International Journal of Energy, Environment and Economics ISSN: 1054-853X
Volume 25, Number 1

THE FIRST LAW OF ENERGY TRANSITIONS AND CARBON PRICING

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ABSTRACT

This paper elaborates on the energy costs/income constants and the 'minus one' phenomenon. Like a pendulum driven by some economic 'gravitation', energy costs to income ratio tends to get back to the narrow zone of sustainable dynamics. The 'gravitation formula' is as follows: for 25-33-years' cycles real energy prices may grow only as much as energy intensity declines. This appears a most important relationship in energy economics. Energy affordability thresholds are identified in all major final energy use sectors. The aggregated economy-wide threshold is a linear combination of those and shows cyclic evolution for decades or even centuries within a sustainable 4-6% range as a fraction of gross output and 8-12% range as a fraction of GDP. These ranges may drift slightly up or down, driven by the economy structure evolution impacted by the role of industrial and services sectors and embodied energy outsourcing. The energy cost share reaches its maximum, when further price increase cannot generate any additional revenue for energy supplier, and it reaches a minimum when price decline undermines the ability of energy suppliers to meet growing demand. The overall energy price elasticity is a weighted sum of price elasticities specific for each group which by the absolute value positively depend on the share of energy costs. This effect makes price elasticities asymmetric. Carbon pricing trap poses restrictions on the magnitude and dynamics of carbon price keeping energy affordable and preventing global economy from stagnation.

Keywords: economic cycles, energy prices, energy cost share, energy intensity, price elasticity, affordability thresholds, carbon pricing, energy transitions

JEL classification: E25, E3, N7, O1, O4, O5, P52, Q3, Q4

1. INTRODUCTION

Bashmakov (2007) formulated and explored a hypothesis on three general laws of energy transitions. The first law states that *in the long-term, energy costs to income ratios are relatively*

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stable with just a very limited sustainable fluctuation range. It was discovered (Bashmakov, 2007), that energy costs to income proportions are relatively stable over decades, if not over centuries, and very similar across regions and large countries. Specifically, these proportions include final energy costs to GDP (or to gross output) ratio; energy cost to gross output in the industrial, services and transport sectors; and housing energy costs to personal income ratio (Bashmakov, 2007; Bashmakov, 2016; Bashmakov and Grubb, 2016). Grubb (2014), testing Bashmakov's concept of the energy spending constant, showed that in the long term, countries with higher average energy prices produce wealth with smaller energy consumption with the implied 'price elasticity' (a measure of the flexibility of countries' responses to price difference) around -1, and so the higher energy prices are fully offset with reduced energy intensity. This paper provides another interpretation of the 'minus one' phenomenon: real energy prices may grow only as much as energy intensity declines. Fizaine and Court (2016) argue that Bashmakov's 'first energy transition law' works for post-Second World War era, yet not for earlier periods.

Additional historical data on the energy cost ratio became available recently (Kander, 2002; Fouquet, 2008; Csereklyei et al., 2014; Stern and Kander, 2012; Fizaine and Court, 2016; Court and Fizaine, 2017) covering periods from 1800, and even from 1300, onwards. Based on such historical data analysis, Csereklyei et al., (2014) and Kander et al., (2014) concluded, that the energy costs to GDP ratio is not stable, but tends to decline by 1% per year, and this trend is a 'typical feature of economic development' (Stern and Kander, 2012). In all of these studies energy costs include manpower. For recent years, this ratio was estimated below 10%, so following this logic, it will get down to null in a decade's time ushering an era of nearly free energy. King (2015) noted this contradiction and correctly commented that this ratio could never reach zero. Anyway, the historical validity of the first law of energy transition obviously requires more investigation. Bashmakov (2016) conducted tests which challenge the accuracy of historical estimates of *ECS* provided for 1300-1900 by Kander (2002) and Fouquet (2008). The first part of this paper (sections 1 to 3) investigates the validity of the 'first energy transition law' based on historical data. The second part highlights Bashmakov's (2007) conclusion that there are energy affordability limits (energy costs to GDP ratio thresholds), and going beyond these limits makes energy shortage act as the 'limit of growth'. It is not just the existence of affordability thresholds that is important for this discussion, but also their quantification and the interaction mechanism of thresholds and economic growth. The last section of the paper deals with the energy cost share trap for carbon pricing. Global internalization of some 20 US$/t CO_2 carbon price for energy-related CO_2 emissions will get global energy costs to GDP ratio up by about 1%. The questions here are: (1) how high can the carbon price be to incentivize GHG emission reduction on the one hand, and stay within the energy affordability limits on the other? and (2) is there trade-off between sustainable economic growth and GHG emission reduction to levels that will limit global warming to 2°C?

2. The Energy Cost Share Constant and the 'Minus One' Phenomenon. The U.S. Experience Since 1949

While additional studies since 2007 considered the evolution of the energy costs to income ratio, now the hypothesis on the stability of the energy costs shares and 'minus one' elasticity may be tested with more data available. However, efforts to explore the evolution of these proportions are still scarce, mainly due to the shortage of aggregated country- or region-level total energy cost data. Scarce statistics are available only for the late 20th century onwards. Among a few statistical periodicals, energy costs for final consumers are reported by the EIA SEDS (2017) for time periods starting with 1970. Very few countries so far regularly report consumers' energy spending and energy costs to GDP ratios. In addition to the U.S., where such data are published on the national and provincial levels, in 2010 Russia also began collecting information on energy costs across the whole economy, by sectors and provinces. In addition, more expert estimates of this ratio became available for individual countries and groups of countries, and a few databases allow it to calculate this ratio with a certain accuracy.

Data sample for the US (1970-2014) was extended by the author (to 1949-2014) to cover a 65 years' interval using fuel and electricity prices indexes, energy use and GDP data from 1949 to 1969.[1] Four factors determine the evolution of the energy costs to GDP ratio *(ECS)*:

$$ECS = \frac{E * PE}{YR * PY} = \frac{E}{YR} * \frac{PE}{PY} = EI * PER\,, \qquad (1)$$

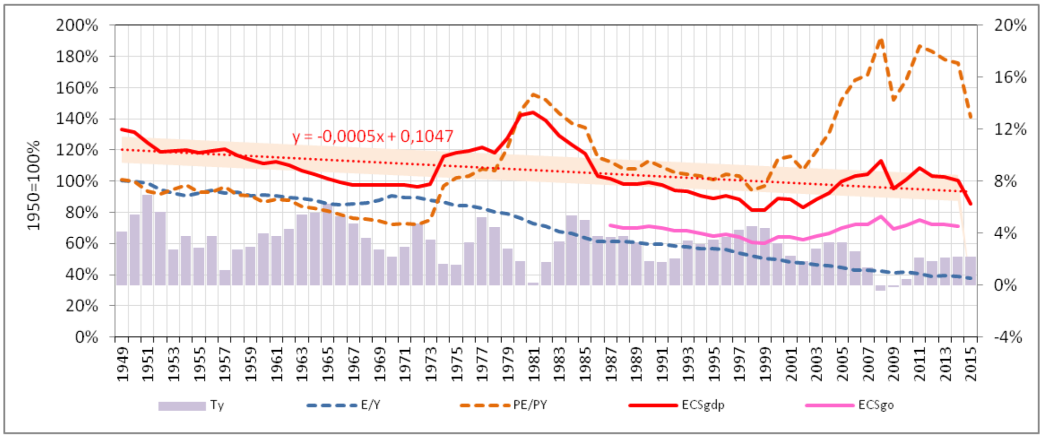
where *E* is energy consumption; *PE* is energy price; *YR* is GDP in constant prices; *PY* is GDP deflator; *EI* is GDP energy intensity; *PER* is real price of energy.

Identity (1) shows, that these four factors may be reduced to major two: energy intensity of GDP and real (deflated) energy price. Figure 1 illustrates the evolution of the last two factors, as well as GDP growth rates and the energy costs to GDP ratio in the U.S. for 1949-2015. While this figure encourages further discussion, it allows for some important observations.

First, the *ECS* evolves cyclically with sustainable fluctuation range limited to a slightly downdrifting zone of 7-9% in the last decade. After the upper limit (threshold) is reached or exceeded (1949-1952, 1974-1985, 2008-2011), the *ECS* drops, and after the lower limit is approached (1965-1973 and 1995-2003), it, on the contrary, grows. Like a pendulum, the ratio driven by some economic 'gravitation' every time goes back to the equilibrium, or to the zone of sustainable dynamics. Initially, this sustainable lane was considered stable (Bashmakov, 2007); however, with a several decades' timeframe a general slowdown trend (by about 0.4% for every 10 years) can be observed. The energy costs to GDP ratio (ECS_{gdp}) stays within the 'sustainable lane' ($\underline{+}$1% around the trend) of 46% of all time. When the share of energy costs in gross output (ECS_{go}) is considered, no downward trend can be observed, but the time sample is too limited (available from national US statistics only since 1987).

Second, there are cycles in the evolution of real energy prices around the upward trend. ECS_{gdp} is driven by the evolution of real energy prices, as well as by energy intensity dynamics. This latter driver substantially mitigates the impacts of the former, but at a fixed time its mitigation potential is limited. Annual energy intensity reduction for developed economies with average GDP growth rates below 3-4% is limited to 2-2.6% per year (see Table 1 below). Therefore, more dynamic energy price growth pushes ECS_{gdp} up.

[1] Tested accuracy of retrospective estimates for overlapping years varies in the range of +0.4%.



Energy costs to GDP ratio (ECSghg – right-hand axis); Share of energy costs in gross output (ECSgo – 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 energy costs to GDP ratio 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.

Sources: developed by author based on data reported in: EIA, 1987; EIA, 2011; EIA SEDS, 2017; EIA, 2016; BEA, 2016. https://www.eia.gov/totalenergy/data/browser/?tbl=T01.07#/?f=A.

Figure 1. Evolution of major drivers behind the energy costs/GDP ratio in the U.S. in 1949-2015.

Third, cycles in the ECS_{gdp} evolution substantially affect energy intensity decline cycles (Table 1). When real energy prices grow, energy intensity declines faster, and the magnitude of energy intensity to real energy price elasticity varies between -0.46 and -0.53. When real energy prices decline, reductions in energy intensity do not cease (being driven by the technological progress, which is independent from the current prices and is largely inspired by delayed reactions to prior price shocks), yet slow down, and the energy intensity to price elasticity becomes positive.

Fourth, in general, evolution of GDP growth rates is reverse to that of the ECS_{gdp}, while the GDP deflator, on the contrary, positively correlates with it. Fifth, if a quarter-to-third of century-long cycles of the energy costs to GDP ratio are considered (see Table 1), then real energy prices grow by only as much as energy intensity declines, with cycle-long elasticity nearly equal to -1. For the two cycles considered, this elasticity is -1.04. *That is exactly the ‘minus one’ phenomenon*. Sixth, there are two lines of adjustments to energy price shocks: (1) acceleration of energy intensity decline, and (2) reduction in real energy prices when the first one fails to completely mitigate the price shock effect.

Complete adjustment to energy price shocks takes about a quarter to a third of a century. Many studies focus on short- and long-term price elasticity of energy demand. It seems important to introduce the notion of a *very long-term (or integrated) price elasticity*, which is -1. In addition to behavioral and technological adaptations to energy price shocks, other factors, such as economic development slowdown, structural shifts, substitution of production factors, and inflation, get to work bringing *integrated price elasticity* to ‘minus one’.

Table 1. Relationship between real energy prices and energy intensity for the US

Period	Energy intensity elasticity to real energy price	Average annual growth rates		
		Energy intensity (E/YR)	Real energy price (PE/PY)	GDP AAGR (Ty)
1949 - 1972	*0,35*	-0,51%	-1,44%	4,16%
1972 - 1985	*-0,53*	-2,60%	4,87%	3,06%
1985 - 2003	*2,57*	-1,71%	-0,66%	3,15%
2003 - 2011	*-0,29*	-1,67%	5,77%	1,56%
2011 - 2015	*0,30*	-2,04%	-6,76%	2,22%
full cycles				
1963 - 1986	***-1,14***	-1,58%	1,39%	3,54%
1986 - 2012	***-0,97***	-1,76%	1,80%	2,61%
two cycles				
1963 - 2012	***-1,04***	-1,67%	1,61%	3,05%

Sources: developed by author based on data reported in: EIA, 1987; EIA, 2011; EIA SEDS, 2017; EIA, 2016; BEA, 2016. https://www.eia.gov/totalenergy/data/browser/?tbl=T01.07#/?f=A.

Lowe (2003) came up with a conclusion that overall energy price elasticity (for a system with multiple energy transformation stages, 'subsystems') asymptotically tends to unity as the number of subsystems increases, even if all partial elasticities for subsystems are below unity. If the concept of embodied energy (see Hammond and Jones, 2008) is applied to the whole economy, then it can be considered as a multi-stage energy conversion system distributed in time, and Lowe's conclusion becomes valid for the whole economy or for a particular sector. Using the material balance method, embodied energy can be assessed as:

$$Eemb = (1-m)*(\sum_i X_i * a_i + E) + Te, \qquad (2)$$

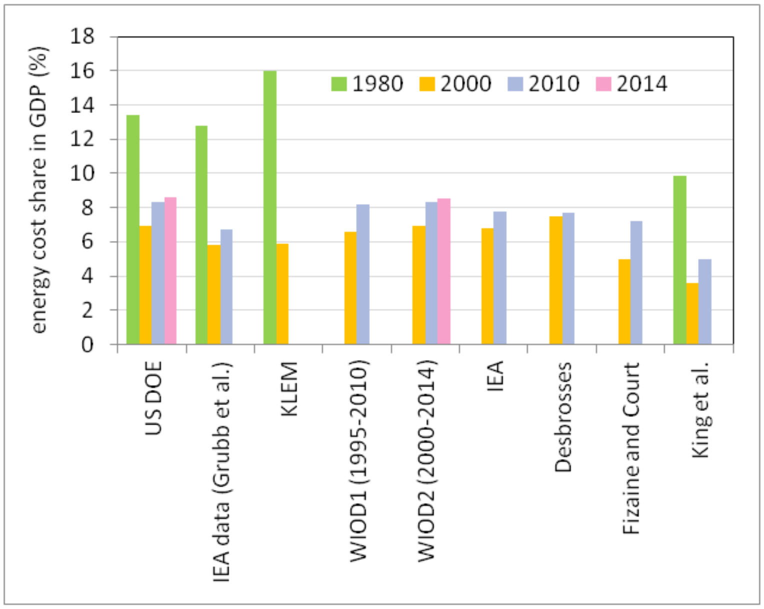
where m – is share of production process loss; X_i – is masses of input materials; a_i – is specific embodied energy use per unit of input materials; E – is energy directly used in given production process; Te – is energy needed to transport the final product. The 'minus one' effect stems from the assumption that at least some subsystems energy efficiencies (a_i) depend on input energy price impulses. This partly mitigates the impacts of energy price due to lower embodied energy. The higher energy price elasticity of energy efficiency within a given process, the smaller price impacts at subsequent stages. The smaller energy price elasticity of energy efficiency at each stage, the longer (or more stages) it takes to completely mitigate initial price impulse with energy efficiency gains. When embodied energy analysis is applied, it means that changes in material efficiency improvements also contribute to the process. If there is overshooting and at some stage energy efficiency to price elasticity exceeds unity, then overall elasticity exceeds unity at the same stage, but later system-wide elasticity starts declining asymptotically from that new, above unity, level back to unity. This explains, how a cycle works in a pendulum regime. Only in a perfectly not price-elastic system energy intensity would not let energy costs decline after an energy price shock. In a perfectly elastic system at some stage energy costs scale down to the initial level. If income is added as a constant to this analysis, then *ECS* comes down to its initial level in the multiyear process. When energy price elasticities at each stage are close to -0.2, it takes about 25 years to get *integrated price elasticity* to unity. This result does not depend on initial energy efficiencies at each conversion stage (or energy efficiency in a given year), but only on energy intensity to price elasticities. This explains why the timing of complete energy cost adjustment to the initial level after price shocks should be relatively similar across systems and countries at different stages of development, providing partial price elasticities are similar. So the cycle duration is a function of energy price elasticity, rather than of the energy efficiency level, and so the minus one phenomenon is relevant for economies across long time horizons and depends on the role of market forces in the economy (economic aspect), as well as on technical opportunities (technical aspect) allowing for faster adjustment of higher price elasticity to price shocks.

