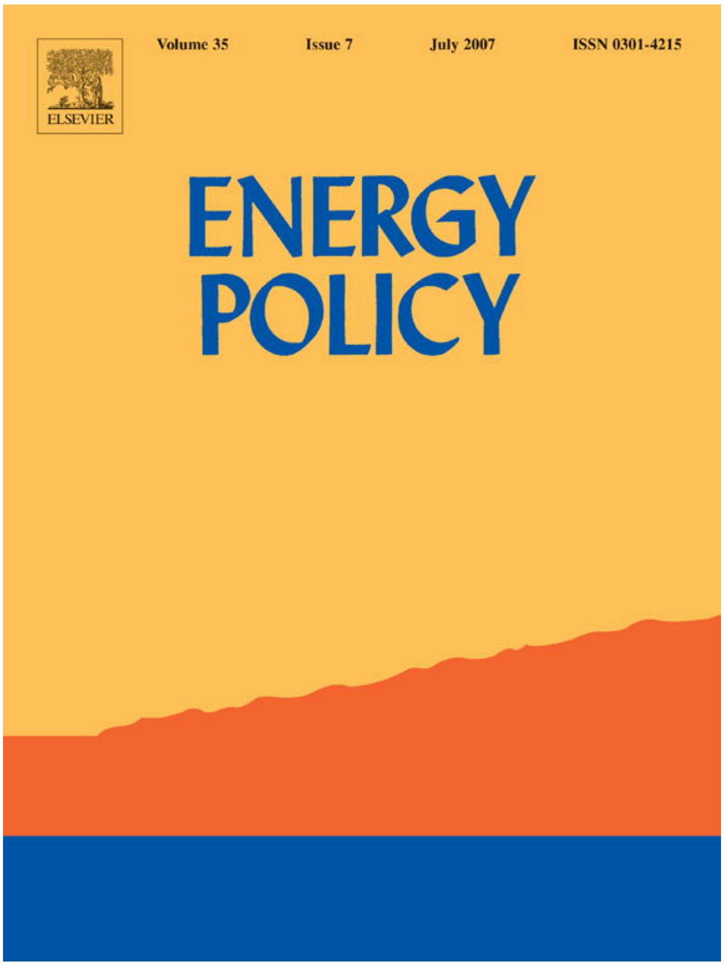
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Three laws of energy transitions

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Abstract

The paper formulates and explores a hypothesis on three general energy transition laws: the law of stable long-term energy costs to income ratio; the law of improving energy quality; and the law of growing energy productivity. These laws are essential for shaping long-term projections and checking for their consistency. All three are rooted in amazingly stable in time and universal across countries energy costs to income ratios. Limited energy purchasing power sets up thresholds, which, if exceeded, bring asymmetry to energy demand to price elasticity. The author believes, that the theoretical postulate on the substantial substitution among production factors, which is used in the production functions theory, may be incorrect. In reality, innovations mainly lead to the substitution of a low-quality production factor with the same yet of a better-quality. Improving energy quality with stable costs to income ratio is accompanied by growing energy productivity. Energy costs to income thresholds are indicators allowing for better projections of oil prices.

Keywords: Energy transitions; Energy efficiency; Energy costs

1. Energy transitions: from 11th to 21st century

What was the energy system like in the 11th century? Any effort to evaluate energy consumption patterns and volumes in this century is very speculative (see Table 1). Energy was basically non-commercial, and was consumed locally, rather than traded. It took the humanity 10 centuries to increase global energy consumption about 2000-fold (around 0.8%/year); increase average per capita energy consumption 6-fold (only 0.1%/year); switch off non-commercial energy resources for two thirds of the global population; and establish large-scale first country-wide, and then regional and global energy markets.

Energy transition rates accelerated in the 19th, and especially since the beginning of the 20th century. However, we have to admit that humanity entered the 21st century with one third of the mankind still relying on millennium-old energy patterns dominated by domestic needs and non-commercial forms of energy. Another third of the global population has energy basis adequate to the new millennium; while the last third is in transition from traditional non-commercial to the modern commercial energy basis. Today, the first third relies on biomass as the major energy source. The role of human and bullock power in the energy balance in those countries is probably still close to 10–15%, like 10 centuries ago. North–South disparities are basically the disparities between residents of industrialized countries of the 21st century and residents of developing countries of the 11th century, who still face poverty and food shortages.

Development of the civilization is accompanied by permanent energy transitions, which accelerate in some periods and slow down in others. Cross-country analysis of many indicators reveals the picture of millennium-long global energy transitions. This is sort of a statistical "time machine", which allows traveling to the past (countries with very low per capita incomes demonstrate indicators, which the global energy system used to have long ago) and to the future, although some leapfrogging may reshape historical trajectories. Current distribution of countries by the share of biomass in their overall energy consumption, or by energy intensity, looks much like the historical dynamics of corresponding global energy characteristics. Biomass, with its space heating and cooking efficiency of 5% to 30%, is continuously losing its share in the energy

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balance. It is primarily substituted by coal, which is more efficient, then by oil and natural gas, and finally, by electricity and district heat. Thus, the trends in the energy balance structure are closely related to the level of development. But even a millennium later, none of previously dominating energy carriers is completely scratched from the energy picture. Biomass still plays an important role (in Canada it presently stays at 5%). Clearly, there is a long way for many countries before they can rely on a modern mix of commercial energy resources.

Against millennium-long time horizon, energy transitions are relatively slow, yet they have grown up to the level, when the scale of energy activities endangers stability of the global climate. Many developing countries are presently going through intensive energy transitions and thus shifting the carbon dioxide emissions increases "downtown" from North to South (see Fig. 1). Therefore, possibilities to 'shave' emission growth triangle, or to get away from the "downtown", to move towards a low-carbon future, to a large degree depend on future energy transitions characteristics in developing countries, which desperately need sustainable development to combat poverty.

More than just conventional wisdom is required to effectively address climate change at affordable mitigation and adaptation costs. Since mid 20th century, a need to foresee possible energy futures has become critical for sustainable development of the global economy. While overcoming "limits of growth", one faces "limits of change": social and economic inertia in the evolution of decision-making and behavioral patterns, as well as in replacing technologies and physical infrastructure.

