The influence of energy production from renewable energy sources on energy efficiency and total factor productivity

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Abstract. The article analyzes the international experience of improving energy efficiency due to increasing the level of energy production from renewable sources and technological changes. Empirical verification of the related hypothesis has been carried out for the USA, China, India, Germany and Russia using econometric tools. The necessity of the transition to a new energy structure based on the active introduction of energy-efficient technologies, renewable energy sources, integrated systems and intellectual energy services based on an open grid architecture is substantiated. The posed hypotheses confirm the following: the production of energy from renewable sources is increasing in all countries, not only in the countries with the lack of fossil energy sources (Germany, India, China), but also in the USA and Russia; the growth of energy consumption caused by the growth of the economy and the population is humped due to the introduction of energy-efficient technologies and due to an increase in the share of renewable energy; growth in the share of renewable sources in energy consumption and total factor productivity increases energy efficiency in terms of GDP per unit of energy used in Germany, India and Russia.

1. Introduction

With an increase in the population of the Earth to 10 billion by 2050 and further urbanization, the problems of providing the population not only with food and water but also with electricity become more acute. Currently, cities consume about 75% of all energy resources with a specific gravity of the urban population of about 53%. According to Schneider Electric forecasts, the share of the urban population will increase to 86% by 2050, which will lead to an increase in energy consumption by 56-58%. Besides, almost 1.3 billion people who did not have access to electricity before will show an additional increase in demand for electricity. At the same time, modern economies and traditional energy are faced with the problem of low energy efficiency, which is basically of a different nature: depreciation of equipment and infrastructure, high losses in grids and environmental pollution.

A key role in improving energy efficiency is played by modern concepts of the development of the electric power industries, which involve greater automation, the development of smart grids and the introduction of renewable energy sources. The emergence of new energy development vectors is dictated by the inextricable link of the industry with economic growth opportunities. Today, the traditional way of developing the energy industry by increasing capacities, expanding the quantitative composition of energy equipment and increasing resource extraction is inferior to an intensive, innovative and breakthrough development path through the active introduction of energy-efficient equipment, advanced energy and information and communication technologies, renewable energy sources, integrated systems and smart energy services built on open network architecture and marks the beginning of the transition to the next energy structure.
New technologies are already yielding tangible results. For example, Germany’s GDP for 1990-2016 increased in constant prices by 48.4%, and annual electricity consumption only by 10.3%. The share of electricity production from primary energy resources (hydrocarbons) decreased from 68.6% to 53.9%, while the energy intensity of GDP decreased by 1.6 times (World Bank, 2020). The indicators for other countries are not so visible, but the trend towards increasing energy efficiency through the introduction of new technologies and renewable energy has been emerging in the last decade. In Russia, the Presidential Council for Modernization and Innovative Development of the Economy in early 2017 approved the EnergyNet roadmap, which provides for specific measures to develop the smart energy market until 2035.

Productivity is a measure of output divided by a measure of input. Following the neoclassical approach, aggregate output (measured as GDP at country-level) growth can be decomposed into contributions from aggregate capital input (K), aggregate labour input (L) and aggregate total factor productivity (TFP) growth as:

$$\Delta \log GDP = \nu_K \Delta \log K + \nu_L \Delta \log L + \Delta \log TFP$$

(1)

where \(\nu_K\) is the output elasticity of capital and \(\nu_L\) is the output elasticity of labour. Under the assumption of constant returns to scale \(\nu_K + \nu_L = 1\). TFP is derived as a residual after the contributions of \(K\) and \(L\) are deducted from GDP growth.

TFP can be regarded as the measure of productivity, which considers not only labour as an input but also physical, human, and other intangible capital. TFP is driven by non-input factors such as technological progress that are not tied to explicit input usage (Solow, 1957). In theory, TFP growth captures technical change and overall efficiency. A review of the literature and TFP growth data analysis suggest there are different key drivers of TFP growth in different groups of countries. Public policy toward R&D, to boost innovation in the private sector, is found to be among these drivers in OECD countries (Duverger & van Pottelsbergh de la Potterie, 2011; Guellec & Van Pottelsbergh De La Potterie, 2003). The effect of technological changes on TFP growth is examined in (Heshmati & Kumbhakar, 2014). The impact of ICT on TFP through an integrative framework of ICT-induced externalities and ICT-leveraged innovations is assessed in (Chou, Hao-Chun Chuang, & Shao, 2014).

