (including intermediate taxes), on *energy use*. The need for comprehensive price and energy consumption data across all different fuels and energy consuming sectors necessarily restricts our study to industrialised countries.[6]

A large part of the variation between available datasets allowing for energy costs shares (*ECSs*) estimates is due to inconsistent coverage and definitions (see Annex A). For example, based on overall fossil fuel use, the WIOD2 dataset results in 12.6 % for global ECS_{gdp} in 2014 versus 8.5 % in 2000, but if non-energy use is excluded it comes down to 12.1 % and 8.3 % correspondingly. Hence, the authors devoted significant effort to construct a new database, using a consistent definition of energy costs to *exclude* non-energy uses, and in which costs are defined as *end-user costs* including taxes and subsidies, to reflect ultimate consumer spend on energy. By definition, this required assembling data on energy use and end-user prices individually by sector, as detailed in the Appendix to Grubb et al. (2018a); this paper extends the time span for this database to 1970–2019. In addition, four datasets covering 1965–2014 (KLEMS, and three variants of the WIOD datasets) also were used to assess *ECSs*. This ultimately yielded a dataset capable of supporting cross-country analysis across a span of 55 years (1965–2019).

3.1. ECSgdp across OECD countries

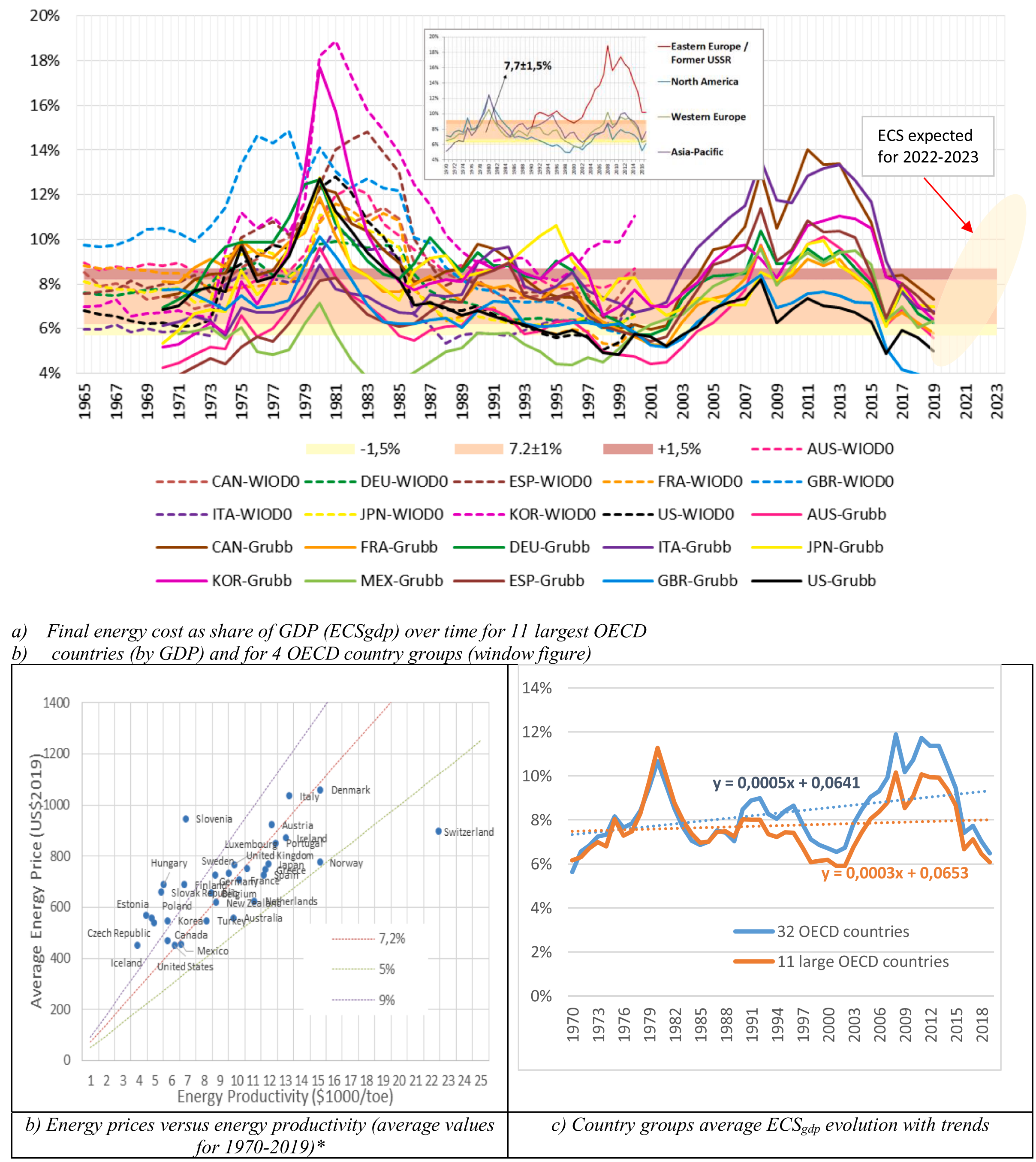
Fig. 1(a) shows the time trends over half century, which for legibility illustrates ECS_{gdp} for the 11 OECD countries with the largest GDP (PPP) and for 4 OECD country groups. ECS_{gdp} assessed for 1965–2000 based on Woltjer et al. (2021) show similar values and time patterns. Limits to the accuracy of ECSgdp evaluation using WIOD and KLEM datasets (see Attachment A) highlight the value of the authors' efforts to build a new dataset.

There is quite limited range of *ECS* evolution across the countries and no sign of the *'stylised fact'* of trend decline in *ECS*, which Csereklyei et al. (2016) noted as 'more of a prediction than a proven regularity', despite this period incorporating the two major oil price shocks. Indeed as Fig. 1c shows, there is an upward trend for 11 large OECD countries country group average ECS_{gdp}, and an even higher slope for the full set of 32 OECD countries, which includes in particular a number of former planned, East European countries as explained below.

For most countries, data available starts around 1970 and ends in pre pandemic 2019. Fig. 1(b) illustrates the subsequent time-averaged 50 years values of the two high-level determinants for each country in the dataset: the average end-use energy price, and the average energy productivity. For 32 countries in the dataset, the (non-weighted by either GDP or population) average ECS_{gdp} for all years is 7.7 %; while for 11

[5] Annex A to this paper explains the different data sources used in this paper, and the derivation of ECS estimates from this data. The report on which this paper draws, details the construction of the original dataset (subsequently updated) and probes illustrative statistics, including estimates of implied cross-country 'elasticities' across the dataset (generally found to be of greater magnitude than −1); it also illustrates that the variation in ECS is substantially lower than the variation in international energy prices.

[6] Although data for developing countries has improved over the years, such disaggregated data for long periods (eg. prior to 2000) remains scarce and of uncertain quality; moreover, because it necessarily omits non-commercial energy (eg. collected wood), such data gives a biased view of overall energy developments. Part of the effort in developing our own database included estimation of data on biomass energy for industrialised countries, where it is generally but not always (eg. Scandinavia) a small component. In principle, ECS calculations (being a share) should be preferably estimated in local currencies to escape possible distortions from the choice of either market exchange rates or purchasing power parity (PPP). This requires adequate and consistent treatment of the energy prices and GDP data, the choice would of course affect estimates of relationship of ECS to energy prices per se.



Note: *Data for Slovenia and Estonia only available from 1990.

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Fig. 1. Energy costs to GDP ratios for OECD economies and energy prices versus energy productivity. ote: *Data for Slovenia and Estonia only available from 1990. Sources: Built by authors based on data from Grubb et al. (2018a) extended by the authors to 2019; OECD (2020) and IEA (2021b) data were used for assessing net embodied energy for window plot.

largest OECD countries (panel 1(c)) it is 7.2 %.

For no curve shown in Fig. 1a, does the ECS_{gdp} remain for long above 10 %, or below 5 %.[7] And for countries outside the range there are clear explanations. For example, the exceptionally high energy-productivity (and low ECS) of Switzerland reflects its high-value service economy (with very little manufacturing). We discuss trade in section 5; for Switzerland, exceptionallyits energy *embodied* in imported goods (not counted in territorial consumption) is comparable with its domestically consumed energy, so incorporating such embodied energy would as much as halve its energy productivity and would bring the data into the outlined zone at Fig. 1b. For Norway, the oil and gas sectors contribute 20–25 % of GDP, but with most of this being high-value exports, the national energy demand is not remotely commensurate.[8]

One striking feature of the data appears in relation to the former planned OECD economies of eastern Europe, as shown by inset in Fig. 1a. Their ECS increased from 1990, with reduced access to subsidised energy from the former USSR, and rose sharply from about 2000, as they sought to move towards market-based energy pricing in a period of rising international prices. Their ECS was over 12 % for several years and averaged 11.5 % over the period,[9] whilst for other OECD country groups - North America, Western Europe and Asia- Pacific – the range of average ECSs' are strikingly narrow - from 7.4 to 7.5 %.

Most of the large Western European countries appear very close to the 7.2 % trend line, along with the US, Canada, and Japan. Korea is the only exception, mostly due very high ECS_{gdp} in 1979–1983 when it was forced to adjust rapidly to an energy price shock from a starting position of low energy productivity (due to dominance of export-oriented heavy industry). Though energy prices in Denmark, Italy, Austria and Ireland averaged more than twice those of the US or Canada during the period, they used half as much energy per unit of GDP, as did Japan and Spain.

This cross-country dynamic analysis of ECS_{gdp} evolution for large 11 OECD countries since 1970 indicates that the ECS_{gdp} has, for *almost all* of these countries and for *most* of the period (77 % of observations) remained in the range 5–9 % ("Bashmakov-Newbery" range), and that 45 % of observations fall in the narrower range 6–8 %.[10] Therefore ECS_{gdp} is found to have varied around similar 'centres of gravitation' for half century, but with inertia.[11] The roughly thirty-year cycle of the two higher *ECS* periods (late 1970s to early 1980s, compared to the decade from 2005) (Fig. 1a) is considered further in Sections 4 and 5. Analysis of summary statistics across the dataset, as well as for US data presented in the next section, reinforce our suggestion that largest market economies tend to spend 7.2 ± 1.5 % of their GDP on energy.

3.2. Decomposition of ECS

At the aggregate level, four factors determine the evolution of the *ECS*[12]

$$ECS = \frac{E * PE}{YR * PY} = \frac{E}{YR} * \frac{PE}{PY} = PER \Big/ EPR = EI * PER, \tag{1}$$

where E is energy consumption; PE – is energy price; YR – is gross output or GDP in constant prices; PY – is GDP deflator; EPR – is energy productivity (reverse ratio to energy intensity); EI – is gross output or GDP energy intensity; PER – is real price of energy.

Identity (1) shows, that these four factors may be reduced to two: energy intensity of GDP (or energy productivity) and real (deflated) energy price. For the energy cost ratio to remain stable, a higher (or lower) price of energy must be coupled by a proportional decrease (or increase) in the energy intensity of the economy. As such, the ratio of changes between these factors in the long run must be around minus 1. This is closely related to the long-run price elasticity of energy intensity to real energy price - note that energy *demand* and energy *intensity* to price elasticities are different (though related) concepts. Note also that the role of energy price in the overall *ECS* includes the effect of producer prices; to the extent that these are fed through into consumer prices, the *ECS* evolution includes the impact of fossil-fuel commodity cycles, with periods of high producer prices inducing exploration and development which, together with demand-side response, limits the period over which both high and low prices are sustained.

3.3. Energy cost as a share of Gross Output

The emergent literature over the past decade on the topic has thus far mainly focused on energy cost-to-GDP ratio, reflecting the common economic interest in GDP and associated data availability. However, from a theoretical standpoint it is a somewhat inconsistent measure, since it compares a gross economic input (energy) with a value-added measure of overall activity (GDP). Energy-GDP ratios are derived by adding sector end-use prices x sector energy, and dividing the total by GDP.