Social inertia is poorly investigated. Present consumption and behavioral patterns are very deeply rooted in the past, a lot more deeply, than one may think. Personalities and institutions have the same drives, as they used to have long ago, and the systems and procedures of decision-making have not been much modified either. People are still trying to obtain more personal freedom and build more privacy, which has become a synonym of prosperity. The concept of well-being for many years has been perceived as a concept of more-having. This is a very important aspect of economic and energy transitions. People move from public transport to personal cars, which

Table 1
Evaluation of global energy consumption in the 11th century (Mtoe)

Energy source	Agriculture	Domestic	Transport	Industry	Total	(%)
Human	0.07	0.24	0.02	0.05	0.38	7.2
Man	0.05	0.07	0.01	0.05	0.18	3.4
Woman	0.02	0.13	0.01	0.00	0.16	3.0
Child	0.00	0.04	0.00	0.00	0.04	0.8
Bullock	0.08	0.00	0.16	0.00	0.24	4.5
Fuelwood	0.00	4.42	0.00	0.19	4.61	86.8
Wind and water	0.04	0.00	0.02	0.02	0.08	1.5
Total	0.19	4.66	0.20	0.26	5.31	100.0
(%)	3.6	87.8	3.8	4.9	100.0	

Calculated based on: Batliwala (1995); Melentiev (1997); and OECD (1998).

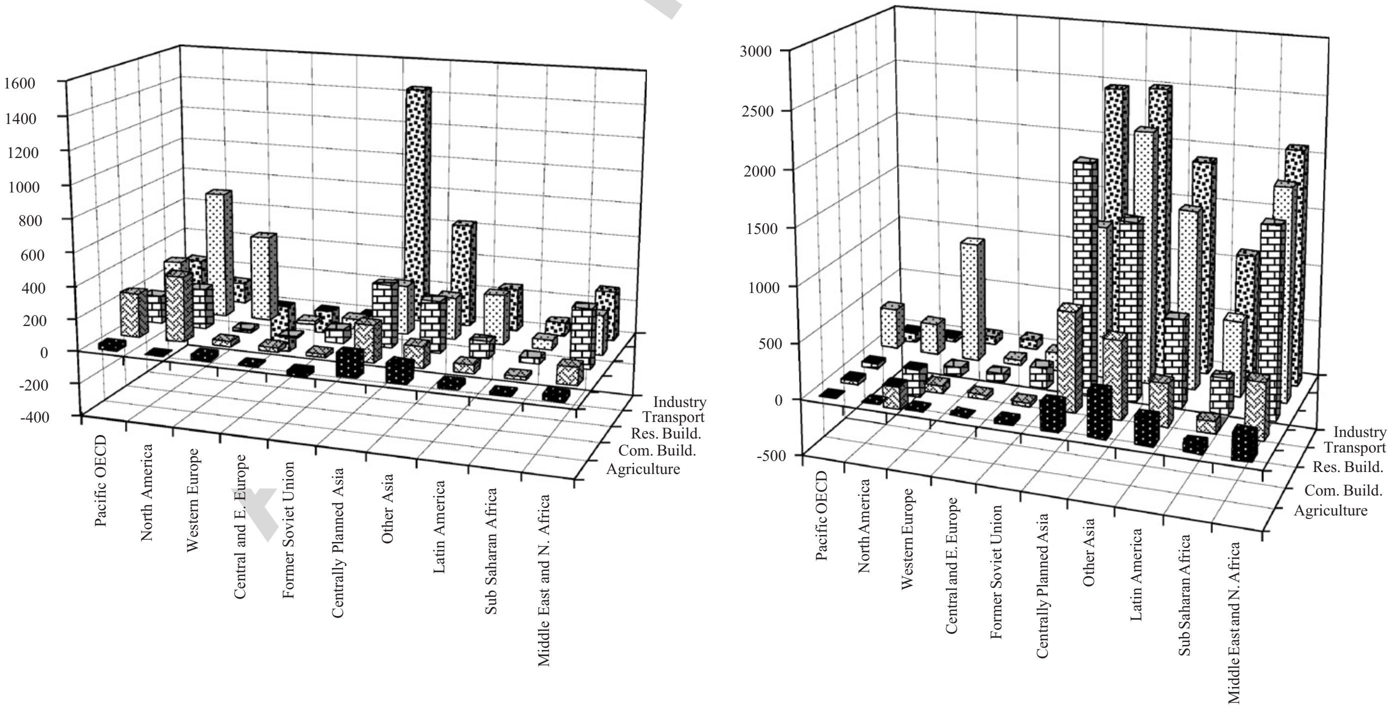

Fig. 1. Geographic (North to South) shift of carbon dioxide emissions increases "downtown". Historical and projected carbon dioxide increases by sector and by region ($MtCO_2$, built on data borrowed from Price et al., 2005)

become larger and larger; from crowded shelters to large flats and further to private housing surrounded by large estates, which keep you from ever seeing your neighbors. Little kids look for small ''secret places'' in big rooms given to them by loving parents. Substantial parts of American and European houses are unused, but still warmed or cooled, waiting for children or friends to come to visit. Cars with backseats are purchased solely to get lower insurance rates, and only dogs use these backseats. Harder work is translated in larger homes and more cars and appliances. Yet so far there is no saturation in per capita living space or car ownership. And growing wealth does not leave much time for leisure and does not make many people happier. On the contrary, growing wealth often drives smiles per hour down. After you retire, privacy turns into loneliness, and a need for communication forces you to realize that you have misplaced your life values. Economy of happiness is not explored yet, but it is different from the present economy. Energy transitions are to a large degree driven by social values, patterns, and lifestyles.

Economics of happiness, sufficiency, values and consumption patterns, innovative life-styles may be very important for the transition from the present to the future. Paul Valeri, a well-known poet, wrote: ''The future is not what it used to be''. Rennie (1995), paraphrasing Valeri, wrote: ''The future now is not even when it used to be''. The future is partly here, but only partly. Over 50 years ago, P. Putnam, based on the analysis of historical energy transitions in several countries since the beginning of the 19th century, published one of the first long-term (for a 50 years' time horizon up to 2000) energy-development forecasts (Putnam, 1953). Most issues related to this subject were presented in his book, including analysis of population growth, energy resources estimates, analysis of fuel transformation technologies, input–output efficiency, and even, amazingly, CO_2 emission estimates. Putnam concluded that, if those trends continued in the population growth, per capita energy demand, and liquid fuels and electricity preferences, then growth in the real cost of coal would cause a strong demand for new energy sources (nuclear) sooner, than many realized. He failed to predict demographic explosion of the 1960s, or fast growth of oil and gas consumption. If in his findings the word 'coal' were replaced with 'oil', one would end up with the same major conclusions as those of the majority of more recent long-term projections of global energy development, yet without a single ''magic'' solution. Hundreds presently available scenarios of global energy system development up to 2100 critically disagree on the scale and structure of future global energy systems and energy transitions pathways, which are stud by ruins of forecasts. Identifying regularities or laws of energy transitions allows it to balance conservatism (while transferring some past to the future) and unlimited imagination, which may tentatively shape the future using the backcasting approach.

2. The law of long-term energy costs to income stability

The first law says: *in the long-term, energy costs to income ratios are relatively stable with just a very limited sustainable fluctuation range.* Energy costs to income proportions are relatively stable over decades, if not over centuries, and very similar across regions and large countries. These proportions include final energy costs to GDP (or to gross output) ratio; housing energy costs to personal income ratio; and energy costs for personal transportation to personal income ratio. There may be more[1]; yet only these three are investigated in this paper.