For emerging economies and oil-exporting countries, such factors as FDI also affect economic growth and productivity (Balashova, Revinova, & Lazanyuk, 2016; Bozkurt, Erdem, & Eroğlu, 2015).

Another measure of productivity is GDP per unit energy use. This indicator is reported by the World Bank and used as a measure of energy efficiency of the economy. The inverse ratio (energy consumption per unit of GDP) is called energy intensity. It tends to decline in nearly all regions of the world (International Energy Outlook 2016, 2016)

We assume that TFP growth can affect the energy efficiency of the economy. A possible channel is the use of more energy efficiency technologies. On the other hand, for the fast-growing economies such as India and China, the growing market boost TFP growth and technological changes, which are not necessarily connected with energy-saving technologies. Manufacturing-focused economies tend to use more energy per dollar of GDP than service-focused economies. Climate and distance between urban areas also influence the energy efficiency of the economy.

The purpose of the analysis is to search for empirical evidence of the contribution of energy from renewable resources and productivity growth to improving energy efficiency in several countries using econometric technique. The answer to this question is not apparent, since energy efficiency is growing unevenly and, in addition to technical innovations and investments, an active program at the state level is required (Allcott & Greenstone, 2013).

The following countries were selected for analysis: Germany as the economic leader of the EU and one of the leaders in developing renewable energy; the USA and China being the locomotives of the global economy and significant investors in Smart Grid technologies; India as one of the fastest-growing developing countries, one of the world leaders in wind energy (Dent, 2013), actively increasing investments in wind and solar generation. Assessments were carried out for Russia as one of the global leaders among oil and gas producers.

2. Methodology and data
To assess the impact of renewable energy on energy efficiency in different countries, we put forward the following hypotheses:

2.1. Hypothesis 1.

The production of energy from renewable sources not taking into account hydropower has been multiplying over the past 25 years. However, the growth rate varies in different countries depending on whether the country is an importer or exporter of energy resources and the level of support for "green energy" at the government level.

A trend model is evaluated to obtain empirical confirmation of hypothesis 1.

\[ RNWX \_ PROD_{it} = A_i e^\gamma_i t \nu_{it} \] (2)

Here \( RNWX \_ PROD_{it} \) is the production of electricity from renewable sources (except for hydropower) in the country \( i \) for a period of time \( t \). \( A_i \) and \( \gamma_i \) - model parameters specific to each of the countries in question. \( \nu_{it} \) - is a random component of the model, meeting the OLS regression assumptions. The parameter \( \gamma_i \) (for small values) is interpreted as the growth rate of renewable energy. To obtain estimates of the parameters, equation (2) is transformed to a linear form. The assessment is made over a pool of countries for the whole period 1990-2017, assuming the parameters of equation (2) to be specific for each country. We assume that the growth rate can be expressed as a linear functions of dummy variables \( D\text{exp} \) and \( D\text{sup} \)

\[ y_{it} = y_0 + \delta_1 D\text{exp}_{it} + \delta_2 D\text{sup}_{it} \] (3')

Where \( D\text{exp}_{it} = 1 \) to energy-rich countries (such as Russia and USA) and 0 otherwise. \( D\text{sup}_{it} = 1 \) for countries with intensive government support for low-carbon energy supply (such as Germany and India).

2.2. Hypothesis 2.

Energy use per capita tends to decrease with the increase of renewable energy production.

A model is estimated of the dependence of the amount of energy consumed on the population, GDP and the share of electricity received from renewable energy sources to test this hypothesis

\[ ENG \_ USE \_ CAP_{it} = \alpha_1 RNEWX_{it} + \alpha_2 GDP \_ CAP_{it} + \alpha_3 \nu_{it} + \epsilon_{it} \] (4)

Here, \( ENG \_ USE \_ CAP \) is the natural logarithm of energy used from all sources (kg of oil equivalent) per capita, \( GDP \_ CAP \) is the natural logarithm of GDP per capita (in constant US dollars 2010). \( RNEWX \) is the share of energy from renewable sources in the total energy consumption from all sources. \( \epsilon \) - random component. The parameters \( \alpha_2,i \) is the elasticities of energy consumption by GDP per capita in country \( i \), \( \alpha_1 \) shows the growth rate of energy consumption with an increase of 1 pp in \( RNEWX \) while controlling other variables (Ayyavzyan, 2014).

