

Analysis of energy intensity trend as a tool for long-term forecasting of energy consumption

Leontiy Eder  · Irina Provornaya

Received: 4 April 2016 / Accepted: 27 March 2018
© The Author(s) 2018

Abstract The paper presents retrospective developments of energy intensity of the world economy differentiated by regions and their levels of economic development. The analysis has revealed the persistent decreasing trend in energy intensity across all the macro-regions and most countries, showing diversity of its course regarding both the starting point and rate of energy intensity reduction. Based on the time series, it has been shown that energy intensity of an economy is best described by an exponential trend, indicating a fairly uniform decline in energy efficiency in the economies. A power index of the exponential equation is one of the critical parameters characterizing reduction rate of energy intensity—the index of energy intensity reduction (IEIR). The authors have proposed an approach to measuring beta-convergence in time series of energy intensity, substantiating thereby convergence of economies. A comprehensive analysis of the time series and trend model served as a basis for prediction of variation in energy intensity of economies of the macro-regions for the period until 2040, which also included its quality

and rationale verification. It has been shown that the trend method can be successfully applied to forecasting energy intensity developments to economically developed regions, whereas for developing countries such a forecast is less reliable. In these conditions, a comprehensive use of the trend model and the convergence model is necessary. The forecast of changes in energy intensity of the world economies grouped into macro-regions until 2040 has shown that the economically developed countries of Europe will remain to be the energy efficiency leaders until the mid-twenty-first century. The energy intensity indicators for less developed regions will gradually converge in their domain; yet, they are not expected to reach the level of the economically developed countries by 2040.

Keywords Energy intensity · Forecasting · Macro-regions · Convergence · Industrially developed countries · Developing countries

L. Eder (✉)

Institute of petroleum Geology and Geophysics of the Siberian branch of the Russian Academy of Sciences, Novosibirsk State University, Economics Department, 3 Koptyg Av., Novosibirsk 630090, Russia
e-mail: EderLV@yandex.ru

I. Provornaya

Institute of Petroleum Geology and Geophysics of the Siberian branch of the Russian Academy of Sciences, Novosibirsk State University, 3 Koptyg Av., Novosibirsk 630090, Russia
e-mail: Provornayaiv@gmail.com

Introduction

The novelty of the study consists in the following. Based on a large amount of econometric data, it has been shown that reduction of energy intensity takes place not linearly in the regions but is described by an exponential function; therefore, reduction in the energy intensity occurs uniformly in time. At the same time, regions have different initial levels of energy intensity and different energy intensity reduction rates. The authors have proposed an approach to determining

convergence of the series of energy intensity in an economy. The specific nature of the proposed approach is checking convergence of the series not for equal time lapses but considering the starting point of energy intensity reduction. The presence of convergence was checked for 108 countries of the world grouped by macro-regions. The authors have demonstrated that the trend method may be successfully applied to forecasting energy consumption in economically developed regions, whereas the use of additional forecasting tools is required for assessing the energy intensity of developing economies.

Analysis of the current state and forecasting the future state of the energy sector are some of the key components of forming a long-term policy of sustainable economic development (Pirlogea and Cicea 2012). The nexus of energy consumption, economic growth, and environmental protection is an important factor in this respect (Omri 2013).

The approaches to simulation and forecasting of the world energy sector essentially differ. Pfenninger et al. (2014) have analyzed the existing models of energy consumption for different families of models. The authors identify four main groups of models: (1) optimization models, (2) imitation models, (3) models of the electric energy market, and (4) qualitative and aggregate models. There are other types of models, as well, but these four are the key groups related to the modern energy policy. In the first group of methods, imitation and forecasts are important; in the second group, optimization and scenarios are essential. In reality, these distinctions may be blurred, and models may have features of both approaches, depending on the context of the studies conducted and the degree of particularization of different aspects of economic analysis.

The objective of this study is to investigate the possibility of forecasting the energy intensity of an economy based on analysis of time series (on the top-down principle), with differentiation by micro regions. In accordance with the objective set, we stated the following tasks which determined the structure of work as a whole:

- (1) Trend analysis of the energy intensity of the economy, with differentiation by macro-regions,
- (2) Studying sustainability of the time series of energy intensity in the economy by regions,
- (3) Checking for convergence of energy intensity in different regions,

- (4) Forecasting energy intensity, as a basis for determining the development prospects of energy consumption as a whole,
- (5) Determining the quality of forecast evaluation.

The above approaches to forecasting development of the global energy consumption in general and for certain groups of countries and macro-regions may be applied based on the top-down and bottom-up principle (Böhringer and Rutherford 2005). Originally, the optimization models were formed using the bottom-up principle, based on detailed consideration of consumption of individual energy carriers with a high degree of particularization. Aggregation of such estimates allows calculation of total energy consumption and assessment of changes in the structure of the fuel-and-energy balance. Best known are the models of MARKAL/TIMES (Fishbone and Abilock 1981; Loulou and Labriet 2008; Hourcade et al. 2006; Messner and Schrattenholzer 2000; Strachan and Kannan 2008), MESSAGE (Schrattenholzer 1981), and OSeMOSYS (Howells et al. 2011). As a rule, such forecasts are detailed enough; they take into account the seasonal component and are characterized by a short forecasting period.

The forecasts made using the imitation modeling principle are also based on the bottom-up approach and include retrospective analysis of energy consumption. Such imitation models consist of several units forming a single integrated unity. The degree of calculation particularization may vary in the units, up to consideration of specific technologies, taking the use of optimization models into account. Here, the models NEMS (Gabriel et al. 2001), PRIMES (E3Mlab 2008; European Commission 2011), and LEAP (SEI 2012) stand out.

When forecasting energy consumption in the framework of the top-down approach, one can analyze directly the energy consumption trends and their relation to different factors, primarily the economic growth rates, the population growth rates, etc. (Frei et al. 2003). At the same time, it is possible to consider specific parameters, for example, the energy intensity of an economy, as a ratio of energy consumption and the GDP growth (Chang 2014). Another widespread parameter is the energy consumption per capita, as a ratio between energy consumption and the population size (IAEA 2005). It is to be noted that a sufficiently complete system of factors influencing the behavior of energy intensity has been formed over the recent years (Ang and Liu 2003).

There are numerous studies dedicated to analysis of trends for both energy consumption as a whole and its specific characteristics. Messner and Strubegger (1987) proposed an approach to forecasting energy consumption trends considering the economic growth and development rates and development of technologies. Harel and Baguant (1991) investigated the ratios between the electric energy consumption trends and GDP and elasticity coefficients. Ang (1992) modeled the dynamics of energy consumption using growth curve models. Heffington and Brasovan (1994) developed mathematical models of growth curves to forecast the level of oil reserves in the USA. Mackey and Probert (1994) proposed modified logistical functions for forecasting the demand for crude oil and natural gas based on saturation curves, to extrapolate the respective energy intensity values. Multi-logistical models of energy consumption in the household sector were developed by Reddy (1995). Rao and Parikh (1996) analyzed the demand for petroleum products in India, using a translog econometric model based on the trends in time series. Using a univariate Box-Jenkins time series and the ARIMA models, Gonzales et al. (1999) proposed an approach to forecasting production and energy consumption in Spain. Kadoshin et al. (2000) analyzed the time series of energy consumption considering the population growth and economic development.

In modern literature devoted to energy consumption, a special place is occupied by the studies aimed at substantiating the key parameters and factors in the forecasting model.

Modern researchers place special emphasis on analyzing the inter-relation between the GDP and economic activity, eventually affecting the developments of energy intensity in an economy (Dergiades et al. 2013; Fuinhas and Marques 2012; Yuan et al. 2008; Baranzini et al. 2013). It is noted that energy consumption in economically developed countries is much more resilient to drastic changes in the economic situation than in developing countries. A reciprocal process of changes in energy consumption, which exerts essential influence on the economic growth, is possible, too (Chiou-Wei et al. 2008).

A number of studies indicate the existing sustainable trend for reducing the energy intensity in different groups of countries. In these studies, most authors focus on analyzing the degree of technologies' influence on reduction of energy intensity in practically all the economic sectors (Voigt et al. 2014). They demonstrate that

reduction of energy intensity in economically developed countries is primarily related to improvement of technologies in the industries and, to a lesser degree, to structural changes in the economy. In developing countries, structural changes in the economy are more important, or both processes are equally significant.

An important aspect of the retrospective analysis of energy intensity of an economy is differentiation of countries by their level of economic development into industrially developed and developing countries (Miketa and Mulder 2005; Duro et al. 2010).

Convergence of energy intensity has been investigated most thoroughly in literature. However, the conclusions of the studies conducted differ regarding convergence of energy intensity. Most authors indicate that the number of countries with sustained energy intensity is limited (Pen and Sévi 2010) and reject the hypothesis regarding convergence of energy intensity in a number of countries of the Middle East, Organization for Economic Cooperation and Development, and Europe (Pen and Sévi 2008).

Special attention is paid to substantiating the starting point of energy intensity reduction. It is shown in Mulder and Groot (2012) that certain countries started to reduce their energy intensity beginning with mid-1990s. Reduction of energy intensity in developing countries and the convergence process are related both to structural changes in the economy and to development of energy-saving technologies, including their diffusion from the developed countries. Therefore, a number of studies are dedicated not only to energy intensity of an economy as a whole but also to energy intensity for individual fossil fuels and alternative and renewable energy sources for developed and developing countries (Herrerias 2012).

In most cases, it is not specified in which prices the GDP is analyzed as one of the characteristics of energy intensity of an economy. However, the use of the GDP calculated by the purchasing-power parity, not by the current exchange rate, is of primary importance for developing countries, especially for such countries as China and India (Liddle 2010).

An important element of analyzing energy intensity is structuring and differentiation of countries based on a geographical principle. Countries with close levels of economic development and situated within one region often have similar models of energy consumption and similar energy intensity behaviors (Markandya et al. 2006).

Convergence is one of the parameters of trend analysis. The issue of convergence of economies of different levels emerged in 1960–1970s, which is related to emergence of the Solow model of economic growth (Solow 1956). The term of “ β -convergence” was introduced by X. Sala-i-Martin (1996).

Over the recent years, there have appeared many studies dedicated to convergence in the energy sector.

As a rule, the results reported in the existing literature either reject convergence or mention essential limitations in the concept of energy intensity convergence. Mulder and De Groot (2007) reject the hypothesis of global convergence, demonstrating the presence of convergence at the local regional levels. Miketa and Mulder (2005) investigated the β -convergence of energy intensity by different industries and regions of the world and came to a similar conclusion. Markandya et al. (2006) investigated the energy intensity in the transitional economies of Eastern Europe and established the signs of convergence to the values of energy intensity in the countries of EU-15. At the same time, differences in the rates of β -convergence are noted. Based on σ - and β -convergence, Ortiz et al. (2009) demonstrated only partial convergence in the energy intensities of the economies of the EU members. Quah (1993, 1996) stressed inconsistency of the σ - and β -convergence criteria for analyzing convergence of time series. He maintained that those criteria were not sufficient and could lead to erroneous conclusions in favor of convergence of energy intensity, for example, in the case of bidirectional convergence of the time series trends of energy intensity.