Studies on these proportions evolution are very scarce, mainly due to the shortage of aggregated country data on total energy costs for final consumers. Some necessary statistics appeared only since the end of the 20th century. Among a few statistical periodicals, energy costs for final consumers were reported by the US DOE (2005) for time periods starting with 1970. Recently, IEA/OECD started publishing aggregated energy prices indicators for final consumers (data series are available since 1978, OECD, 2005a).

Energy costs to GDP ratios for the US[2] and OECD are plotted in Fig. 2. Sustainable variations of energy costs to GDP ratios are limited to 8–10% for the US and 9–11% for the OECD. The range for energy costs for final consumers to gross output is even narrower: 4–5% for the US and 4.5–5.5% for OECD. After the upper limit is reached or exceeded (1949–1952, 1973–1985, and starting from 2005), the ratio drops, and after the lower limit is approached (1998–1999), it, on the contrary, grows. Every time, like a pendulum, the ratio driven by some economic gravitation gets back to the equilibrium, or sustainable dynamics zone. Only some indirect statistics may be used to reveal more historical periods of approaching either the upper or the lower thresholds of sustainable energy costs of the GDP lane. Based on the data presented by Holdren (1992) and British Petroleum (2006) we can assume, that the upper threshold in the US was exceeded around 1920 and 1900. Based on the data on price dynamics and coal use in England and France presented by Kondratiev (1922) and Putnam (1953), we can assume that three other peaks in energy costs to GDP were observed around 1810, 1835, and 1870. So energy costs to GDP ratio evolves with about 25–30 years' cycle, and mere blind extrapolation of this ratio means, that around 2005–2010 another peak may be expected followed by a decline.

Stability of energy costs to income ratio results from the existence of energy affordability thresholds and behavioral constants. When energy costs to income ratio is below the threshold, there is no correlation between the burden of energy costs, energy efficiency and activity levels. However, when this threshold is exceeded, economic activity slows

[1]For example, stable energy costs to industrial output ratio.

[2]Data for 1949–1969 were reconstructed by the author based on energy consumption and energy price data published by DOE.

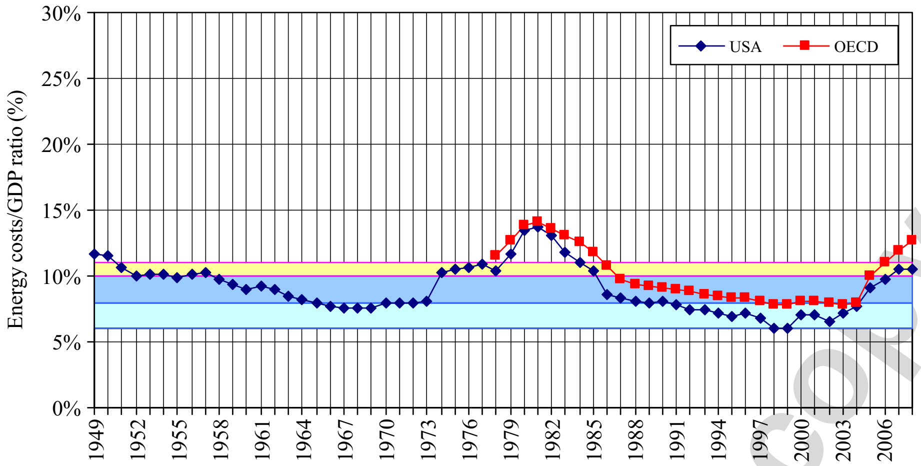

Fig. 2. Energy costs to GDP ratio evolution in OECD and the USA.

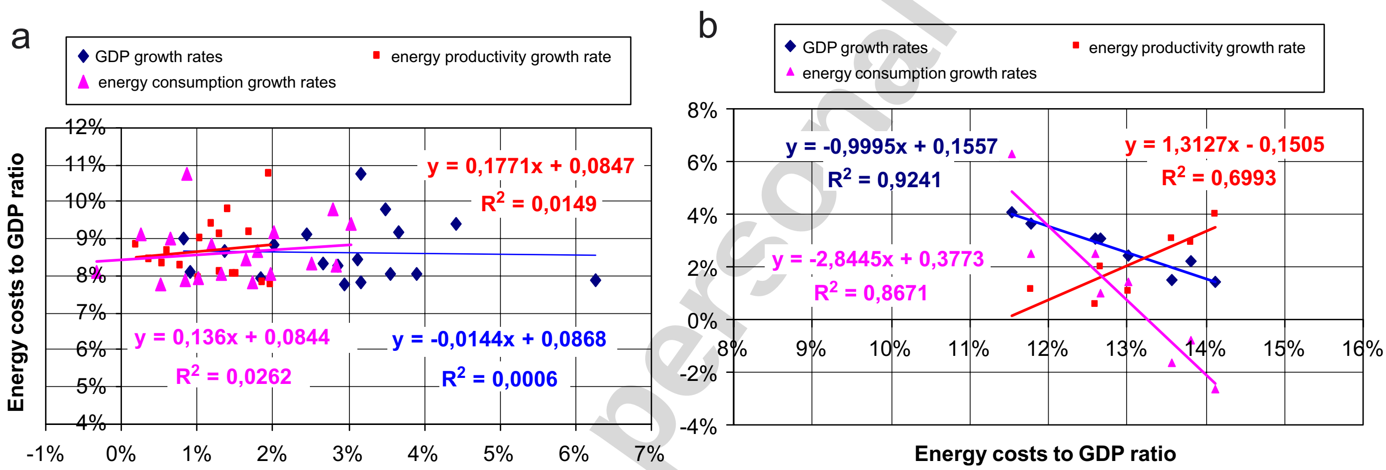

Fig. 3. Relationships between energy costs to GDP ratio and GDP growth rates (blue), energy productivity (red), and energy demand (lilac) for OECD, (a) energy costs to GDP ratio stays below 11%, (b) energy costs to GDP ratio exceeds 11%.

down; energy productivity accelerates; energy demand slows down or declines until the ratio is back to the sustainable range (see Fig. 3).