2.3. Hypothesis 3.

An increase in total factor productivity impacts on energy efficiency, due to the implementation of modern energy-saving technologies, complementing the impact of renewable energy consumption (% of total final energy consumption).

The depended variable is GDP per unit of energy use (constant 2011 PPP $ per kg of oil equivalent). The explanatory variables are the share of renewable energy in total energy consumption \( RNWZ_{it} \) and the total factor productivity \( TFP \).

Thus, to test hypothesis 3, we evaluate the model

\[ GDP \_ ENG_{it} = \beta_1 + \beta_2 RNWZ_{it} + \beta_3 TFP + \epsilon_{it} \] (5)

The estimation is carried out for each country individually by the least-squares method with the correction of standard errors according to the Newey-West method due to autocorrelation in the residuals.

Here \( GDP \_ ENG_{it} \) is the natural logarithm of GDP per unit of energy spent in the current period \( t \) for the country \( i \), \( \epsilon \) - random component, subject to autocorrelation.
We retrieve data for TFP growth from the Total Economy Database (TED). TED is a comprehensive database with annual data covering growth accounting variables for 123 countries in the world (“Total Economy Database,” 2019). Data for the other time series are retrieved from the World Bank database and OECD.

3. Empirical Analysis Results

3.1. Renewable energy growth

Renewable energy sources include the following types: solar energy, geothermal energy, wind energy, hydropower, ocean energy (thermal gradient, wave power and tidal power), biomass, draft animal power, firewood, peat, shale and tar sands. The most widely used for technological purposes is hydropower. According to Renewables 2017 Global Status Report for 2016, the share of renewable energy sources in the total final consumption in the world is more than 19.3%, and according to the most optimistic forecasts, by 2050 it can reach 35%. Renewable energy plays a vital role in the concept of the 17 Sustainable Development Goals for the next 15 years. One of these goals is "Sustainable Energy for All", which implies increasing efficiency and expanding the use of renewable energy sources.

Among the countries, the United States accounts for the enormous amount of electricity from renewable sources (excluding hydropower). Germany leads the EU in the share of electricity generated from renewable energy sources. Since 2000, China and India have been increasing their volumes and increasing the share of renewable energy sources in electricity production. In Russia, the volume and share of renewable energy sources are tiny, although, start growing since 2000s (Figure 1).

![Figure 1. Production of electricity from renewable sources (excluding hydropower) (left axis, billion kW), the share of RES from the generation of total electricity (right axis, %). Source: Compiled by the authors based on the World Bank statistics.](image-url)
Table 1. The estimated growth rate of electricity production from renewable sources

|               | Germany | USA    | China  | India  | Russia |
|---------------|---------|--------|--------|--------|--------|
|               |         |        |        |        |        |
| 1990-2015     |         |        |        |        |        |
| $\gamma$     | 0.20*** | 0.06***| 0.31***| 0.32***| 0.13***|
| $R^2$         |         |        |        |        | 0.977  |
| 2000-2015     |         |        |        |        |        |
| $\gamma$     | 0.17*** | 0.10***| 0.35***| 0.22***| 0.12***|
| $R^2$         |         |        |        |        | 0.99   |

We conclude from table 1 a rather steady growth rate of electricity production from renewable sources, excluding hydroelectric, for all considered countries. The low growth rate for the USA is related to a relatively high production already in early 90-es and the effect of shale revolution (Huntington et al., 2020).

The estimation of the equation (2') supports the hypothesis that the growth rate of electricity production from renewable sources is very high for countries with insufficient fossil resources and significantly low for energy-rich countries. However, for the considered group of countries we cannot verify the assumption that government support has a particular impact on the growth rate of the production, because according to the International Energy Agency, all the countries considered have government programs to support green energy (International Energy Agency, 2017).

It should be noted that according to New Energy Outlook 2017 forecasts, more than 70% of investments in the energy sector will go to renewable energy production, and the amount will increase to $ 400 billion annually by 2040. Among the leaders in this segment of the industry will be Germany, the USA, China and India.