In reality a sizeable share of energy is used to produce intermediate goods. Thus, a more theoretically consistent indicator could be energy costs in relation to gross output. The identity Eq. (1) could then be applied at sectoral levels (with YR as sectoral output), which add up to the gross indicator. ECS_{go} is the share of energy costs in gross output and it is used more widely as a metric for competitiveness and for evaluation of energy cost burden in industry. The dataset we developed has no gross output counterpart from other sources. However, the four available (KLEMS and three versions of WIOD) datasets include both energy costs and gross sectoral output, from which we have sought to eliminate non-energy components, to calculate these on a consistent approach. In Fig. 2 we show the resulting ECS_{go} trends for the eleven largest (by GDP scale) OECD economies from 4 datasets.[13] WIOD1 data fits the best adopted in this paper energy costs concept - ultimate consumer spend on energy.

Partial overlapping of samples from different datasets for each country reveals a similarity of temporal patterns.

The relatively narrower range of ECS_{go} (Fig. 2) has a plausible explanation. Compared to services, industry has a higher energy

[7] The third energy shock provoked by the war in Ukraine would shift curves for 2022-2023 in the Fig. 1 to the right. For the EU-27 real energy prices in 2016-June 2022 more than doubled, energy productivity improved by 10–12%, so ECS_{gdp} is expected to double in 2022 to reach 7–16% in many countries with 10–12% average for EU-27, coming back or even over all time (in 50 years sample) high 1980 levels.

[8] In EU countries, ECS in the oil and gas sector is amongst the lowest across all sectors (European Union, 2018).

[9] If for comparability reasons, Slovenia and Estonia, with limited number of observations, are excluded from theEastern Europe OECD, then the slope coefficient comes down to 9.3%.

[10] For all 32 countries corresponding numbers are 60% and 34%.

[11] Bashmakov and Myshak (2018), using KLEMS and WIOD datasets, show that for separate sectors with more consistent energy cost accounting the similarity of the 'centres of gravitation' is even more visible. As data quality improves to better reflect the adopted energy costs concept, 'spaghetti' curves tend to become more compact.

[12] ECS_{gdp} is not a share or fraction of GDP in purely economic terms, as energy costs are mostly composed of elements of intermediate product. ECS_{go} is the share of energy costs in gross output.

[13] The outliers associated with KLEMS data for Japan and Korea are notable, but excluding these, the sustainable range for ECS_{go} across countries is even narrower than for ECS_{gdp} and shrinks to 4.2 + 0.8, as gross output is about twice as high as GDP. Except for China and South Korea, where the ratio is close to 3 due to higher share of industry in GDP and lower share of value added in industrial gross output. WIOD datasets provide more consistent ECS_{go} estimates.

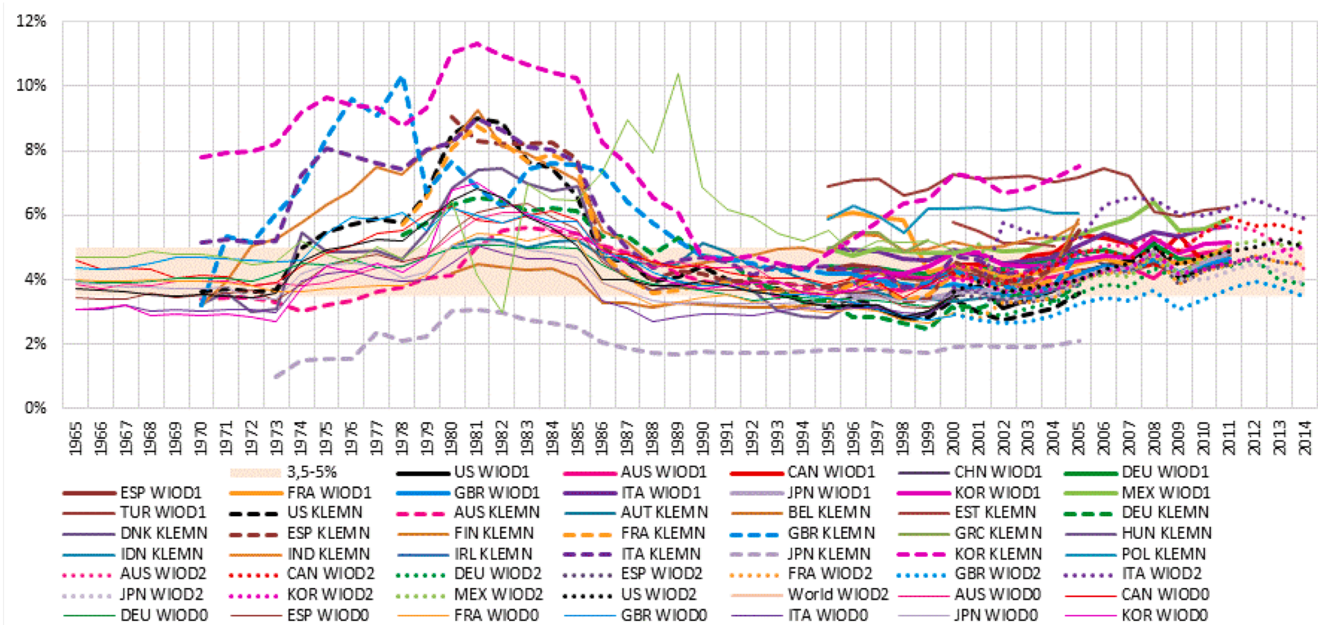


Fig. 2. Final energy cost as share of Gross Output (ECS_{go}) for 11 major industrialised economies. Sources: Built by authors based on data from Timmer et al. (2011) and Timmer et al. (2015); Woltjer et al. (2021).

intensity but lower value-added. Consequently, changes in industrial structure – notably the 'de-industrialisation' of many but not all OECD economies - would be expected to impact ECS_{gdp} much more than ECS_{go}. Consequently, it is likely that differences in the 'centres of gravitation' between countries are in part to do with varying shares of services within total GDP. We estimate that every additional percent of services share in GDP is associated with ECS_{gdp} decline by about 0.1 % (Bashmakov, 2017). The 'stylised fact' of ECS_{go} trend decline is not apparent in the data.

4. Components and dynamics of adjustment: the US experience

Having established a broad empirical basis for the proposition of a constrained range of sustainable $ECSs$ across many countries over several decades, we now turn to consider interpretations, components of adjustment and causal mechanisms. To explore more closely the dynamics of adjustment processes,[14] we turn to the most detailed, extensive and lengthy US EIA dataset for the US.

Fig. 3 illustrates the evolution of the energy intensity of GDP and real energy price, as well as GDP growth rates and the ECS_{gdp} in the US for 1949–2022. With this as backdrop, we derive a number of 'stylised facts' which we examine in three main groups:

- Timescales and cycles of adjustment processes;
- The impact of structural changes and in particular international trade (Section 4);
- The relationship between ECS and economic growth (Section 5).

First, concerning timescales and cycles of adjustment. Over the full 74 years of this EIA data, the average ECS_{gdp} (including non-energy use costs) is 8.5 %, with a slight downward trend, both being influenced significantly by the exceptional intensity of the post-war decade (see Annex A). For convenience we refer to the lower and upper levels of the range indicated as 'thresholds'; in the final part of the paper we return to consider the nature of these ranges and likely determinants of the corresponding 'thresholds.'

After the upper ECS_{gdp} threshold is reached or exceeded (1949–1950, 1974–1985, 2008–2014), the ECS_{gdp} drops, and after the lower threshold is crossed (1965–1973, 1995–2003), it, on the contrary, grows. Like a pendulum, the ratio returns towards the sustainable range. The cycles around the long term trend in ECS_{gdp} are clear in Fig. 3(b) which shows the evolution of the two main components, illustrating the two long cycles over this period and the overall slope which defines the average ECS_{gdp}. Fig. 3(c) shows the relationship of ECS_{gdp} to US GDP growth rates, discussed further in Section 6. Based on US data, initially, the ECS_{gdp} range was considered stable (Bashmakov, 2007b). With a nearly seven decades' timeframe a slow trend decline (by about 0.6 % for every 10 years) can be observed in ECS_{gdp},[15] which in the following section we suggest can be associated with a shift of energy intensive production abroad. ECS_{gdp} is within +1 percentage point of the trend for almost half (46 %) of the period and within the +1.5 % for 70 % of the time.

The ECS_{gdp} is thus driven by the evolution of energy prices, mitigated by energy intensity. Annual energy intensity reduction for the US has been limited to 2–2.6 % per year. Therefore, energy price growth at higher rates than this pushes ECS_{gdp} up. Starting from 2000, registered real energy price growth was much higher, compared with 1972–1981. But the halving of energy intensity between 1972 and 2008 prevented ECS_{gdp} from rising by 2008 to a likely economic growth-stopping level of ≈18 %. Radical energy efficiency improvements also reduced the amplitude of ECS_{gdp} fluctuations.

[14] The EIA provides direct data on total energy expenditure, but only from 1970 onwards. We extended cost estimates back to 1949 using the EIA's data on fossil fuel production prices and average electricity retail prices, to create a harmonised energy price index, using fuel and electricity prices indexes, and energy use and GDP data from 1949 to 1969. Data for US real GDP from 1949–1969 were downloaded from the Federal Reserve Economic Data (FRED), and data for US energy consumption for the same period were downloaded from the US EIA. We tested accuracy of these retrospective estimates for overlapping years, with variations in the range of +0.4%. Note that the EIA data includes fossil fuel inputs for non-energy products, which as noted adds almost 1 percentage point to ECS_{gdp} estimates compared to the dataset we developed (see the Annex A for comparisons).

[15] The slope value depends on the initial and the final sample years selection. If starting and final years are selected for similar cycle phases (1952 and 2014), then the slope scales down to 0.0004