Data description

The of energy intensity may be calculated by several main methods depending on how the GDP is calculated: (1) by the current exchange rate, (2) by the purchasing power parity (PPP), (3) in fixed prices, and (4) in the current year’s prices. As a result, the level of energy intensity of the economies will be essentially different in different countries and regions. It is assumed in the study that the GDP will be considered by the purchasing power parity, which is significant. Converting GDP using PPP, rather than using foreign exchange rates, does have important implications for developing country data. In

addition, energy intensity of economies was considered both in current and fixed prices.

In addition, depending on the type of energy, it is possible to calculate the consumption of primary and final energy. Primary energy represents the sum of all produced energy sources. Final energy, as a rule, is the consumed electric energy. The paper discusses the energy intensity (primary energy intensity) and final energy intensity (electricity intensity). Methodological approaches to analyzing energy intensity and final energy intensity will be identical.

Statistical data from the Energy Information Administration, the International Energy Agency, the Organization of Petroleum Exporting Countries, the World Bank, and the International Monetary Fund were used as a database for the study.

We calculated the energy intensity of economies by countries and regions as a ratio of energy consumption and the GDP. This allowed grouping of countries according to the objectives set. We sought for sustainable trends and mechanisms of changes in the energy intensity of economies, aggregating the countries according to two main characteristics: the geographic location and the level of economic development. In terms of the geographic location, seven macro-regions were identified: North America, Central and South America, Europe, Africa, APR, the former Soviet countries, and the Middle East. In addition, the macro-regions were differentiated by their level of economic development and were divided into two groups: countries-members of the Organization for Economic Cooperation and Development (industrially developed countries) and countries not incorporated into this organization (developing countries). All the countries of North America were included into the group of developed countries. The countries of Latin America, Africa, and the former Soviet countries were included into the group of developing countries. The European countries and the countries of the Asian-Pacific region were divided between both groups: developed and developing countries. Considering the role and influence of China on the world energy sector, this country was assigned an individual position. Such a breakdown is caused by several factors. Firstly, development of the world energy sector is discussed here in the light of world markets’ functioning and of forming the respective supply and demand of the energy resources on them. Secondly, developed and

developing countries are characterized by different energy consumption models. Thirdly, in the framework of the indicated regions, countries close in terms of their economic development level have similar behaviors of their energy intensities, which allows them to be grouped into respective groups.

Consumption of primary energy resources was analyzed by the data from the British Petroleum Statistic (BP), and data from the International Energy Agency were examined for a number of countries.

In evaluating the energy intensity, the behavior of the GDP was considered both in current and fixed prices. The GDP data in current prices were taken from the International Monetary Fund. To rule out the influence of the price component on the behavior of energy intensity, the GDP values were recalculated into the fixed prices of 2012 using the GDP deflator. The GDP deflator was taken in accordance with the World Bank data. In both cases, the GDP was considered by the PPP.

All the data were examined for the time period of 1980–2015: this period was optimal for considering the behavior of the energy intensity of the economies, based on the available data on the regions. However, given that global energy crises occurred in the considered time interval having an appreciable impact on the level and dynamics of energy consumption, this paper focuses on a shorter period of time spanning from 1990 to 2015. Making forecast from the econometric standpoint requires analysis of longer periods of time in order to obtain valid results. To this end, further shortening of the reviewed time period would be inappropriate.

Theory and methodology

This research consists of five major parts: (1) time series analysis of the world economies and regions with differentiation by their level of development and geographic features; (2) identification of stable trends in the time series of the economy-wide energy intensity with the focus on the onset of decline and the period of energy intensity index (EEI) reduction; (3) trend approximation and selection from time series of the energy intensity of the economy; (4) construction of a convergence model in accordance with the period marked as the onset of decline in energy intensity; and (5) on the basis of selected trends and convergence model, making forecast

for the economy's energy intensity development across the world regions until 2040 (Fig. 1).

Time series analysis of country- and region-specific energy intensity in terms of their level of economic development and geographic features

This section deals with construction and analysis of time series of energy intensities across countries with further differentiation in terms of their level of economic development (developed and developing) and geographic features (the world's macro-regions).

Identification of persistent trends in time series of energy intensity across countries and the world's regions—the onset of decline and the period of energy intensity index reduction

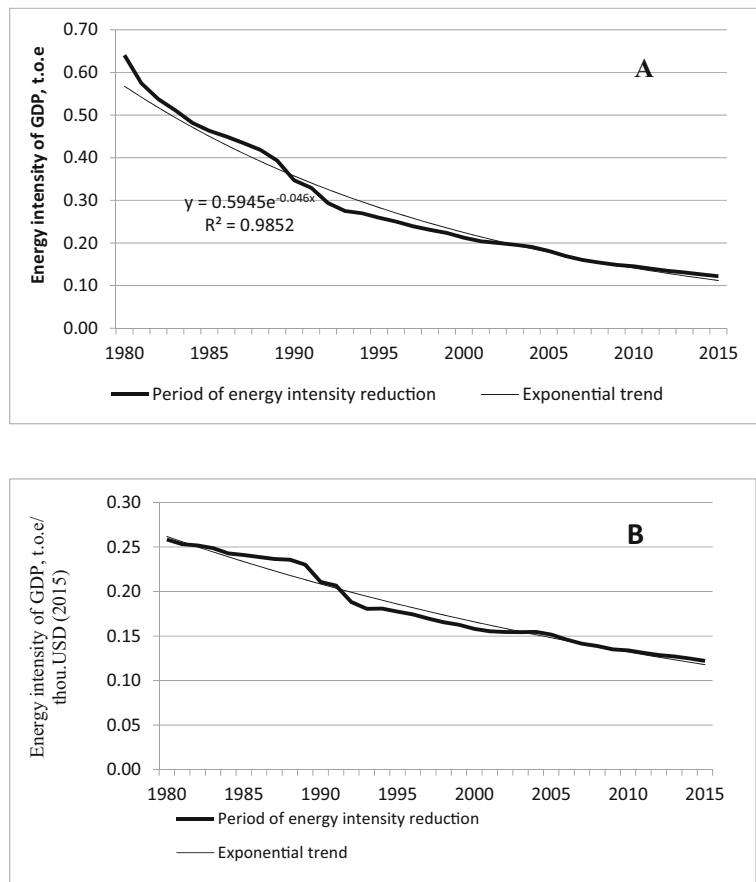
This section analyzes early stages of decline in energy intensity (EI) of the economy, along with the period of EI reduction (i.e., low or negative energy use). The world's developed countries have a longer period of reduction of this indicator. While energy intensity of the developing countries have recently shown a generally declining trend (with the exception of the Middle East, where economic growth continues to be high), the year of its onset and the period of EI reduction for the developing differ across these economies, which indicates the need for a detailed analysis of this phenomenon.

Approximation and selection of the best trend from time series of energy intensity of the economy

In the econometric analysis, it is customary to examine a time series for determinacy and stochasticity in order to reveal regularities to make a forecast. Retrospective trend analysis of the energy intensity of an economy has shown that reduction of the energy intensity of an economy proceeds in accordance with a determined model, i.e., allows application of a trend model to forecasting the future behavior of a subject.

In making a forecast of the energy intensity of an economy, an important step is to reveal the optimal trend describing a change. Selection of the best trend is based on the test-criteria: the determination coefficient, the Fisher criterion, the mean approximation error, and the Student's *t* test.

Fig. 1 Energy intensity of GDP (from PPP) across the world in the current (a) and constant prices (2015) (b)



In accordance with the period when the energy intensity began to decrease, the construction of the β -convergence model

The notion of beta-convergence has earned recognition through its use in the literature for more than 25 years, meaning the time-dependent growth (decrease) rate of the indicator, according to its initial level. This accounts for the fact that with time, the values of time series converge.

Using classical approaches, we offer a number of solutions with which good results may be obtained, allowing demonstration of the presence of convergence.

Traditionally, the rate of absolute β -convergence is evaluated as (X. Sala-i-Martin 1996; Ang 1992):

$$\frac{\ln y_{i,T} - \ln y_{i,0}}{T} = \delta + b * \ln y_{i,0} + \varepsilon_i \tag{1}$$

where $y_{i,T}$ and $y_{i,0}$ are the values of the yield per capita at the terminal and original moments of time; δ is a constant; ε is a random deviation; b is the coefficient

characterizing the process of β -convergence; i is a region or country; T is the duration of the examined time series. If $b < 0$, convergence is observed, if $b > 0$, divergence takes place.

Using the model of β -convergence, we can determine its characteristics: the annual rate of β -convergence (β) and the time (τ) of covering half the distance required for reducing the inter-regional (inter-country) inequality for the parameter in question.

$$\beta = -\frac{\ln(1 + T*b)}{T} \tag{2}$$

$$\tau = \frac{\ln(2)}{\beta} \tag{3}$$

In effect, β -convergence is understood as dependence of the growth rates (reduction rates) of a parameter in time, depending on its original level. This means that, as time goes, convergence of the values of time series takes place.

It is proposed in the study to consider several parameters characterizing the rate of changes in time, which is related to the following factors.

As shown above, there are numerous studies proving the absence of β -convergence of energy intensity of an economy by regions. It is proven that the initial level of energy intensity is poorly related to the dynamics of its reduction. The current studies apply the principle of calculating convergence considering an equal number years in the energy intensity trends.

In our opinion, convergence of energy intensity can be described as the rate of energy intensity reduction depending on the initial value, which has to be considered not during equal spans of time but from the moment of the start of respective reduction in the specific region or country. Such a principle was implemented previously in analyzing economic parameters; however, such an approach has been applied to analysis of energy intensity for the first time.

The paper considers two variants of beta-convergence calculation—the rate of energy intensity reduction by objects in time. The first option is classic, when the energy intensity of the economy is taken at the same time interval, and the second option is author's, when the energy intensity of the economy for each region is taken from the moment the energy intensity begins to decrease.

Classical approach

The values of energy intensity for regions and countries are taken within equal time spans; in the equation, the ratio of the initial (1980) and current energy intensity levels is taken to be a dependent variable, and the level of energy intensity in 1980 is taken to be an independent variable. The parameters are logged:

$$v = \frac{\ln y_{i,2015} - \ln y_{i,1980}}{T_i} \quad (4)$$

where v is the rate of reduction of energy intensity by objects and time.

Authored approach

The values of energy intensity of an economy for each region are taken from the moment of the start of the energy intensity (t_{i0}) reduction; in the equation, the ratio of the initial (the year of the start of reduction) and of the current levels of energy intensity is taken to be a dependent variable, and the level of energy intensity at the moment of the start of its reduction is taken to be an independent variable. The parameters are logged:

$$v = \frac{\ln y_{i,2015} - \ln y_{i,t_{i0}}}{T_i} \quad (5)$$

Calculation of β -convergence was made for 10 macro-regions and 108 countries. Originally, analysis was essentially based on the regions' specific features; and, as only 10 macro-regions were identified, individual analysis was made for the countries of the world to corroborate the established ties.