In the long term, the center of economic ‘gravitation’ is stable. Its identification depends on how energy costs are accounted for. The results of the ECS_{gdp} evaluation depend on how energy costs are estimated (for which energy users and energy carriers: whether it is primary energy for primary energy users, or delivered energy for final energy users), what energy resources and carriers are taken into account (only commercial or non-commercial as well; including or excluding manpower and cattle power; using manpower and cattle power or food and fodder needed to provide them), what prices are used (prices of primary energy resources or of final energy users; including or excluding taxes and subsidies; representative prices; country weighted average prices; or some proxies). Sometimes, like in Russia, companies directly report energy costs.

EIA State Energy Data System (SEDS) calculates energy costs by multiplying estimated price by estimated consumption. The latter is adjusted to remove process fuel, intermediate petroleum products, electricity exports, and other consumption that has no direct fuel costs. IEA estimates energy costs to final users, which should be lower by the amount of electricity used in the energy supply sector, including power plants, refineries and other energy transformation losses. Bashmakov (2007) for OECD and Grubb et al., (2017) for individual OECD countries used a similar approach. Energy costs are estimated as a sum of final energy uses multiplied by corresponding prices (including taxes) of each energy resource delivered to final users. Non-energy use is excluded. Fizaine and Courte (2016) calculated not consumer, but primary energy costs by multiplying primary energy use for each resource by corresponding energy price (residential electricity prices were used for primary electricity). This method ignores additional value of secondary energy resources (enriched coal, petroleum products, heat, fossil fuel electricity, and delivery costs, including energy transmission and distribution), as well as many of the taxes collected at the point of secondary energy sale. Besides, this approach ignores the trade balance of secondary energy resources (for example, primary energy can be used to produce exported electricity, which domestic final users do not pay for). Globally, the energy sector converts more than 75% of total primary energy supply into electricity, heat, refined oil products, coke, enriched coal, and processed natural gas. Therefore, this approach substantially underestimates the energy costs covered by final energy users, especially for more recent periods, as the share of primary energy converted in the energy sector continuously grows. King et al., (2015), while explaining the method of energy costs accounting, do not mention transportation energy use or the cost of fossil fuel electricity supply. Their method is closer to primary energy costs accounting. This explains why, when alternatively assessing the energy costs based on WIOD data (see below for details), they came up with a 20-40% higher *ECS* estimate, or got additional 2-3% points for *ECS*. For the whole world the gap is close to 2%, particularly for years with low *ECS* levels.

Two additional datasets were used: EU KLEMS Database (Timmer et al., 2011) and the World Input-Output Database (WIOD) (Timmer et al., 2015). The first dataset provides information on intermediate energy inputs at current purchasers' prices for many OECD countries. It allows it to estimate the energy costs to GDP ratio and the share of energy costs in gross output; however, it does not include all energy costs, as it misses out some household energy uses (in private houses and by personal transport). Time series on intermediate energy inputs in the EU KLEMS database end in 2005. WIOD database was used to cover more recent years. This database includes 35 sectors and standardizes input-output tables for 40 countries and the world for each year of the 1995-2011 period. Another set of WIOD data organized as a single IOT for 35 sectors and 40 countries cover 2000-2014. It provides information to estimate not only the energy costs to GDP ratio, but also the energy costs to gross output ratio. 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. The sum of these three aggregates shows a biased up estimate of the energy costs. It overestimates 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 WIOD presents data in basic prices, not all of the taxes are accounted for, bringing the whole estimate down. The biased estimates are partly compensated improving the accuracy of the final assessment. For the U.S., the maximum WIOD deviation from the data reported by EIA State Energy Data System was 1% in 1995-1996 and has been below 0.6% since 2000. EU KLEMS and WIOD databases allow it to estimate not only the ECS_{gdp}, but also the share of energy costs in gross output. These two datasets do not perfectly match each other.

The difference between energy costs accounting methods is illustrated based on data for the U.S. Sources of data and details for energy costs calculation explain some differences in energy cost estimates (Figure 2). Estimates based on WIOD and IEA information provide the best approximation of EIA energy costs share data. When primary energy cost approach is used (King et al., 2015; Fizaine and Court, 2016), ECS_{gdp} is substantially underestimated.[2]



Sources: SEDS, 2014; IEA (2011); Desbrosses, 2011; IEA, 2011; Timmer et al., (2015) and Timmer et al., (2011); King et al., (2015) and Fizaine and Court (2016)

Figure 2. Differences in the energy costs to GDP ratio assessments for the U.S. depending on energy costs accounting method and data sources.

3. Energy Costs Constants in the Cross-Country Analysis

Cross-country analysis for the post-Second World War period (Figure 3) shows that, like for the U.S., the energy cost to GDP ratio is relatively stable, varies around similar, yet country-specific, 'centers of gravitation' for nearly seven decades with about 25-33 years' cycles. If the differences in energy costs accounting methods used by different authors and variations in data completeness and quality are mitigated, similarity of 'centers of gravitation' would be more visible.

Data only for large countries (with populations of more than 40 million) are shown in Figure 3. For such countries a cyclical evolution of the *ECS* can be observed mostly varying between 7 and 12% with just a few exceptions: Japan (lower values), Russia, China, and Korea (higher values). KLEM data do not provide a reliable result for Japan up to 2005. Estimates based on the IEA data (Grubb et al., 2017) assess *ECS* at 6% on average for 1978-2012, which

[2] There is another interpretation of the share of energy costs in GDP – the reverse ratio: energy return on investments (EROI), which shows how much energy one can get for one dollar spending relative to how much it takes to generate an average dollar of output from the economy (King et al (2015). The higher the EROI, the larger the amount of net energy delivered to society in order to support economic growth (Fizaine and Court, 2016). King et al., (2015) and Fizaine and Court (2016) use primary energy cost approach to estimate EROI.

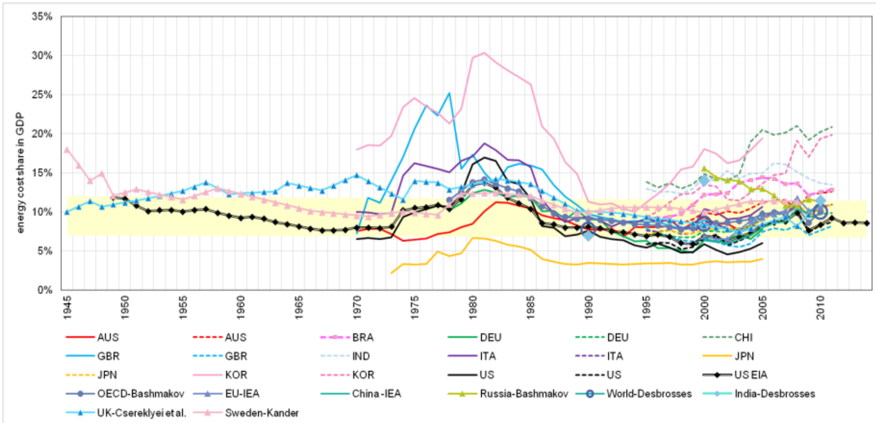
is much closer to WIOD data. The result was also tested on national IOT for Japan: the *ECS* for 2000 was estimated at 6.8%, which is far above the low assessment based on KLEM data. For Russia, statistically reported 2011 energy costs, after being adjusted for small enterprises' and households', provide an assessment of *ECS* at 11% of GDP, while the estimate based on WIOD data is much higher: 19.9%. For China, *ECS* based on WIOD data for 2011 is also very high: 20.9%, versus 11.6-13% as reported by three other sources, including IEA. WIOD-based *ECS* estimate for South Korea was tested with IOT for this country and the high *ECS* was reproduced, while *ECS* as estimated based of the IEA energy use data by sectors, energy carriers and corresponding prices generate 8% ECS for 2011-2012, as well as WIOD dataset for 2000-2014. For Korea and China, the share of intermediate products in the gross output is 65-67%, which is much above that in many other countries. Therefore, while *ECS* in gross output is quite similar to other countries (see below), *ECS* in GDP is at much higher levels. To sum it up, WIOD data for large developed OECD countries are quite adequate to illustrate ECS_{gdp}, while for some other countries a double or triple check is needed to obtain more robust ECS_{gdp} values.

Estimates of the *ECS* evolution were provided by IEA (2011) for China, EU, Russia and the U.S. (Figure 3) for only limited time frame (2000-2011). IEA estimates of *ECS* evolution are quite close to the cycle pattern as reported by other data sources. *ECSs* were evolving from 6-7% in 2000 to over 10% for the EU, China and Russia in 2011. *ECS* in the EU exceeded 11.8% in 2008. For the U.S., the data presented by IEA do not fit the information reported by the EIA due to the technique applied (see discussion for Russia below). For China, IEA estimates *ECS* for 2011 at 11.6%, which is lower, than the value reported by Desbrosses (13.5%), but keeps *ECS* evolution very close to the cycle pattern. For Russia, IEA used final energy consumption and relevant end-use prices (in US$2010), and after the energy costs were estimated, they were expressed as percent of GDP at market exchange rates (in US$2010 prices) for other years.[3] Therefore, this approach takes no account of gaps in energy prices and GDP deflator evolution, and can hardly provide correct estimates. The author's estimates for Russia are also shown in Figure 3. Two methods were used. First, final energy use by sectors and energy carriers was multiplied by corresponding energy prices and divided by GDP in current prices in the local currency, and second, energy costs reported by large businesses were complemented with statistical data on energy costs in residential sector along with the estimates of energy costs for SMEs. Both methods provided similar outcomes (Bashmakov, 2014). They get close to the IEA estimate only in 2010, however, the direction of the *ECS* evolution is quite opposite. As the oil&gas portion of the Russian GDP (about 22% in 2010) was driven up by increasing hydrocarbon prices, the denominator of the *ECS* was growing faster, than the numerator, driving *ECS* not up, but down.

The use of WIOD dataset for 2000-2014 results in 12.6% global ECS_{gdp} in 2014 versus 8.5% in 2000. According to Desbrosses (2011), global energy spending more than doubled between 1990 and 2010 and reached 10% of the global GDP. In many regions, ECS_{gdp} varied between 6% and 13.5% in 2010. For the world, 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. Desbrosses' estimates are based on the Enerdata data set, which does not include biomass or other non-commercial fuels. This brings the ratio for Africa down to 6%. Bashmakov (2014) estimated *ECS* for OECD at 10% in 2010. Additional estimates

[3] Personal communication with Tim Gould (IEA).

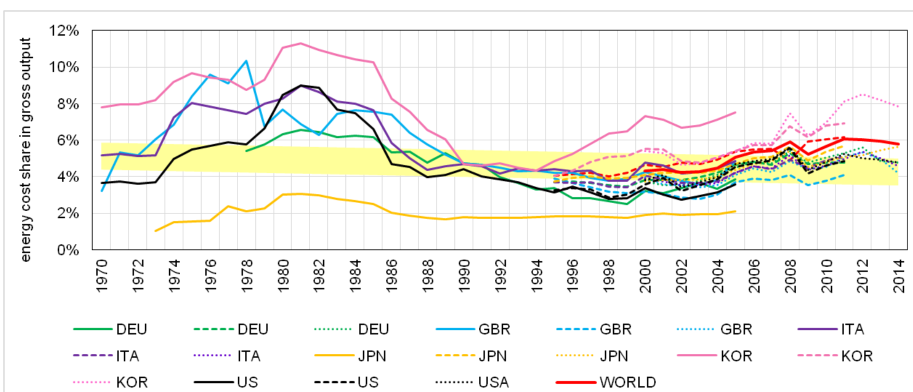
for some countries (China, Canada and Tajikistan) provide close values and keep this ratio evolution very close to the plotted pattern varying between 6% and 12%.



Solid lines show EU KLEMS-based *ECS* estimates. Dashed lines show *ECS* estimates based on WIOD1 data. Estimates from other sources are marked with compact source identification. Data for the UK (Csereklyei et al., 2014) show *ECS* in the sum of energy, labor and capital costs. Data for Sweden (Kander, 2002) were corrected by author to exclude man muscle power from the energy balance.

Sources: Timmer et al., (2015); Timmer et al., (2011); Desbrosses (2011); Government of India (2014); ONS UK (2015); INSEE (2015); White House (1982-2016); IEA (2011); NrCan (2005, 2009); UNDP (2011); EIA (2014); Bashmakov (2014); EIA SEDS (2014); US Department of Commerce (2015); Csereklyei et al., (2014); Kander (2002).

Figure 3. Evolution of the energy costs to GDP ratios for the world, world regions and large countries.