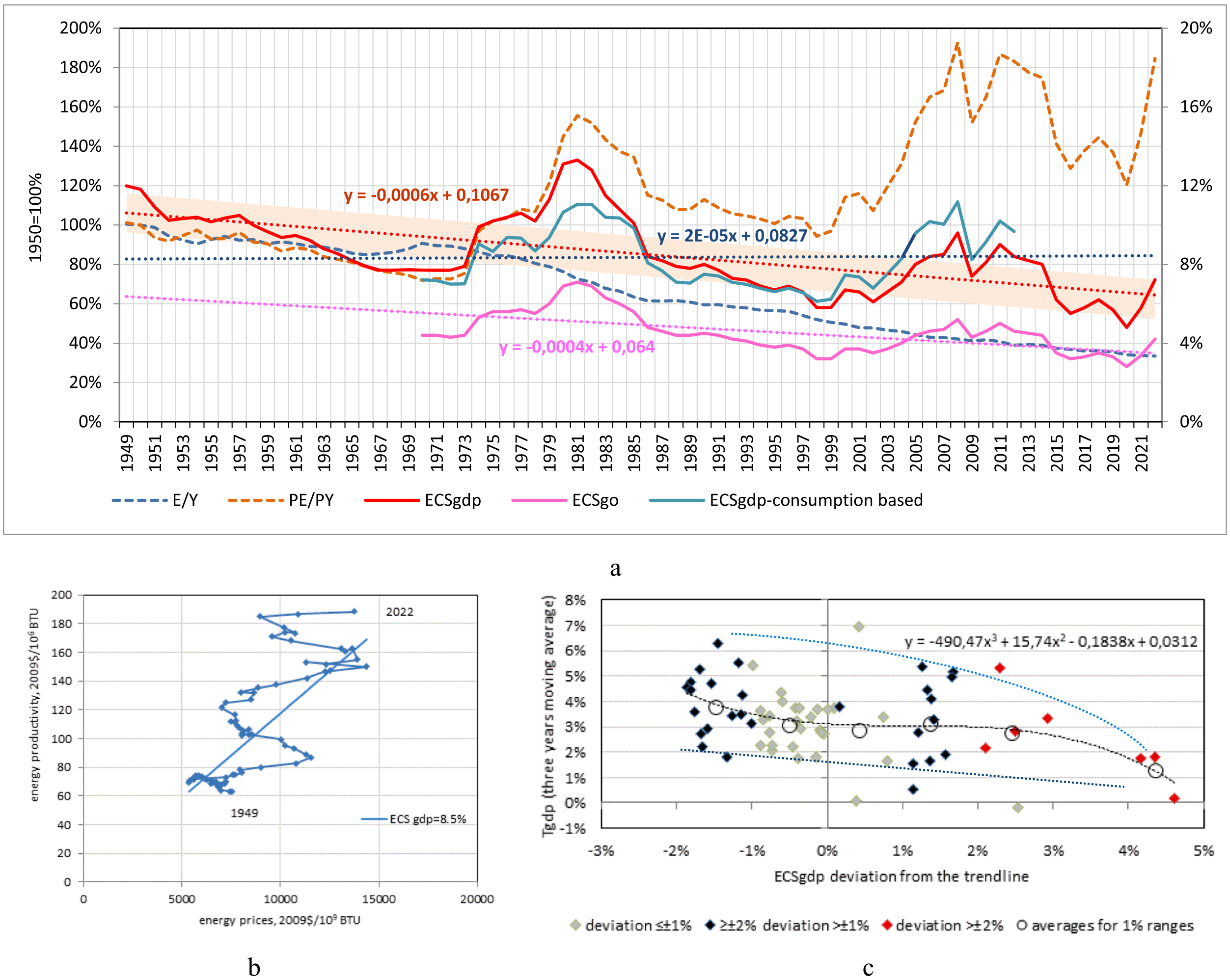


Fig. 3. Evolution of major drivers behind the energy costs/GDP ratio (ECS_{gdp}) in the US in 1949–2017.
a) Energy costs to GDP ratio (ECS_{gdp} – right-hand axis); Share of energy costs in gross output (ECS_{go} – right-hand axis); GDP energy intensity index (E/Y, 1950=100, left-hand axis); real energy price index (PE/PY, 1950=100, left-hand axis); GDP growth rate (Ty, three years moving average, right-hand axis, chained 2009 dollars). The ECS_{gdp} for 1949–1969 was estimated based on the E/Y and PE/PY data. Energy costs include taxes wherever data are available. Energy costs (expenditures) developed in the EIA State Energy Data System (SEDS) are calculated by multiplying the price estimates by the SEDS consumption estimates. The latter are adjusted to remove process fuel, intermediate petroleum products, electricity exports, and other consumption that has no direct fuel costs. ECS_{gdp} for 2021 was assessed based on annual EIA annual data and for 2022 – based on EIA data for first 4–6 months of 2022.
b) Evolution of energy price-energy productivity relationship along ECS_{gdp} isoquant equal to average 8.5 % for 1949–2022.
c) Relationship between the ECS_{gdp} and GDP growth rates (three years average), or 'wing' function for the US (1949–2022). Black dashed line represents aggregated relationship with data clustered in ranges by ΔECS_{gdp} values: below -2 %, from -2 to -1 %, from -1 to 0 %, from 0 % to 1 %, from 1 % to 2 %, from 2 % to 3 % and above 3 %.
Sources: developed by authors based on Bashmakov (2016) and data reported in: EIA (1987), (2011); EIA SEDS (2019); EIA (2022); BEA (2019)

There is a tendency for energy prices to move up as energy quality improves (Bashmakov, 2019). If not fully compensated by energy efficiency improvements, this provides incentives to outsource embodied energy from countries with lower energy, labour and materials prices. This in turn brings services share in GDP up, and energy intensity down. Cycles in ECS_{gdp} tend to result in a long-term decline in energy intensity. When real energy prices grow, energy intensity declines faster. However, when real energy prices decline, the subsequent rates of efficiency improvements may be slowed down, but reductions in energy intensity do not reverse: most of the gains from earlier improvements are embodied in capital stock, human capital (know-how and practices, primarily within supply chains), and there is lagged take-up of technological progress which is largely inspired by delayed reactions to prior, and expectations of future, price rises. So the resulting rebound effect is quite limited.

The cycle duration is determined by the speed with which the energy and economic systems may adjust to energy price shocks. After ECS_{gdp} peaked at 11–14 % of GDP, a combination of inflation, energy intensity reduction and energy supply side responses, driven by both technological and structural factors, eroded real energy costs. It took 5–10 years to get ECS_{gdp} back to the range 7–9 %, but accumulated inertia[16] pushed this ratio further down towards and in a few cases below 6 % for a further 12–15 years, compressing the 'spring' which, over the subsequent 10–12 years, drove the ECS_{gdp} to a new peak. Empirically, the whole cycle takes about a quarter to a third of a century.

[16] In most cases, we would expect innovation in energy efficiency to lag energy prices. But in principle the opposite could be the case – e.g. where a government makes a credible declaration of intent to raise energy prices. One would then expect to see at least some anticipatory activity to reduce exposure to future energy price rises.

5. Impacts of economic structure and shifting trade patterns

We now examine the role of international trade and corresponding structural effects, and then consider the relationship with economic growth itself. The EIA data used above are published on a territorial basis. This neglects the effects of shifting trade patterns in energy intensive products. For the US net embodied energy imports in 2010 was estimated at 207 Mtoe in 2010, which is 9 % of TPES (KAPSARC, 2013). A fuller picture requires attention to energy embodied in traded manufactured goods – exported, and 'offshored' energy consumption.[17] The effect has been included in Fig. 3 above (see $ECS_{gdp\text{-}consumption\text{-}based}$ at Fig. 3a). Given the inadequacy and complexity of historical trade data, the effect for the US was estimated only from 1970[18], and for 32 OECD countries from 1995.

In 1970 the US was a net embodied energy exporter. It moved to being approximately neutral over 1985–1995 and after the mid 1990s, with globalisation and the rise of China, the US became a net importer. US $ECS_{gdp\text{-}consumption\text{-}based}$ since 1970s has been almost entirely in the range 6–10 % of GDP and the amplitude of fluctuations of this variable have changed little. Therefore, ECS_{gdp} adjusted for the energy embodied in international trade show no declining trends and clear manifestation of long-run energy cost constancy.

When similar analysis was undertaken for the UK, the declining trend in ECS_{gdp}, which, at 0.4 % per 10 years, is similar to the US trend, changes sign if the carbon-based data are converted the same way and at UK energy prices.[19] Given the higher UK energy prices, the outsourcing of production of energy intensive products reduces the apparent energy cost burden for the UK not only by attribution effects (shifting domestic energy costs to imported goods) but also genuine price effects (shifting production to regions with cheaper energy resources).

To extend analysis across countries, the EIA data on ECS_{gdp} were adjusted (see ECS_{gdp} consumption based at Fig. 3a) to reflect embodied energy trade, drawing on trade data from analysis by Wood et al. (2019). The results, displayed for the 11 major OECD countries in Fig. 4, indicate that inclusion of international trade effects eliminates the structural decline in *ECS,* which is centred on 8.3 % (non-energy used included), leaving no discernible trend.

Detailed estimation to narrow uncertainties and separate components was beyond the scope of this paper, but the qualitative impact of adjusting for energy embodied in international trade would clearly tend to make national *ECS*'s closer to one another, and narrow the range of 'spaghetti' curves in Fig. 1.[20] A similar ESC_{gdp} constancy result was observed for the global economy (which is closed economy) for the period 1850–2010, by Fizaine and Court (2016).

Analysis on $ECS_{gdp\ consumption\ based}$ conducted for 32 OECD countries (based on dataset developed by authors) supports conclusions made for the US and UK (Fig. 4):

- there is no declining trend. Values in 2020–2021 are expected to be back to 1995–2000 levels;
- the deviation from the average of $ECS_{gdp\ consumption\ based}$ is narrow: ±2 %;
- the average value for 1995–2019 for 11 large OECD countries is 7.5 % and that for 32 OECD countries is 8.2 %.[21] If former planned economies are excluded, the average for other OECD countries comes down to 7.5 %;
- trajectories for 11 large and all 32 OECD countries averages are quite close; cost shares and vulnerability to energy prices shocks for all 32 are higher due to inclusion of formerly planned economies with relatively low energy productivity.

If quarter-to-third century-long cycles of energy costs (adjusted to net embodied energy import) to GDP ratio are considered, then real energy prices in the OECD countries have grown by only as much as energy intensity declined. That is exactly what one would predict from the 'minus one' phenomenon over long periods.[22]

Many econometric studies use 'long-term' elasticity to refer to accumulated effects of initial price impulses via distributed lag (eg. Koyck) models – in which typically, the vast majority of impact (> 95 %) is estimated to occur within a decade. It seems important to introduce the notion of a very long-term (or *integrated*) energy intensity to price elasticity. We suggest the term *integrated* because there are multiple avenues of adjustment to energy price shocks. In addition to direct behavioural and technological adaptations, other factors include (1) rationing and acceleration of energy efficiency improvements (induced by both price and other policies); (2) reduction in real energy prices from a combination of demand reduction and supply-side expansion and innovation; (3) changes in infrastructure (eg. urban form including public transit and housing density, road vs rail transport)[23] and (4) structural change including shifting energy intensive production abroad. Moreover, these relationships may be quite different for different ranges of *ECS*, which is not well recognized in the econometric analysis and which we consider in Section 6. All these appear to combine to eventually bring *integrated price elasticity* to around the 'minus one' relationship found in the cross-country data.

[17] To reflect this, we used the database of the Carbon-CAP project, which evaluated a number of different multi-region input-output databases of international trade (Carbon CAP, 2016). It examined how much of the apparent reduction in CO_2 emissions in industrialized countries may be attributed to 'offshoring' of energy-intensive manufacturing to developing countries (Wood et al., 2019).

[18] To account for trade effects, we make an approximation by attributing the net embodied CO_2 trade to a basket of coal, oil and electricity production embodied in the traded goods, using the Carbon-CAP data (see previous note). For simplicity we assume an equal basket of these energy sources (neglecting natural gas, of which a higher proportion tends to be used for household uses so less relevant to embodied trade), and attribute US energy prices by energy type, as a proxy for how much the US would have spent, had the traded goods been manufactured in the US.

[19] Barrett et al., 2013 underline the impact of trade on UK consumption-based emissions, and estimates of the UK's net embodied energy imports range from 15.6 Mtoe in 1997 and 32.5 Mtoe in 2011 (7.1% and 17% of TPES respectively); Xu et al., 2013, up to 87.5 Mtoe, 43% of 2010 TPES (KAPSARC, 2013).

[20] Correspondingly, for Russia, the net embodied energy *export* in 2010 is 126 Mtoe (18% of TPES), and for China it is 408 Mtoe (16% of TPES, KAPSARC, 2013). Accounting for trade effects presented in Section 5, ECS_{gdp}s for Russia and China identified by IEA (2011), Desbrosses (2011) and Bashmakov (2014) for 2010–2011 would scale down by 1.5–2 percent points and match better ECS_{gdp} for large OECD countries presented at Fig. 1.

[21] This is not fully comparable with production-based ECS_{gdp} as the time span is 15 years shorter.

[22] It can be renamed 'plus one' in case energy productivity substitutes energy intensity in the expression (1).

[23] Over decades, structural change may include changes in housing density and settlement patterns, with associated impacts on energy use in domestic, industrial and transport sectors (Newman and Kenworthy, 1989).