Oil and energy demand functions are often referred to as having low price elasticity. This is true, as long as energy costs to GDP ratio is kept within a sustainable range. Existence of purchasing power thresholds makes energy demand to price or rather to energy costs/GDP elasticity asymmetric (Bashmakov, 1988a and 2006a). 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. Description of this phenomenon can hardly be found in the literature on asymmetric price reactions. When the threshold is exceeded, economic growth is hampered or even stops. In this case, assumption on the independence of the revenue factor (*Y*-GDP) and prices (*P*) in traditional energy demand functions ($E = A \times Y^{ey} \times P^{ep}$) is not correct. Energy demand growth rate (*Te*) may be presented as $Te = e_y \times Ty + e_p \times Tp$; with *Tp*—energy price growth rate, *Ty*—GDP increase rate, and e_y and e_p—income and price elasticities. When energy costs to GDP ratio is above the threshold, $Ty = Typ\text{-}b \times Tp$, with *Typ*—potential GDP growth rate. In other words, $Te = e_y \times Typ + (e_p - e_y \times b) \times Tp$. Price elasticity ($e_p$) is below zero, and it grows absolutely by $e_y \times b$. Therefore, energy and oil demand functions turn out to be functions with dynamic elasticity factors. When the upper limit of the energy costs to GDP ratio is approached and exceeded, energy price growth is accompanied by price elasticity growth. The function of tax collection on the tax rate and the function of housing and utility payments collection from residents (Bashmakov, 2004a) are functions of the same class.

DOE, generalizing some US studies on asymmetric elasticities states, that (a) in oil price shock conditions GDP growth rates to oil price growth elasticity is twice as high as under less substantial oil price growth; (b) in either case, the effect doubles for the second year (DOE, 2006). In reality, the explanatory factor is not the scale of oil price growth, but rather the fact of approaching and exceeding the upper purchasing power thresholds.

Drifts of elasticity coefficients for energy demand functions have been observed by modelers since early 1980s (Kouris, 1981), and were initially addressed through simple trend models (Girod, 1983). After energy price elasticity coefficients declined in the late 1980s, it became clear that time was not a driving force of such evolution. Bashmakov (1988a) created an energy demand model with dynamic price elasticity coefficient as a function of 3 years moving average real energy prices. So as energy prices grow, price elasticity coefficient escalates, and income elasticity coefficient correspondingly declines. In econometric functions with two factors, the drift of one elasticity coefficient is a negative linear function of another coefficient drift (Bashmakov, 1985). Haas and Shipper (1998) have shown that for many countries energy price elasticities are higher when prices are rising. Ghalwash (2007) has shown that price elasticity for the tax portion of the energy price in Sweden is higher, than for its base part.

Recent empirical and modeling literature on asymmetric price reactions also explains this effect through the unevenness of technological and behavioral change (Huntington, 2003; Gately and Huntington, 2002; Griffin and Shulman, 2005; Jimenez-Rodriguez and Sanchez, 2005; Soria, 2006) and through purchasing power thresholds, which drive unevenness of technological and behavioral change (Bashmakov, 2006a).

The relationship between energy demand and energy costs to GDP may be described through a "wing" function (see Fig. 4). Until the share of energy costs reaches the threshold, all other factors determine the rates of economic growth. This makes the function range pretty wide. Energy does not perform the "limit of growth" function. But when energy costs to GDP ratio goes beyond the threshold, it eliminates the impact of factors contributing to the economic growth and slows it down, so the potential economic growth is not realized.

The "wing" function range is continuously shrinking, as the threshold is left further and further behind, forcing energy demand to decline and completely blocking the

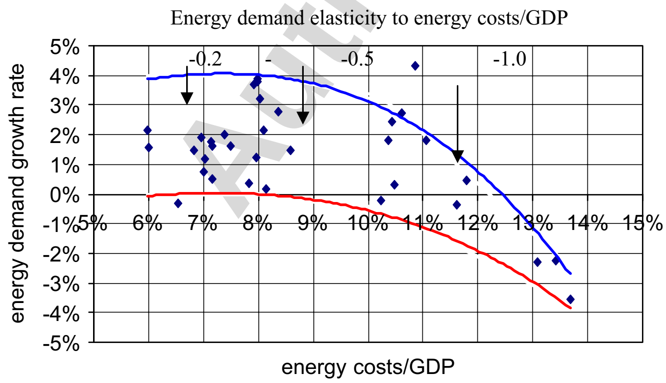

Fig. 4. Energy costs to GDP "wing" function (based on three years' moving averages for the USA for 1970–2004).

impacts of all other factors providing potential for the economic growth:

$$Te = Tep \text{ if } ES < \overline{ES},$$

$$Te = -93.9 \times ES^3 + 9.6 \times ES^2 + 0.1 \times ES + 0.02,$$
$$\text{if } ES > \overline{ES} \text{ upper boundary},$$

$$Te = -42.1 \times ES^3 + 2.5 \times ES^2 + 0.3 \times ES - 0.02,$$
$$\text{if } ES > \overline{ES} \text{ lower boundary},$$

with Te—rate of energy consumption growth, Tep—potential rate of energy consumption growth, ES—energy to GDP ratio, $\overline{ES}$—upper limit of energy to GDP ratio.

This is determined by three reasons. First, a theorem was proved that, with very simple assumptions, at any period of time there is the lower limit of energy consumption, which prevents from realization of potential economic growth (Bashmakov, 1988a). Second: energy purchasing power, although large and relatively elastic, is limited. Possibilities of financial markets to cover consumer budget or country balance of payment deficit is limited at any given moment. The upper energy price limit is determined by the upper boundary of energy purchasing power with an account of all possible financing mobilization. Only a portion of economic agents' revenues may be allocated for purchasing energy: apart from energy, they have to purchase other production factors or meet other needs. Third, there is a possibility to partially replace energy supplied by a monopoly with energy from competitive suppliers, or with energy efficiency improvements. As energy price grows, these alternatives become attractive. Thus, blindly increasing the price, any monopoly grips the "price vice", which squeezes it from the market. When energy cost to GDP ratio approaches the upper threshold, real energy supplier's revenues growth is limited by the rate of economic growth, but the latter becomes negative (see Fig. 3), bringing energy supplier's revenues down. This happened in the US in 1951–1954, and again in 1981–1983. After the purchasing power limit is reached, price growth by 1% leads to energy demand reduction by more than 1% through lower economic activity, competitive supply, and energy efficiency. Any further energy price increase results in a monopoly's reduced revenues, and so further price growth is halted. Thirty years following the first "oil shock" are a good proof of this theory of limited purchasing power. However, it was not clear, where the limit is. In 1979–1980, OPEC used to evaluate it practically "blindly in the darkness": there were 9 increases of the oil price. Because there is a whole chain of delayed effects of price growth, the mistakes of the pricing policy became obvious after the prices had skyrocketed.