Russia has also joined the race for the leadership in renewable energy issues. Investments allocated to R&D in the energy sector are yielding results. In addition to equation (1), we estimated the ADL (1,1) model (5) for Russia

$$\log(RNWX_{PROD})_t = \alpha_1 + \alpha_2 \log(RNWX_{PROD})_{t-1} + \alpha_3 \log(RD\_EG)_t + \epsilon_t$$ (6)

Here $RD\_EG$ are the R&D expenditures in the energy sector (source - OECD database¹). The estimation was carried out using the least-squares method with correction of autocorrelation in the residues according to the Newey-West method (Greene, 2008) for the period from 1995 to 2014.

Estimation of the parameter $\alpha_3 = 0.7$ (significant at all levels) suggests that in the short term, an increase of 1% in R&D expenditures in the energy sector corresponds to a 0.7% increase in electricity production from renewable sources in the next period. In the long run, the return on growth in R&D expenditures by 1% increases to 2.5% (parameter $\alpha_2$ can be interpreted as 1 minus the speed of adjustment, the estimation $\alpha_2 = 0.715$ is significant at all levels). It should be recognized that in Russia, R&D expenditures in the energy sector are small compared to the other countries under consideration. For example, in 2012, according to OECD estimates, R&D expenditures in the energy sector from all sources of financing were only $1,551 million (constant 2010 international $) in Russia (of which $360
million were the state-funded), and in Germany, only from state sources the amount of 1,184 million dollars (international $^{2}$) was spent on R&D in the energy sector. Nevertheless, R&D expenditures in this area indicate attention to the problems of energy, both from the side of the business and from the government.

3.2. Energy consumption and renewable energy

In the world, energy consumption is growing with an increase in world GDP and a growing world population. According to the World Energy Agency, the demand for electricity will increase by 58%, or the average growth will be 2% per year by 2040.

The dynamics of energy consumption are multidirectional in the observed countries (Fig. 2). Consumption growth, both gross and per capita, is observed in China, although the growth rate of per capita consumption is declining. A similar situation is for India, though the growth rate is lower than in China. The amount of energy consumed per capita in India is four times less than in China and ten times less than in the United States. In Germany and the United States, there has been a trend towards lower energy consumption (Figure 2).

![Figure 2. Energy use (kg of oil equivalent), left axis, and energy use (kg of oil equivalent per capita), right axis. Source: Compiled by the authors based on World Bank statistics.](image-url)

The time series in equation (3) is proved to be I(1)), based on the ADF test (Dickey & Fuller, 1981). Thus, we assess parameters of equation (3), using first differences of the logs to eliminate linear trends (Fig.2). Consequently, we estimate the impact of changes in the share of renewable sources in electricity production on the growth rate of energy use per capita, controlling for the growth rate of GDP per capita (Table 2).
Table 2. The estimated impact of changes in the share of renewable sources in electricity production on the growth rate of energy use per capita based on equation (3)

|          | Germany | USA   | China | India | Russia |
|----------|---------|-------|-------|-------|--------|
| Dependent variable $\Delta \log(ENG\_USE\_CAP)$ |         |       |       |       |        |
| $\Delta(RNEWX)$ | -0.01** | -0.0005 | 0.0004 | -0.005* | -0.01** |
| $\Delta \log(GDP\_CAP)$ | 0.42* | 0.82*** | 0.99** | 0.5*** | 0.45*** |
| $R^2$ | 0.22 | 0.57 | 0.20 | 0.35 | 0.80 |

Variables are the log differences of the initial time series except for RNEWX, which is the difference of the share of renewable sources in electricity production.

From the estimation results, we can conclude that an increase in the renewable electricity output (% of total electricity output) decreases energy use per capita, controlling for GDP per capita in Germany, India and Russia. In the case of the USA, the sign of the coefficient is what is expected; however, the estimation is insignificant. As can be seen from Fig.2, the energy consumption is very high in the USA, and tend to decrease only since late 2000-s.

In China, energy consumption per capita increases during the whole considered period despite the growing rate of renewable energy production. The share of renewable sources in China is rather small (Fig.1) and do not impact on overall energy savings.

In the ranking of the American Council for an energy-efficient economy in terms of energy efficiency, the United States is given the thirteenth place in the world. In terms of energy consumption per capita, the United States (like Australia and Canada) is one of the most wasteful in the world - 6.8 TOE against 3.3 TOE for the EU. The US federal government allocates less money in comparable terms for energy-saving events than the EU. However, the US has great potential for energy efficiency growth. According to a McKinsey study, the installed capacity of energy-efficient technologies in the United States will be able to reduce energy consumption by 23% by 2020, according to Rhodium Group estimates, the widespread introduction of energy-saving technologies and equipment can reduce energy consumption in the USA by 42-59%. Note that since 2009, a large-scale program for the creation of “smart energy grids of the 21st century” has been carried out, which provides for a series of measures to modernize trunk transmission lines and distribution networks using advanced electronic control and measuring equipment, communications and computer technologies. According to the calculations of the National Laboratory of Energy Technologies, the implementation of the program involves attracting investments of $17-24 billion annually for 20 years (Dmitriev, 2014).