According to the selected trend and convergence model, the forecasts of energy intensity dynamics for the world's economies have been projected until 2040

This section is devoted to forecasting of energy intensity of regional economies across the world made on the basis of selected trends and convergence model and the construction of confidence intervals, with the confidence level factor to monitor the forecast estimate quality.

The proposal in [“In accordance with the period when the energy intensity began to decrease, the construction of the \$\beta\$ -convergence model,”](#) author's approach, allows to more closely evaluate the target period of the convergence model. In this context, the convergence model can be appropriate for forecasting the energy demand, given that the relevant period of energy intensity reduction is allocated for all the time series under consideration. Thus, on the world's macro-region scale, the onset of long-term reduction of energy consumption in Central and South Americas and Africa was reported in 1999. A retrospective period from 1999 through 2015 was therefore selected for the forecast of energy intensity of the economy of all the considered macro-regions.

Given that the both starting level ($y_{i, 0}$) and the time period for energy intensity analysis ($\frac{\ln y_{i,T} - \ln y_{i,0}}{T}$) are subject to changes, the convergence model is time-dependent. Moreover, the rate of convergence and its determining parameters: coefficients b and δ .

Therefore, it is critical to:

- 1) To construct annual convergence models and to determine the values and long-term trends in changes of the variables under consideration (b and δ).
- 2) Estimate their long-term forecast values, with due consideration of the retrospective analysis of the variables.

Concurrently, a forecast for the energy intensity of the economy is to be made on the basis of trend models. Their results allow to integrate trend models and convergence models in forecasting of energy intensity of the economy, which is particular importance for the time series with periods of energy intensity reduction being not lengthy. Moreover, in this case, the convergence model allows a more

substantiated approach to forecasting the levels of energy intensity in a long-term perspective.

When selecting the best trend for energy intensity of the economy (energy efficiency trends), it is critical to establish an interval (regional) estimate, allowing to more effectively determine the potential intervals for this indicator in the long term.

A confidence interval for a general trend is determined by the formula (Damodar 2004):

$$\tilde{y}_t \pm t_\alpha s_{\tilde{y}} \quad (6)$$

where \tilde{y}_t is the calculated value y_t , t_α is the value of t statistics of Student, and $s_{\tilde{y}}$ is the mean square error of the trend. With the time $t = T + L$, a confidence interval is determined for a trend extended for L units of time.

The relation may be rewritten as:

$$\tilde{y}_t \pm t_\alpha s_y K^* \quad (7)$$

Thus, we obtain an expression for the confidence intervals of a forecast of an exponential trend model:

$$a * n * t * \log(\log \tilde{y}_{t+L} \pm s_y K^*), \text{ где } s_y K^* = t_\alpha s_y \sqrt{1 + \frac{1}{n} + \frac{1}{\sum t^2} t_L^2}$$

The ratio between the value of the trend and the upper bound of the confidence interval may serve as a key parameter reflecting the accuracy of the forecast:

$$D = \left(\frac{\bar{u}_{i,T+L}}{y_{i,T+L}} - 1 \right) * 100, \quad (9)$$

where $\bar{u}_{i,T+L}$ is the upper bound of the level of the energy intensity of an economy for i country or region at the last moment of the forecast L , $y_{i, T+L}$ is the trend model for i country or region at the last moment of the forecast L .

We have thus obtained a trend data-driven consolidated forecast of energy intensity of a given economy taking into account the convergence model.

Empirical results

Characterization of persistent trends in time series of national and global energy intensities

The energy intensity of the regions has been characterized in considerations of a number of parameters: the starting time of energy intensity reduction for i region (t_{i0}), the level of the energy intensity at the beginning of reduction ($y_{i,t_{i0}}$), the level of the energy intensity in 2015 ($y_{i, 2015}$), the energy intensity reduction level from the starting point of the reduction ($\Delta y = y_{i,t_{i0}} - y_{i,2015}$), the reduction rate of the energy intensity of an economy ($v_1 = \Delta y / T$, where T is the number of years), and $t_{1/10}$ —how many years the level of intensity reaches one-tenth of the initial value at the starting point (Table 1).

Table 1 Parameters of energy intensity reduction by regions in 1980–2015

Regions	t_{i0}	$y_{i,t_{i0}}^a$	$y_{i, 2015}$	Δy	v_1	$t_{i, 1/10}$
North America	Before 1980	0.273	0.128	0.145	0.0041	113
Developed countries of Europe	Before 1980	0.209	0.100	0.109	0.0031	133
Developing countries of Europe	1989	0.496	0.087	0.410	0.0158	56
Developed countries of APR	Before 1980	0.163	0.107	0.056	0.0016	150
Developing countries of APR (except China)	1999	0.121	0.096	0.025	0.0016	117
China	Before 1980	0.710	0.152	0.558	0.0159	57
Central and South America	1999	0.120	0.109	0.011	0.0007	72
Africa	1994	0.127	0.083	0.043	0.0021	90
FSU countries	1992	0.530	0.185	0.345	0.0150	45
Middle East			0.167			

^aFor North America, developed countries of Europe, and APR, as well as China

The starting point of energy intensity decline in the economy is selected on the basis of the time series analysis. Given there is a tendency for energy intensity of the economy to decrease over a period longer than 5 years, the first year of such decline is chosen as its onset.

In 1980–2015, the energy intensity of the global economy demonstrated a sustained trend for reduction over the entire period of time in question. Based on the purchasing power parity and expressed in the prices of 2015, the energy intensity dropped by almost twice from 0.258 to 0.122 t of oil equivalent/thousand USD during this period. Calculation of the respective parameter in the current prices showed even more intensive reduction—from 0.5 to 0.185 t of oil equivalent/thousand USD (Fig. 1). Analysis of the behavior of the time series over this period of time has shown uniform reduction of the energy intensity rates of the economies.

The energy intensity of the economy in industrially developed countries in 1980–2015 in the comparable prices of 2015 decreased a little less than twice from 0.258 to 0.122 t of oil equivalent/thousand USD. Reduction of this parameter in industrially developed countries started back in the years of the first energy crisis of 1973–1974. Therefore, the intensity and the process of reduction of this parameter are essentially extended in time and are less expressed than those of the developing countries, which started to join the process much later than the industrially developed countries. The industrially developed countries have largely exhausted their potential of significant reduction of the energy intensity of their economies. In this regard, this

parameter is being reduced at relatively moderate rates. On the contrary, the developing countries are at the stage of fast reduction of energy intensity, which brings the values of their energy intensity close to those of the industrially developed countries.

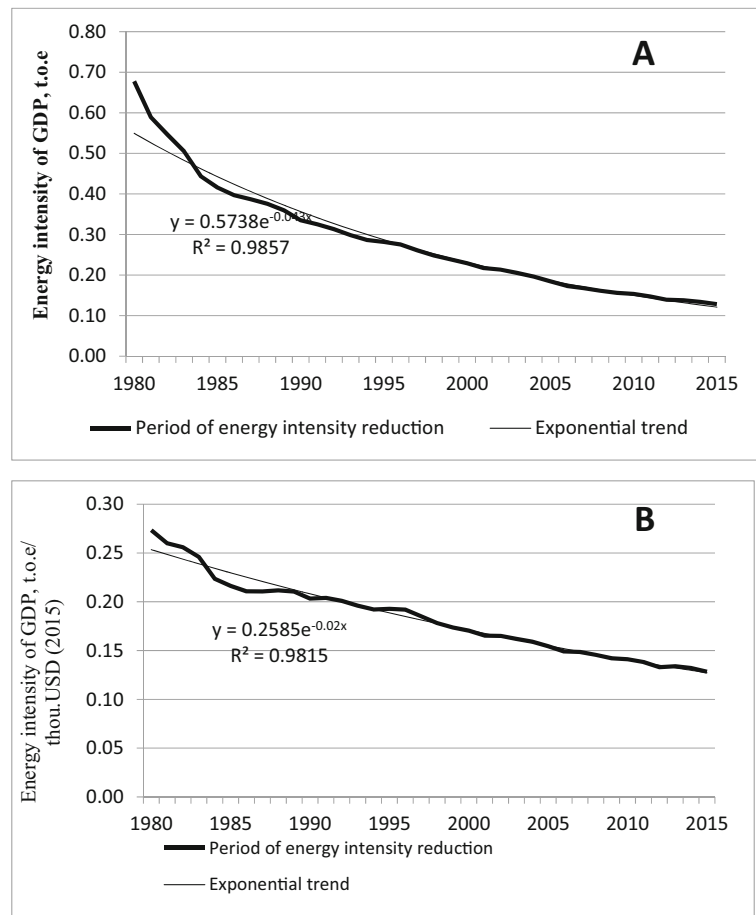
Over the recent two decades, intense reduction of the energy intensity of GDP has been typical of industrially developed countries, even in the regions which have been actively raising this parameter until recently. Reduction of the energy intensity level in industrially developing countries takes place as the economies undergo structural transformations and energy-efficient technologies are introduced. Since 1980, the energy intensity level in industrially developing countries has reduced more than twice from 0.378 t of oil equivalent/thousand USD to 0.166 t of oil equivalent/thousand USD. Since the beginning of 1990, the energy intensity reduction rates have been decreasing.

North America

At the beginning of the 1980s, the USA demonstrated one of the highest values of the energy intensity of its economy measured in 2015 Dollars (0.273 t of oil equivalent/thousand USD), which is related to the energy wasting stereotype of economic behavior, the prevalence of heavy industries, and a high figure of energy use in transport and in the other industries of the economy (Fig. 2).

From the middle of the 1970s, the energy intensity of the US economy began to go down relatively fast. The main period of this parameter's reduction was in the

Fig. 2 Energy intensity of GDP (from PPP) in the countries of North America in 1980–2015, in the current (a) and constant prices (b)



middle of the 1980s. Under conditions of a significant fall of the oil prices, the energy intensity of the economy began to decrease less fast. Over the recent 30 years, the energy intensity in North America has decreased slightly less than by 50% from 0.273 to 0.128 t of oil equivalent/thousand USD. Over the recent decades, the countries of North America have been taking certain efforts to reduce the energy intensity of their economies. The trend for reducing the energy intensity is sustained and does not demonstrate any significant deviations.

The current figures describing the energy intensity of the economies of North America are still much higher than those for Europe, as well as for Central and South America, and are approximately equal to the level of the former Soviet countries (approximately 0.128 t oil equivalent/thousand USD). Since the beginning of 2000s, the trajectory of energy intensity reduction has been close to the average global figure. This is largely explained by a higher level of the average annual

temperatures, the structure of the economy, and a number of other factors.