There are several important findings of such analysis (Bashmakov, 2006). First, energy demand and energy productivity are more functions of energy costs to income ratio, rather than of income and price separately. Second, elasticity coefficients are drifting, as purchasing power thresholds are approached and exceeded. Third, when purchasing power thresholds are exceeded, income and energy price are not independent variables any more: growth of the energy costs burden halts GDP growth, provides favorable conditions for accelerated energy productivity; brings energy demand down; and finally halts the growth of energy suppliers' revenues, as prices further escalate. Forth, it is important to monitor energy costs to GDP ratio as an important business cycle indicator. It has a very narrow sustainable (with no negative impact on the economic growth) evolution range. It is important to develop corresponding statistics. According to the DOE, in 2030 total energy expenditures will go down to 5% of GDP (DOE, 2006). An assumption that under such low ratio energy intensity decline is sustainable, conflicts the above findings. When this ratio for several years stays much below 8%, the GDP energy intensity improvement slows down or (and) GDP growth escalates. Recognition of long-term energy costs to income stability law allows for the development of more realistic energy projections story lines and for the rejection of the scenario outcomes, which contradict this law.

Energy costs to GDP threshold cannot exist on the macro level, unless it is revealed in different proportions. Results of the thresholds evaluation look more robust, when supported by an additional historical data study for both housing and transportation energy costs to personal income ratios. Personal vehicles and residential energy supply are responsible for about 40% of energy end-use in the OECD countries.

The first surprise is that the ratio of energy to housing costs/personal income (before tax) is very stable over decades. The second surprise: this ratio is very similar in very different countries or groups of countries. The energy costs to income ratio for Japan has been varying around 3.2% for 56 years; in the US around 2.6% for 45 years, in India around 3.5 for 43 years. In the EU-15 it was 3.2% in 1999, in China 2.3% in 2000, in Russia it went up to 3.4% in 2006 (see Fig. 5). While households with high energy consumption require 50% more (high income) and 100% more (low income) energy, than households with low energy consumption, the share of energy costs in the household income is only 4% higher for the high income households (Vringer et al., 2007). Bashmakov (2004b) presented a ''wing'' function for the housing sector energy payment discipline based on the data for the Russian Federation.

Stability of this ratio for over half a century is a clear indication of the existence of the threshold. For countries, irrespective of the stage, model, and pattern of economic development (which had been changing a lot over half a century and differs widely across presented countries), the sustainable range of variation of the housing energy costs to income ratios is very limited ($\pm 0.5\%$). Going beyond the upper threshold is only possible for a limited time. Consumers react by reducing their consumption, at first through sacrificing some comfort, and then by improving energy efficiency. Energy demand declines, getting household energy prices down, and, finally, the ratio goes down. In addition, the higher the share of energy costs in the income, the lower the demand for housing real estate. So going beyond average thresholds results in declining investments in new housing and slowing down economic growth. All this makes this indicator very important and informative among other economic activity indicators.

The share of transportation services costs in personal income in the US has also been relatively stable over half a century (see Fig. 6). The share of personal transportation is less equally distributed across the income groups. Therefore, as incomes grow, modern transportation (commercial) replaces walking, bicycles, and animal-driven transport (non-commercial). In Japan, the share of transportation went up and reached the US level in the mid-1980s and has been stable at this level for already 20 years. A research by the World Business Council for Sustainable Development (Mobility, 2001) revealed amazing stability of time spent traveling across various countries at very different development stages and across time periods in the same countries. The share of income spent on traveling goes up, as commercial transport replaces non-commercial one, and then stabilizes. The oscillations of the graph for the US transportation were produced by fluctuations of the share of fuel for private transport costs

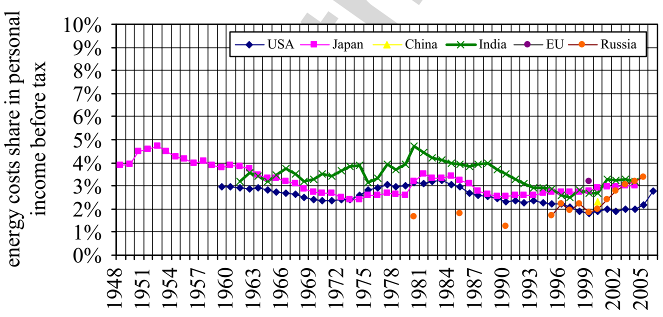

Fig. 5. The share of housing energy costs in personal income before tax for several countries and EU. (Calculated based on China Statistical Yearbook, 2004; Council of Economic Advisers, 2006; Eurostat, 2001; Government of India, 2001, 2006; Japan, 2006; Russian Statistical Yearbook, 2005).

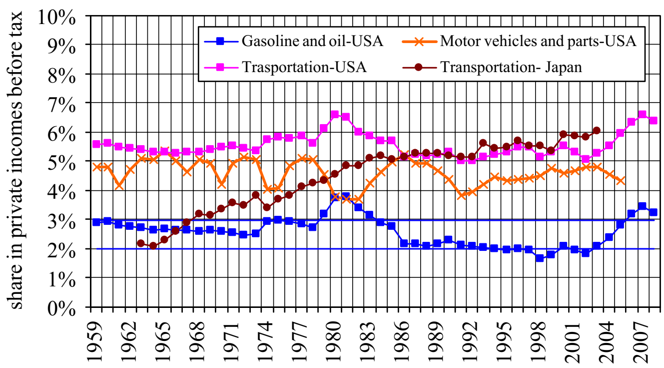

Fig. 6. The share of H&U costs in personal income before tax for several countries and EU.

around the half century average of 2.5%. In EU-15 countries, this share was in the range between 2.5% and 4.0%, and for Russia around 2%. So again, there is a stable and pretty universal proportion. Importantly, purchasing motor vehicles and parts negatively correlates to the share of income spent on fuels for personal motor vehicles. So, when the fuel costs to income ratio exceeds the threshold, the driving distances get shorter, more efficient cars are on the roads, more people use public transport, and cars population growth slows down. Finally, this ratio is back within the sustainable lane.

There is some evidence of the stability of energy costs to overall costs in the industrial sector in the range of 10–13% depending on the industrial sector structure. Welsch and Ochsen (2005) based on German statistics for what they call "production sector" 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. Based on the data for Danish industrial companies Bjorner et al. (2001) proved, that the higher the share of energy costs in the production costs, the higher the energy price elasticity. In Russia, the energy costs to overall costs ratio in industry, after escalating in the beginning of transition period from 13% in 1993 to 21% in 1998, went back to 12% in 2005. The relationship between the share of energy costs in the production sector and its capacity load has the "wing function" shape. The further we step over the energy cost to income ratio threshold, the lower is the production facilities load factor and corresponding energy consumption. More research is required to verify this law for the industrial sector.