Solid lines show estimates based on EU KLEMS, which does not include household or government energy spending. Dashed lines show estimates based on WIOD database, which are biased as well. The greatest mismatch in these two data series is for Japan. Japan IOT data show that WIOD is more reliable.

Sources: calculated by author based on data from Timmer et al., (2015) and Timmer et al., (2011).

Figure 4. Evolution of the share of energy costs in gross output based on EU KLEMS and WIOD databases.

EU KLEMS and WIOD databases allow it to estimate not only ECS_{gdp} (which is not a share or fraction in purely economic terms, as energy costs are mostly composed of elements of intermediate product), but also the share of energy costs in gross output (Figure 4). As already discussed, these two datasets do not perfectly match each other, but they show fluctuations around relatively stable, similar across counties, shares varying mostly in the range close to 4-5% for more developed countries and to 6-7% for countries with a lower level of development (based on the WIOD data, which are not plotted in Figure 4). This relatively low share of energy costs in gross output has led to the understatement of the role of energy in the mainstream economic research, where energy was not viewed as an important production factor (Stern and Kander, 2012). As data quality improves, ECS_{go} 'spaghetti' curves get more compact and better reproduce the cyclic pattern of the ECS_{go} evolution with 15 to 20 years declining phase and a twice shorter (8-10 years) rising stage. The range for ECS_{go} shrinks compared to ECS_{gdp}, as gross output is about twice as high as GDP.

Analysis shows, that the trends around which both ECS_{gdp} and ECS_{go} are evolving, are basically functions of the contribution made by the service sector to the GDP (Figure 5). The service sector has (a) higher value added to gross output ratio in comparison with agriculture or industry, and (b) lower ECS_{go} in sectors' gross output (Bashmakov, 2016; Bashmakov and Grubb, 2016). The sustainable range of ECS_{go} in the industry is 3-5% versus 1-3% in the services sector.

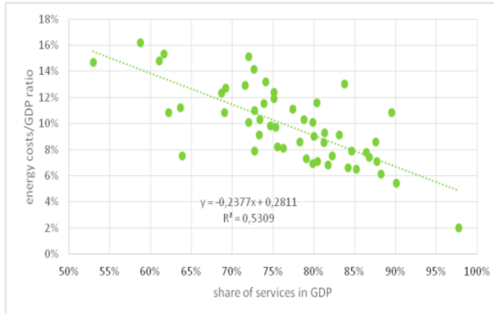
IEA (2015) reports, that the creation of one unit of value-added in the manufacturing sector requires 4 to 22 times as much final energy input, as in the services sector. Assuming ECS_{go} at 5% for industry and at 3% for services, a simple calculation shows: when the share of services goes up from 40% to 60% at the expense of industry and agriculture, average for the whole economy ECS_{go} declines by 0.4% (other conditions equal). Data for U.S. states both on energy costs and state-level GDP are calculated based on the same methodology and so are more consistent compared to the cross-country analysis. ECS_{gdp} for individual U.S. states varies mostly between 6.6% and 12.7% with a few exceptions: fully services-dominated Washington, D.C. and New York (with the share of services above 90%) from the lower end and industrialized Louisiana, Mississippi, North Dakota and Wyoming (with the share of services below 65%) from the higher end. Cross-country comparison provides similar results based on less consistent data. This finding contradicts Kander's (2002) statement that transition to the service economy doesn't lead to energy intensity decline, because growing contribution from the services sector to GDP is neutralized by growing transportation energy demand.[4]

In 1970, UNIDO (2009) reported the share of services in global GDP at 51.2%, and according to the World Bank it escalated to 68.5% by 2015 (including transport, without transport it equals to 62%), or by 0.38% per year.[5] For the U.S. states, 1% average contribution of the service sector to GDP growth led to 0.24% ECS_{gdp} reduction (Figure 5a). For the cross-country plot (Figure 5c), every additional percent contributed by the service sector to GDP led to ECS_{gdp} decline by 0.11%. If the slope shown in Figure 5c is valid for the global economy, then the share of energy costs has to decline by about 0.04% per year (0.38%*0.11). This fits well the slopes shown in Figure 1 and Figure 3-4. This decline could slow down in the future

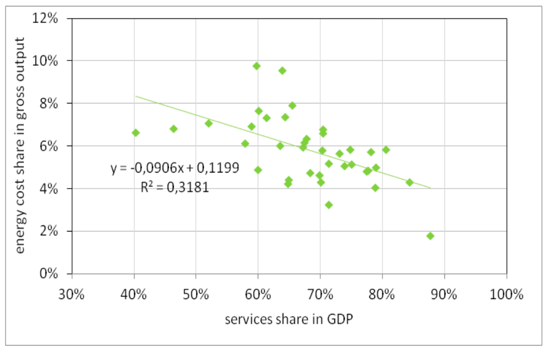
[4] It will be shown below, that the share of the transport sector in both GDP and gross output is relatively stable at various stages of development.

[5] http://data.worldbank.org/indicator/NV.SRV.TETC.ZS?locations=NA-1W.

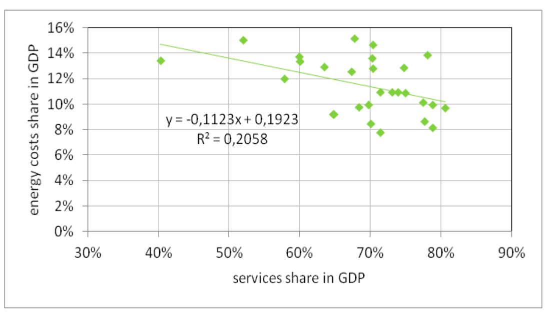
for two reasons: slower growth of the service sector's share and a shift towards information and communication services which are more energy intense compared with trade.



Share of services in GDP and ECS_{gdp} for U.S. states in 2012



Share of services in GDP and ECS_{go} for countries (based on WIOD)



Share of services in GDP and ECS_{gdp} for countries (based on WIOD)

Data for U.S. states are based on the same methodology, and so are much more consistent. The quality of data for different countries is discussed above. There are problems of data comparability and, therefore, reliability. This is why all observations for countries with ECS_{gdp} above 15% were removed from the sample (see discussion for China, Korea, and Russia above).

Sources: developed by author based on data from EIA SEDS (2014) and the U.S. Department of Commerce (2015); Timmer et al., (2015); 2016 StatisticsTimes.com.[6]

Figure 5. Share of services in GDP and the energy cost to GDP and to Gross output ratios.

[6] http://statisticstimes.com/economy/countries-by-gdp-sector-composition.php.

It is hard to say, at what level the share of the service sector in fully closed (global) economy can saturate. In large developed countries the share of the service sector has already approached 80% with corresponding ECS_{gdp} about 8%. In cities like Washington, D.C., New York, or London the share of services already exceeds 90% and ECS_{gdp} could go even below 6%. Energy intensity in activities related to financial intermediation is just one third of average for the service sector (Mulder et al., 2013).[7] For countries (and particularly for their leading cities – global financial centers) extremely high shares of services are rooted in a shift of heavy industry and agriculture to other parts of the country or of the world. Therefore, it seems reasonable to assume, that the service sector can hardly reach 90% in a fully closed global economy. The question is, at what level the share of services in GDP gets saturated in large countries and globally, and what kind of evolution we can expect after the saturation? How will the share of the service sector evolve in countries entering the de-growth stage? The whole process can be described with a logistic function with steadily slowing down growth of the share of services that ends with saturation. If the level of saturation for the global economy is close to 80% (say, by the end of the 21th century[8]) versus current 69%, then (assuming ECS_{gdp} decline by 0.1% per each additional percent of the share of services) ECS_{gdp} may be slowly drifting down from present 10-12.6% to 8%, or by about 0.03% per year, which is fully consistent with the historically observed trend.

There is another angle to look from. Xu et al., (2013) show, that UK's net embodied fossil energy imports were up from 15.6 Mtoe (7.1% of TPES) in 1997 to 32.5 Mtoe (17% of TPES) in 2011. Therefore, 'offshoring' energy intense activities, if accounted for, brings UK's *ECS* in 1997 up by about 0.5% to 7.4%, and in 2010 up by 1.3% to 8.9%. This largely explains the growth of the role of the service sector and nearly eliminates the declining slope in the *ECS* evolution. Alternative sources estimate UK's net embodied energy imports in 2010 at a much higher level – 87.5 Mtoe, which is 43% of TPES (KAPSARC, 2013). For the U.S., it is estimated at 207 Mtoe in 2010, which is 9% of TPES, while for Russia the net embodied energy export is 126 Mtoe (18% of TPES), and for China it is 408 Mtoe (16% of TPES). Therefore, *ECSs* for net embodied energy importers are to be increased to include about 1-1.5% 'offshored' energy (by 9-17% from the registered 7-9%), while those for large net embodied energy exporters are to be decreased by about 2% (by 16-18% from the registered 11-13%). This makes countries' *ECSs*, adjusted for energy embodied in international trade, much closer to one another, and the range of 'spaghetti' curves shown in Figure 3 and 4 becomes even denser. If embodied net carbon import is taken into account, the declining *ECSs* slope for the UK and the U.S. completely disappears (Grubb et al., 2017).

There is statistical evidence that the sustainable range of the share of energy costs in gross output in the industrial sector is 3-5%, or 8-15% of industrial value added, keeping in mind that intermediate product forms 60-75% of industrial gross output depending on the industrial sector

[7] Mulder et al., (2013) in their very detailed study on determinants of energy intensity in the service sector (split by many subsectors) in 1980-2005 provided a number of important findings: (a) the shift towards a service economy has contributed to lower overall energy intensity in the OECD, but this contribution would have been considerably larger if the service sector had realized the same degree of energy efficiency improvements as the manufacturing sector; (b) in most OECD countries energy intensity levels in the service sector tend to decrease relatively slowly after 1995, while structural changes within the service sector fail to compensate growing energy intensities in one third of OECD countries; (c) deployment of information and communication technologies contributed to energy intensity growth in the service sector, while energy prices played a limited role in driving variations in energy productivity.

[8] IEA (2016) expects services share (without transport) to grow from 62% in 2015 to just 64% in 2040.

structure (Bashmakov, 2016). Differences across countries stem from the industrial sector's product and technological structures. Based on the German statistics for the 'production sector' Welsch and Ochsen (2005) concluded, that in the long-term the share of energy costs in the overall costs is stable, and all changes induced by production factors substitution are mutually neutralized in the end. For 1976-1994 they report the share of energy costs in gross output varying between 4.2% and 6.4%. Bardazzi et al., (2015), based on panel data for manufacturing companies in Italy, report that for 3,425 firms and nearly 19,000 observations over 2000-2005 the share of energy costs in gross output keeps in the range between 3.8 and 6.2% and is nearly proportional to energy intensity. Based on panel data for 6,806 firms and 54,962 observations over 1992-2012 for India, Sadath and Acharya (2015) also show, that the share of energy costs in sales was ranging from 3.3% for the first decile of companies (largest in the sales size) to 8.7% for the ninth decile and down to 5.3% for the last one. If companies are ranked by energy intensity, again there is about linear correlation with the share of energy costs. There is not much in common between German, Italian and Indian firms, yet the share of their energy costs is about the same. So both aggregated macroeconomic time series data and microeconomic panel data confirm that the sustainable lanes of ECS_{go} are quite narrow and similar across different countries. With similar energy prices the ECS_{go} is nearly proportional to energy intensity. Therefore, companies that are unable to compensate for higher energy costs with lower energy intensity are at risk. They try to mitigate this risk, and the higher the ECS_{go}, the higher the energy price elasticity (proved by Bjorner et al., 2001, based on data for Danish industrial companies). Therefore, the higher the energy intensity, the higher energy price elasticity.

ECS_{go} in services shows a cyclic evolution mostly in the range of 1-3% of services gross output; the differences between countries are not so much impacted by competition, as many services are only traded domestically; there are no obvious declining trends for ECS_{go}; the fluctuation amplitude is smaller; a shift towards the service economy is a converging factor and makes the evolution of the economy-wide ECS_{go} more stable.

ECSs for freight transport and public passenger transport were assessed using WIOT database. They mostly fluctuate between 5 and 10% of transport gross output and substantially vary by countries depending on the share of motor vehicles in the transport mix. They are relatively stable in time and mostly follow trends in liquid fuel prices. The share of transport service costs in personal incomes has also been relatively stable over half a century in many countries, where personal automobile transport penetrated early (85 years ago in the U.S.), mostly staying between 2 and 3% of personal income before tax. Globally, IEA's (2016) assessment is 2.1% of disposable income in 2015 and projected to vary in a narrow range 1.7-2.1% by 2040. Stability of residential energy cost to GDP or to personal income before tax deserves a special study. Fouquet (2008) shows that back in 1500-2000 residential energy cost to GDP ratio in the UK (for heating, cooking and lighting) was fluctuating around 2-3%. If personal income is assumed at about two thirds of GDP, it translates into 3-5% of personal income before tax. Fouquet (2013) also shows, with references to historic studies, that back in the 1790's in the UK consumers spent about 5% of their budget on fuel. Fouquet also cites the results of the 1857 study by E. Engel on Belgian workmen in the 1850's showing that the share of fuel and light spending remained constant across income levels at 5% of the total budget (this study did not include upper income classes). In 1875, C. Wright found, that in 1870 Massachusetts households spent a virtually constant share of their incomes for fuel and light (6%) and proposed *Engel´s Third Law*: 'The percentage of outlay … for fuel and light is invariably the same, whatever the income' (see Stigler, 1954). More recent cross-country comparisons of the share of housing costs in personal incomes (before tax) show that: (a) the share is relatively stable not only for recent decades, but over centuries as well, and (b) this share is very similar in very different countries and at very different stages of their economic development (Bashmakov, 2016). The share of energy costs in income for Japan was varying around 3.2% for 65 years; in the U.S. it was around 2.5% for 85 years; in India at about 3.4% for 52 years; in China at around 4.4% in 1995-2012[9] (for urban households only, which is higher than for rural households; and including water supply and sewage charges enlarge this share by about 0.5-1%); in the UK at 3.9% for 51 years (the share in personal expenditures, which would be about 0,6% lower when compared with income before tax); in Russia at around 3% in 1997-2014; in France at around 3.1% over 63 years.[10] Relative stability of this ratio over centuries is a clear indication that the threshold exists. For all countries, irrespective of the stage, model, or pattern of economic development (which had been changing a lot over decades and differs widely across countries), the sustainable fluctuation range of the housing energy costs to income ratio is very narrow. After correction for comparable indicators (only the share of energy costs in income before tax) for the above countries the average share stays in a quite narrow range of 2.5-3.5%. Globally, IEA's (2016) assessment is 2.3% of disposable income in 2015 and projected to stay in the range 2.1-2.4% till 2040. This range largely depends on the living space to income ratio in individual countries. Going beyond the upper threshold, or staying much below the lower threshold, is only possible for a short time. The existence of these thresholds and the market inertia generate consumer reactions overshooting in either direction and finally determine the cyclic nature of the share of housing energy costs in income.