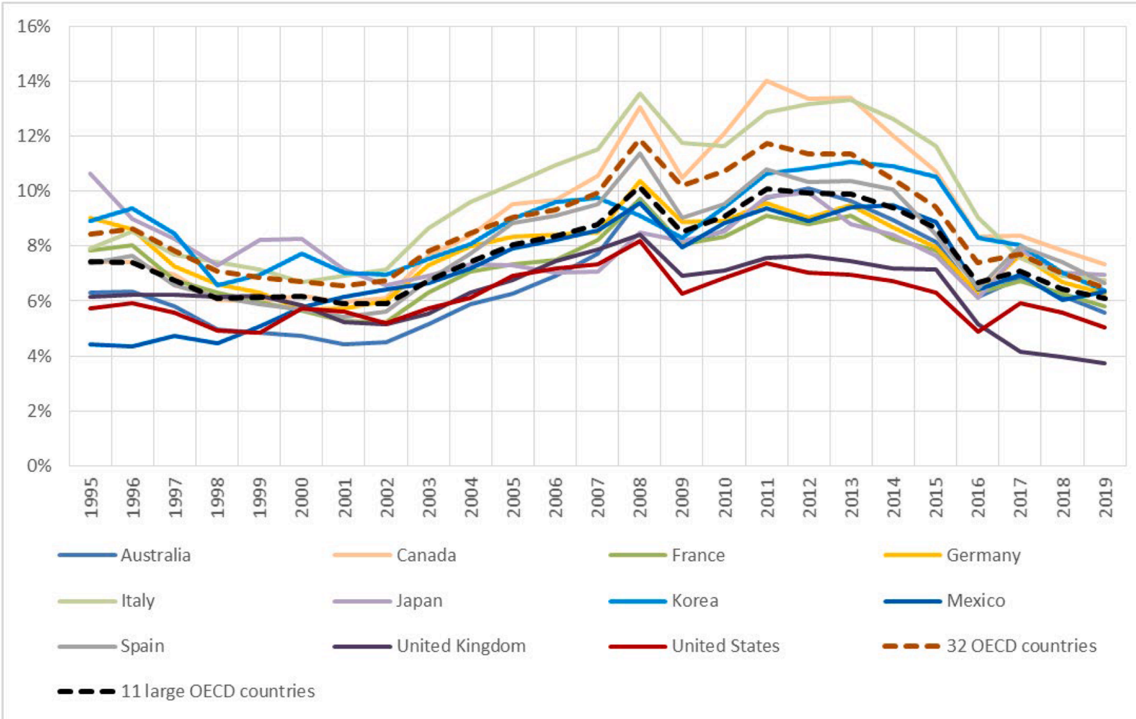


Fig. 4. Adjusted to external trade energy costs to GDP ratios for 11 OECD economies. Sources: Built by authors based on data from Grubb et al. (2018a) extended by authors to 2019.

6. Limits of energy affordability and economic growth

The *ECS* has a complex relationship with economic growth. The standard economics literature on the role of energy is limited theoretically, by the fact that the production functions in growth theory rarely include energy explicitly, whilst those that do, struggle with an empirical foundation because many other factors are involved in disentangling the role of energy prices. This remains a wide debate. We suggest that a focus on energy cost share, rather than price *per se*, may offer a more useful lens, albeit one that still requires careful interpretation. This section offers some observations.

Bashmakov (2019) points out, that, despite ECS_{gdp} being almost an order of magnitude (7–9 times) below the share of labour costs or the intermediate product cost to GDP ratio (energy cost deducted), the ECS_{gdp} fluctuation range in the USA in 1950–2016 was larger than that for the share of labour cost, yet smaller than the intermediate product cost to GDP ratio evolution range. Accounting for the positive correlation of the latter with ECS_{gdp}, he found that ECS_{gdp}-driven impact becomes the dominant influence on the volatility of the ratio of total production costs to GDP. He argues that the importance of a production factor is to be judged, not by its average cost share (level), but rather by its volatility (profits eroded by energy costs), and by the vulnerability of economic growth to such volatility.[24] The theorem was proven (Bashmakov, 1988) that there is always a low energy use threshold, below which economic growth is not possible. With limited purchasing power, a sharp increase in energy prices brings purchased energy volumes below this threshold.

Qualitatively, the three main peaks in *ECS* in the US (Fig. 3) preceded economic recession. Although economic downturns are never caused by energy price increase only, there is little doubt that the 1970s oil shocks helped to knock the global economy from growth at 4–5 %/year down to around 1 %; other recessions have also been associated with high oil prices (Hamilton, 2009). The energy price increases of 2003–2015 were less abrupt, and the global recession was driven among other factors by the credit crunch of accumulated debt, but a partial link may still be argued through less direct mechanisms.[25]

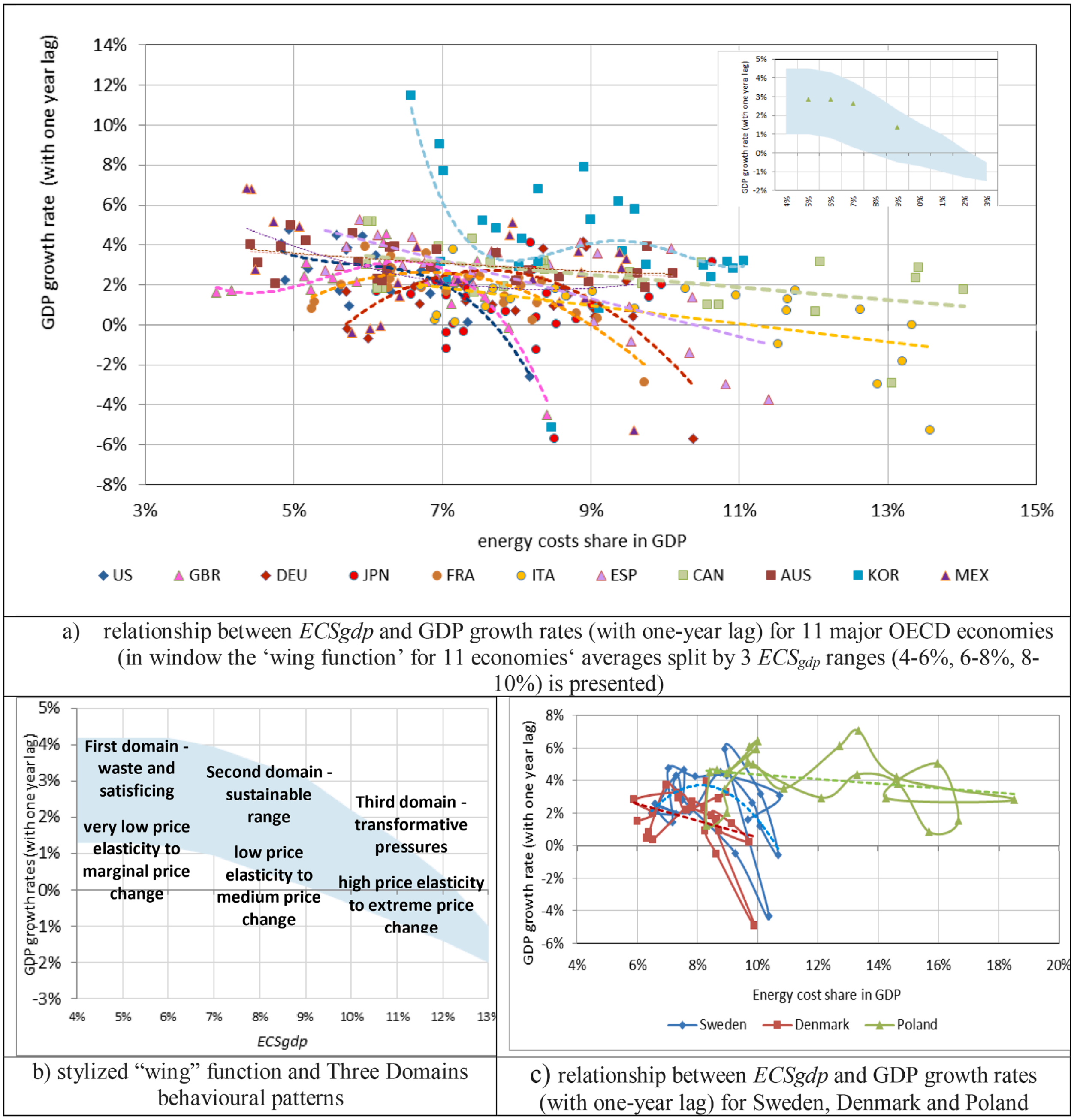
US data. Again, the US is the most studied. Our US data suggest that the relationship between GDP growth rates and the ECS_{gdp} is highly non-linear, being stronger when ECS_{gdp} deviation from the trend exceeds 2 % ('wing' function, Fig. 3c). Whilst Murphy and Hall (2011a,b) focused on gasoline expenditures, Bashmakov (2007a) estimated that for periods when US overall ECS_{gdp} has exceeded 11 %, every additional 1 % of ECS_{gdp} has been associated with an equivalent 1 % reduction in GDP growth rate; and Lambert et al. (2014) found recessions occurred when US ECS_{gdp} exceeded 10 %.[26] Fizaine and Court (2016) more formally associate an increase in ECS_{gdp} with lagged impacts on unemployment and Granger-causal declines in economic growth; though they cautioned about the limited sample size, they observed that the US had not sustained positive GDP growth whilst allocating more than 11 % of its GDP to energy expenditure.

International data: Fig. 5a shows the apparent spread of the relationship across the 11 biggest OECD economies with the most reliable

[24] The relatively small ECS_{go} (close to 4%) was the reason for many neoclassical economists to consider energy as a minor and easily substitutable production factor.

[25] Dispute remains about causality of oil-GDP relationships, as the direct cost impacts are insufficient to explain recessionary effects; one view is that the impact of rising oil prices on inflation prompted central banks to raise interest rates and reduce investment, 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 Manera, 2013, and an associated analysis of GDP impacts in Morana (2013).

[26] Fizaine and Court (2016) intended to test statistically Bashmakov's threshold effects, i.e. sharply negative correlation between ECS_{gdp} and rates of US GDP growth after an ECS threshold is exceeded, but found the sample too small to allow for robust statistical results. They suggested that using cross-country panel data may help in such analysis. US data at such levels, mostly associated with the aftermath of oil crises of the 1970s, are sparse.



a) relationship between *ECSgdp* and GDP growth rates (with one-year lag) for 11 major OECD economies (in window the 'wing function' for 11 economies' averages split by 3 ECS_{gdp} ranges (4-6%, 6-8%, 8-10%) is presented)

b) stylized "wing" function and Three Domains behavioural patterns

c) relationship between *ECSgdp* and GDP growth rates (with one-year lag) for Sweden, Denmark and Poland

Fig. 5. 'Wing function' relationship between *ECSgdp* and GDP growth rates (with one-year lag) for major OECD economies, 1995–2019.
Sources: Utilising data from Grubb et al. (2018a) extended by authors to 2019 for ECS_{gdp} and Worldbank for GDP growth rates.

data on ECS_{gdp}. Most show weakest GDP growth at times of highest ECS_{gdp}. In general, recessions in OECD countries have mostly occurred at times with ECS_{gdp} above 8–10 %.[27] Limitations on the econometric analysis of high ECS_{gdp} impacts on GDP growth rates include the limited number of observations with very high ECS_{gdp} levels, since historically economies have quickly adjusted back to the sustainable range, and the numerous other factors besides ECS_{gdp} that may dominate economic growth. Nevertheless, we performed a Granger test to identify the possible causal relationship between ECS_{gdp} and GDP growth rate for 11 countries across 1995–2016. The tests show a statistically significant one-way negative Granger causality from ECS_{gdp} towards one year lagged GDP growth rates for most countries (except Korea) at the 1 % significance level.[28]

Most of the energy-GDP literature consists of searches for a generalised smooth relationship with energy *price*; but our observations on the ranges of energy cost constancy suggest the possibility of non-linearity above *thresholds* associated with relative energy cost. The corresponding hypothesis is for a general form with non-linearly increasing (negative) impact on GDP at times of high ECS_{gdp}, as depicted in *Fig. 5 (a)*. When ECS_{gdp} stays within the 'sustainable range', the relationship is weak (see Figs. 3c and 5a; the dot in 5a inset window showing cross-country average for GDP growth at mid-range ECS_{gdp} is only slightly below from that for low ECS_{gdp}). Above the range of ECS_{dgp} 7 – 9 %%, the rate of GDP growth declines – averaged across these countries (and see *national variations*, below), by about 0.6 % for each additional 1 % higher ECS_{gdp}. The generalised pattern of a non-linear 'wing function' (Bashmakov (2007a)) suggests formalisation with multipliers correcting the potential GDP growth rate up and down (Bashmakov, 2016, 2017).