Energy affordability approach allows for some more findings:

- Limits of energy affordability for all groups of final energy consumers keep the sustainable lane for energy costs to income fluctuation very limited;
- Mitigation response to carbon and energy tax policy brings different results, depending on the relationship of the energy costs to GDP or income ratio to the threshold. Carbon and energy tax policy may be more effective, if the rates are flexible: when energy-costs to GDP ratio is high, the tax rates may be reduced to avoid economic growth slow down, and when the prices are low, the tax rates may be increased to keep motivation for more effective and less carbon intense energy use. Work done by Ghalwash (2007) supports this statement;
- High oil prices cannot be sustained for a long time. Energy costs for housing and transportation to income, as well as energy costs to GDP, may stay above the thresholds for several years, and then oil demand elasticity to price gets below -1, and the revenues of oil exporting countries begin dropping with further price growth. Oil price goes down and is eroded by the escalated inflation, so these ratios are back to sustainable lanes. The proposed approach equips research and business communities with a compass in the sea of volatile energy prices (Bashmakov, 2005, 2006a).

3. The law of improving energy quality

The second law, of improving energy quality, is formulated in the following way: *growing overall economic productivity requires a better quality of energy services.* Economy is an organic interaction of constants and variables. Analysis of economic growth constants deserves more attention, than it currently gets. Some macroeconomic proportions are extremely stable, including the ratio of the intermediate product to GDP; the share of labor costs in GDP; the share of energy costs in the gross output; etc. Fluctuations of these proportions beyond very narrow limits of sustainable dynamics give birth to cycles in the economy (including Kondratiev's long waves), which re-establish the economic equilibrium, but on a new technology basis. When back in the 1920s N. Kondratiev explored long business cycles, he did not have macroeconomic time series on the GDP or gross output at his disposal; they appeared later. So he normalized economic indicators to the population size. Even with such data, he ended up with two important findings: first, the existence of long cycles in coal consumption dynamics (dominant commercial fuel at that time) in the UK and France; and second, positive correlation of coal consumption cycles with the cycles of relative salary dynamics and negative correlation with the return on capital (Kondratiev, 1922). Given lack of historical data on the energy costs to GDP ratio, the labor costs to GDP ratio may be used as a proxy. Positive correlation of these two ratios is supported by both historical and more recent macroeconomic statistics. Unskilled labor is a common substitute for energy (Welsch and Ochsen, 2005), so when energy becomes expensive, demand for unskilled labor grows, as well as the share of labor in the overall costs. Recent reduction of unemployment rate in some West European countries is associated with growing energy costs to GDP ratios. Menshikov and Klimenko (1989) found, that during 1889–1982 in the US labor costs were rising as fast as labor productivity. This means, that the share of labor costs in GDP has been stable (with just minor fluctuations) over almost 100 years. Analysis of factors costs to GDP or to gross output ratios shows, that they vary in very narrow ranges, in spite of the significant changes in the economic development patterns, technical and resource basis over the last 200 years. Growing share of energy costs in gross output brings up the share of intermediate product in gross output, as well as the share of labor costs in GDP at the expense of profits (net operating surplus). In the US in 1959–2004, the share of labor costs in gross value added of non-financial corporate business varied in the range of 63–67%. In Japan in 1990–2003, it varied in the range of 61–67% of national disposable income. In EU-15, after the share of energy costs had grown up, the share of labor costs in the national income went up to 72% in 1980, and then dropped to 66% by 2004. If the labor costs to GDP ratio is used as a criterion, in Japan it varied in the range of 52–54% in 1990–2003, in China it was 51% in 2000, and in the Netherlands in 1813–1913 this ratio was varying between 43% and 61% with 50% average (Groningen Growth and Development Centre, National Accounts of the Netherlands, 1813–1913). All this gives grounds to an assumption, that labor costs to GDP, same as energy costs to GDP, have been staying relatively stable for over 200 years.

When the share of energy costs grows, the rate of return drops, thus slowing down economic growth and shrinking sustainability zone for the economic dynamics. As noted by Kondratiev, in the crisis phase of a long cycle, mid-term crisis and depression phases are longer and deeper. Reducing remuneration of capital depreciates its value, which may grow up again only after the market pulls innovations from previously accumulated knowledge stock to rebuild the technology basis to improve overall efficiency (total factor productivity or 'Solow residual'), which allows it to overcome previously faced limits of growth. Fixing the rate of return is possible only through replacement of low-quality production factors with better quality ones. To a certain limit, the production functions theory allows for the replacement of production factors. However, a relatively stable share of *KLEM* production factors costs means the same growth rates of factor remuneration and productivity. The price of labor of a certain quality (determined by its productivity) has been about the same for about 200 years. In other words, technology improvements are motivated by declining remuneration of capital and do not allow it to replace labor with capital; rather *the induced technology change leads to the substitution of low-quality production factors with the same production factors only of a better quality*. This finding has many implications for induced technology change modeling, technology diffusion, spillover effects, and sustainable development. Menshikov and Klimenko (1989) came to a conclusion, that exactly investments in the improvement of production factors productivity are the real drivers of long cycles in the economy. 'Learning by researching' and 'learning by doing' speed up a lot with such investments, allowing for the acceleration of economic growth rates.

In general, 'learning rates' are higher, if innovations were introduced right after considerable energy costs increases. Technological progress is accompanied by improving energy quality/productivity. The notion of good quality energy resources was evolving across times: fuel wood, coal, petroleum products, natural gas, compressed air, heat, chill, electricity, hydrogen. There are different approaches to the evaluation of consumed energy quality. Presently, it is basically characterized by

- the share of electricity in final energy consumption (globally, it went up since the beginning of electricity use to 10.6% in 1971 and then to 18.1% in 2002 (OECD, 2005a) and is expected to reach or exceed 50% in 2100, irrespective of future scenarios assumptions (Edmonds, 2006; Sano et al., 2006);
- the share of natural gas in the power sector fuel mix (globally up from 13.3% in 1971 to 19.1% in 2003 and expected to grow further, supplemented by gasification of coal and biomass);
- carbon intensity of primary energy use (carbon to energy factor was globally declining by 1.8%/year in 1990–2003 (OECD, 2005c)).

From the economic standpoint, the quality of energy is mirrored by its contribution to the overall economic growth and to the total factor (not just energy alone) productivity. Demand for better quality energy services means demand for cleaner and easier-to-handle, and so less overall production factors intensive, fuels and energy carriers. They appear less expensive, when it comes to lifecycle costs of integrated energy service systems. In 2000, average price for electricity in OECD was 1171 US$/toe for households and 701 US$/toe for industry; for premium unleaded gasoline (95 RON)—713 US$/toe; for natural gas—387 US$/toe for households and 186 US$/toe for industry; for heavy fuel oil—176 US$/toe; and for steam coal—66 US$/toe for industry (OECD, 2005b). Final users switching from coal to petroleum products, gas, and electricity pay more for a unit of consumed energy, but not for a unit of energy service. When price for higher-quality energy source (electricity) goes up, it requires more lower-quality energy sources (coal, petroleum products) to substitute it, than visa versa (Kim and Labys, 1988; Mahmud, 2000; Urga and Walters, 2003). If it were not for energy price volatility, the best way to compare the quality of energy carriers would be to use energy prices. Learning rates are another important consideration: as better quality energy resource is applied more widely, its specific costs decline, and this effect for some time may even neutralize the costs growth resulting from the growing share of better quality energy carriers in the total energy mix.