Energy affordability thresholds are identified in all major final energy use sectors (Bashmakov, 2016; Bashmakov and Grubb, 2016). The aggregated threshold is just a linear combination of those for individual sectors with weights equal to contributions of respective sectors to either gross output or GDP with an account of the GDP to gross output ratio (Table 2). The aggregated value range is very consistent with those presented in Figure 1 and Figure 3. With extreme values excluded from both ends of the range, the sustainable range of the share of energy costs in gross output is 4-6%, and of the energy costs to GDP ratio is 8-12%. These ranges of sustainable evolution can be shifted slightly up or down depending on the country's specific economy structure and its evolution.

Theoretical explanation of energy costs constants and of the 'minus one' phenomenon needs to show the relationships between energy demand and energy price elasticities, energy intensity and energy price elasticities and energy costs share elasticites – all of them different. This will allow for an illustration of estimate ranges for short-term, long-term, and integrated (very long-term) elasticities so as to relate empirical results to energy constants findings.

[9] In 1990, the share of housing and communal services (H&CS) (excl. rent) in urban family's income was 4%. Assuming that energy costs amount to a half of H&CS costs results in about 2% energy costs share.

[10] For some East European countries, estimates based on the data from EU KLEMS database (Timmer et al., 2011) provided larger shares for 2011: up to 7.6-10.7% in Hungary, Poland and Slovak Republic (in disposable income). They would be lower, if assessed as shares in income before tax. With data from WIOT database the shares are smaller: 4.3% for Poland, 6.2% for Hungary, and 9.3% for the Slovak Republic. These are shares in personal expenditure and include water and sewage charges. When recalculated to exclude water payments and estimated as shares in income before tax these shares would go down to about 3% for Poland, 4% for Hungary, and 6% for the Slovak Republic, which is quite consistent with the ranges shown above. These shares are larger, than those in EU15 countries, due to the legacies of central planning, when housing space distribution was very different from income distribution, and when both buildings and utilities were very energy inefficient, which is still not completely overcome.

Table 2. Composition of aggregated energy costs to income ratios

Sectoral energy consumption	Share of sector in gross output	Share of energy costs in the sector's gross output	Share of energy costs in total gross output	Share of energy costs in GDP
Industry	20%-60%	3-5%	0.6-3%	1.1-5.4%
Services	80%-20%	1-3%	0.2-0.7%	0.4-1.5%
Agriculture & construction	1%-15%	0.5%-3%	0.01-0.03%	0.02-0.04%
Transport (freight and public)	3%-8%	3-10%	0.1-0,5%	0.2-1%
Personal energy consumption	Share of compensation of employers in GDP	Share of energy costs in personal income		
Housing energy	55-80%	2-4%	0.5-1.5%	1.1-3.2%
Fuel for personal transport	55-80%	2-3%	0.5-1.2%	1.1-2.4%
Total (excluding extremes)			**4-6%**	**8-12%**

Sources: For energy costs/income ratios see sources for Figures 1-8. For the share of costs in gross output and share of compensation of employers in GDP see KLEM database (Timmer et al., 2011; Timmer et al., 2015).

If energy demand is a log linear function of income and energy price, we can express it in average annual growth rates (T_e) as follows: $T_e = a * T_y + b * T_p$, where T_y is income growth rate and T_p is real energy price growth rate. Elasticity of energy intensity to real energy price (c) is described by the formula:

$$c = \frac{T_{e/y}}{T_p} = \frac{T_e - T_y}{T_p} = \frac{aT_y + bT_p - T_y}{T_p} = (a-1) * {T_y}/{T_p} + b \qquad (3)$$

If any autonomous technological progress is induced by previous price increments and drives energy demand down ($\gamma < 0$), then: $c = (a-1) * {T_y}/{T_p} + b + {\gamma}/{T_p}$. Energy intensity to energy price elasticity is a function of energy demand price elasticity corrected for income elasticity and for the ratio of average annual income growth rates to average annual real energy prices growth rates. Assuming ($\gamma = 0$), these two elasticities are equal only as long as either $T_{y.} = 0$, or $a = 1$. Theoretically, b is negative. T_y and T_p can be either positive, or negative. If $a < 1$, and both T_y and T_p are positive, then $c < b$. When energy prices are declining, or T_p is negative, then $c > b$. During price shocks, when T_p is very high and T_y is relatively small, and so T_y/T_p is quite low, $c \rightarrow b$. So when a is given, T_p sign mostly determines the sign of the first component, and therefore the relationship between c and b. Due to the instability of $T_y/T_{p,}$ the elasticity of c is not constant, but evolves as both energy prices and rates of economic growth or income cyclically fluctuate. It will be shown below, that both a and b are drifting and so are not constants either. Therefore, evolution of these energy demand elasticities, along with the T_y/T_p

ratio, inject much dynamics to the elasticity of energy intensity to real energy price for specific years, making its long-term (cycle-long) stability at 'minus one' even more amazing.

Only whole cycle-long energy intensity to real energy price elasticity (integrated, or very long-term, elasticity is equal to -1). For time series, which start and end at different cycle phases, *c* can vary a lot with given *b*, depending on the combinations of parameters of another equation (3). Adofo et al., (2013) show, that estimated energy demand elasticities are sensitive to the time period chosen for the estimation.

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

If the whole cycle-long time frame is taken, then for the U.S. the ratio of GDP growth rates to real energy prices growth rates was 2.5 in 1963-1986, 1.5 in 1963-2014, and 1.9 in 1963-2014 (see Table 1). So in the long-term, in the U.S. ($b \approx 1-2a$), but the coefficient before *a* was different for two cycles. For OECD-Europe, this ratio in 1981-2013 was 2 as well.

In order to check the energy costs constants for consistency with empirical studies on energy demand and price elasticities and avoid referencing numerous studies on this subject, below we refer mostly to reviews and meta-analysis papers that generalize numerical empirical findings in a systematic manner. Normally, such papers estimate elasticities, yet do not provide data on average annual growth rates for income and real energy prices. Karimu and Brännlund (2013) offer a historical review of estimated aggregated energy use price and income elasticites starting from studies conducted back in 1966 and ending with those accomplished in 2011. They show that, with a few exceptions, long-term price elasticities (LTPE) varied from -0.1 to -1.15 and income elasticities from 0.44 to 0.87. Based on nonparametric model specification, they also show for 17 OECD countries that energy consumption demonstrates only a weak reaction to price changes (-0.19 to -0.18) and linearly but weakly depends on the income, while income elasticity evolution fluctuates around the general declining trend as a function of per capita income. Bashmakov (2008) reports average for a number of studies short-term income elasticity 0.85, long-term income elasticity 1.56, short-term price elasticity (STPE) -0.32, and LTPE -0.47. If for the whole cycle T_y/T_p ratio for aggregated energy use is 1÷3 and b = -0,2÷-0,6, based on (3), *c* = -1, if *a* is in the range 0.2÷0.8, which is pretty consistent with empirical studies.

Adeyemi and Hunt (2014) analyzed literature on asymmetric price elasticities for OECD countries and conducted their own analysis of short- and long-term income and price elasticities for industrial energy use in 15 OECD countries. For 14 studies published in 1981-2010, they found energy demand income elasticity on average equal to 0.97, while those assessed based on time series were 1.17 and those estimated based on panel data equaled 0.71. Regarding energy price elasticity, studies with no asymmetric components show average elasticity equal to -0.37 for time-series studies and -0.46 for panel data studies. Adeyemi and Hunt (2014) present their own estimates of long-term income elasticities for 15 OECD countries for 1962-2010 ranging between 0.34 and 0.96 with 0.63 average. By decomposing energy price by 3 components (first, dynamics of previous maximum price; second, a price recovery below the previous maximum; and third, price cut) and using Koyck lags they found long-term price elasticity for the first component in the range between -.06 and -1.22 (-0.44 average), for the second component from 0 to -0.27 (-0.06 average), and for the third one from 0 to -0.18 (-0.06 average). Average across 14 earlier studies with asymmetric price elasticities are -0.68, -0.51, and -0.3 respectively. Therefore, for industry there are empirically estimated *a* and *b*, which are consistent with c = -1, or $b = (1-a) * T_y / T_p - 1$, when $T_y/T_p = 1 \div 3$.

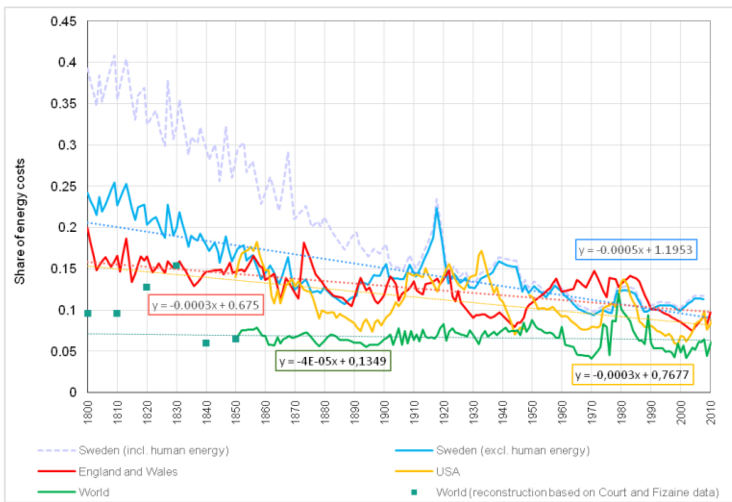
Brons et al., (2008) also state, that cross-section studies generate higher energy price elasticities, than time-series studies. Analysis for industry (Adeyemi and Hunt, 2014; Bardazzi et al., 2015; Haller and Hyland, 2014) yields the same result. So panel or cross-section studies show what is closer to very-long-term price and income elasticities. First, elasticitities at lower level of aggregation are higher; second, firms had sufficient time to adjust to long standing production factors price proportions. By using translog model for Italian firms, Bardazzi et al., (2015) showed that own energy price elacticity is -1.13, which is consistent with a similar finding by Haller and Hyland (2014) for Irish firms (-1.46). So VLTPE is close to -1 for industrial companies.

Another meta-analysis was conducted for gasoline demand (Brons et al., 2008) and can be considered representative for automobile transport. Based on meta-analysis, they found mean short-run price elasticity of -0.34 and long-run price elasticity of -0.84. They showed that in 43 studies covered there is a distribution of STPEs and LTPEs with means of distribution close to their meta-analysis results. For $T_y/T_p = 1 \div 3$, where T_y – is average annual growth rates of personal disposable income, c = -1 for the cycle duration if income elasticity is 0.8-1, which again matches empirical estimates. Bashmakov (2008) shows, that for residential sector several studies provide average long-term income elasticity of 0.5 (ranging from 0.17 to 1.11), which is very consistent with living space to income elasticity and LTPE at -0.22 (ranging from -0.11 to -0.5). This again fits the condition of c = -1, when $T_y/T_p = 1 \div 3$ (T_y – is average annual growth rates of personal disposable income). Therefore, empirically verified combination of equation (3) parameters, including assessed long-term income elasticities and LTPEs for the whole cycle-long time series or for panel data, as well as T_y/T_p ratios for aggregated energy demand, industry, transport and residential sector empirically confirm the 'minus one' phenomenon and so energy costs constants phenomena.

This section can be concluded with the following statements. So far there is no commonly recognized and adopted country-wide energy costs accounting method. However, despite some disagreement in *ECS* assessments, it is clear that: (1) as the quality of statistics improves with time, the convergence of *ECSs* across countries becomes more visible; (2) ultimately, for many regions and countries, that are quite different in terms of their levels of economic development, most of the time *ECSs* evolve in a narrow and quite similar range – around centers of 'economic gravitation' with an upper and a lower thresholds; (3) going beyond either of these reverses the trajectory: when *ECS* goes too high or too low the 'economic gravitation' brings it back to the 'sustainable lane'; (4) there is a cyclical evolution of *ECSs* around values which are quite stable in time and similar across large countries; (5) the aggregated threshold is just a linear combination of those for individual sectors; (6) the differences among countries are mostly rooted in the sectorial structure of GDP: as the share of services in GDP grows, the 'center of gravitation' very slowly drifts downwards (for many developed countries this reflects energy outsourcing); (7) the 'minus one' phenomenon manifests for many countries over a-quarter-to-third-of-a-century-long cycles, so over the cycle real energy price grows only by as much as energy intensity declines.

4. The First Law of Energy Transitions in the Historical Analysis

Even for the recent history, and even for countries with good statistical systems, there is a lot of disagreement in terms of assessing the share of energy costs (see Figure 4). Historical energy analysis is largely based on expert estimates. Kander (2002) illustrates, how the share of expert estimates in energy aggregate assessments declines from nearly 100% for 1800-1850 to about 60% for 1900 and further to just a few percent for the recent years, being replaced with statistical data. Historical data related to energy use and costs are uncertain, and so is information on income, including GDP. Therefore, any result on *ECS* obtained using historical analysis must be treated with sound precaution.



*Share of energy costs in the cost of energy, capital, and labor.

** Share of primary energy costs. For the U.S. after 1949 – energy costs to final users are used. For 1949-1969 – authors' estimates based on DOE data (see Figure 1) and from 1970 onwards – SEDS (2016) data on the share of energy costs are used. As data for the U.S. show, the global share of energy costs, when calculated as final users' energy costs, is 1,5-3% higher, than the share of primary energy costs (see Desbrosses, 2011).

*** Global data for 1800-1950 were reconstructed based on average fossil fuel prices and energy intensity (including wood) provided by Court and Fizaine (2017). They use data for the U.S. as global proxy and provide no data on wood prices. In 1800-1850, wood was more expensive, than coal, in the UK (Fouquet, 2008), but less expensive in countries covered by forests, such as Sweden (Kander, 2002).

Sources: Csereklyei et al., (2014) and author's verification for Sweden to account for human energy based on Kander (2002); Fizaine and Court (2016); SEDS, 2014; Court and Fizaine (2017).

Figure 6. Share of energy costs in England and Wales*, Sweden*, the U.S.**, and the world**: 1800-2010.