Note that there may be relatively short-term impacts of extreme prices. Bretschger (2014) distinguishes between negative static (short--term) and positive dynamic (long-term) growth effects of high energy prices. Based on panel data for 37 developed countries for 1975–2009, he found moderate, but significantly negative, correlation between five-year averages for energy intensity and GDP growth rates with about -0.08 elasticity. Energy price shocks abruptly raise ECS_{gdp} above the sustainable range and undermine GDP growth potential in the short term. But according to the "Minus 1″ logic, either energy intensity subsequently declines or prices go down over time, bringing ECS_{gdp} back within the sustainable range, facilitating GDP growth once more.

National variations. Fig 5(a) does however suggest substantial differences between countries, for which it is useful to consider potential causal relationships and likely national variations in these. At least for countries with limited energy subsidies or taxation, among which the US is the most studied, ECS_{gdp} is a measure of the resources devoted to energy procurement.[29] The impact of international energy price movements may in the short run either be exacerbated or offset by trade effects, so one obvious source of potential variation is the levels of energy taxation, export / import dependency and the share of industry in GDP, which soften the non-linearity.

Most of these eleven larger economies were net importers of fossil fuels, and increasingly of energy-intensive products, over the period. Fig. 5(a) shows little sign of threshold effects for Canada (net fossil fuel exporter in recent decades) or Korea (large manufacturing products exporter), and Australia (which anomalously avoided a high *ECS*).[30] For exporters, the implications are not simple: high energy export prices give a temporary economic boost but also drive up costs in non-fuel industries and impact exchange rates, with mixed implications.

To explore the impact of such large differences, Fig. 5(c) traces the *evolution* of ECS_{gdp} plotted against 1-year lagged GDP for the largest east European country in our dataset, Poland,[31] and for two import-dependent countries known for long-standing high energy taxation, namely Denmark and Sweden. Despite high energy taxation, in none of these Scandinavian countries did ECS_{gdp} exceed 10 % and there is scant evidence of adverse GDP impacts – the brief dips to very low or negative GDP growth directly reflect dislocation and credit crises induced by global recessions.

Limits to substitutability? For all these reasons, the idea of a universal ECS_{gdp} threshold is problematic, but despite these caveats, there are clear reasons to expect that a high ECS_{gdp} could negatively impact economic welfare by reducing resources available to acquire materials, labour and capital. However threshold effects would suggest non-linearities in the production function. Until the ECS_{gdp} exceeds the 'sustainable range', energy is 'affordable' and other production factors dominate economic growth rates, but as ECS_{gdp} goes beyond the threshold it increasingly eclipses other factors that promote economic growth. This would not occur under standard assumptions of substitutability between energy and other factors of production and also between different sectors. It seems relevant then that Bashmakov and

[27] Of course, several factors suggest caution in attribution. The 1970s oil shocks, which generated the highest *ECS* levels, involved substantial dislocation effects due to their sudden (and global) nature; and the co-incidence of the 2008 financial crisis with peak international energy prices obviously complicates causal inference from these years. Nevertheless, some other studies have suggested thresholds internationally, beyond which high *ECS*, at least in primary energy costs, have increasingly impacted GDP across many OECD countries. Based on the analysis of ECS_{gdp} (primary energy costs accounting) for 44 countries and for the world for 1978–2010, using one functional form, King (2015) concluded that: for many countries and globally ECS_{gdp} substantially and negatively impacts annual changes in both GDP and total factor productivity (TFP) with one-year lag; globally averaged, additional 1% of ECS_{gdp} slows down global GDP (GWP) growth by 0.37–0.45% and TFP by −0.5% (similar to the result for the US at Fig. 3c); the threshold resides near 8% of GDP (between 6% and 10%) for developed economies.

[28] We tested both the assumption that ECS_{gdp} is not Granger causing GDP growth and the assumption that GDP growth is not Granger causing ECS_{gdp}. The number of lags for the test was chosen based on information criteria and residual testing. The results support a similar finding to that of Fizaine and Court (2016) for the US; that we can reject the hypothesis that the level of ECS_{gdp} does not Granger cause economic growth rates. We can also reject the assumption of dual causality of ECS_{gdp} . Data for Fig. 1a have been checked for stationarity using KPSS unit-root test at level 0.05. Data for Spain, Korea, Mexico and Australia failed the test, while first differenced data for those countries passed it. Thus, first differences have been used while conducting Granger causality tests for those countries.

[29] The US *ECS* is composed almost entirely of primary energy and conversion costs, with very low contribution from taxation. After the 1970s shocks it maintained this structure, whilst many other OECD countries introduced energy taxation – which kept *ECS* higher initially, but provided domestic revenue and served as a buffer to external price shocks. The converse was true of Russia and many east European economies, which subsidized energy throughout the 1970s shocks and maintained low prices which – particularly for the eastern European countries joining the EU – then rose sharply during the 2000s, but in the context of stronger market integration and structural support from the EU.

[30] The Australian economy also boomed during the 2000s era of high energy and other commodity prices. However though energy-intensive in many ways, its correspondingly high exchange rate led to a strong 'Dutch disease' effect as heavy manufacturing industry moved abroad, curtailing its *ECS* which never reached high levels, so it is barely visible on Fig 5.

[31] Poland, conversely, with legacy of high energy intensity from the times of planned economy, faced very high *ECS* (11–15%) in 2006-2013, despite which it continued to grow by several percent a year (up to the financial crisis, from which they recovered more quickly). This was associated also with their economic boost from marketisation (and financial support) in joining the European Union, which also rapidly drove down *ECS*: By 2016 ECS_{gdp} in Poland was down to 7.9%. However *ECS* will stay higher for East European countries for some time, as they have lower share of value-added in their gross output (industry share of both GDP and GO is larger, and industry has lower VA/GO ratio); also have higher *ECS* for housing, with a background of inefficient buildings supplied by inefficient utilities.

Myshak (2018) find that the idea of limited *ECS* ranges also applies at sectoral level.[32]

The substitutability between different sectors and factors of production commonly assumed in standard economic production functions thus appears very limited in practice. Consequently overall, when the ECS_{gdp} goes beyond the upper threshold (10–11 % for the US), it starts to undermine potential contribution of many factors to economic expansion in non-linear ways, by impacting on both production and consumption systems that can only respond slowly, thus curtailing growth. Again, this points to complex interactions between *ECS* levels, and timescales of adjustment, as discussed for the US in Section 3 and, below, in relation to the literature on price elasticities. In the short-term energy price shock pushes ECS_{gdp} towards or over the threshold. As long as the energy price growth matches the energy intensity decline, higher energy prices are fully offset by reduced energy intensity. Otherwise, in the medium-term they decline to match limited energy intensity improvement rates. Consequently, in the very-long-term, the integrated-energy-price elasticity approaches "Minus 1".

Finally, we consider the other direction of causality, from GDP to ECS_{gdp}. Mathematically, a faster rate of GDP growth would reduce ECS_{gdp} only if real energy price lags behind energy intensity. This might contribute to a slight slope in Fig. 5 at lower ECS_{gdp} levels, but as noted that also appears unsustainable – very low ECS_{gdp} has never endured. In the next section we discuss more important dimensions of the way in which GDP may impact ECS_{gdp}, in developing a fuller theoretical framework.

7. Towards an integrated theory of energy cost ranges

The broad response of energy systems has traditionally been understood by economists as the interaction of energy demand and supply forces in response to price fluctuations, expressed through elasticities on which there is a huge literature. At low prices, energy demand increases (faster than it otherwise would), and investments in energy supply are less profitable. Rising demand and dwindling supplies tighten the market, driving up prices. Demand is curtailed as energy prices rise, new investments in energy supply become profitable and these new sources drive down the price. This is the conventional theory, based on a common understanding of the market behaviour that drives many commodity cycles.

This conceptualisation is valid but insufficient to explain our observations. First, this standard economic approach rests on underlying notions of price-driven substitution – a static conception, albeit with lags - but as our data show, the phenomena are clearly highly dynamic, and do not return to former states of 'equilibrium'. A fuller theory would need to embody the dynamics of induced innovation and structural change, for example drawing upon recent insights into both generalised heuristics (Cardinale and Scazzieri, 2022), and the specific role of energy in technological dynamics (Carra, 2022).

Against the background of broader debate on economic dynamics and associated technological and structural change, in this section we address a more specific, energy-related question: why does the ECS have a long-run tendency towards "minus 1″ and what are some of the specific policy implications of this. Specifically, we suggest that Bashmakov's first law of energy transition and the relationships between ECS_{gdp} and GDP growth rates can be explained by bringing together complementary insights specifically in relation to energy systems analysis: the Three Domains framework of Grubb et al. (2014, 2015, 2023), together with the formal rationale of Lowe (2003) on why energy price elasticities would be expected to asymptote towards (minus) 1 for multi-stage energy conversion systems.

7.1. On elasticities and the sustainable ECS range

A common conclusion from studies of the price elasticity of energy demand is that energy demand is relatively price inelastic – substantially smaller than "−1″. The meta-analysis by Labandeira et al. (2015) noted in Section 2 surveyed 416 papers published 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 (STPE) and −0.6 to −0.66 in the long-term (LTPE), but with quite wide ranges.

This raises two challenges: why do elasticity estimates obtained from longitudinal studies vary so much; and why do they appear so inconsistent with the cross-country estimates? As noted, a constancy of energy expenditure – and the pattern of Fig. 1(b) - implies an elasticity of approximately "minus 1″; this appears more consistent with a growing tendency in econometrics literature on *cross-country panel data* to suggest that long run energy elasticities might actually be of this order (notably, Saunders, 2015). Hence, given the existing terminology, and the emphasis of our previous sections on *very* long term (Section 4) and *integrated* (Section 5), our suggested terminology *very* long-term, *integrated* energy intensity to price elasticity (VLTIPE).

It is increasingly acknowledged that cross-sectional studies generate higher energy price elasticities than time-series ones (Brons et al., 2008; Adeyemi and Hunt, 2014; Bardazzi et al., 2015; Haller and Hyland, 2014). The differences cannot be adequately explained by income elasticities.[33]

The wide range of elasticities observed across different studies, timescales, countries, and analytical techniques, suggests a need to step back and consider more carefully. How useful is it to try and squeeze a complex web of interactions into a single number? How misleading may it be to then use a single number in models and in doing so assume away all the complexity of actual responses? The wide range of elasticities – and the fact that almost all the literature reports numbers that are lower than the 'minus 1′ average suggested by energy cost constancy – may actually be indicating something more interesting.

The cycles of course involve both supply and demand. In the fifteen years after the price crash of 1986, intensity improvements slowed down but did not reverse – they had become embodied in capital stock and better technologies, which continued to diffuse.[34]

On the supply side (as summarized more formally in Annex C), cheap

[32] Bashmakov and Myshak (2018) argue that: (i) high *ECS* in the industrial sector squeezes the profit margins of industry for as long as the prices cannot be fully passed through, making industry sensitive to *ECS* escalation with low chances of keeping growth positive after ECS_{go} exceeds 3.5–4%; and (ii) thresholds for industry vary between countries depending on each country's economic structure and its sensitivity to energy cost growth. They also find that the *ECS* for other sectors have their own limiting ranges, and for some (e.g. households) the impact of high *ECS* may be more obviously measured in terms of welfare, as well as squeezing consumption, and show that the countrywide *ECS* threshold is a linear combination of those for separate sectors.