4. The law of growing energy productivity

The third law, of *growing energy productivity*, says: as energy quality improves against relatively stable energy costs to income ratios, energy productivity grows, or energy intensity declines (Bashmakov, 1992, 1999). Penetration of more expensive, better quality energy carriers has to be accompanied by improved energy productivity—growing GDP per physical unit of finally used energy. Indeed, energy costs to GDP ratio fluctuations determine energy productivity evolution with the entire complexity of this process.

Plotted data of GDP energy intensity for 1850–2005 support this statement (see Fig. 7). Very often a curve, which mirrors the evolution of commercial energy intensity

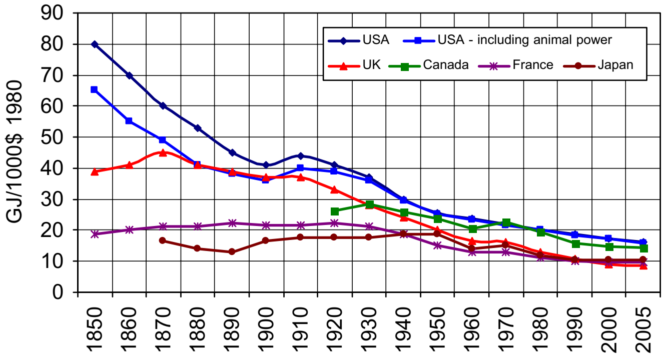

Fig. 7. Energy intensity of GDP: 1850–2005.

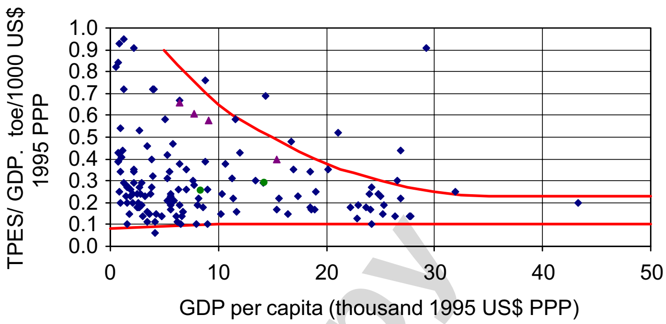

Fig. 8. Energy intensity as a function of GDP per capita 2001.

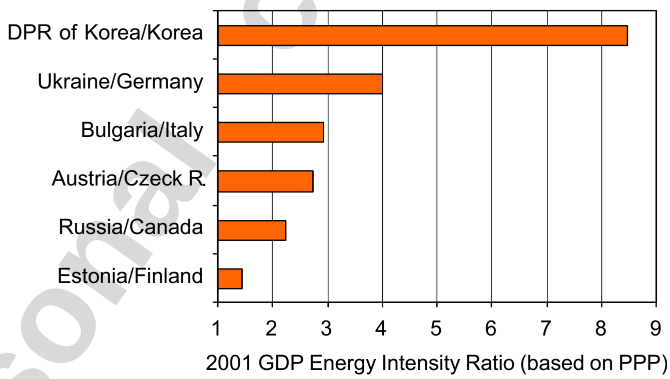

Fig. 9. Energy intensity ratio in countries with presently or previously dominated central planning versus their marker economy counterparts with similar climate conditions.

of GDP called "a hill of energy intensity", is cited as a general trend for this index. But thorough calculations should account for traditional non-commercial energy resources, which predominated pre-industrial energy balances. In the latter case, a general trend of declining energy intensity or growing energy productivity appears, although this trend was punctuated by periods of stabilization and even some decline. For some countries on the graph, only fuel wood was taken into account. If animal power is also included for the US, the general trend of energy intensity reduction becomes obvious, further strengthened by inclusion of water and wind energy consumption (Bashmakov, 1992; Nakicenovic et al., 1998).

Average annual energy productivity growth rates decline, as time frame expands: Russia (1998–2005)—5,0%; China (1971–2003)—4.2%; Japan (1960–2004)—1.9%; UK (1960–2004)—1.5%; Canada (1926–2003)—0.8%; the US (1850–2004 with biomass and animal power included)—1.0%. It took the US and the UK 50 to 70 years to halve energy intensity and 130–150 years to reduce it 4-fold. So factor 4 is possible; the question is: how soon? China managed to get its factor 4 over 35 years (since 1971) and is seeking for getting additionally factor 3–5 prior to 2050 (Kejun, 2006). Germany is looking into possibilities to reduce energy intensity by factor 3 over 50 years (2000–2050) for a low-carbon society scenario (Erdmenger, 2006).

OECD/IEA (2004) reports growing energy intensity for Africa, and stable one for Latin America in 1971–2003. This statistics includes biomass, but not human and animal power, or traditional water and wind energy. If these are also taken into account, energy intensity will hardly increase, but rather decline or stay stable. Distribution of countries across GDP per capita–energy intensity relationship (see Fig. 8) displays energy intensity evolution, very similar to the historical range. For all countries, the way to the future is only possible along the energy intensity reduction arch.

The rate of energy productivity improvement has been and will be the key issue which affects the long-term energy future. In the 21st century, like it used to be earlier, this trend will provide a decisive contribution to addressing global energy problems. It was noticed (Kohler et al., 2006), that end-use technologies are displaying higher learning rates, than energy supply technologies. The direction of causality is still not very clear: whether cost reduction inspires higher market niche or visa versa, but is looks like there is a cycle, in which, with a high energy costs/GDP ratio and introduction of a new energy efficiency technology, the whole social and physical infrastructure further promoting this technology starts developing, reducing capital costs for the implementation and improvement of this technology.

R&D makes technical energy efficiency potential renewable, but market imperfections leave it the least-exploited energy resource. Technical potential presents the value, by which energy efficiency may be improved through the implementation of technologies or practices that have been demonstrated irrespective of costs. With high energy costs to income ratios more funds are invested in R&D, so technical potential (with some delay) grows, as well as economic potential, which shows what works when it comes to decision-making by all market agents (not by the government itself) at social discount rates, including the cost of taxes. If decisions are made by a government, the scope of the potential shrinks substantially due to inability of the central government to collect and process all information required for effective decision-making and to timely take action (see Fig. 9). If the decision-making responsibility is not delegated, and managers are reluctant to take it up, decisions are mainly made according to the principle "one size fits all", and are far from being efficient. So the economic potential differs depending on the decision-making frameworks.