Csereklyei et al., (2014) provide historical data on the share of energy costs for two regions: England and Wales, and also for Sweden for 1800-2009 (Figure 6). Total costs are split into the costs of energy, capital, and labor (Csereklyei et al., 2014), taking no account of materials.

If materials were accounted for, ECS_{go} would have declined from about 10-15% right after 1800 to about 5-6% closer to 2000.

For Sweden, Kander (2002) reports a decline in ECS_{gdp} from about 100% in 1800 to about 10% in 2000. This result needs to be logically tested. Data for Sweden include human muscle power, which should rather be viewed as another production factor – labor force.[11] They were adjusted by the author to exclude human muscle power based on energy use and energy prices provided by Kander (2002). For agricultural societies, the ratio of intermediate consumption (including materials and energy) to gross output (share of materials and energy costs) is about 20-30%, or about 25-45% of GDP[12], which is much below 100% estimated by Kander for energy alone. As Vollrath (2011) shows based on a number of studies, the share of labor force cost in agricultural output in England for 1600-1850 was fluctuating around 40%, with a similar share for French agriculture in the 17th and 18th centuries. He notes that this share is matched in other regions of the world, but for countries with dominating rice production this ratio historically was about 50%. The share of capital remuneration was about 30% and land cost (rent) was about 10% (Liebenberg and Pardey, 2012). Therefore, the value added share of gross output was composed of labor costs (40%) and capital and rent costs (30-40%). With the share of materials and energy costs (20-30%) added, it increases to 100%. This test illustrates, that with an account of a certain share of materials costs (say, 10-20%) *ECS* in gross output should historically stay below 10%; in the cost of energy, capital, and labor below 13-15%; and in GDP below 14% (10%/70%). These shares match the data for England and Wales, the U.S. and the world, yet the estimates for Sweden are questionable. Based on these proportions, the energy costs to GDP ratio in 1800 should not exceed 13-15%.

Here's another logical test. Kander (2002) shows, that the share of household energy consumption in total energy use was about 70% in 1800 and over 50% in 1870. These data correlate well with shares in other countries (Putnam, 1953). There is historical evidence that in 1790-1870 customers spent 4-6% of their budget on fuel for homes (see above). Depending on the share of personal income in GDP this is equivalent to 3-5% of GDP. If ECS_{gdp} is 100%, then energy price for the remaining 30-50% of energy use is to be 20-90 times that for housing, which makes no sense, because prices for households should be higher due to higher fuel distribution costs. If equal energy prices for other energy users (consuming 30-50% of energy) are assumed, then the energy cost to GDP ratio in 1800-1870 would have not exceeded 10% of GDP. Fouquet (2013) estimates the share of consumer expenditures for heating, lighting and transport in 1850-2010 at 10% of overall consumer expenditures, which would be equivalent to about 8% of personal income and about 5-6% of GDP. Assuming again that energy prices in other sectors are equal to those for households, and that the share of heating, lighting and transport is close to 50-70% of total energy use, the share of overall energy costs in GDP should stay in the range of 8-12%. In other words, logical tests based on macroeconomic proportions support the finding of relatively stable energy costs to GDP ratio for over two centuries at a level very close to the present ratio (10%). Results with much higher *ECS* do not pass the above logical tests.

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[11] In a nested CES production function Stern and Kander (2012) used capital and labor factors together with the energy factor, which included human muscle power, which is exactly what labor used to be in early 19th century. They make a point that 'in a preindustrial society a major use of energy was as food for workers'. Therefore, looks like the labor component was double-counted.

[12] According to Krantz and Schön (2007), in Sweden, 83% of 1800 GDP were produced in agriculture (47%) and services (36%), where the share of intermediate product in gross output is about 20-30%.

Historical data on England and Wales, Sweden, and the U.S. show that the energy costs to income ratio was not constant, it rather fluctuated around a very weak downward trend (average decline by 0.03-0,05% per year, or close to 1% per quarter of century-long cycle, or by 3-5% over a whole century). It is exactly what was found for the U.S. (Figure 1). But this does not go for the world and is hardly correct for longer time horizons. On the millennium-long time span, it would mean that the *ECS* on the eve of the second millennium was some 40-60% of GDP (about 10% today plus 30-50% for a thousand years) leaving very little room for compensation of other production factors. This contradicts the results of the logical tests (see above). Such conflict of data may stem either from incorrect expert assumptions used for the reconstruction of energy use and costs data for remote historical periods, or from much slower, if any, slope of the costs share trend before 1800. Therefore, a slow downward trend in *ECS* largely determined by the growing share of services in GDP may, in fact, be much weaker, than 3-4% per century, or its intensity may vary: it was minor or absent before the industrial revolution. Data for the world with no such declining trend support this last assumption.

Services revolution in Britain started only since the mid-20th century. The percentage of labour force in the service sector in England and Wales was 22% in 1700, 30% in 1820, 33% in 1841, and 40-41% in 1890-1911. For that time, it was a good proxy for the share of services (excluding transport) in gross output.[13] It took 100 years for this share to climb up to 72% by 2000, thus growing by only 0.07% per year in the 18th century, by 0.1% in 19th century and by 0.3% per year in the 20th century. With the trend coefficient from Figure 5c applied, ECS_{gdp} declines by only 1% over century for the 18th and 19th centuries and by 3% over the 20th century. In the U.S., 15% of labour was employed in the service sector back in 1820. So during the 18th century it was growing very slowly. Between 1850 and 1920, the share of services in gross output grew up from 29% to 50% and the share of industry was up from 29% to 43%.[14] The share of services was growing by 0.26% per year, which corresponds to 2-3% decline in ECS_{gdp} over the century. As Figure 6 shows, *ECS* for the U.S. in 1850 and 1950 were assessed at 16% and 15%. So the growth in the share of industry nearly compensated the impact of services on *ECS*. Before 1840-1850, the service sector both in England and Wales, as well as in the U.S., was slowly gaining its 30-38% contribution to gross output. Before 1800, gross output growth was limited to about 1% per year (before 1700 to just 0.5% per year (King, 2015; OECD, 2006)) and its structure was evolving so slowly, that the structural impact on the *ECS* long-term trend was negligible. Part of the growing service sector contribution can be attributed to the growing share of net embodied energy imports. Before the beginning of the 20th century, embodied energy in international trade was probably small.[15] For colonial empires it could be significant compared to domestic energy use even before the 20th century. The shift of energy intense activities to other counties during the last century explains about half of the slope shown in Figure 6, as well as its absence for global *ECS* due to the compensation with relative *ECS* growth by net embodied energy exporters (such as China or Russia). The factor of embodied energy trade had limited impacts on the *ECS* evolution before the 20th century and particularly before the 19th century. This is an additional argument to support the statement that for earlier periods this slope was much less significant.

[13] This statement is supported with data of the Bank of England (Hills et al., 2015).

[14] https://www.minnpost.com/macro-micro-minnesota/2012/02/history-lessons-understanding-decline-manufacturing.

[15] Judged based on carbon leakage, it becomes visible for the US and EU-15 only starting from the early 1970's (Grubb et al., 2016).

Fizaine and Court (2016) argue that consistency with Bashmakov's 'first energy transition law', which deals with the stability of energy costs to income ratios, is valid for the post-Second World War era, yet not for earlier periods. They and King (2015) refer to the UK experience between 1300 and 2008 based on data provided by Fouquet (2008) to support this statement. It is very difficult to statistically prove that *ECSs* were either relatively stable or unstable before 1800, merely because not much data are available and multiple assumptions are needed to 'quantify history'. Statistical 'time machine' is never perfect, and we will never have better historical data for statistical reconstructions of the past. However, to a certain degree digital history reconstruction can be done by collecting data that already exist. In his marvelous book Fouquet (2008) estimates energy expenditure to GDP ratios for England and then the UK from 1500 onwards by sectors and processes. Non-domestic power in his study includes human (muscle) and animal power. He provides historical prices for all energy inputs and the scale of these inputs. This allows it to exclude human power costs from the total energy costs. Keeping in mind that in 1800 human power cost was 20 times that of animal power and 10 times that of steam, and that the share of human power in non-domestic power was estimated at 17%, we come up with an estimate of human power costs input of 80% of total. Therefore, non-domestic power cost net of human power cost goes down from 25% of GDP to just 5%, which is quite close to the present value of combined industrial and services energy costs to GDP ratio (see Table 2). Even more amazing is that the ratios of energy costs to GDP in individual sectors in 1500-2000 are very close to the present levels (see Tables 2 and 3). In 1550-1800, ECS_{gdp} varied between 7-8% (1600 and 1650) and 14%-15% (1550 and 1800). For 1800 it is also very close to the *ECS* level presented by Csereklyei et al., (2014) for England and Wales and by Fizaine and Court (2016) for the U.S. (Figure 6). 1850 and 1900 are a problem. Based on data (not quite complete) provided by Fouquet (2008), ECS_{gdp} may be estimated at 23% and 29% respectively. Csereklyei et al., (2014) show that for both these years this ratio is much lower. By 2000, according to Fouquet (2008), ECS_{gdp} went down to about 9%.

Fouquet's data also show that the declining trend in ECS_{gdp} is not permanent. In 1550, this ratio was nearly as high as in 1800, so there may be some 200-250 years' long cycles driving very long-term slope value. According to Fouquet, in 1800-1900 there was an upward trend, while Csereklyei et al., show a declining trend. There is an agreement about the negative slope in 1900-2000. In other words, there are no sufficient statistical grounds to prove that the declining trend manifested before 1800.

After correction for manpower costs for 1850, 1900, and 1950 based on the data provided by Fouquet (2008), ECS_{gdp} can be assessed at 23%, 29% и 21% respectively. Fouquet states that such *ECS* growth compared to 1550-1800 is mainly the result of explosive growth in transport energy costs to GDP ratio. He makes a point that in 1900-1950 freight transport energy costs constituted 7-12% of GDP, and passenger transport energy costs contributed another 6-14% to GDP. If we assume the share of personal transport in passenger transport below 50%, then freight and public passenger transport costs were 11-20% of GDP. For large economies at different development stages value added in transport is normally below 10% (UNIDO, 2009; Timmer et al., 2015); Timmer et al., 2011). According to UNIDO (2009), in 1970-2008 in all major world regions (Africa in 1970 or Europe in 2005) the share of transport in GDP varied between 5.5 and 8.7%.[16] *ECSs* in transport sector value added, according to

[16] A research by the World Business Council for Sustainable Development (Mobility, 2001) revealed an amazing stability in the time spent for travelling across various countries (about 1 hour) that are at very different stages

WIOD data, are much below 50% in all countries irrespective of the level of development. So in all regions with very different levels of development *ECSs* in transport is below 4% of GDP. A 14-20% estimate seems too high to be taken for granted and needs to be checked for consistency.

According to WIOD, in 1995-2011 UK transport (freight and public passenger) contributed about 5% to both GDP and gross output. According to the Bank of England retrospective data (Hills et al., 2015), in 1855-2011 value added in transport and communication in constant prices grew 3.3 times faster, than GDP. So in 1855, the share of transport in GDP was below 1.5% (5%/3.3) in 2000 prices. According to Fouquet, in 1855, the ratio of energy prices for transport to consumer price was 2-2.5 times higher, than in 2000. So, expressed in current prices, transport share in GDP back in 1855 was about 3-4%, which is quite close to the present level. According to Sefton and Weale (2006), incorporated in the Bank of England data (Hills et al., 2015), transport share in GDP in 1920-1948 varied between 6.2 and 8.5% (in 1938 prices), and in 1949-1990 between 4.2 and 5.6% (in 1985 prices). So the transport share (excluding personal) in 1855-2011 varied between 4 and 9% of GDP. According to Fouquet (2008), energy cost share in railroad gross output in 1840 was below 4%. According to WIOT, in 1995-2011 UK transport energy costs were 2.7-3% of gross output and 5-6% of value added, so about 0.3% of GDP (5%*6%). Even if we assume that transport energy costs to value added ratio in the 19th century and the first half of the 20th century was much (say, 10-20%) above the present 5-6%, then transport energy costs to GDP ratio would stay at 1.6% (8%*20%), which is 5-10% below Fouquet's estimate (7-12%) for freight transport alone.

According to Fouquet (2008), the UK's energy costs for passenger transport in 1850-1950 were in the range between 6 and 15% of GDP, which is equivalent to 7-18% of personal income and about 9-22% of personal expenditures. For 1688 the share of personal transport in GDP is assessed by the OECD (2006) at just 0.8%. Data on personal transport energy costs for the UK are available since 1963. In 1963-1970, such costs constituted 1.6-2.8% of consumer expenditures, which is less than 1-2% of GDP. For earlier years U.S. data may be used as a proxy. In the U.S., the share of fuel costs for personal transport in income before tax was 2% in 1929, which equals to 1.8% of GDP. In the UK at the same time fuel prices were higher, and the level of car ownership much lower, than in the U.S. When accounting for the 2-2.5 higher ratio of energy prices for transport to consumer price in 1850-1920 compared with the 1960'es, the share of personal transport energy cost to GDP ratio should stay below 2-5% in the 19th and the first half of the 20th century. Total transportation energy costs to GDP ratio was limited to 5-8%, not to Fouquet's estimate of 18-20%. Therefore, total energy cost to GDP ratio for 1850-1950 is overestimated by Fouquet by at least 12-13%, and the estimate comes down from 21-29% to 10-16%, which is consistent with the estimate of Csereklyei et al., (2014).

Fizaine and Courte (2016) compile all data provided by Fouquet in one plot and show results from 1300 to 2000. When manpower (or 'food' in Fouquet's calculations) is excluded, ECS_{gdp} for 1300-1650 is basically stable. If fodder is replaced with animal power and all the corrections described above are made, the conclusion is that since 1300 the share of energy costs in GDP was relatively stable with fluctuations mostly between 7 and 15%.

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of development, and across time periods in the same countries. If we deduct 8 hours daily for sleep, then the share of time budget spent on traveling is 6.3%. If freight transport takes about as much energy as personal vehicles (see GEA, 2012) and energy costs are close to 50% of all transport costs, then total energy costs in transport as a share of country-wide gross output must be close to 5-7%. This very much fits real data.