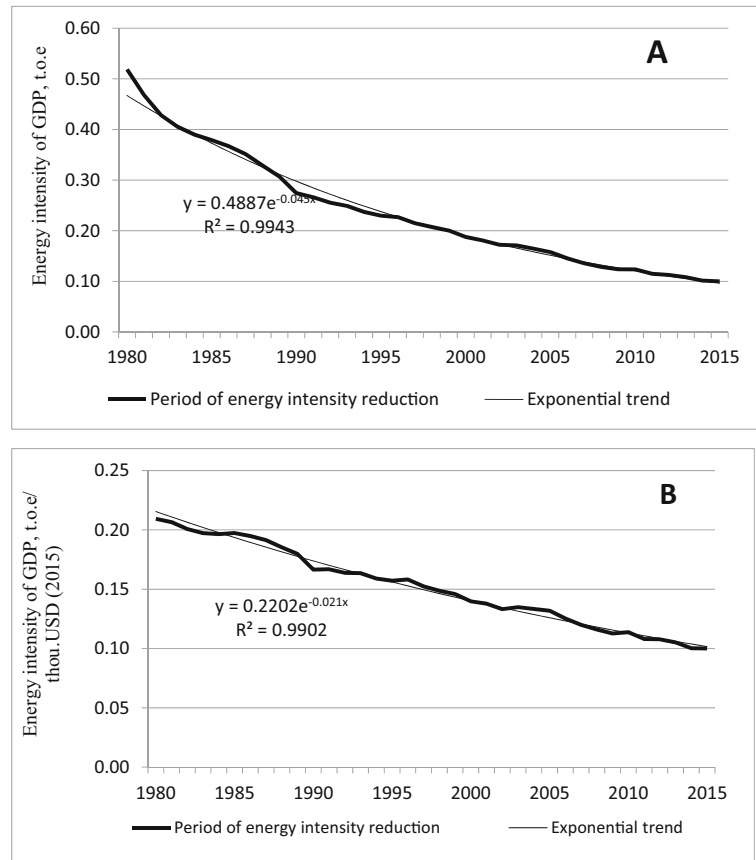
Europe. Industrially developed countries

Currently, the energy intensity level in the industrially developed countries of Europe is the lowest among the regions of the world, including both developed and developing economies (Fig. 3).

Reduction in the energy intensity in the industrially developed countries of Europe started before the beginning of the 1980s; as a result, by this time, the developed European countries have one of the lowest energy intensity figures, compared to the other regions of the world—0.209 t of oil equivalent/thousand USD. The European countries are traditional leaders in conducting the policy of raising the energy efficiency of their economies.

In the period of 1980–2015, the energy intensity of the European economy decreased by 52% to 0.107 t of oil equivalent/thousand USD. Europe demonstrates the

Fig. 3 Energy intensity of GDP (from PPP) in developed countries of Europe in 1980–2015, in the current (a) and constant prices (b)



most sustainable trend for reducing the energy intensity of its GDP, compared to the other regions of the world. This suggests that there is high elasticity between energy consumption and GDP. Fluctuations in the economic situation of the developed economies of Europe lead to symmetrical changes in energy consumption, and this relation in time has a sustainable trend for reduction. Small fluctuations in the energy intensity are related to the specific economic situation, the prices of energy resources, and a number of other parameters.

Under conditions of a limited resource base of the fossil fuels and of conducting environmental policies restricting the CO₂ emissions, the industrially developed countries of Europe became one of the first to pursue a policy of energy-saving and of active reduction of energy consumption in their economies.

Europe. Developing countries

Reduction of the energy intensity in the developing economies of Europe started in 1990s from the highest

level in the world (0.496 t of oil equivalent/thousand USD). In the period of 1980–2015, the energy intensity of these economies reduced by 79%.

The Asian-Pacific region. Developed countries

At the beginning of the 1980s, the developed countries of the APR had one of the lowest levels of the energy intensity of GDP among the industrially developed regions of the world (Europe and North America)—0.163 t of oil equivalent/thousand USD, caused by the fast technological development of Japan, Australia, and the other countries of the OECD.

Over the recent 30 years, the level of the energy intensity decreased and had unstable (sinusoid) behavior, which is related to the impact of the economic crises of the second half of 1990s, which struck the economies of the developed countries of the APR, primarily of Japan. Plunging of the economic parameters brought about certain growth of the energy intensity, however,

after 2000s, time series of the energy intensity returned to the trajectory of 1980s.

The Asian-Pacific region. Developing countries (without China)

The energy intensity of the developing countries of the APR (without China) has a slightly higher level than that of the developed countries of the APR. The extensive growth of the economies and economic industrialization of the developing countries of the APR contributed to the increase of the energy intensity to the average world level. Total reduction of this parameter in the region was recorded only in late 1990s–early 2000s.

At the time of reduction, the energy intensity level in the developing countries of the APR (without China) was about 0.121 t of oil equivalent/thousand USD. Currently, this parameter is about 0.096 t of oil equivalent/thousand USD, while the average value of the reduction rate is about 0.0031 t of oil equivalent/thousand USD, which is a rather fast reduction rate. The developing economies of the APR (without China) demonstrate a steady rate of energy intensity reduction in the period of time considered.

The Asian-Pacific region. China

Over the entire period of time considered, China was actively reducing the energy intensity of its economy. In 1980–2015, the energy intensity of China steadily reduced. Over this period, this parameter decreased by 0.56 t of oil equivalent/thousand USD—from 0.710 to 0.152 t of oil equivalent/thousand USD. This is the most significant reduction of the energy intensity of the economy among all the regions of the world. In terms of annual rate of energy intensity reduction, only developing countries of Europe (0.0158 t.o.e./thousand dollars) and the FSU countries (0.0150) can approach China (0.0159 t.o.e./thousand dollars).

The former Soviet countries

At the beginning of 1990s, the countries of the former Soviet Union had the highest level of the energy intensity of their economies. The structural social and economic crisis of 1990s and the low efficiency of the economy in general essentially influenced the efficiency of energy consumption, too (Korzhubaev et al. 2009, Kontorovich et al. 2012).

However, completion of a stage of certain institutional transformations in the economies of the former Soviet countries and the growth of prices for oil and gas allowed those countries significantly to raise their GDP without noticeable increase in the energy consumption level, which positively influenced the value of energy intensity of GDP, which has decreased by more than 2.5 times over recent 20 years. Another factor of reducing the energy intensity of the former Soviet economies is decrease of the share of energy-intensive industries in the economies, primarily machine-building, in the general production.

In addition, programs for reduction of energy intensity were adopted in the economies, which allowed the effectiveness of energy consumption to be raised (Kontorovich et al. 2008, 2013, 2016).

Central and South America

In Central and South America, the energy intensity of the economy in the current prices was reducing over the entire period of 1980–2015, whereas in fixed prices this parameter increased until the late 1990s. Over the recent decade, the trajectory of the energy intensity reduction in the economies of Central and South America coincided with the respective trend of the industrially developed countries. Currently, the energy intensity of the countries of Central and South America is rather low (about 0.109 t of oil equivalent/thousand USD).

Africa

In Africa, just like in Latin America, reduction of the energy intensity in current prices has continued for the recent 30 years. However, in the fixed prices, this process started only from the middle of the 1990s.

In the early 1980s, Africa had a relatively low industrial level of development. The energy intensity of the African economy was nearly two times lower than the respective value for North America and nearly 1.5 times lower than that of the APR. However, the growth of the industrial sector in the structure of the GDP boosted the increase in the energy intensity. This process continued till the beginning of the 1990s, followed by stabilization, and from the end of the 1990s, steady reduction of the energy intensity began to be observed. The behavior of the energy intensity reduction over the considered period is very close to that of Latin America and the countries of OECD.

Middle East

Among other considered regions, only the Middle East thus far has shown no decreasing trend in energy intensity of the economy. In the countries with a supernormal level of the oil and gas production sector, where the main income of the state is formed by the export of energy carriers, the changes in the energy intensity of the economy are largely related to changes in the energy prices on the world market.

As a result, considering essential volatility of the world oil prices, it is practically impossible to speak about stabilization of the existing trends regarding the energy intensity changes in the countries of the Middle East.

Approximation and selection of the best trend for describing retrospective analysis of energy intensity

In this work, selection of the trend most suitable for describing the energy intensity of an economy was based on complex comparative analysis of such parameters as R^2 , the coefficient of determination, A , the average approximation error, S , the mean-square deviation from the trend, t statistics, and F criterion. It was established based on the statistics calculated that the behavior of the energy intensity reduction of the economy in the entire world, in individual macro-regions and in most countries, both in the current prices and in the prices of 2015, is described by an exponential function. Verification of the results and conduct test data (for the last 25–30 years) for energy intensity and final energy intensity are presented in Appendix Tables 7 and 8.

Formalization of an exponential trend record

Considering the basic factors being part of the exponential function responsible for the energy intensity reduction dynamics in the economy:

$$y = b_0 + b_1 * e^{-\gamma t} \quad (10)$$

where b_0 —asymptote, b_1 —index determining initial energy intensity of the starting year, γ —energy intensity reduction index (EIRI), and t —the current year.

Introduction of the asymptote b_0 to the exponential model requires a special rationale for the level to which the energy intensity of the economy will strive. The abscissa designates the actual level. Exponential trend

of energy consumption will tend to zero throughout the time, never reaching it, though. To this end, it is assumed that $eb_0 = 0$.

Industrially developed regions

Reduction in the energy intensity of the economies of Europe and North America has a long history, and over the entire period, the trend is well approximated by an exponential function. The time series of these countries may be taken as samples with which the time series of the developing countries of the world will be further compared.

In accordance with statistical analysis, the exponential trend for the developed countries of Europe best describes the behavior of the energy intensity of the economies. The statistical parameters for North America have close values.

Analysis of the behavior of the energy intensity of the developed countries over 35 years (1980–2015) has shown that reduction of this characteristic in time occurs non-linearly. Uniform decrease of the reduction rates of the energy intensity in an economy took place, with small fluctuations of this parameter, related to changes in the economic situation, changes in the world energy carrier prices, and a number of other parameters.

At the early stage, when respective programs are conducted for energy-saving and gradual change in the structure of the economy (the growth of the services segment), intense reduction of the energy intensity takes place. Then the energy intensity reduction rates for the industrially developed countries become more moderate. As the energy-saving technologies are introduced, essential reduction in the total potential of saving fuel and energy takes place, given the existing technologies. At the final stage (2000s), the reduction rates of the energy intensity in the economy are characterized by relatively low values. This is related to the fact that the larger part of the energy-saving potential has already been exhausted for the existing level of technological development. Each subsequent reduction of energy intensity is possible due to significant investments and use of the newest technologies.

The conducted econometric analysis has shown that for the majority of the world's regions, the time series of the energy intensity of the economy can be best described by an exponential trend. In case of the developed countries, the exponent describes well the time series of the energy intensity of the economy over the entire 1980–2015 period.

Additionally, a shorter period of time spanning from 1990 through 2015 was considered for the world's developed economies. The analysis showed that the existing trends in energy intensity of the economy are described well also by an exponential trend.

When forecasting the energy intensity of the economy, the use of the linear trend will lead to a virtually zero level of energy consumption in the next decade.