Market potential refers to energy productivity growth as a result of actions inspired by market forces alone in the absence of any governmental intervention. To a large degree, it depends on the energy price level and current decision-making patterns. It shows the outcome of private decisions with existing prices, budget limitations, and business discount rates. Decision-makers have limited information on the costs and benefits of potential actions, so the more information on opportunity costs is provided, the more energy efficiency is injected into the behavioral stereotypes, the wider is the scope for appropriate decision-making. To go from the information to decision-making and action-taking, the market agent identifies its own budget limitations, or a lending institution evaluates his creditworthiness. The stricter the budget limitation, or the higher the risk perception, the higher are then the business discount rates, and the lower is the market potential. The poor have the highest discount rates, so energy productivity progress is slow in low-income countries. Income distribution and development of financial institutions are important factors in promoting energy efficiency. Higher prices bring economic potential closer to the technical one, and market potential closer to economic one, and so energy productivity growth accelerates for several years or even decades.

There is no doubt that a large potential for cost-effective energy efficiency improvements is everywhere, but policies and measures are required to exploit it to overcome four major barriers: lack of motivation, lack of information, lack of coordination, and lack of financial resources. Enhanced market potential is based on the system of enhanced decision-making and action-taking created by specific policies to motivate market agents to realize a larger scope of available options. In Russia, mere dissemination of technologies, not the best worldwide available, but rather those already applied in Russia over the last decade, may cost-effectively halve its energy consumption. To keep the motivation spring charged, energy and carbon taxation policies have to keep energy costs to income ratios close to the thresholds, thus motivating for a better efficiency at no impact on the economic growth. When affordability thresholds are approached, energy productivity growth escalates shaving down a large part of potential energy demand growth.

Additional energy supply was not the main resource, which let the global economy go beyond the "limits of growth" after 1973. Since 1973, improving energy productivity globally provided 50% of additional demand for energy services. Reduced energy intensity of global GDP in 1973–2006 allowed it to mitigate energy consumption growth in 2006 by about 5 billion toe. Overall production increase of primary energy carriers over 1973–2006 was below 5 billion toe, while global oil extraction in 2005 equaled only 3.9 billion toe. Accelerated growth of any energy supply subsystem is a failure to compete with energy efficiency.

5. The law of long-term energy costs to income stability as a tool for oil prices projections

Presently, people are most concerned with oil price evolution. Economists call it the major risk for the global economy. Many market agents need short-term, medium-term, or long-term oil and gas prices projections. Neither energy exporters, nor importers, producers, or consumers can implement economic policy without some projections of oil and energy prices. For the Russian Federation and other oil exporters, oil price is the major parameter for the federal budget development.

A large part of professional community believes that oil prices are unpredictable in principle, and this belief builds on numerous erroneous projections. The author does not share this pessimism. Oil price trajectory is a "cardiogram" of uneven, very complex global energy–economic system development sensitive to political instabilities and natural calamities, but driven mainly by economic factors. The complexity of this system makes oil prices projections a very difficult, but not hopeless, effort.

In various periods of time, the author used three approaches to project long-term oil price evolution. The model of oil supply and resources additions ranked by production costs balanced with oil demand asymmetric to oil prices to the year 2030 allowed for a conclusion, that oil prices might stay low only until 2000, and then will substantially grow (Bashmakov, 1988b). Adjusted for inflation, it is shown as a green zone in Fig. 10. Using ENERGYGLOB model (11 regions, 6 sectors, 6 primary energy resources, and 6 secondary energy carriers), oil price

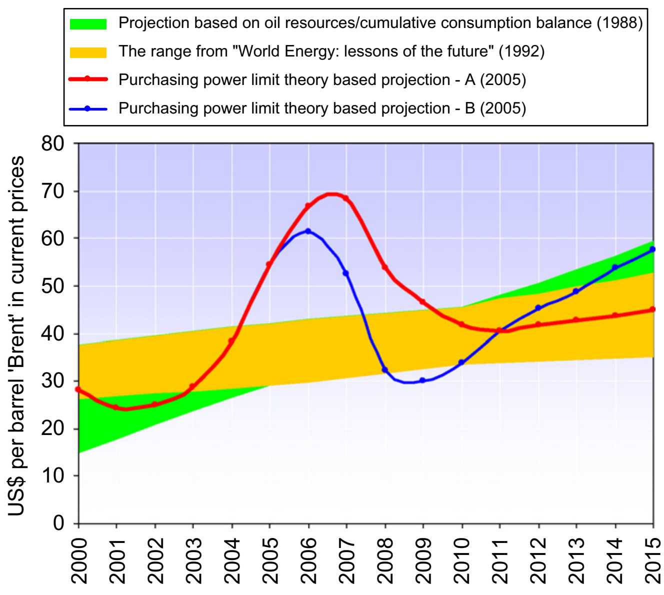

Fig. 10. Projections of oil prices based on limits of pursuing power theory.

projections were developed for 7 global scenarios until 2020 (brown zone in Fig. 10), (Bashmakov, 1992b, c). These two long-term oil price evolution ranges are still valid for expected oil price evolution. Finally, a new set of oil prices projections was based on energy cost to GDP thresholds, or on purchasing power limits theory (Bashmakov, 2005, 2006a, b).

Knowledge of energy costs to income thresholds allows for getting simple indicators for discharging the potential for further energy price growth. Substantial and durable oil price growth with some delay (escalation of other energy prices started only in 2004) leads to the increase of all energy prices faster, than energy productivity, and so to overcoming the upper energy costs to GDP threshold. As mentioned above, after energy costs exceed purchasing power limit, further energy prices growth does not bring additional revenues to suppliers. The closer to the threshold, the stronger is the energy price asymmetry and economic growth depression effects. Exceeding the thresholds is expected for OECD countries in 2007. The threshold for transportation was exceeded in 2006, and for the housing sector will be exceeded in 2007. It will put an end to energy price growth and then push oil prices down in 2008–2009 (see Fig. 10). In other words, oil prices start going up when OPEC production capacity is loaded at 85% or more, and stop rising when energy costs to GDP ratio of OECD countries exceeds 11%. It is a very simple rule for very complex processes.

Uncertainty zone for price evolution is often painted as divergent cone. In reality, price trajectory within this cone is never straightforward. If prices stay low for some time, they will escalate, and visa versa. The integral below the real energy costs curve for 25–30 years is the same, irrespective of prices. In the US in 1973–2005, real energy prices doubled, while energy intensity halved. If energy prices stay as low, as they did before 1973, energy demand will double compared to the present volume, and so final energy users will pay the energy costs as they have been paying with all price jumps over the last 30 years. The higher energy prices are rising today, the deeper they will drop tomorrow. The force of action is equal to the force of counteraction. There are never real evolutions along either upper or lower boundary of the cone, market forces switch in the direction of energy prices evolution.

More studies to improve the knowledge of energy transition laws and purchasing power thresholds are required. Accounting for these laws in global energy models may considerably reduce and reshape the "uncertainty cones" of future energy demand and GHG emissions and make local energy and GHG mitigation policies more robust.

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