Table 3. Aggregated and sector-specific energy cost shares in 1550-2010 (excluding extreme deviations)

Energy use sectors	Data sources and energy cost accounting	1550-1800	1800-1900	1900-2010	1970-2010**
Industry, agriculture, construction and services	Fouquet (2008)	25-40%	17-24%	4-17%	
	excluding manpower	5-9%	5-8%	3-5%	5-7%
Residential	Fouquet (2008)	4-6%	3-4%	0,8-3%	1-3%
Freight transport	Fouquet (2008)	2-4%	4-12%	1-12%	
	author's correction based on macroeconomic statistics	2-3%	2-3%	<1%	0,2-1%
Passenger transport	Fouquet (2008)	0,1-3%	3-7%	2-7%	
	author's correction based on macroeconomic statistics	0,1-3%	3-4%	3-4%	1-2,5%***
Total	Fouquet (2008)	21-48%	30-41%	9-39%	
	Fouquet (2008) with author's corrections*	**7-15%**	**13-15%**	**7-15%**	**8-12%**
	Kander (2002)		17-40%	10-17%	
	Kander (2002) excluding manpower		**10-25%**	**9-16%**	
	Csereklyei et al., (2014)		**7-15%**	**7-12%**	

* Excluding manpower and with corrections of values for transport based on British macroeconomic statistics.

** Bashmakov (2016).

***Only personal transport.

Sources: Csereklyei et al., (2014); Fouquet (2008); Kander (2002); Bashmakov and Grubb (2016); Bashmakov (2016).

Despite a wide range of *ECS* fluctuations in individual sectors for five centuries (1500-2014), when an effort is made to get energy costs accounting comparability and exclude manpower from the energy balance, the estimates are very close to recently observed values (Bashmakov, 2016; Bashmakov and Grubb, 2016). In 1550-2010, (corrected by the author) total ECS_{gdp} varied between 7% and 15% (Table 3).

Analysis of presented data allows it to state that:

- In 1300-1500, the share of energy costs was not much different from what it was in 1500-1800;
- In 1550-1800, in 1800-1950, and in 1950-2014, total energy costs to GDP ratio in large countries and in the world mostly varied between 7 and 15% of GDP;
- Over the recent 65-70 years, for many large countries the average of this range was close to 10% (±2%) with a slow declining trend manifested due to the growing share of services in GDP and energy outsourcing to other countries;

- Half-a-millennium-long history of this ratio evolution can be split into several components:
  - 200-250 years' long cycle of the trend slope, which reflects mostly long-term shifts in the structure of the economy (composition of agriculture, industry and services):
    - Nearly absent in the pre-industrial era;
    - Growing trend appeared in the industrial revolution period;
    - Replaced with a small declining trend in the post-industrial era due to growing contribution of services;
    - The declining trend may disappear or be replaced with a growing trend after the share of services saturates and a new development model appears;
  - Average duration of cyclical fluctuation around the basic trend is 25-33 years with growing synchronization as energy markets become more internationalized and finally global;
- Volatility and deviations from the basic trends can manifest for a variety of reasons, such as economic restructuring, technological breakthrough, resource limitations, political instability, and other factors, which can be characterized as structural shocks from energy demand and supply sides (Kilian, 2008);[17]
- Aggregated macroeconomic energy costs share constant is a weighted sum of sectorial constants, and the 'minus one' phenomenon is an aggregated projection of its manifestation in individual sectors. Therefore, a trend in the aggregated energy costs share is a composition of trends in sectors weighted by their relative importance.

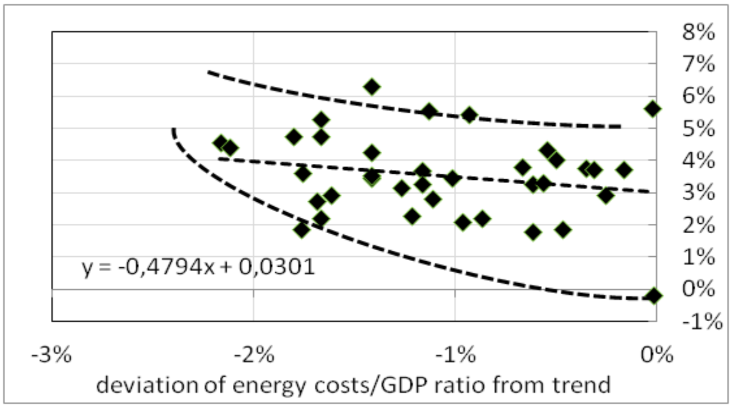
Based on the above analysis, the first law of energy transitions (Bashmakov, 2007) may be slightly reformulated: in the long-term, energy costs to income ratios are relatively stable with just a very limited sustainable fluctuation range (with very small upward or downward trend for this range, reflecting centuries-long shifts in the structure of the economy). Or it may be alternatively formulated as follows: in the long-term real energy prices can grow only by as much as energy intensity declines.

The contribution of the long-term trend to the evolution of ECS is limited to 0-1% per a 25-33 years' cycle. Formulated like this, first law is valid not only for the post-Second World War era (Fizaine and Court, 2016), but is consistent with half-millennium-long historical data, if manpower is excluded from the energy balance and viewed as another production factor, and with efforts taken to attain energy costs accounting comparability as well as consistency with historical macroeconomic proportions. This very much contradicts with the position of Csereklyei et al., (2014) and Kander et al., (2014), that ECS_{gdp} tends to decline by 1% per year and this is a 'typical feature of economic development' (Stern and Kander, 2012). Protagonists of this statement had problems explaining why ECS_{gdp} was so high in Sweden in 1800 and particularly why we do not expect ECS_{gdp} to approach zero in or before 2020, while it was about 10% in 2000-2010.

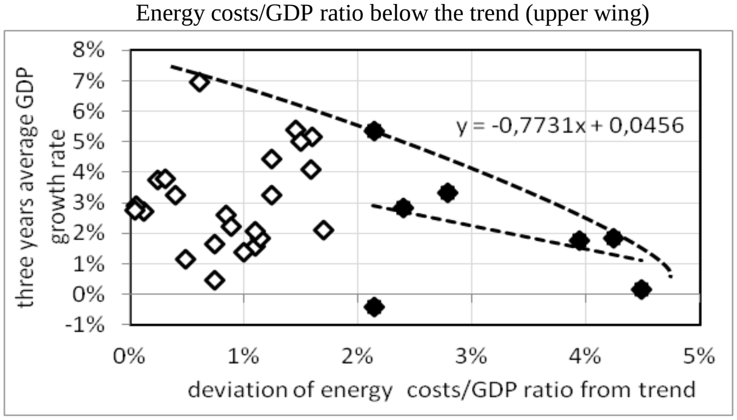
[17] In addition to these two, Van de Ven and Fouquet (2014) describe 'residual' price shocks that determined price growth whenever energy supply was not declining, and the economic activity was not growing, as well as weather cycles (keeping in mind that in the pre-industrial era most of the energy consumption was attributed to space heating).

5. 'Economic Gravity' and Energy Affordability Thresholds

The above findings provoke several (rarely, if at all, asked) questions and illustrate the need to fill in the knowledge gaps. Why is the sustainable fluctuation zone relatively narrow and which factors determine the upper and the lower thresholds? What happens when *ECS* goes beyond the upper or the lower threshold? Why is the ECS_{gdp} evolution cyclic in nature? The section looks to provide some answers.



Energy costs/GDP ratio below the trend (upper wing)



Energy costs/GDP ratio above the trend (lower wing)

The trend from which deviations are estimated is shown in Figure 1. Trendline in b) is shown only for deviations that exceed 2%.

Source: Updated and modified from Bashmakov (2016).

Figure 7. Relationship between deviations from the energy costs/GDP ratio and three years average GDP growth rates ('wing' functions) for the U.S. (1949-2015).

The thresholds are boundaries of the sustainable *ECS* evolution zone, yet by no means are they 'holy borders' with crossing prohibited. Crossing is possible… but at a price. The price is an impact on the economic growth which, depending on the threshold crossed, may be either positive or negative. In (Bashmakov, 2007) the author used the 'wing' function to show that until the *ECS* reaches its upper critical threshold, it is all the other production factors that determine economic growth rates, while energy does not perform the 'growth limiting' function. However, as soon as ECS_{gdp} goes beyond this threshold, it eliminates the impacts of other factors that contribute to the economic growth and slows the latter down, so the potential economic growth is not realized. It was shown that after ECS_{gdp} exceeds 11% for the U.S., every additional 1% of ECS_{gdp} reduces GDP growth by 1% (Bashmakov, 2007). These findings are supported by more recent studies. Murphy and Hall (2011) show that in 1970-2007, the U.S. economy went into recession whenever petroleum expenditures exceeded 5.5% of the U.S. GDP. Lambert et al., (2014) show that recessions occur once energy expenditures rise above 10% of the U.S. GDP. Based on the analysis of ECS_{gdp} (primary energy costs accounting) for 44 countries and for the world for 1978-2010, 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, growth rates to ECS_{gdp} elasticity is close to (-0.45), which means that additional 1% of *ECS* slows down global GDP (GWP) growth by 0.45%. Elasticity coefficient for global TPF is close to (-0.5). He points out that the threshold resides near 8% of GDP (between 6% and 10%) for developed economies. With ECS_{gdp} above this level, economy went to deep recessions. There is no growth experience in the post-World War II economy for ECS_{gwp} over 10% for an extended period of time. Fizaine and Court (2016) show that an increase in ECS_{gdp} lead to an increase in the unemployment rate two years later and a decline in the economic growth for three years following the ECS_{gdp} rise. They also concluded that Granger tests consistently reveal a one way causality running from the ECS_{gdp} to economic growth in the U.S. between 1960 and 2010. Fizaine and Court (2016) intended to statistically test Bashmakov's thresholds effects, i.e., the negative correlation between ECS_{gdp} and the rates of U.S. GDP growth after the share of energy costs thresholds (8%) is exceeded, but found the sample too small for robust statistical results and made a point that using cross-country panel data may help in such analysis. They concluded, that 'statistically speaking, the U.S. economy cannot afford to allocate more than 11% of its GDP to energy expenditures in order to have a positive growth rate. This corresponds to a maximum tolerable average price of energy of twice the current level'.

Numerous studies that attempted to assess the impacts of energy prices on the economy do not address the energy affordability thresholds and behavioral constants. When the ratio of energy costs to income is between the upper and the lower thresholds, there is no correlation between the pressure of energy costs, energy efficiency, and activity levels. However, the economic activity slows down whenever the upper threshold is crossed, and accelerates every time the lower threshold is crossed (Figure 1). The relationship between GDP growth and ECS_{gdp} can be described with a 'wing' function (see Figure 7).

Until the share of energy costs/GDP reaches the upper energy affordability threshold, energy does not put any 'limits to growth', and the economic growth rate is driven by a variety of other factors. This makes the lower 'wing' function range pretty wide, and the relationship in this zone quite uncertain. But when ECS_{gdp} goes beyond the upper threshold, it eliminates the impact of many factors that contribute to the economic activity expansion and slows it down, so the potential economic growth is not fully realized. If the potential growth is determined by the production function $F(X_{1.}....X_n)$, where $(X_{1.}....X_n)$ are inputs, then the 'wing' functions correct the potential growth via the 'wing' multipliers:

$$T_y = F(X_{1.}....X_n) * (1 - a * \frac{\Delta ECS}{\Delta ECSe^{\max}}), \text{ when } \Delta ECS > 0, \tag{4}$$

$$T_y = F(X_{1.}....X_n) * (b * \frac{\Delta Se}{\Delta Se^{\min}}), \text{ when } \Delta ECS < 0, \tag{5}$$

where ΔECS, $\Delta ECS^{\max}$, and $\Delta ECS^{\min}$ – are given moment, maximum (allowing to avoid recession) and minimum (from trend to the lower threshold) deviations of the share of energy costs from the trend.

Therefore, high rates of economic growth are not attainable with a high share of energy costs. When there is overshooting, and $\Delta ECS > \Delta ECS^{\max}$, a recession begins. The reverse is also true: there is not a year between 1949 and 2015, when the growth rates in the U.S. were below 2%, and the energy cost to GDP ratio was below the lower threshold.

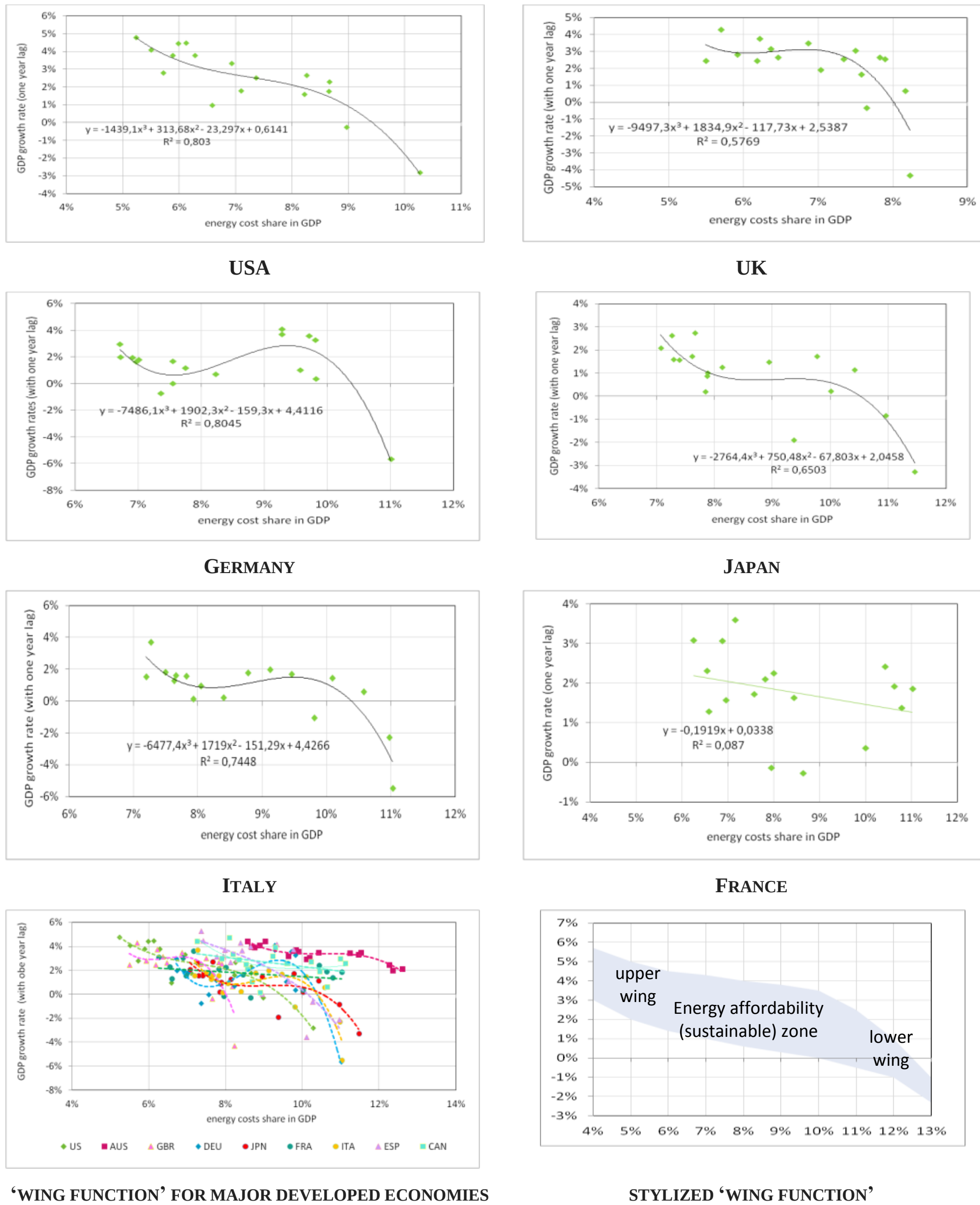
To test the validity of the 'wing function' for other countries WIOD data set on ECS_{gdp} for 1995-2011 was selected as an argument to ensure consistency of the energy cost accounting method across time and countries. The 1995-2011 time frame includes periods with low (1995-2000), medium (2001-2006), and high (2007-2011) *ECSs*. GDP growth rates with one year lag were selected as a function. Data only for developed countries were selected due to the above conclusion that WIOD-based assessments of *ECS* for developing countries are less reliable. Generalization of the 'wing function' for 9 countries and a stylized 'wing function' are presented in Figure 8. Plots for different countries (except for France) reproduce a very similar pattern, which is generalized in a stylized 'wing function'. For net energy exporters (Canada and Australia) the level of the upper threshold is higher: escalation of global energy prices drives up not only the numerator, but also the denominator of *ECS*, raising the level of the energy affordability boundary.