[33] See Bashmakov and Myshak, 2018 for a technical discussion linking energy and price elasticities to the "minus 1" observations, and how energy intensity price elasticity may be equal to -1, while energy demand price elasticity remains below 1 (Annex B)). Panel studies show what is closer to *very-long-term* price and income elasticities. Also it is known that elasticities tend to increase for higher levels of aggregation, and for panel data reflect the fact that firms had sufficient time to adjust to long standing production factors price proportions. Even at the micro level, there are a few studies which suggest values exceeding 1: for Italian firms, Bardazzi et al. (2015) found own energy price elasticity of −1.13, whilst Haller and Hyland (2014) find −1.46 for Irish firms. So *very* long term elasticity is sometimes estimated at close to −1 (or larger) for industrial companies.

[34] IEA (2018) shows that since another energy price collapse after 2014, the global GDP energy intensity declined (China excluded) in 2016 and 2017 with the slowest rate since 2010.

oil discoveries lagged consumption, tightening supply. Even the oil companies were, to an important degree, myopic. Thus were conditions laid for the price rises that began after 2000, impacting most strongly those economies that had done least with respect to their energy intensity improvements.

Given the economic impacts of high and/or sharply rising *ECS*, at high *ECS* one gets a strong reaction on both demand (the rapid acceleration of intensity improvements, eg. noted in Fig. 3 coupled with GDP growth slowdown) and supply. The latter was clear in the development of offshore oil after the 1970s shocks, and the shale revolution after the 2000s; and in initial developments in new renewables from the 1970s, which finally took off at scale as governments in the 2000s responded to the combination of environmental pressures with rising energy prices. A striking feature is the non-linearity of these responses. These were mostly strategic measures (often supported by the confluence of economic, security and environmental concerns), which went far beyond the behaviour of markets as normally measured, and which – along with the ongoing shift of much heavy industry - served to bring the *ECS* back to within acceptable levels.

Economics traditionally measures elasticities as constant, and normally assumes that response to price increases and falls are symmetric. This seems too constrained to summarise the behaviour of energy systems. There is no theoretical or empirical reason to assume either constant elasticities, or symmetry. The very few studies to have attempted to measure this do indeed find that elasticities tend to rise with energy prices[35] (and we can add, with *ECS*) - Annex B also indicates reasons why this would be expected from analysis of distributional considerations – with asymmetry also observed.[36] Knotek and Zaman (2020) add recent evidence to a small but long-standing literature documenting asymmetry in response to energy prices, finding (in US data) larger asymmetries from larger shocks, such that with "large shocks, the cumulative consumption responses are three to five times greater for positive than negative shocks." . Our interpretation is not only that elasticities vary, but they do so in *systematic ways*, and in ways that structurally yield a sustainable range of *ECS* that corresponds to a *VLTPE* of energy intensity of about minus 1 for sound theoretical reasons. Thus, when *ECS* is below the sustainable range, elasticity is low, close to zero; when *ECS* exceeds the upper threshold, it rises rapidly.

[35] Eg. Bjorner et al. (2001), based on data for Danish industrial companies, find that the higher the share of energy costs in the production costs, the higher the energy price elasticity. 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 *ECS*s 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. Ghalwash (2007) demonstrated that price elasticity for the tax portion of the energy price in Sweden is higher, than for its base part.

[36] Haas and Shipper (1998) and Tajudeen (2021) showed that for many countries energy price elasticities are higher, when prices are growing. Recent empirical and modelling literature on asymmetric price reactions explains the asymmetry through an uneven technological and behavioural change under different energy price regimes (Huntington, 2003; Gately and Huntington, 2002; Griffin and Shulman, 2005; Jimenez-Rodriguez and Sanchez, 2005; Soria, 2006); through different consumers' reaction to threethree 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 behavioural change and impact on economic activity (Bashmakov, 2007a, b). All of these factors may be important.

7.2. Theoretical explanations: economic frameworks

Bashmakov (2016) shows that there is positive correlation between price elasticity for separate income or energy intensity deciles from the specific for it *ECS*. This matches closely the framework of Grubb et al. (2014, 2015) who argue that the evolution of energy systems can best be understood in terms of three different domains of economic behaviour. The standard assumptions of neoclassical economics, with the system characterised by representative agents optimising their use of resources based on relative prices and 'rational expectations', comprises the central (second) domain (Fig. 5b).

However, in reality many agents, for much of the time, *satisfice* rather than *optimise* (Simon, 1956) – in this terminology, exhibiting first domain behaviours characterised by inattention, habits, myopia, and risk aversion (e.g. with respect to new technologies or practices) on the part of individuals and organisations. This may be amplified by contractual and principal-agent failures and other systemic constraints. This results in them being far from the technology frontier: they are using more energy than would be optimal, in the conventional meaning of the word.[37]

At the opposite end, high *ECS* not only drives classical substitution but motivates third domain behaviour – associated more with innovation, infrastructure and structural change. This leads to the *transformation* of systems and hence is all about moving the technology / systems frontier, rather than just optimising resource choices within the confines of existing technologies and systems. Grubb et al. (2014) emphasise that these three different domains are not competing explanations but rather, describe different processes that operate at different social and temporal scales; for recent elaboration relating to primary economic foundations, policy evaluation, and interactions between the domains see Grubb et al. (2023).

Satisficing behaviour generates structural inefficiencies (growing distance from the technology frontier) in individuals and organisations, many of whom do not consciously manage their energy, or do so only with short time horizons. Low *ECS* encourages satisficing behaviour, with disinterest in energy choices, and weakens government motivation to counteract the resulting energy wastage.[38]

At the opposite extreme, price shocks – and more particularly, *ECS* levels above the sustainable range - not only motivate attention to energy, but also drive innovation and deeper changes to infrastructures, and justify strong government support for relevant innovation in both supply and demand technology – yielding changes which impact markets only slowly but which endure, and diffuse globally. Whilst innovation is sometimes equated with public-led R&D, in reality much innovation is induced by market conditions and demand-pull incentives; a major systematic review of literature (Grubb et al., 2021) on induced innovation in energy technologies emphasises the extent to which energy innovation over recent decades has indeed been induced by combinations of direct price impacts, and more targeted government incentives (themselves, mostly motivated by combinations of energy security/price shocks, and environmental concerns).

It follows that we should expect observed elasticities *not* to be constant: on the contrary, we would expect them to increase for higher

[37] This qualification is important. If one factors in the scarcity and opportunity cost of human attention, the concept of optimality has to change, in a way that might allow us to accept that it may be optimal to not be on the technology frontier. Simon (1956) was clearly aware or this. A key factor is that if agents do move closer to the technology frontier, for whatever reasons, they are unlikely to subsequently go backwards, introducing asymmetry and path-dependence.

[38] US energy efficiency standards on vehicles for example remained frozen for almost 3 decades after 1980, and the US became steadily further behind the frontier of vehicle efficiency, due in part to the power of incumbent manufacturers, over periods in which energy prices were insufficient to generate significant pressures to improve from either consumer demand or policies.

prices and *ECS*s, and as the economic space considered (temporal and geographical) expands to encompass structural changes. If the measured space is large enough - in time (to encompass periods of high *ECS* and the effects of capital stock, infrastructure and innovation), and wide enough (to encompass structural change and international diffusion, as revealed also in cross-country comparisons) we can get to the large elasticities being postulated in some of the more recent literature (eg. Saunders, 2015). However, this aggregates very different phases and aspects of elasticity, which is exactly what is implied by the Three Domains perspective with the qualitatively different processes involved. Particularly from this perspective, the varied elasticity estimates in the literature are entirely explicable: they are measuring responses in qualitatively different aspects of what are highly non-linear processes.

7.3. Theoretical explanations: physical foundations

There is, moreover, a clear theoretical reason to expect the elasticity to converge towards (minus 1). Lowe (2003) shows that for a system with multiple energy transformation stages, ('subsystems') the price elasticity must increase as the number of subsystems increases, and tend asymptotically to unity even if all partial elasticities for subsystems are below unity. If the whole economy may be considered as a multistage energy conversion system distributed in time, then Lowe's conclusion should apply for the whole economy, and 'minus 1′ – energy cost constancy - becomes theoretically what one would expect.[39]

The original proof of Lowe's theorem assumed constant sub-system elasticities, but is entirely consistent with component elasticities that rise with increasing *ECS*s. Moreover, the approach also reveals an aspect of inertia. Energy system infrastructure furthest upstream tends be large, long-lived and slow to respond. Rapid responses to abrupt rises in energy cost therefore concentrate downstream, and this response is larger than would be the case in a fully equilibrated system, because of the lack of shielding (a term defined by Lowe 2003) that would have been provided by more efficient upstream infrastructure. Nevertheless, efficiency improvements in downstream systems become "baked in", and are not reversed when upstream infrastructure finally responds. Particularly for large price rises therefore, the combined effect of different timescales for evolution of upstream and downstream systems can therefore be a long-term elasticity > 1. Lowe's theorem offers not only a reason to expect system elasticities to be significantly higher than any individual components reported in the literature, but to asymptote towards (minus) one.

Given independent theoretical rationales to expect non-constant elasticities, combined with the data observed,[40] the question is no longer why do long-term elasticities tend to -1, but how could they not? Moreover, the theories are mutually reinforcing. National and global energy systems comprise a complex mix of energy uses and multi-stage energy systems of varying lengths. At very low *ECS*, satisficing dominates throughout much of the system; only the most energy intensive industries (or those exposed to strong, energy-price-related competition) have much reason to pay attention to their energy use, and governments have little incentive to expend political capital on addressing the many structural barriers to efficient use. At high *ECS*, far more of industry finds its profits eroded by energy costs, and more and more consumers find energy squeezing their discretionary budgets; they will both respond directly, and place governments under pressure to act to relieve these pressures. There are opportunities to respond correspondingly at many points in the multiple stages of energy systems, on both supply and demand, until the *ECS* declines and the system restores to the economically sustainable and politically acceptable range.

8. Policy implications

The recognition of a sustainable range of Energy Cost Shares suggests a new focus for policy, including but going beyond market-based policies of subsidies and carbon pricing. The *strategic* narrative implies a positive message: prices can rise without people and businesses ultimately paying a larger share of income on energy. However, 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 important. Very low prices, for example as a result of subsidies, also carry risks because they lead to inattention and waste. Overall, the analysis has implications for both the scale of effort and the instruments of policy, notably in the context of climate change.

Intuitively, inertia and long timescales of adjustment imply a need to start stronger and earlier, whilst the scope for induced innovation and structural changes suggest benefits to action beyond those of immediate emission reductions. The former is illustrated by analysis of 'when starting with the most expensive makes sense' (Vogt-Schilb et al., 2018), which highlights the need for early targeting of components, such as long-lived infrastructure, which are hardest to change. The latter – the benefits of induced innovation – similarly amplifies the benefits of action (eg. Campiglio et al. (2022)). Other analysis introduces a stylised representation of these combined dynamic features, in terms of the aggregate 'pliability' of an economic system and its characteristic transition time, and finds that the optimal effort is substantially higher in systems which do have such adaptive capacity, as is implied by our empirical findings.[41]

In terms of policy instruments, the traditional economic conception is that prices are the most efficient way to drive improvements in efficiency and innovation through market mechanisms. However, the discrepancy between traditional measures of elasticity ($<<1$), and the evidence and logic of our analysis, along with our theoretical observations, indicates this to be seriously incomplete. Energy costs above the 'sustainable range' appear to involve increasingly high economic and welfare costs – and certainly, political obstacles. So, the policy message is not that governments can just impose higher prices (subsidy removal, carbon pricing) and tell a better story about it (long-run bills may not rise). Rather, energy/carbon pricing needs to be accompanied by timely, complementary measures to improve energy/carbon intensity.