Developing regions

Analysis of the econometric characteristics of the developing countries shows that, apart from the exponential function, time series are well described also by linear trends. This is related to the fact that the developing regions (Africa, Central and South America, and Asian-Pacific region without China) have a rather short-term tendency of energy intensity reduction. In fact, these regions are at the initial stage of energy intensity reduction; therefore, in addition to the exponential function, this process is also well described by a linear dependence. However, in the course of time, the reduction rates of energy intensity reduction will begin to decrease, and in this case, the linear function will give way to the exponential function.

Besides the exponential function, the energy intensity of China is also well described by a logarithmic relationship. This is related to a more intense period of energy intensity reduction at the first stage, compared to the subsequent dynamics of this parameter's reduction.

Developing countries have a shorter period of time of energy intensity reduction versus the developed countries. Given a shorter period of time, the linear trend also shows good econometric indicators. However, over a longer period of time, the uneven behavior of energy intensity reduction is manifested more expressly.

The trends in energy intensity of the economy and the IEIR values differ for developed and developing economies due to their specific features related to several key characteristics:

- Developed countries, primarily those of Europe, have relatively low starting levels of the energy intensity reduction and, accordingly, moderately low rates of energy intensity reduction (IEIR for the developed countries of Europe is 0.021 that for the countries of North America is 0.020) (Table 2). These countries launched the policy of reducing the energy intensity of their economies earlier than the

Table 2 IEIR of the large macro-regions of the world

Region	IEIR
North America	-0.020
Developed countries of Europe	-0.021
Developed countries of APR	-0.006
Developing countries of Europe	-0.063
Developing countries of APR without China	-0.016
Central and South America	-0.013
Africa	-0.022
FSU countries	-0.058
China	-0.044
Middle East	

developing countries; therefore, the process of reducing the energy intensity was rather uniform and long-lasting. In addition, this reduction was accompanied by respective gradual development of the energy-saving technologies.

- During the 30 years considered, the reduction rate of the energy intensity of GDP of developing countries was much higher than that of the developed countries (the former Soviet countries—0.058, developing countries of the APR without China—0.016, China—0.044, Africa—0.022). This is related to the fact that, given the existing technologies, developing countries accomplish the distance as far as the low level of energy intensity within a shorter time. In literature, such a phenomenon was called the “the catching-up development.”

As it will be shown below, the reduction rate of the energy intensity in the countries and regions is largely related to the starting level of the energy intensity. This phenomenon is called “convergence.”

Similar data were obtained in final energy intensity in both current and constant prices. At current prices, the situation is most determined due to the effect of inflation (Appendix Table 8). In this regard, statistical verification was carried out in constant prices. However, even in constant prices, the trends are best described by the exponential trend since the start of the sustained decline of final energy intensity.

Similar results were obtained in the analysis of energy consumption in the transport sector (Eder and Nemov 2017; Eder et al. 2017).

Construction of a convergence model in accordance with the starting period of decline in the energy intensity of the economy

As shown earlier, there exist numerous studies showing the absence of β -convergence of the energy intensity of economies by the regions. It was shown that the starting level of the energy intensity of an economy is weakly related to the rate of its further reduction. In calculating convergence, the preceding literature has used the principle of considering the energy intensity trends within equal periods of time (years).

At the same time, in the authors' opinion, convergence of energy intensity which is the reduction rate of the energy intensity depending on the initial value of a country or a region should be considered not during equal periods of time but from the moment of the start of respective reduction in the specific region or country. In this case, there is a close tie between the starting value and the rate of the current reduction of the energy intensity.

This paper discusses two approaches (classical and authored) for calculating beta-convergence values:

1. Classical variant. Energy intensities of the regions are taken on the same time interval ($t_{i1980} - t_{i2015}$), while the ratio of the energy intensity of the economy as of 1980 to the current level of energy intensity takes the logarithm, i.e., it is reduced to a linear trend;
2. Authors' variant. The values of the energy intensity of the economy for each region are taken from the moment when energy intensity begins to decrease ($t_{i0} - t_{i2015}$), while the ratio of the initial to the

current energy intensity levels take the logarithm, i.e., they are reduced to a linear trend.

β -Convergence with differentiation by the regions

Analysis of the calculations made has shown that there is β -convergence by the regions. However, traditional approaches to β -convergence demonstrate not very good results—classical variant (Table 3). For the best variant (authored), the annual convergence rate was determined, which constituted 3.9%, as well as the time required for halving inter-regional inequality of the energy intensities of the economies, which amounted to 13.9 years.

β -Convergence with differentiation by the countries

Analysis of the presence of β -convergence uses the countries which have entered the stage of reducing their energy intensity, i.e., they are moving towards reduction, and not the countries which demonstrate a trend for the growth of this parameter. This is related to the fact that a hypothesis is tested that the rate of reducing the energy intensity is related to the initial level of this parameter and the principle of the catching-up development in the economy. To check the existence of β -convergence, 96 countries were analyzed, in which the reduction of the energy intensity was observed for more than 5 years.

In accordance with the evaluations of the convergence of the energy intensity of the countries' economies by two variants, it was demonstrated that the authors' approach to evaluation of convergence of the

Table 3 Assessment of the unconditional convergence model for the economies of ten (10) regions of the world (significance level 0.05)

Variable		Coefficient	Standard error	<i>t</i> statistics	<i>P</i> value
Classical approach					
Constant	<i>b</i>	−0.0577	0.003042	−18.9692631	4E−09
Logarithm for energy intensity of economy in 1980	$\frac{\ln y_{i,2015} - \ln y_{i,1980}}{T}$	−0.0247	0.003621	−6.820378638	5E−05
Coefficient of determination: 0.6231					
Authored approach					
Constant	<i>b</i>	−0.048	0.012	−3.992	0.003
Logarithm for energy intensity of economy in the starting year of energy intensity reduction	$\frac{\ln y_{i,2015} - \ln y_{i,t_{i0}}}{T_i}$	−0.028	0.008	−3.478	0.006

Coefficient of determination: 0.9105

energy intensity shows the best results (Table 4). The annual convergence rate determined according to the authored variant accounted for 3%, and the time required for halving the inter-country inequality of the energy intensities of their economies amounted to 22 years.

Thus, establishing the presence of β -convergence among countries and regions is a rather important aspect of forecasting the behavior of energy intensity for a long-term perspective, as it allows analysis of the degree of energy intensity reduction depending on the starting level of the respective process. However, this regularity is manifested for a number of countries which have entered the phase of active reduction of the energy intensity. If a country continues increasing this characteristic, it is sufficient to determine the time of the start of its reduction, in order to understand how fast the country or the region will implement the strategy of the catching-up development.

Forecasting the energy intensity

Based on the analyzed time series, a forecast was made for changes in the energy intensity of an economy for a long-term perspective till 2040.

All the regions (except for the Middle East) considered have entered a steady phase of energy intensity reduction of their economies. However, only the developed countries (Europe, North America, and the Asian-Pacific region), as well as China, are characterized by reduction of energy intensity throughout the entire period of time considered—1980–2015. At the same time, developing countries have a relatively short period of

time (11–21 years) for building satisfactory forecasting models. Industrially developed countries (Europe and North America) have a sufficiently high value of the coefficient of determination and a low mean-square deviation value. In addition, the time series of energy intensity is well described for the developing countries of the APR, China, Africa, the countries of the former USSR, and South America.

Divergence of the confidence limits from the trend value is a significant parameter characterizing the quality of these forecast estimates made. For the developed countries of Europe and North America, the width of the confidence interval is within 5–1%, which is a very low figure, characterizing the quality of the model selected and the adequate forecasting value of the trend (Fig. 4). Parameter D for the developing countries of the APR, Africa, and South America is below 30%, indicating certain divergence of the confidence interval from the trend values. The distance from the trend to the confidence limits for the countries of the former USSR and the developing countries of Europe exceeds 100%.

Calculation of the respective statistics for the considered macro-regions has shown that a relatively satisfactory forecast of energy intensity on the basis of a trend may be made only for the developed regions of the world. Developing a reliable forecast of energy intensity for the developing regions of the world on the basis of retrospective analysis of the behavior of this parameter does not provide satisfactory evaluations.

When making forecasts for the energy intensity of the economy with the use of convergence model, we analyzed δ —constant and b —coefficient from 1999 (the year in which energy intensities were decreasing across all regions) to 2015. It was found that within a relatively

Table 4 Assessment of the unconditional convergence model for the economies of 96 countries of the world (significance level 0.05)

	Variable	Coefficient	Standard error	t statistics	P value
Classical approach					
Constant	b	−0.029	0.003	−9.652	0.000
Logarithm for energy intensity of economy in 1980	$\frac{\ln y_{i,2015} - \ln y_{i,1980}}{T}$	−0.010	0.001	−6.571	0.000
Coefficient of determination: 0.3194					
Authored approach					
Constant	b	−0.0635	0.0034	−18.8226	0.0000
Logarithm for energy intensity of economy in the starting year of energy intensity reduction	$\frac{\ln y_{i,2015} - \ln y_{i,t_0}}{T_i}$	−0.019	0.002	−9.908	0.000

Coefficient of determination: 0.6507

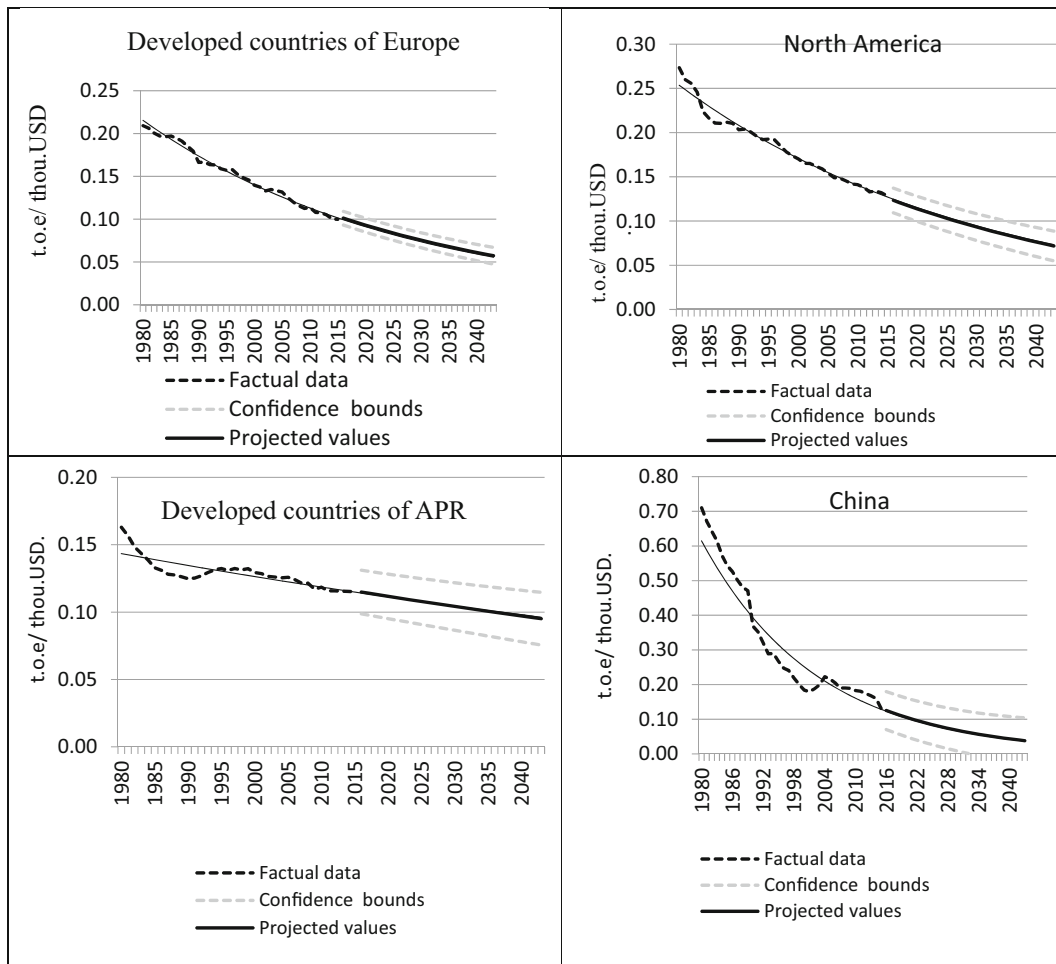


Fig. 4 Calculation of confidence intervals and projected estimates for energy intensity until 2040