Plots presented in Figure 6 and Figure 7 are very much relevant to three energy policy domains formulated by Grubb et al., (2014). The First Domain – *ignore/satisfice* – is well reflected by the upper wing in the stylized 'wing function'. The share of energy costs is so low, that it doesn't motivate for cost reduction. The Second Domain – *compensate/optimize* – is the energy affordability sustainable zone, the area reserved for neoclassical economics, general equilibrium models and optimization. Energy costs are already important enough to start looking into reduction options, yet are not considered as a barrier to economic growth both in theory and in regulative practices. 'The Third Domain is characterized by strategic planning and investment to secure the integrity of our energy, economic and environmental systems and to transform them to keep within safe limits' (Grubb et al., 2014). Meaningful dependence of economic growth on *ECS* after 'safe limits' are passed is highlighted by the lower wing of the stylized 'wing' function, and it is clear that this dependence is nonlinear.

Differences in the relationship between *ECS* and economic growth for different ranges of *ECS* are the reasons that determine the complexity of its econometric evaluation using a single function form for all *ECS* ranges (see King, 2015; Grubb et al., 2017). It takes time, from half a year to three years or more – fuel transportation and storage time; time to embody more expensive energy in new products and services – for the initial price shock to spread over the whole economy according to Lowe's model adjusted to reflect embodied energy (see section 1 above). Growing energy prices lead to an increase in *ECS* without jeopardizing economic growth only until the threshold is reached. But when the upper threshold is approached (7-10% for different countries), elasticity of GDP growth rates to *ECS* increments is getting to -1, and after this threshold is exceeded, it goes even below -1. This happens when the reduction in energy use is in excess of the growth in the energy price, and so energy supplier gets no additional income from growing prices. As the threshold is left further and further behind, the 'wing' function range shrinks further, forcing energy demand to decline and completely blocking the impacts of all other factors that can promote economic growth. This process is determined by three reasons (Bashmakov, 2007). First, a theorem was proved that, with very simple assumptions,[18] at any period of time there is a lower limit to energy consumption, beneath which no economic growth is possible (Bashmakov, 1988). This means, that elasticity of substitution drops to zero, and the production function is transformed into Leontief's production function with energy shortage limits to growth. Stern and Kander (2012) explain this by thermodynamic minimum energy use to produce given output. We still have a long way to go before we can reach thermodynamic minimums in the production of goods or services, and so the lowest value of energy consumption is determined by the possible minimum (with lock-in present technologies) energy use to maintain the current levels of production. Second: energy purchasing power, albeit large and relatively elastic, is limited. The ability of financial markets to finance energy users' payment deficit are limited at any given moment. The upper energy price limit is determined by the upper value of energy purchasing power with an account of all possible mobilization of finance. Economic agents can only spend a fraction of their revenues and attracted financing for energy, because they also need to purchase other production factors or meet other basic needs and finance investments. Reallocation of total expenditures in favour of energy costs at the expense of profits leads to the decrease in investment, and at the expense of other inputs to reduced capacity load. Either way, GDP growth is slowed down or blocked. Third, there is a possibility to partially replace costly energy resources with alternatives supplied by competitive sources or suppliers, or reduce energy demand through energy efficiency improvements. As energy price grows, these alternatives become attractive. Therefore, if energy price keeps growing further, the 'price vice' will squeeze expensive suppliers off the market. With *ECS* approaching the upper threshold, the growth of real revenues of energy suppliers is limited by the economic growth rate, but the latter becomes close to zero or even negative, and so energy suppliers' revenues get frozen or even decline.

We need to explain, why energy intensity to price elasticities are not symmetric, and what drives them towards 'minus one' and beyond, when the share of energy costs goes beyond the affordability hurdles, and to about zero, when it reaches the lower boundary. The answers to these questions should be a key for explaining the existence of the upper and lower *ECS* thresholds and 25-33 years' long cyclical *ECS* dynamics. This line or research elaborates on the 'wing' functions, demonstrating how stepping over the upper threshold undermines investment, slows down economic growth, and forces customers to sacrifice the indoor comfort or undermines their payment discipline decreasing the revenues of energy suppliers despite growing energy prices. At the same time, stepping over the lower threshold accelerates economic growth and drives energy demand to a level where it cannot be met by energy suppliers if they keep energy prices low.

[18] Production of some goods and performing some works requires at least the 'thermodynamic minimum energy use'. Therefore, there is a physical limit to substitution.



Sources: *ECSs* are calculated based on WIOD data (Timmer et al., 2015); GDP growth rates are taken from OECD Economic Outlook database (http://www.oecd.org/eco/outlook/economic-outlook-annex-tables.htm)

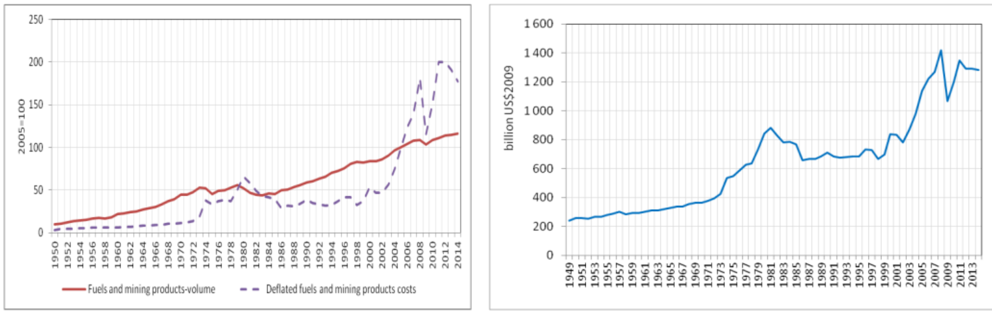
Figure 8. 'Wing function': relationship between ECSgdp and GDP growth rates (with one-year lag) in 1995-2011.

Empirical and theoretical analysis shows, that the points of downturn in the energy costs share dynamics coincide with the actual magnitude of the energy sales maximum (Figure 9). The 'wing' function shows that, after the upper threshold is approached, elasticity of GDP growth rates to *ECS* gets to -1 and below. In other words, energy use reduction is larger, than energy price growth. After the latter reaches the threshold, additional price increase generates no additional revenue and *ECS*, after climbing up, first stops and then starts to decline with both real energy price reduction and energy intensity reduction contributing to *ECS* downhill trajectory. After 1949, for the U.S., maximum real energy costs share was reached three times: in 1949; 1981; and 2008. The same is true for the lower threshold. Long declining energy costs share first stops to decline further and then starts growing, because additional energy price reduction generates virtually no additional revenues via additional demand. For the U.S., this happened twice: in 1972 and in 1998-1999 (see Figure 1). Energy sales (energy costs) behave slightly differently. After reaching the peak, they first decline to adjust to the existing purchasing power. When real energy sales reach the bottom level, they are fixed close to it for a few years, while real energy prices keep slowly declining against the background of accelerated energy use and energy production, and accompanied by energy production costs reduction. For domestic final energy use markets, energy sales demonstrate very modest growth. For global fossil fuel markets, where price trends are formed, they stay relatively stable close to a new equilibrium. And vice versa, after real energy sales reach the temporal maximum, energy production slows down or declines, as previous level of energy use is no longer affordable for many customers. In other words, real energy sales demonstrate 'stop, reverse, and go' dynamics.

Average annual growth rates of energy sales (T_{esales}) can be presented as $T_{esales} = T_p + T_e$ and $T_{ECS} = T_p + T_e - T_y$, thus $T_{ECS} = T_{esales} - T_y$. When maximum energy sales are reached, then $T_{esales} = T_e + T_p = 0$, or $T_e = -T_p$. At this moment T_y is close to zero and so $T_{ECS} \approx T_{esales} \approx 0$. Therefore, energy costs levels and *ECS* reach their maximums at nearly the same time, but do not simultaneously reach their bottoms. After the 'stop and reverse' part of the energy sales' trajectory pattern is over (it takes 5 to 6 years), energy sales then keep relatively stable at a new equilibrium level, while *ECS* keeps declining, as nearly fixed energy costs are divided by growing GDP. T_{ECS} gets to null after energy prices stop to decline. The reason is because energy demand, stimulated by previous energy prices and *ECS* decline, can no longer be met, if prices continue to decline. So energy supply slows down and energy prices grow. This brings energy sales up, and when $T_{esales} = T_y$, the $T_{ECS} = 0$. Then *ECS* starts a new, 10-12 years' climb to the next peak.

Price elasticity is asymmetric. It is higher by absolute value, when *ECS* reaches and crosses its upper threshold, and is lower, when it reaches or crosses the lower one. When *ECS* peaks, energy price elasticity can block the growth of GDP and energy sales. When *ECS* drops below the lower threshold, energy supply faces limits of profitable production with declining energy price. When the rate of additional energy supply growth gets limited in absolute value to the rate of price decline, no additional income is generated. Therefore, if sales growth is to be restored, price decline should be first halted and then reversed. After energy price decline reaches a bottom, a new cycle of rising prices begins.

Oil and energy demand functions are often referred to as having low price elasticity. This is true, as long as energy costs share is kept within a sustainable range. Existence of purchasing power thresholds makes energy demand to price, or rather to *ECS*, elasticity asymmetric (Bashmakov, 1988a, 2006a, 2007, 2016). Price reactions of energy demand are much more prominent, when relative energy costs stay high, than when they stay low, whereas conventional modeling has symmetric reactions. Adeyemi and Hunt (2014) concluded, that many assessed econometric studies confirm asymmetric energy demand responses to energy price evolution: energy demand declines faster, when energy prices are rising, than it increases, when prices are declining. They also found both endogenous and exogenous technical progress reflected in energy demand equations specifications for 15 OECD countries. But both level and slope parameters in the underlying energy demand trend appear (a) not relevant for all 15 countries, and (b) very small (mostly fluctuating in the range of 0.00002-0.0005) and consistent with the slope parameters shown in Figure 1 and Figure 6. So the role of exogenous technical progress is relatively small.



(a) Global. Fossil fuels and mining products export volumes and deflated value indexes (2005=100)

(b) U.S. Deflated energy costs to final users

Sources: UNCTADstat. http://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=16421 and developed by author based on data reported in: EIA, 1987; EIA, 2011; EIA SEDS, 2017; EIA, 2016; BEA, 2016. https://www.eia.gov/totalenergy/data/browser/?tbl=T01.07#/?f=A.

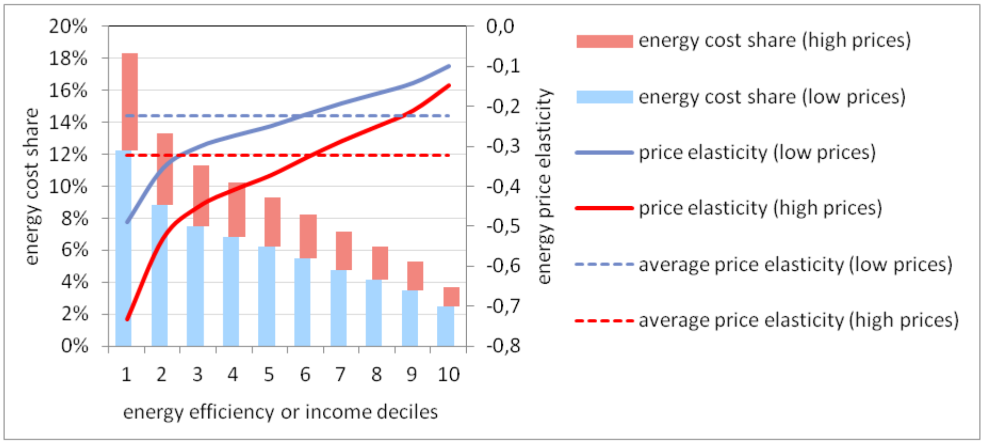
Figure 9. Evolution of real energy costs.

Depending on the model specification used to assess the parameters of the energy demand function, energy price asymmetry may be differently reflected. Beyond the threshold, the economic growth is hampered or even discontinues. If this is the case, the assumption that income and prices are independent in traditional energy demand functions ($T_e=aT_y+bT_p$) is not valid any more.[19] With *ECS* above the affordability threshold, $T_y = T_{yp} - mT_p - l_eT_p$. In other words, price elasticity grows absolutely by *am*. Oil prices drive the evolution of energy prices. For the oil demand function, parameter l_e becomes quite important reflecting the reduction in the share of oil in total energy balance, as oil is substituted with other energy carriers. For oil monopoly, l_e may reflect additional oil supply by independent producers stimulated by higher oil price. Therefore, oil sales are saturated faster, than energy sales, and even faster for oil monopoly – a price forming center. When the upper energy affordability thresholds are crossed, for oil monopoly demand price elasticity is: $\bar{b} = am + b + l_e$, where *m* and l_e are negative, and so $\bar{b} < b$. When $\bar{b} \leq -1$, oil monopoly sales are saturated preventing oil price from further growth with no additional revenue, but rather losses for the monopoly. Depending on energy and oil demand model specifications, these effects may be not separated and reflected as growing energy and oil price elasticity.