The Three Domains framework offers a clear mapping to three corresponding pillars of policy. Grubb et al. (2014, 2023) emphasise that each behavioural domain implies corresponding pillars of government policies to improve energy outcomes, categorised as Pillars #1 ("Minimum standards and Engagement"), #2 ("Markets and Pricing"), and #3 ("Strategic investment").

The role of 'Pillar 1′ policies – notably, on energy efficiency – is thus to ensure that all social groups and businesses are utilising energy-efficient technology, so that higher prices do not drive them, or the

[39] Because the result flows from analysis of multi-stage energy conversion systems, and full response is constrained by the timescales of the most resistive components, it follows that measured elasticities will increase with the economic scope and timescale of the systems studied. The logic extends to structural change, as sectors with low elasticity are gradually displaced by those more able to accommodate higher prices, and as technologies and infrastructures evolve to better accommodate the relevant stages of the production chain.

[40] This is also supported by the explanation provided in Annex II, showing that at any moment, depending on *ECSs* all economic agents are distributed along Three Domains and driven by energy prices such distribution evolves explaining asymmetric price reactions.

[41] In Grubb et al. (2024), pliability is presented formally in terms of a transitional cost element that leads to enduring adaptions of technology, resource needs and structures, but requiring pressure to do so; this is multiplied by a characteristic timescale of transition. This finds 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, and imply a very different path of emission reductions as adjustments accumulate.

overall economy, outside the range of sustainable energy expenditure. Policies promoting energy efficiency should run in parallel with – and help to create the political space for – higher energy taxes, rather than being driven retrospectively by them.

Similarly, 'Pillar 3′ policies drive innovation in technology, infrastructure, and market structures to help to accelerate and orient energy innovation so as to ensure that both businesses and consumers are armed with options to respond to higher energy prices, and environmental pressures. It is well documented that major breakthroughs in efficient, low-cost, low-carbon technologies have come mainly from targeted policies that induced innovation through a mix of R&D and substantial strategic investment ('demand-pull') (Nemet, 2019; EEIST, 2021), which allows significant reduction in the long-run costs of global decarbonisation and of a transition away from fossil fuels. Mazzucato's (2013) term, "mission-oriented innovation", is relevant not only to the mission of low carbon innovation, but also to the mission of paving the way for economies in which high carbon / fossil fuel taxes can be comfortably accommodated by the whole economy.

Energy / carbon taxation has a particular role in this context. In its absence, 'Minus 1′ implies a potentially high degree of rebound from government energy-efficiency policies on their own – potentially offsetting the apparent gains – particularly if and as they lead to satisficing behaviours. However, pricing on its own risks neglecting key issues at both ends of the distributional spectrum – consumers for whom energy prices are negligible and ignored entirely, leading to structural wastage; and industrial consumers who could be driven away by high prices, rather than invest in innovative solutions.

As the system adjusts, the combination of policies in turn can create a tax and infrastructural wedge[42] between primary and final energy costs, making the economy less susceptible to the dislocation and trade impacts of external price. Moreover, because part of the end-user cost accrues as public revenues, rather than reflecting primary resource costs, higher *ECS* levels may also have lower GDP impacts compared to equal primary energy costs. Lowe (2010) has offered a short reflection on possible responses to this conundrum.

A focus on *ECS* also carries implications for the timing of policy efforts to put a price on carbon or other environmental damage. The period from the late 1980s to mid-2000s, during which environmental policy broadly strengthened, was an opportune time to introduce environmental pricing and fuel duties, because energy costs were low. Many countries did take advantage of this – and benefited not only through a cleaner environment, but often through lower national energy bills as prices then rose, as we have demonstrated.

These policies did however then hit political limits derived from the very real economic and social impacts of high *ECS*. The late 2000s were a bad time to try to introduce new energy-environmental pricing – most of all for an entity like the EU which had recently enlarged to include 10 states that were not only poor, but also saddled with the legacy of decades of central-planning-led, inefficient energy infrastructure. The pain was very real and the consequence was a deep and damaging politicisation of clean energy policy in Europe. One way to reduce the risks of ad-hoc political interventions might be to give greater regulatory certainty by using escalators which would automatically freeze if overall *ECS* rises above key thresholds (as in 2022), and then resume as-and-when those costs decline.[43]

The time and place for ambition in energy/environmental pricing is when and where relative energy expenditures are well within the sustainable range, so as to navigate the economic and political constraints on *policies* that raise overall energy costs much above the sustainable *ECS* range, in addition to other aspects of innovation economics.

9. Conclusions

The data covered in this paper adds additional empirical evidence and insights to the idea of a sustainable range of energy expenditure, which tends to gravitate back towards a range which empirically is 4.2 ± 0.8 % relative to Gross Output, or 7.2 ± 1.5 % of GDP, across the countries studied – principally OECD and Russia, due to data limitations around developing countries.[44] Including non-energy uses of fossil fuels and (for OECD importers) consumption-based adjustments for international trade may add around 1 percentage point of GDP. This goes along with the implication that long-run energy intensity responses to energy price fluctuations have a collective impact corresponding to a *very-long-term integrated price* elasticity (VLTIPE) of "minus 1", which is higher than almost any in-country estimates. We suggest that this, as indicated, is all consistent with mutually reinforcing theoretical reasonings from multiple perspectives of energy chain interactions (Lowe, 2003) and the Three Domains framework (Grubb et al., 2014), and distributional considerations (Bashmakov, 2016; Bashmakov and Myshak, 2018).

Overall, this suggests that energy systems have considerable capacity to adapt to pressures and shocks – as most obviously expressed through energy prices - through combinations of several factors. In an environment of high price or supply risks, as characterised most obviously by the 1970–80 s oil shocks and the policy aftermath, energy efficiency and structural changes which affect intensity, innovation, and supply-side changes, all acted to bring the *ECS* 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.

Ultimately, both the data and logic imply that, given action across all the three pillars of policy, the energy system is highly adaptive - and a key aspect of these adaptive processes is that they act to restore overall energy bills/income ratios to within a sustainable range, for which this paper has provided new and additional evidence.

Directions for further research may include clustering countries based on the structure of the economy and energy trade patterns; analysing further the interactions of demand (mostly national) and supply-side (mostly international for fossil fuels and local for renewables) responses to price changes; initial insights from responses to the 2021–23 energy crisis; and developing datasets further to include non-OECD countries; and examining ECS phenomena by major sectors.

CRediT authorship contribution statement

Igor Bashmakov: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Grubb:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation,

[42] The single best example of an infrastructural wedge is the development of efficient district heating systems in Denmark and Sweden. This intermediate infrastructure has then provided a platform for deployment of technologies (such as large-scale energy storage) that would otherwise not have been deployable.

[43] In the UK, a "fuel duty escalator", which was introduced in 1993, was frozen in the face of rising political protests. A similar approach to carbon pricing, with an escalator on the UK carbon floor price intended to follow the social cost of carbon, was similarly frozen in the face of political pressures in context of rising energy costs from multiple sources.

[44] See note 6 on data limitations for developing countries. If these limitations can be addressed, the extent to which our conclusions extend to developing countries would be a valuable topic of research.

Conceptualization. **Paul Drummond:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Lowe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Myshak:** Visualization, Formal analysis, Data curation. **Ben Hinder:** Visualization, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Bashmakov, Igor; Grubb, Michael; Drummond, Paul; Lowe, Robert; Myshak, Anna; Hinder, Benjamin (2024), "Data for "Minus 1" and energy costs constants", Mendeley Data, V1, doi:10.17632/73kbfvbpfb.1.

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Annex A: Energy costs accounting methodologies and data

The results of energy cost share (*ECS)* evaluation depend on multiple factors:

- how energy costs are accounted (for which energy users and energy carriers: whether it is for primary energy users, or for final energy users);
- what energy resources and carriers are taken into account (only commercial, or non-commercial as well);
- what prices are used (prices of primary energy resources or of final energy carriers; including or excluding taxes and subsidies; representative prices; country weighted average prices; or some proxies); and
- the timescales covered: energy economies are complex adaptive systems with considerable inertia, and particularly in the face of price shocks, 'cost constancy' only emerges for periods covering one or more cycles, which we estimate as being at least 2–3 decades.

The US EIA State Energy Data System (SEDS) calculates energy costs by multiplying the price estimates by the consumption estimates. To avoid double counting, the later are adjusted to remove costs of process fuels, intermediate petroleum products, electricity exports, and other consumption that has no direct fuel costs. Data are presented also as energy costs for different energy carriers and sectors as well as share in GDP. This approach provides the most robust assessment of energy costs paid by final consumers still subjected to revisions based on better data and accounting methods. However it includes non-energy use (e.g. conversion of hydrocarbons into non-energy products such as fertilizers and plastics), which is reported as a part of industrial energy use.

King (2015) estimated energy expenditures for primary energy for 44 countries by multiplying primary energy use for each resource by corresponding energy price. Fizaine and Courte (2016) use a similar approach. This energy cost accounting method ignores additional value of secondary energy resources as well as taxes collected at the point of secondary energy sale. Therefore, this approach substantially underestimates the energy costs paid by final energy users, especially for more recent periods, as the share of primary energy converted in the energy sector has continuously grown throughout the period analysed.

Aside from the EIA data, four widely-available datasets are used in this study for energy costs accounting: EU KLEMS Database (Timmer et al., 2011) and the three releases of World Input-Output Database (WIOD) (Timmer et al., 2015; Woltjer et al., 2021). The first provides information on intermediate energy inputs at current purchasers' prices for many OECD countries since the 1970s, useful for assessing business energy use, but omits domestic consumption and ends in 2005. KLEMS thus allows us to estimate energy costs shares in gross output, however, it does not include household energy uses (in private houses and by personal transport). Energy costs are assessed as the sum of energy costs for all sectors deducted energy costs from "mining and quarrying of energy producing materials", "coke, refined petroleum and nuclear fuel" and "electricity and gas" to avoid double counting. Energy inputs to "chemicals and chemical products" and to "rubber and plastics" were deducted as a proxy for non-energy use.

Three variants of the WIOD datasets are more comprehensive in coverage but only cover limited time frame each (with some overlap) and involve aggregation which may bias energy cost estimates.

The WIOD1 dataset includes 35 sectors and standardizes input-output tables for 40 countries and the world for each year of the 1995–2011 period. WIODI provides data (time series for 'supply' and 'use' tables) for coal, lignite and peat, crude petroleum and natural gas, uranium and thorium ores, as well as electricity, gas, steam and hot water supply as intermediate energy costs items for each sector. This allows for better accounting of energy costs, as some non-energy related inputs (like water from 'electricity, gas and water' supply) are removed. But this additional disaggregation is only provided by IOT rows, not by columns, and doesn't allow the separation of energy inputs to energy-related and other activities aggregated in 'mining and quarrying' from energy used in 'electricity, gas and water supply'. 'Coke, refined petroleum products and nuclear fuels' inputs to 'chemicals, chemical products and man-made fibers' as well as to 'rubber and plastic products' were deducted to exclude non-energy use from the energy costs accounting. Since WIOD1 presents data (time series for 'use' tables) in purchaser basic prices, all taxes are accounted for.

Another set of WIOD data is organized as a single input-output table (IOT) for 35 sectors and 40 countries covers 2000–2014 (WIOD2). WIOD2 provides information to estimate both the ECS_{gdp} and ECS relative to gross output (ECS_{go}). Of the 35 sectors in this dataset, 3 reflect energy supply activities: mining and quarrying; coke, refined petroleum and nuclear fuel production; and electricity, gas and water supply. However, the sum of these three aggregates in the WIOD2 data over-estimates the energy costs, by the value of non-energy costs in the mining sector and in water supply, yet does not exclude fuel use for non-energy purposes. Energy export is deducted, while energy import is taken into account. To present end-use energy costs, the mining product used in the mining sector is deducted (because energy used on site at fields and mines is not traded), same as the cost of primary energy used for coke production and refinery and power plants inputs. Wholesale and retail mark-ups are added. Taxes less subsidies for three energy sectors are also included in the energy costs. Since WIOD2 presents data at basic prices, not all of the taxes are accounted for, bringing the whole estimate down.