stable period from 1999 to 2007, there was a fairly high convergence of energy intensities of the economies of the world's regions and the relationship between the initial level and the rate of subsequent reductions.

At a time of unstable situation of the global energy market, such a bond tends to be lost, though. With the stabilization of world prices for energy raw materials, convergence parameters rebound to the pre-crisis values. Generally, we note an increase in the rate of

convergence of the regions in energy intensity of the economies (δ and b). As a result, it was accepted in this work that this trend will continue until 2040, intermittent with some fluctuation periods, and the values of δ are projected to be 0.13 and b to be 0.05 (Table 5).

The value of the forecast energy intensity of the economy can be affected by fluctuations. However, as shown by statistics over the past 30 years, developed regions show stable dynamics of reduction of energy

Table 5 Parameters of unconditional convergence for energy intensities of the economies of ten (10) regions of the world from 1999 through 2040

	1999	2001	2005	2007	2008	2009	2013	2014	2040
b	-0.032	-0.033	-0.034	-0.028	-0.016	-0.024	-0.041	-0.035	-0.050
δ	-0.08	-0.08	-0.09	-0.08	-0.05	-0.07	-0.10	-0.09	-0.13
Determination coefficient	0.69	0.60	0.59	0.58	0.13	0.20	0.24	0.61	

intensity of the economy with relatively minor fluctuations (Europe, North America). Therefore, in the long term, the value of the intensity may slightly vary from the established trend. In developing regions, which have not a long period of reduction of intensity, fluctuations become stronger. Possible fluctuations are taken into account in the confidence intervals.

The value of the forecast of energy intensity can influence the possible fluctuations of the energy intensity of the economy. However, as shown by statistics over the last 30 years, the developed countries show stable dynamics of reduction of energy intensity of the economy with relatively minor fluctuations. Therefore, in the long term, the energy intensity of the economy can vary slightly within the established trend. Developing regions, which have a relatively long period of reduction of energy intensity at the moment, they are more prone to fluctuations. Actually, possible fluctuations are taken into account when constructing forecasts using confidence intervals.

Thus, the values obtained on the basis of trend and convergence models are found to be identical in this research.

The forecasts made have shown that the developed countries of Europe will remain leaders for the level of the energy intensity of their economies at least till the middle of the twenty-first century (Fig. 5). The other regions will gradually converge, but they will not be able to reach the level of the developed countries. To a large degree, reduction of the energy intensity will be determined by the level of technological development, primarily, by the level of energy-saving technologies

and the shifts in the structure of the economy. According to the authors' estimates, in 2040, the energy intensity ($y_{i, T+L}$) of the developed countries of Europe will decrease to 0.057 t of oil equivalent /thousand USD, that of the APR will reduce to 0.095 t of oil equivalent /thousand USD, and that of North America will drop to 0.072 t of oil equivalent /thousand USD. China is also expected to reduce its energy intensity of (at about 0.059 t.o.e/thousand USD) in 2040. Besides, the countries of Africa (0.068 t of oil equivalent/thousand USD) and of Central and South America (0.075 t of oil equivalent/thousand USD) will retain the relatively low levels of the energy intensity. Despite the accelerated reduction of the energy intensity in developing countries, these regions will be characterized by relatively low values of effectiveness of energy consumption in 2040, too. The value of the energy intensity in the developing countries of Europe may reduce to 0.069 t of oil equivalent/thousand USD, that in the countries of the former Soviet Union may drop to 0.094 t of oil equivalent /thousand USD, that in the developing countries of the APR (without China) may amount to 0.109 t of oil equivalent/thousand USD (Table 6).

Changes in the energy intensity of the economies of the regions considered for a long-term perspective may be analyzed by comparing such parameters as (1) the ratio between the energy intensity of the economy at the current moment and that at the start of its reduction ($\frac{y_{i,T}}{y_{i,t_0}}$) and (2) the ratio between the energy intensity of the economy in 2040 and that at the current moment ($\frac{y_{i,T+L}}{y_{i,T}}$). As a result, within the nearest 25 years, reduction

Fig. 5 A trend-based aggregate forecast of energy intensity with convergence model taken into account until 2040 (1980–2015—factual data)

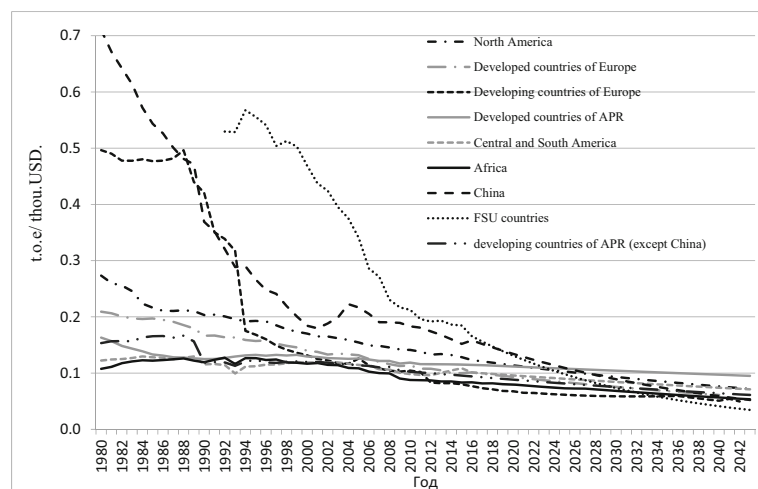


Table 6 Basic quality parameters of the long-term energy intensity forecasts

Regions	$\frac{y_{i,2015}}{y_{i,t_0}}$	$\frac{y_{i,2015+L}}{y_{i,2015}}$	2040			
			$\bar{u}_{i,2015+L}^*$	$y_{i,2015+L}$	$u_{i,2015+L}^*$	D
Developed countries of Europe	0.478	0.574	0.067	0.057	0.048	16.971
Developing countries of Europe	0.199	0.417	0.122	0.069	0.016	76.812
FSU countries	0.532	0.335	0.210	0.094	0	123.032
Developing countries of APR without China	0.778	0.578	0.126	0.109	0.092	20.783
China	0.214	0.344	0.129	0.059	0	118.644
Developed countries of APR	0.707	0.826	0.115	0.095	0.076	20.588
Central and South America	0.908	0.607	0.095	0.075	0.054	27.608
Africa	0.657	0.567	0.084	0.068	0.052	23.966
North America	0.469	0.560	0.089	0.072	0.055	23.416

Source: the author's calculations

of the energy intensity in the developed countries will be not as fast as over the preceding 30 years. On the contrary, the developing countries may essentially reduce the energy intensity of their economies: the countries of the former Soviet Union may reduce the value of this parameter from 0.53 to 0.33 t of oil equivalent/thousand USD, those of the APR may reduce it from 0.77 to 0.58 t of oil equivalent/thousand USD, the countries of Africa may reduce it from 0.66 to 0.57 t of oil equivalent/thousand USD, and the countries of Central and South America may reduce the energy intensity of their economies from 0.91 to 0.61 t of oil equivalent/thousand USD. This is related to the fact that duration of the period of reduction of the energy intensity for developed economies is 10–20 years, and therefore, the main phase of reduction of this parameter may be observed in the nearest 25 years. For regions whose lower boundary hits values lower than zero with time, this boundary is assumed to be zero lower boundary.

In the Persian Gulf countries, consumption of energy resources displays poor elasticity for the behavior of economic parameters and is characterized by relatively low effectiveness. In the perspective, the energy intensity of the economy will be largely determined by the behavior of the GDP and hence by the oil and gas prices.

Conclusion

The retrospective analysis of the behavior of the energy intensity by the regions allows a number (except for the

Middle East) of conclusions to be made: all the largest macro-regions of the world have started the process of reducing the energy intensity of their economies; the starting point and the degree of intensity of these processes essentially differ. In 1980–2015, practically all the regions, except for the economies of the Middle East, cut down the energy intensity of their economies in current prices. However, in fixed prices, this trajectory is primarily typical, in fixed prices, of the developed economies of North America, Europe, and the APR. In fixed prices, the energy intensity of the economies of Central and South America, Africa, and the former Soviet Union entered the trajectory of steady reduction of this parameter in 1990–2000.

Based on the comparative analysis of the existing econometric characteristics, it has been shown that the exponential trend is the best trend describing the energy intensity of an economy in permanent and variable prices both for developed and developing regions of the world. The figures shown serve as qualitative description of time series by an exponential trend, especially of the developed regions. At the same time, the time series of the developing regions of the world demonstrate volatility in relation to this trend.

The presence of the exponential trend in the energy intensity reduction indicates that the rates of enhancing the efficiency of energy consumption reduce uniformly in time. The retrospective analysis of exponential reduction of the energy intensity of the developed countries and regions may be arbitrarily divided into several stages. At the first stage, when respective programs of energy-saving

are conducted and gradual changes in the structure of the economy take place (the growth of the services sector), the most drastic reduction of the energy intensity occurs. Then, as the energy-saving technologies are introduced, the total potential of saving fuel and energy diminishes, given the existing technologies. Over the recent 35 years, the developed countries of Europe and North America may be viewed as exemplary regions with which the developing regions will be further compared. The developing regions are primarily at the first stage of energy intensity reduction; therefore, apart from the exponential trend, these regions are well described by a linear trend.

The exponent of a power in an exponential equation is one of the most important parameters characterizing the reduction rate of energy intensity of the economy in the countries and regions. In this work, this parameter is named the index of energy intensity reduction—IEIR. This index indicates the reduction rate of energy intensity of the economy in the countries and regions.