[19] Kilian (2009) insists, that oil, and so energy prices are not independent from economic growth either.

Empirical and modeling 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 3 components of energy prices via keeping in investment and management decisions good memory for previous price maximums, different perception and reaction on price declines and price recoveries after decline (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, 2006a and 2007). All of these factors may be important, and there is no agreement about the causality of asymmetric price reactions. One possible explanation is given above and it is about the dependence of income growth on energy prices after energy affordability thresholds are crossed. Additional explanation of these phenomena is provided below (Bashmakov, 2016).

If for the whole sector the energy demand function is presented as $E = AY^{a}P^{b}$, and for every quintile or decile i of energy users it is $E_i = A_i Y_i^{ai} P_i^{bi}$, then overall energy price elasticity is a weighted sum of price elasticities specific for each group with weights equal to the share of this group's energy use in the total energy consumption corrected to long staying ratios of average energy price to the one specific for the given group (ρ_i): $b = \sum_i b_i * d_i^e * \rho_i$. Energy consumers are grouped in quintiles or deciles based on the share of energy costs either in their income or in gross output. It is assumed, that energy prices elasticities are different for each group and by absolute value positively depend on the share of energy costs: $b_i = f(S_{ei})$, and negatively depend on the income or profit margin. The higher the share of energy costs, the higher energy price elasticity. With energy prices growing faster, than income, the share of energy costs in income grows for all income (or energy efficiency) quintiles. Thus, each group drifts along the price elasticity coefficients distribution curve making each b_i, and so total aggregated b, higher, and vice versa. This effect is illustrated in Figure 10. After energy price has escalated by 50%, the share of energy costs grows by more percentage points for the decile with the highest energy costs (6.1% in Figure 9), than for the one with the lowest energy costs (only 1.2% in Figure 9). This makes energy price elasticities higher for each group, with growth by absolute value proportional to the increase in the share of energy costs, and so uneven. The average price elasticity becomes higher as well, but weights of each group in the energy use change. Groups with high *ECSs* and so with high energy price elasticities reduce their consumption more dramatically compared with low *ECSs* groups, and so the weight of the latter increases. To a certain degree, this effect mitigates the increase in average energy price elasticity. With over 6% increase in the share of energy costs, the most energy inefficient group may lose the whole profit margin and become unprofitable, and so may reduce the loads of the most energy intensive equipment or retire the whole facility. It will keep reducing energy demand, thus increasing price elasticity. The reverse is also true: if energy prices decline 1.5-fold, every income- or energy efficiency decile faces declining price elasticity, profit margins grow, previously retired facilities may be brought back to work (rebound effect), and average price elasticity declines. This mechanism explains energy price elasticity asymmetry and drifting.



Source: updated from Bashmakov (2016).

Figure 10. Evolution of decile-specific energy costs shares and energy price elasticities.

Energy efficiency distribution curve for similar facilities in different sectors looks very similar to the *ECS* distribution curve (given similar energy prices). It consists of three parts: the first part shows facilities with energy efficiency parameters close to BATs (practical minimum); the middle part is where energy intensity of facilities steadily grows; and the third part is the most energy inefficient units. Distributions with a large share of highly energy intense facilities are more vulnerable to rising energy prices. The shape of the curve itself is a product of long-standing energy price differences. The pressure of energy prices on the most energy inefficient facilities is much higher, than on the most efficient ones. Firms have to face declining profits or increasing output prices followed by reduced demand for their products. This, in turn, implies reduced facilities' load and energy use. In the long-run, they have to switch away from energy intensive inputs (Breitenfellner et al., 2015). When it comes to the households' energy efficiency distribution, it becomes clear that the poor suffer most of all from energy price shocks, producing three possible reactions: reduced payments (if default on payments cannot be reduced technically or otherwise), or reduced energy demand and indoor comfort, or both.

6. Carbon Pricing Trap

King (2015) assesses, that introduction of 20US$(2005) carbon price adds about 1% of global energy cost share to the 2010 GDP.[20] He agrees, that for each economy there is a threshold value which, if crossed, completely blocks economic growth, and estimates this value at 8% for the global economy (with the uncertainty range from 6% to 10%).

With *ECS* at 8% in 2010, carbon pricing at 40-50 US$2005/$CO_2$ escalates *ECS* to 10%, and with 100 $2005/$CO_2$ to 12%. Reaching critical growth-stopping *ECS* value induces recession followed by CO_2 emissions and carbon price decline. King (2015) highlights the fact, that

[20] Global GDP measured at exchange rates in 2014 was about 73 trillion in US$2005. Energy- and industry-related CO2 emissions, according to EDGAR database, were about 36 billion t CO2. Therefore, 20 US$2005 carbon price will cost 720 billion US$2005, or 1% of GDP. 20 US$2005 is equivalent to about 25 US$2017.

Kyoto protocol was signed when the global share of energy costs in GDP was low. It was high in 2009, and so Copenhagen agreement failed. The Paris Agreement was reached after this share started to decline from the 2008-2012 peak.

The 'minus one' phenomenon means, that with limited annual energy intensity decline rates, it takes time for the economy to adjust to energy price shocks and during the adjustment period *ECS* goes beyond the threshold blocking the economic growth. After *ECS* peaks, the energy price growth trend reverses. Finally, the whole cycle-long real energy price growth is limited to the degree of attainable energy productivity growth. This is cutting edge for energy, and also carbon, pricing. Any price increase beyond this level will be eventually compensated with subsequent decline. King highlights, that carbon prices, as identified by IPCC 5AR to keep global warming within 2°C limits, may push *ECS* beyond the threshold, and so economic growth will be compromised.

Affordable carbon price, P_c, can be estimated as:

$$P_c = (ECS_{thershold} - ECS_t) * (GWP_t / E_t) * (E_t / GHGEM_t), \quad (6)$$

where *GWP* – is global GDP and *GHGEM* – is global annual GHG emission.

So if ΔECS =0, the upper *ECS* growth-stopping level is already approached, carbon price can further grow only at a rate equal to average GWP energy intensity decline plus GHG emission per unit of energy reduction rate. With initial carbon price 20 US\$2015/CO_2, energy intensity declining by 3%, and carbon intensity of energy by 1% per year, then by 2050 carbon price can be as high as 80 US\$2015/CO_2 and by 2100 equal 580 US\$2015/CO_2. Both estimates fit the ranges specified in IPCC 5AR (Clark et al., 2014). If attainable carbon intensity reduction is 1%, and energy intensity reduction is only 2% with GWP growth by 3%, only stabilization of GHG emissions is possible. In this case carbon prices at 57 and 253 US\$2015/CO_2 for 2050 and 2100 respectively will only do the stabilization work, whereas excessive carbon pricing can bring GHG emission decline only at the expense of slowed down economic growth. If ΔECS >0, these estimates can be multiplied by $ECS_{thershold}/ECS_t$, or can be divided by this ratio, when $\Delta ECS < 0$.

Bashmakov (2007) and King (2015) point out, that many integrated assessment models assume constant TFP, and some assume autonomous technical progress. Therefore, they do not account for damages to economic growth induced by *ECS* stepping over the threshold driven by high carbon prices. Limiting warming to 2°C requires annual global GHG emission decline on average by 1.5-3.4% by 2050 (IPCC 5AR). If potential GWP growth rate to mid-21th century is 3% per year, sustainable for decades GWP energy intensity decline is limited to 2% per year (which is close to the recently observed values), and energy decarbonization is 1% per year (in contrast to the stabilization in the last three decades), then global energy-related GHG emission will be frozen, yet no decline will be achieved (option 1 in Table 4). Prior to estimating the effect of introducing carbon prices it should be noted, that when *ECS* stays within the sustainable range, its increment by 1% slows down GWP growth by about 0.5%, but after the threshold (say, 10%) is crossed, each additional percent of *ECS* slows down GWP growth by 1% or more. With these assumptions, annual energy price growth by 6-6.6%, driven by escalating carbon prices, allows it to reduce GHG emissions by 2-3% per year, but at the expense of recession (option 3 in Table 4). As King (2015) states, after World War II, developed world economy was in recession every time *ECS* exceeded 8%. As he uses primary energy costs accounting, we can adjust this growth-stopping *ECS* level to 10% for final energy use accounting. It takes 4 years to escalate the share of energy costs from base 8% to growth-stopping 10% by internalizing carbon price at the level of about 60 US$2015/$CO_2$ (King's estimate is 50 $2005/$CO_2$). Carbon Pricing Leadership Coalition (2017) concludes: 'In a supportive policy environment, the explicit carbon-price level consistent with the Paris temperature target is at least US$40–80/t$CO_2$ by 2020 and US$50–100/tCO2 by 2030'. With a lower carbon price, 3% annual decline in GHG emissions is not attained (option 2); whereas with a higher energy price, global economy is affected by a strong 'headwind' and not just stagnates, but enters the de-growth, or shrinking economy phase (option 5). This is what, by analogy with King's 'energy trap' (2015), may be called the 'carbon pricing trap'. The way to escape from the trap is to radically accelerate energy productivity and energy decarbonization. Carbon Pricing Leadership Coalition (2017) stresses, that 'carbon pricing by itself may not be sufficient to induce change at the pace and on the scale required for the Paris target to be met, and may need to be complemented by other well-designed policies tackling various market and government failures, as well as other imperfections.'

Table 4. Quantitative illustration for energy costs share 'carbon pricing trap'

Indicators	Options					
	1	2	3	4	5	6
AAGR of GHG emission reduction	0,0%	-1,0%	-3,0%	-4,8%	-2,0%	-2,8%
AAGR of energy price growth	2,0%	4,0%	6,6%	10,0%	4,0%	5,0%
AAGR of GWP	3,0%	2,0%	0,0%	-1,8%	2,5%	2,3%
AAGR of GWP energy intensity	-2,0%	-2,0%	-2,0%	-2,0%	-3,0%	-3,5%
AAGR of energy carbon intensity	-1,0%	-1,0%	-1,0%	-1,0%	-1,5%	-1,5%
Energy costs share of GWP	8,0%	8,8%	10,0%	11,8%	8,4%	8,6%

Source: author.

The question is, if it is possible to speed up joint rates of energy intensity of GWP and energy decarbonization up to 4-5% per year in response to the escalation of real energy prices by 4-5% per year? Is it possible to double by 2030 the global rate of improvement in energy efficiency, as required by Goal 7 of SDG? Substantial efforts and resources are required to spur GWP energy efficiency improvement and decarbonization so as to benefit from GHG emission reduction and at the same time keep energy affordable. This is the only possible escape from the 'carbon pricing trap'. Otherwise, the trade-off between maximizing economic growth and minimizing GHG emissions is inevitable (King, 2015). If maximum sustainably achievable energy productivity improvement is up from the current 2% to 3-3.5%, carbon pricing does not need to go beyond the threshold *ECS* and so has small or no negative impact on the economic growth.

To keep the motivation spring charged, energy and carbon pricing policies have to keep *ECS* close to, yet below, the upper threshold, thus motivating efficiency improvements and decarbonization without sacrificing economic growth. Carbon pricing and energy tax policy can be more effective, if more flexible: when affordability thresholds are approached, the carbon price should be lower, and vice versa (Bashmakov, 2007; King, 2015). This naturally happens, when energy prices shocks limit economic dynamics and carbon price, as shown by the EU ETS experience.

In many projections, the uncertainty zone for price evolution is often presented as a divergent cone. In reality, price trajectory within this cone is never straightforward. If prices stay low for a while, they will escalate, and vice versa. The integral below the *ECS* curve for 25-33 years is the same, irrespective of prices. The higher energy prices grow today, the deeper they will drop tomorrow, if not compensated with energy efficiency improvements. Every action has an equal and opposite reaction. There are never real evolutions along either the upper or the lower boundary of the cone, as market forces switch the direction of the energy price trend.

Are about all technological changes and many structural shifts endogenous with energy price effects distributed over time via different channels? It needs to be explored, if energy productivity can accelerate well beyond 2% per year. But if the answer is negative, we are in a carbon pricing trap. More studies are needed to improve the knowledge about the first and the other two laws of energy transitions. Integration of these laws in global energy models and policy packages may considerably reduce and reshape the uncertainty zones of future energy use and GHG emissions and make energy and GHG mitigation policies more robust and efficient.

CONCLUSION

This paper elaborates on the energy costs/income constants and the 'minus one' phenomenon. The first law of energy transitions states: *in the long-term, energy costs to income ratios are relatively stable with just a very limited sustainable fluctuation range (with very small upward or downward trend for this range, reflecting centuries-long shifts in the structure of the economy).* Like a pendulum driven by economic 'gravitation', energy costs to income ratio tends to get back to the narrow zone of sustainable dynamics. The 'gravitation formula' is as follows: in the long-term, real energy prices can grow only by as much as energy intensity declines. Energy affordability thresholds are identified in all major final energy use sectors. The aggregated economy-wide threshold is a linear combination of those in different sectors and shows cyclic evolution for decades or even centuries within a sustainable 4-6% range as a fraction of gross output and 8-12% range as a fraction of GDP. These ranges may drift slightly up or down, driven by the evolution of the economy structure affected by the role of industrial and services sectors and embodied energy outsourcing. The energy cost share reaches its maximum, when further price increase cannot generate any additional revenue for energy supplier, and it reaches a minimum when price decline undermines the ability of energy suppliers to meet growing demand.

In reality, 'limits to growth' are, in fact, affordability thresholds. Scarce resources, including energy, become more expensive and slow down the economic growth until new technologies and new resources allow it to provide energy services to multiple economic activities with less physical resources, thus reducing the pressure of limited resources and allowing for faster growth until a new affordability limit is faced and so a new cycle is launched.

Carbon pricing trap poses restrictions on the magnitude and dynamics of carbon price keeping energy affordable and preventing global economy from stagnation. Mitigation response to carbon and energy tax policy yields different results, depending on the *ECS'* position against the threshold. When *ECS* is high, carbon prices can be reduced to avoid the slowdown of economic growth, and when energy prices are low, carbon prices can be increased to promote more effective and less carbon-intense energy use.

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