Longrun WIOD (WIOD0) dataset covering 1965–2000 appeared last (Woltjer et al., 2021). As well as WIOD2 it is organized as a single input-output table, for 23 sectors and 25 countries. Same as in WIOD2, there are three sectors reflecting energy supply activities. Calculations made on WIOD0 database are the same as described above for WIOD2.

Given the limitations of these publicly-available datasets, to explore the issues more robustly and to eliminate costs of fuel used for non-energy purposes, we developed an alternative dataset specifically for energy-related expenditure, for OECD countries for 1970–2019. 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 (details are specified in the methodological Annex I to Grubb *et al.*, 2018a). A lower level of IEA data disaggregation was used by CENEf-XXI to extend the *ECS* time sample to 2015.

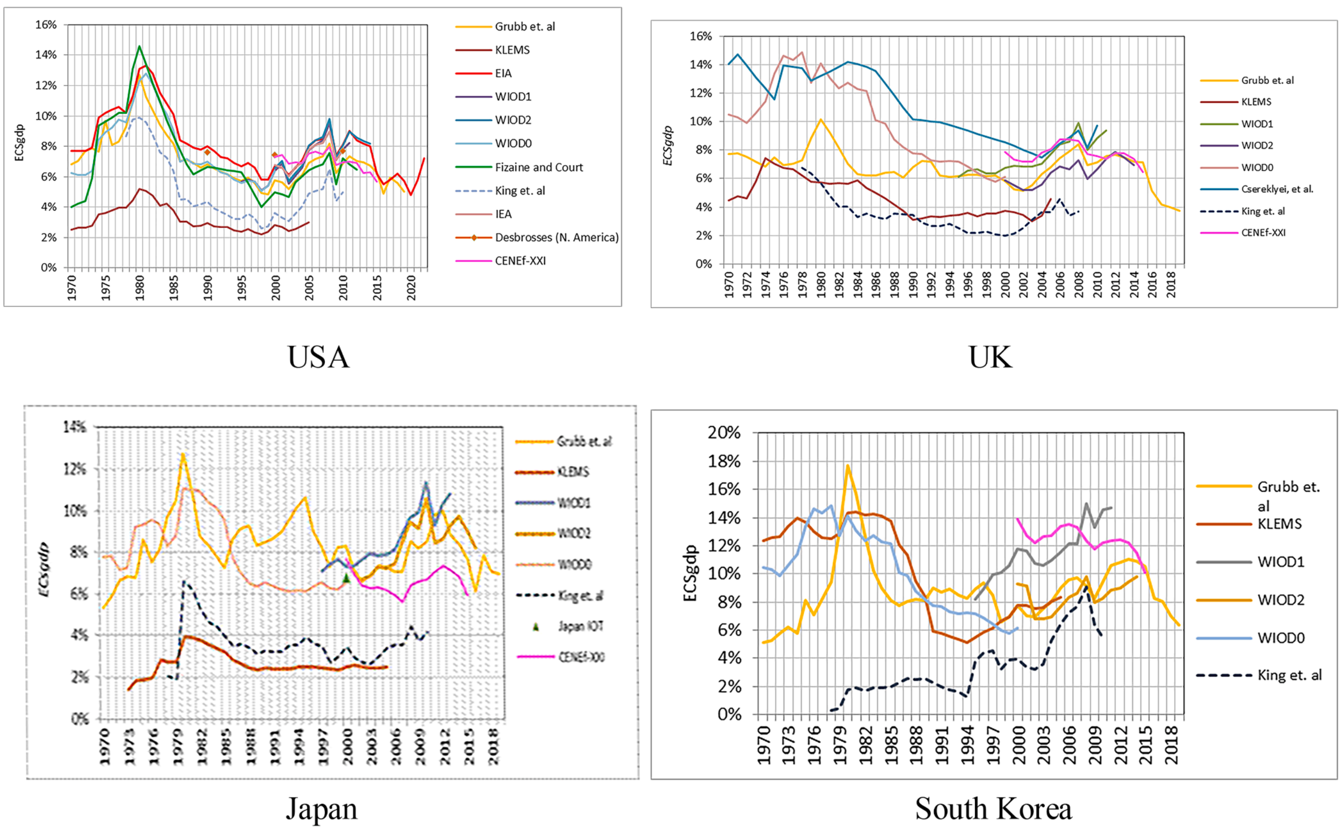

Fig. A.1. Differences in energy cost to GDP ratio assessments for the four countries depending on energy costs accounting method and data sources
Sources: Authors based on data from Cserеklyei, et al. (2014) Desbroses (2011); Fizaine and Courte (2016); Grubb et al. (2018a) extended by authors to 2019; IEA (2011); King (2015); SEDS (2019)*; Timmer et al. (2011) and Timmer* et al. *(2015); Woltjer* et al.*, 2021).*

Fig. A.1 compares the ratio of energy costs to GDP from these various sources and cost accounting methods for four countries – two relatively central in cost ranges (US and UK), and two which appear at extremes over time, namely Japan and Korea. Different sources of data, definitions and details of energy costs calculation explain a great deal of the apparent differences:

- When the primary energy cost approach (missing additional value of secondary energy resources and many taxes) is used, the energy costs share is substantially lower: King's primary energy *ECS* for the US is on average 3.3 percentage points below EIA data, and the difference is bigger for the other countries. This is because energy conversion costs are significant and together with energy taxes (which are generally larger for the non-US countries) create a large difference between primary and final energy costs;
- KLEMS data omit costs for energy use in housing and private transportation, and hence show much lower *ECS* except for Korea, where an exceptionally high share of non-energy use (excluded from the Grubb et al. dataset) appears to dominate particularly the WIOD data
- Except for these, all the dataset converge quite closely for the US and UK particularly from the early 1990s, but the WIOD datasets show growing and higher *ECS* for Japan and Korea due to its inclusion of non-energy use as well as domestic sector energy prices including intermediate taxes (not included in King, 2015);
- Due to its exclusion of fossil fuels used for non-energy products (mainly petrochemicals), the *ECS* estimated by Grubb et. al (2018a) is on average almost 1 % below the EIA estimate for the US, and otherwise tends to indicate a more stable *ECS*, intermediate between the other datasets.

All datasets for the US are consistent in their reproduction of the temporal pattern of *ECS* evolution. However, temporal patterns do not match each other so well for the UK and even less so for Japan and South Korea. A large part of the discrepancy is attributed to non-energy use component included in EIA and WIOD2, which is responsible for 5 % of final energy use in the UK, 8 % - in the US, 12 % - in Japan and 26 % in South Korea, due to its large petrochemicals industry. The cost equivalent of this component is proportionately larger, as it dominated by relatively expensive liquid fuels.

The larger differences for the non-US countries also suggests a role of inconsistencies in exchange rates applied while building IEA, KLEM and

WIOD datasets, which can affect all components of input-output tables. The *ECS* is dimensionless, so for the best estimates, local currencies should be used to calculate both energy costs and value added or gross output; however in practice, all use US$ for their construction.

Much improvement is needed to develop more robust and consistent energy cost data. Constructing *ECS* estimates based on national currencies, which would preclude use of current international published datasets, was beyond the scope of this paper and is suggested as a focus for future research; it would help if national and international statistical bodies started to report energy costs and *ECS* data derived directly from primary input data collection.

In this paper we focus on the *final ECS* as paid by energy consumers, i.e. including direct energy taxes, not the primary inputs.

Annex B. The relationship between energy demand and energy intensity price elasticities

If energy demand is a log linear function of income and energy price, its average annual growth rates (T_e) can be presented as: $T_e = a * T_y + b * T_p$, where T_y and T_p are correspondingly average annual income and real energy price growth rates. Energy intensity to energy price elasticity (c) 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:

$$c = \frac{T_{e/y}}{T_p} = \frac{T_e - T_y}{T_p} = \frac{aT_y + bT_p - T_y}{T_p} = (a-1) * T_y / T_p + b \tag{4}$$

It is volatile as instability of T_y/T_p, forces c cyclically fluctuates with given a and b, Elasticities c and b are equal only when either T_y=0, or $a = 1$. Theoretically, b should be negative. T_y and T_p can be either positive, or negative. Only whole cycle-long energy intensity to real energy price elasticity equals to -1. So, to estimate this, time series should start and end not at any points, but only at the same cycle phases. For the 'minus one' phenomenon, c= -1, or $\frac{a-1}{b+1} = -\frac{T_p}{T_y}$, and therefore,$b = (1-a) * T_y/T_p - 1$.

Depending on the *ECS* position relative to thresholds both a and b are not constant either, they are drifting. Energy demand to price elasticity (b) is asymmetric.

If for the whole sector the energy demand function is presented as $E = AY^aP^b$, and for every group i of energy users ranked by the level of *ECS* it is $E_i = A_iY_i^{ai}P_i^{bi}$, then overall energy price elasticity can be presented as a weighted sum of price elasticities specific for each group with weights equal to their shares in the total energy consumption. If those groups are regularly using energy resources of different quality this also should be corrected to long staying differences of average energy price specific for the given group to average price across all groups (ρ_i): $b = \sum_i b_i * d_i^e * \rho_i$. The higher the *ECS*, the higher energy price elasticity. When energy prices are growing faster, than income, the ECS_i increase and thus each b_i, grows (by absolute value) and so b drifts up and vice versa. This is one simple explanation of energy price elasticity asymmetry (see Bashmakov, 2016 for more details) .[45] Therefore, evolution of energy demand functions' elasticities (a and b), along with the dependence between the T_y and T_p for high *ECS* ($T_y = T_{ep} - mT_p$) and instability of the T_y/T_p ratio, all inject much dynamics to the elasticity of energy intensity to real energy 13 different sectors (Bashmakov and Myshak, 2018) as well there are no contradictions between empirically estimated low b for energy demand price elasticities and cycle long '-1' energy intensity to energy price elasticity.

Annex C. Limits of low costs energy resources availability

After reaching the peak, real energy sales first decline to adjust to the existing purchasing power and after reaching the bottom level, they remain close to new equilibriums for a few years, while real energy prices keep slowly declining. This period lasts for 10–12 years or longer with $T_e \approx T_y$ as $T_{esales} = T_e + T_p = 0$. This price and *ECS* decline accelerates energy demand. It should to be met with low energy prices and thus with low production costs. Alternative suppliers face difficulty even to keep achieved production volumes after prices fall, and all additional demand is to be covered by producers with low production costs. But with low energy prices they had limited incentives to escalate their capacities and so capacity load for low costs supply is growing until it unable to meet growing demand. To re-establish the balance finally energy prices start growing. Duration of this stage very much depends on availability of low cost energy supply capacities and resources. This brings energy sales up, and after$T_{esales} = T_y$, the$T_{ECS} = 0$. After reaching the bottom, *ECS* starts a new, 10–12 years' climb to the next peak, driven by energy prices growing in excess of energy intensity decline. So, energy sales (energy costs) behave slightly differently from *ECS* and limits of low costs energy supply options are responsible for first stopping *ECS* decline, reaching the bottom level and then reversing its trajectory.

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[45] Empirical literature on asymmetric price reactions explains the asymmetry effect through the uneven technological and behavioral change under different energy prices regimes; through different customer reactions to different components of energy prices via (Adeyemi and Hunt, 2014); risk aversion of human nature (van de Ven and Fouquet, 2014); as well as through purchasing power thresholds, which drive uneven technological and behavioral change and affect economic activity (Bashmakov, 2007a, b). All of these factors may be important, and there is no agreement about the causality of asymmetric price reactions.

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