The issue of convergence of the energy intensity of the economy of the countries and regions is widely discussed in the modern literature. Over the recent 35 years, the spread of values of the energy intensity of the economy has reduced by more than 1.5 times, with the exception of the Middle East. Countries and regions are drifting together for the level of their energy intensity. In the existing approaches, one of the principles of calculating the β -convergence is analysis of the time series at equal intervals of time. At the same time, it is proposed in this work to consider β -convergence for countries and regions not at equal intervals of time but from the moment of the start of reduction for each specific region. In this work, a close relationship is demonstrated for countries and macro-regions between the rate of energy intensity reduction and the initial value of the energy intensity considered.

When making forecasts for the energy intensity of the economy with the use of convergence model, we analyzed δ —constant and b —coefficient from 1999 (the year in which energy intensities were decreasing across all regions) to 2015. It was found that within a relatively stable period from 1999 to 2007, there was a fairly high convergence of energy intensities of the economies of the world's regions and the relationship between the initial level and the rate of subsequent reductions.

At a time of unstable situation of the global energy market, such a bond tends to be lost, though. With the

stabilization of world prices for energy raw materials, convergence parameters rebound to the pre-crisis values. Generally, we note an increase in the rate of convergence of the regions in energy intensity of the economies (δ and b). As a result, it was accepted in this work that this trend will continue until 2040 intermittent with some fluctuation periods.

Based on the time series analysis, forecast of the change in the energy intensity of the economy was made for a long-term perspective till 2040. The resulting forecasts have shown that the level of energy intensity of developing economies will gradually converge to catch up with the level of energy intensity of the developed economies.

To a large degree, reduction of the energy intensity will be determined by the level of technological development, primarily, by the level of energy-saving technologies and the shifts in the structure of the economy.

The study of the quality of the forecasting estimates is an important aspect in this respect. The quality of the forecast made will be determined by the duration of the retrospective analysis and the number of the points observed, the coefficient of determination, the mean square deviation of the actual values from the trend, and the ratio between the trend value and the upper confidence limit (2040). Calculation of the respective statistics for the considered macro-regions has shown that a relatively satisfactory forecast of energy intensity on the basis of a trend may be made only for the developed regions of the world. Making a forecast of energy intensity for the developing countries is much less reliable, and here, too, essential variations may be observed. To forecast development of the world energy sector for developing countries, it is necessary to analyze a large number of factors.

Thus, the values obtained on the basis of trend and convergence models are found to be identical in this research.

Funding information The authors are grateful for financial support to the Russian Foundation for Basic Research № 17-0600537, The Grant Of The President № 6476.2018.6.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix 1

Table 7 Statistical parameters of different types of the model; the dependent variable is energy intensity, 2015

Trend model	Coefficients and evaluations	Coefficients	t criterion, confidence level 0.05		F criterion, confidence level 0.05		R^2	Mean-square deviation	Approximation error	DW	Actual value	
			Table value	Table value	Actual value	Table value					Actual value	Table value
Developed countries of Europe, 35 observations												
Logarithmic	Y-crossing	0.19	44.89	2.021	205	4.08	0.869	0.0830	4.48	0.19	1.38; 1.51	
	X	-0.05	14.32									
Exponential	Y-crossing	-0.76	348.99	3890			0.992	0.0019	1.12	1.54		
	X	-0.01	62.39									
Linear	Y-crossing	0.00	21.5	2247			0.986	0.0025	1.54	0.60		
	X	0.17	193.9									
Power	Y-crossing	-0.69	44.2	48			0.833	0.0095	5.20	0.17		
	X	-0.17	12.5									
Developing countries of Europe, 35 observations												
Logarithmic	Y-crossing	0.34	16.49	2.021	47	4.08	0.600	0.0364	12.37	1.01	1.38; 1.51	
	X	-0.05	6.82									
Exponential	Y-crossing	-0.56	23.86	52			0.627	0.0398	11.80	1.56		
	X	-0.01	7.21									
Linear	Y-crossing	0.28	19.36	33			0.519	0.0400	12.40	1.07		
	X	0.00	5.78									
Power	Y-crossing	-0.46	12.16	48			0.606	0.0409	12.60	0.64		
	X	-0.22	6.90									
North America, 35 observations												
Logarithmic	Y-crossing	0.30	55.78	2.021	404	4.08	0.929	0.1449	4.21	0.26	1.38; 1.51	
	X	-0.09	20.09									
Exponential	Y-crossing	-0.58	117.31	948			0.968	0.0075	2.15	1.61		
	X	-0.01	30.79									
Linear	Y-crossing	0.26	84.35	516			0.943	0.0085	2.68	0.29		
	X	0.00	22.71									
Power	Y-crossing	-0.38	16.95	65			0.670	0.0127	5.06	0.81		
	X	-0.29	15.00									
Countries of the former USSR, 23 observations												
Logarithmic	Y-crossing	0.65	18.21	2.093	44	4.38	0.700	0.3304	.11.7	0.25	1.22; 1.42	
	X	-0.24	6.66									
Exponential	Y-crossing	-0.45	15.19	266			0.933	0.0324	5.18	1.47		
	X											

Table 7 (continued)

Trend model	Coefficients and evaluations	Coefficients t criterion, confidence level 0.05		F criterion, confidence level 0.05		R^2	Mean-square deviation	Approximation error	DW	
		Actual value	Table value	Actual value	Table value					Actual value
Linear	X	-0.04	16.30							
	Y-crossing	0.60	53.41	311		0.942	0.0248	4.42	0.49	
Power	X	-0.02	17.62							
	Y-crossing	-0.15	3.69	38		0.669	0.0686	12.93	0.21	
Developing countries of APR without China, 16 observations										
Logarithmic	Y-crossing	0.19	41.33	2.179		0.787	0.0397	3.58	0.38	1.08; 1.36
	X	-0.04	6.69							
Exponential	Y-crossing	-1.68	160.53	274		0.958	0.0030	1.49	1.39	
	X	-0.02	16.56							
Linear	Y-crossing	0.19	42.20	180		0.968	0.0549	1.26	1.41	
	X	0.00	1.08							
Power	Y-crossing	-0.72	53.99	39		0.764	0.0070	3.81	0.36	
	X	-0.10	6.24							
China, 35 observations										
Logarithmic	Y-crossing	0.19	41.33	2.021		0.939	0.0397	8.23	1.57	1.38; 1.51
	X	-0.04	6.69							
Exponential	Y-crossing	-0.38	9.41	357		0.920	0.0361	9.41	1.54	
	X	-0.04	18.90							
Linear	Y-crossing	0.64	32.68	232		0.882	0.0549	14.94	0.10	
	X	-0.02	15.23							
Power	Y-crossing	0.03	0.81	220		0.876	0.0788	11.36	0.25	
	X	-0.43	14.82							
Central and South America, 16 observations										
Logarithmic	Y-crossing	0.16	34.69	23		0.655	0.0066	3.99	0.35	1.08; 1.36
	X	-0.01	4.77							
Exponential	Y-crossing	-0.80	120.89	99		0.892	0.0038	2.17	1.38	
	X	-0.01	9.94							
Linear	Y-crossing	0.16	77.86	106		0.898	0.0036	2.01	1.45	
	X	0.00	10.27							
Power	Y-crossing	-0.80	53.57	22		0.644	0.0068	4.15	0.35	
	X	-0.08	4.66							

Table 7 (continued)

Trend model	Coefficients and evaluations	t criterion, confidence level 0.05		F criterion, confidence level 0.05		R^2	Mean-square deviation	Approximation error	DW	
		Actual value	Table value	Actual value	Table value				Actual value	Table value
Africa, 21 observations										
Logarithmic	Y-crossing	0.19	33.32	2.11	56	4.45	0.767	4.84	0.36	1.18; 1.40
	X	-0.04	7.49							
Exponential	Y-crossing	-1.70	122.11		299		0.946	2.37	1.41	
	X	-0.02	17.30							
Linear	Y-crossing	0.18	107.29		438		0.963	1.91	1.51	
	X	0.00	20.93							
Power	Y-crossing	-0.71	38.93		46		0.7302	5.28	0.32	
	X	-0.13	6.78							
Developed countries of APR, 35 observations										
Logarithmic	Y-crossing	0.16	47.75	2.021	49	4.08	0.613	3.77	1.51	1.38; 1.51
	X	-0.02	7.01							
Exponential	Y-crossing	-0.83	105.37		23		0.421	4.1	0.14	
	X	0.00	4.75							
Linear	Y-crossing	0.15	56.47		22		0.414	4.05	0.15	
	X	0.00	4.68							
Power	Y-crossing	-0.80	77.21		46		0.597	3.74	1.56	
	X	-0.06	6.77							

Source: calculated by the authors

Appendix 2

Table 8 Statistical parameters of different types of the model; the dependent variable is final energy intensity 2015

Trend model	Coefficients and evaluations		t criterion, confidence level 0.05		F criterion, confidence level 0.05		R^2	Approximation error		DW
	Actual value	Table value	Actual value	Table value	Actual value	Table value		Actual value	Table value	
Developed countries of Europe. 32 observations										
Logarithmic	Y-crossing	-0.07	44.77	2042	128	4.17	0.81	4.49	0.22	1.37; 1.50
	X	0.33	11.33							
Exponential	Y-crossing	-0.51	154.86		979		0.98	1.14	1.29	
	X	-0.01	31.28							
Linear	Y-crossing	0.00	31.18		1422		0.98	1.27	1.41	
	X	0.30	193.11							
Power	Y-crossing	-1.18	632.3		985		0.97	1.61	0.72	
	X	-0.01	126.4							
Developing countries of Europe. 32 observations										
Logarithmic	Y-crossing	1.05	16.87	2042	111	4.17	0.787	15.64	0.60	1.37; 1.50
	X	-0.24	10.52							
Exponential	Y-crossing	-0.06	2.12		225		0.881	28.10	1.40	
	X	-0.02	14.87							
Linear	Y-crossing	0.80	20.90		121		0.805	25.36	0.80	
	X	-0.02	11.12							
Power	Y-crossing	0.17	1.62		22		0.424	21.04	0.79	
	X	-0.53	6.09							
North America. 32 observations										
Logarithmic	Y-crossing	0.37	35.34	2042	55	4.17	0.65	5.01	1.16	1.37; 1.50
	X	-0.03	7.42							
Exponential	Y-crossing	-1.06	315.19		304		0.91	2.21	1.39	
	X	-0.01	61.44							
Linear	Y-crossing	0.34	114.48		384		0.93	1.95	0.76	
	X	0.00	19.64							
Power	Y-crossing	-0.43	26.53		51		0.63	4.28	1.16	
	X	-0.10	7.15							
Countries of the former USSR. 20 observations										
Logarithmic	Y-crossing	0.77	26.12	2101	157	4.41	0.898	7.69	0.55	1.20; 1.41
	X	-0.16	12.62							
Exponential	Y-crossing	-0.15	10.49		376		0.954	6.71	1.38	
	X	-0.02	19.29							

Table 8 (continued)

Trend model	Coefficients and evaluations	Coefficients		t criterion, confidence level 0.05		F criterion, confidence level 0.05		R^2		Approximation error		DW	
		Actual value	Table value	Actual value	Table value	Actual value	Table value	Actual value	Table value	Actual value	Table value	Actual value	Table value
Linear	Y-crossing	0.66	36.99	233		0.929	8.81			1.03			
	X	-0.02	15.37										
Power	Y-crossing	-0.06	1.04	33		0.665	12.52			0.50			
	X	-0.37	6.91										
Central and South America. 12 observations													
Logarithmic	Y-crossing	0.19	151.26	23	2228	4.96		0.860	1.97	1.87		1.08; 1.36	
	X	0.00	7.86										
Exponential	Y-crossing	-0.72	199.87	25		0.716	0.64			1.09			
	X	0.00	5.02										
Linear	Y-crossing	0.19	122.92	106		0.715	1.1			1.06			
	X	0.00	5.00										
Power	Y-crossing	-0.80	53.57	22		0.644	0.00			0.35			
	X	-0.08	4.66										
Africa. 19 observations													
Logarithmic	Y-crossing	0.17	104.30	56	2201	4.84		0.9115	1.16	1.09		1.08; 1.36	
	X	-0.01	10.65										
Exponential	Y-crossing	-0.77	140.69	47		0.811	0.88			0.53			
	X	0.00	6.88										
Linear	Y-crossing	0.17	83.40	46		0.8079	1.69			0.51			
	X	0.00	6.80										
Power	Y-crossing	-0.76	162.27	105		0.906	0.64			0.98			
	X	-0.06	10.27										

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Ang, B. (1992). The use of growth curves in energy studies. *Energy*, *17*(1), 25–36.
- Ang, B. W., & Liu, F. L. (2003). Eight methods for decomposing the aggregate energy-intensity of industry. *Applied Energy*, *76*, 15–23.
- Baranzini, A., Weber, S., Bareit, M., & Mathys, N. A. (2013). The causal relationship between energy use and economic growth in Switzerland. *Energy Economics*, *36*, 464–470.
- Böhringer, C. & Rutherford, T. (2005). Combining top-down and bottom-up in energy policy analysis: a decomposition approach. Centre for European Economic Research. Discussion Paper No. 06–007.
- Chang, M. (2014). Energy intensity, target level of energy intensity, and room for improvement in energy intensity: an application to the study of regions in the EU. *Energy Policy*, *67*, 648–655.
- Chiou-Wei, S. Z., Chen, C. F., & Zhen, Z. (2008). Economic growth and energy consumption revisited—evidence from linear and nonlinear Granger causality. *Energy Economics*, *30*, 3063–3076.
- Damodar, N. (2004). *Gujarati: Basic econometrics, fourth edition*. New York: The McGraw–Hill Companies.
- Dergiades, T., Martinopoulos, G., & Tsoulfidis, L. (2013). Energy consumption and economic growth: parametric and non-parametric causality testing for the case of Greece. *Energy Economics*, *36*, 686–697.
- Duro, J. A., Alcántara, V., & Padilla, E. (2010). International inequality in energy intensity levels and the role of production composition and energy efficiency: An analysis of OECD countries. *Ecological Economics*, *69*(12), 2468–2474.
- E3Mlab. (2008). PRIMES model.
- Eder, L. V., & Nemov, V. Y. (2017). Document forecast of energy consumption of vehicles. *Studies on Russian Economic Development*, *28*(4), 423–430.
- Eder, L. V., Filimonova, I. V., Nemov, V. Y., & Provornaya, I. V. (2017). Forecasting of energy and petroleum consumption by motor transport in the regions of the Russian Federation. *Economy of Region*, *13*(3), 859–870.
- European Commission. (2011). Energy roadmap 2050. In *Technical Report COM/2011/0885 final*. Brussels: EC.
- Fishbone, L. G., & Abilock, H. (1981). MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version. *International Journal of Energy Research*, *5*, 353–375.
- Frei, C., Hadi, P., & Sarlos, G. (2003). Dynamic formulation of a top-down and bottom-up merging energy policy model. *Energy Policy*, *31*(10), 1017–1031.
- Fuinhas, J. A., & Marques, A. C. (2012). Energy consumption and economic growth nexus in Portugal, Italy, Greece, Spain and Turkey: an ARDL bounds test approach (1965–2009). *Energy Economics*, *34*, 511–517.
- Gabriel, S. A., Kydes, A. S., & Whitman, P. (2001). The national energy modeling system: a large-scale energy-economic equilibrium model. *Operations Research*, *49*, 14–25.
- Gonzales, C. S., Xiberta, B. J., & Coalla, L. H. (1999). Forecasting of energy production and consumption in Asturias (northern Spain). *Energy*, *24*, 183–198.
- Harel, P., & Baguant, J. (1991). A growth prediction for electrical energy consumption in Mauritius. *Energy*, *16*, 707–711.
- Heffington, W. M., & Brasovan, M. W. (1994). Prediction of US crude oil-production using growth curves. *Energy*, *19*, 813–815.
- Herrerias, M. J. (2012). World energy intensity convergence revisited: a weighted distribution dynamics approach. *Energy Policy*, *49*, 383–399.
- Hourcade, J. C., Jaccard, M., Bataille, C., & Ghersi, F. (2006). Hybrid modeling: new answers to old challenges. *The Energy Journal*, *2*, 1–12.
- Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., & Roehrl, A. (2011). OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. *Energy Policy*, *39*, 5850–5870.
- IAEA. (2005). *Energy indicators for sustainable development: Guidelines and methodologies*. Vienna: IAEA.
- Kadoshin, S., Nishiyama, T., & Toshihide, I. (2000). The trend in current and near future energy consumption from a statistical perspective. *Applied Energy*, *67*, 407–417.
- Kontorovich, A. E., Korzhubayev, A. G., Filimonova, I. V., Eder, L. V. (2008). Development of hydrocarbon raw material deep processing in Russia. *Neftyanoe khozyaystvo - Oil Industry*, *(5)*, 24–27.
- Kontorovich, A. E., Eder, L. V., Nemov, V. Yu. (2012). Balance of the work of Russia oil industry in 2011. *Neftyanoe khozyaystvo - Oil Industry*, *(7)*, 66–70.
- Kontorovich, A. E., Eder, L. V., Nemov, V. Yu. (2013). Oil and gas in the Russian economics. *Neftyanoe khozyaystvo—Oil Industry*, *(1)*, 4–8.
- Kontorovich, A. E., Eder, L. V., Filimonova, I. V., Mishenin, M. V., & Nemov, V. Y. (2016). Oil industry of major historical centers of the Volga-Ural petroleum province: past, current state, and long-run prospects. *Russian Geology and Geophysics*, *57*(12), 1653–1667.
- Korzhubayev, A. G., Filimonova, I. V., Eder, L. V., Sokolova, I. A. (2009). Strategy of development of an oil-and-gas complex Siberia. *Neftyanoe khozyaystvo - Oil Industry*, *(3)*, 14–17.
- Liddle, B. (2010). Revisiting world energy intensity convergence for regional differences. *Applied Energy*, *87*, 3218–3225.
- Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model. Part I: model structure. *Computational Management Science*, *5*, 7–40.
- Mackey, R. M., & Probert, S. D. (1995). Energy and environmental policies of the developed and developing countries within the evolving Oceania and south-east Asian trading block. *Applied Energy*, *51*, 369–406.
- Markandya, A., Pedroso-Galinato, S., & Streimikiene, D. (2006). Energy intensity in transition economies: is there

- convergence towards the EU average? *Energy Economics*, 28, 121–145.
- Messner, S., & Schrattenholzer, L. (2000). MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. *New Horiz Environ Econ*, 25, 267–282.
- Messner, S., & Strubegger, M. (1987). A framework to analyze the consumption of energy. Proceedings of the Workshop of Economics, Modeling, Planning and Management of Energy, Trieste, Italy. 315–28.
- Miketa, A., & Mulder, P. (2005). Energy productivity across developed and developing countries in 10 manufacturing sectors: patterns of growth and convergence. *Energy Economics*, 27, 429–453.
- Mulder, P., & De Groot, H. L. F. (2007). Sectoral energy- and labour-productivity convergence. *Environmental and Resource Economics*, 36, 85–112.
- Mulder, P., & Groot, H. L. F. (2012). Structural change and convergence of energy intensity across OECD countries, 1970–2005. *Energy Economics*, 34, 1910–1921.
- Omri, A. (2013). CO₂ emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models. *Energy Economics*, 40, 657–664.
- Ortiz, R. A., Bastianin, A., Bigano, A., Cattaneo, C., Lanza, A., Manera, M., Markandya, A., Plotegher, M., Sferra, F. (2009). Energy efficiency in Europe: trends, Convergence and Policy Effectiveness. MPRA no. 15763.
- Pen, Y. L., & Sévi, B. (2008). *On the non-convergence of energy intensities: evidence from a pair-wise econometric approach*. Centre de Recherche en Économie et Droit de l'Énergie Creden.
- Pen, Y. L., & Sévi, B. (2010). What trends in energy efficiencies? Evidence from a robust test. *Energy Economics*, 32, 702–708.
- Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, 10, 281–311.
- Pirlogea, C., & Cicea, C. (2012). Econometric perspective of the energy consumption and economic growth relation in European Union. *Renewable and Sustainable Energy Reviews*, 16, 5718–5726.
- Quah, D. T. (1993). Empirical cross-section dynamics in economic growth. *European Economic Review*, 37, 426–434.
- Quah, D. T. (1996). Empirics for economic growth and convergence. *European Economic Review*, 40(6), 1353–1375.
- Rao, R. D., & Parikh, J. K. (1996). Forecast and analysis of demand for petroleum products in India. *Energy Policy*, 24, 583–592.
- Reddy, S. (1995). An econometric analysis of energy use in urban households. *Energy Sources*, 17, 359–372.
- Sala-i-Martin, X. X. (1996). The classical approach to convergence analysis. *Economic Journal*, 106, 1019–1036.
- Schrattenholzer, L. (1981). *The energy supply model MESSAGE*. Laxenburg: IIASA.
- SEI. (2012). LEAP documentation.
- Solow R. M. (1956) A contribution to the theory of economic growth. *Quarterly Journal of Economics*, (70), 65–94.
- Strachan, N., & Kannan, R. (2008). Hybrid modelling of long-term carbon reduction scenarios for the UK. *Energy Economics*, 30, 2947–2963.
- Voigt, S., Cian, E. D., Schymura, M., & Verdolini, E. (2014). Energy intensity developments in 40 major economies: structural change or technology improvement? *Energy Economics*, 41, 47–62.
- Yuan, J. H., Kang, J. G., Zhao, C. H., & Hu, Z. G. (2008). Energy consumption and economic growth: evidence from China at both aggregated and disaggregated levels. *Energy Economics*, 30, 3077–3094.