3.3. Energy efficiency and total factor productivity

Various transmission channels exist through which total factor productivity may have an impact on energy efficiency. TFP reflects the spillover of technological changes and the use of modern technologies and efficient business processes in the production of goods and services. The link between renewable energy and energy efficiency is not so strong. However, the use of solar panels by
householders proved to decrease energy consumption in USA (Balashova et al. 2020, Ratner, S., & Ratner, P. 2017). The results, presented in Table 2, also speaks in favour of the link between the share of renewable energy and energy use, controlling for GDP. So, we can expect, that controlling for technological changes an increase in the share of renewable sources in energy consumption helps to increase the energy efficiency (in terms of GDP per unit of energy use).

To estimate the equation (4) we first check the time series for weak stationarity using the ADF test. To avoid the spurious regression, we use the first differences of the natural logarithm of the series GDP_ENG and the first difference of the series RNWZ. Note, that data on TFP is retrieved from TED as a difference between GDP growth and capital and labour growth and thus measure the TFP growth rate. Results of estimation of modified equation (4) are reported in Table 3.

As seen from Table 3, hypothesis 3 is supported for Germany and India. India is fighting to decrease its colossal energy losses, which drops from 28% in 2000 to 19% in 2014, but still very large. TFP growth is associated with the energy efficiency increase in this country. In Germany, we also see the upward trend in energy efficiency, and the impact of TFP growth and renewable energy consumption (% of total final energy consumption) on energy efficiency is positive and significant.

Table 3. The estimated impact of changes in the share of renewable sources in energy consumption and total factor productivity on the growth rate on GDP per unit of energy use based on equation (4)

| Germany | USA | China | India | Russia |
|---------|-----|-------|-------|--------|
| Δ(log(GDP_ENG)) | Δ(RNWZ) | 0.023** | 0.002 | 0.03*** | 0.02*** | 0.035 |
| Δ(log(TFP)) | 0.68** | 0.02 | 0.32 | 0.87*** | 0.63*** |
| R² | 0.33 | 0.005 | 0.43 | 0.70 | 0.68 |

GDP per unit of energy use is increasing in China, and it is in line with the increase in electricity production from renewable sources, excluding hydroelectric (% of total). However, the TFP growth is negative in China after the global financial crisis, and so its impact on energy efficiency for the period 1990-2017 is not significant (Shen, Y., 2020).

The growth rate of energy efficiency in the USA is very volatile and cannot be associated with renewable energy consumption (as well as production) or TFP growth rate. The estimates obtained accurately capture the trend in energy efficiency over the past 25 years. In Fig. 3 shows the actual and estimated values of this indicator.
According to Fig. 3, Germany has the highest energy efficiency rate among the countries in question. Germany is actively increasing the share of energy from renewable energy sources in its final consumption. In 1990, this value was only 2% and increased by more than seven times to 14.6% in 2015 (according to Eurostat). Note that according to Strategy 2020, the average target for EU countries is 20%. In the framework of this strategy, each country has its target indicator depending on the initial values, the potential for using renewable energy sources and the level of economic development; for Germany, the target indicator of the share of energy received from renewable energy sources in the final consumption is 18% by 2020.

In the USA, energy efficiency is not as high as in Germany, and at comparable prices, it is slightly lower than in India. The increase in energy efficiency in the United States only in the last decade can be attributed to an increase in the share of renewable energy sources, which reached almost 8% in production (excluding hydropower, Fig. 1) and almost 9% in total energy consumption. In India and China, energy efficiency tends to increase in the period under review, which can be primarily associated with the high growth rates of the economies of these countries. However, the contribution of RES to energy efficiency growth has not been recorded, despite the increased share of these sources in electricity production (Fig. 1). In the final energy consumption in China and India, the share of fossil fuel energy consumption increased significantly (88% in 2014 versus 76% in 1990 in China, in India growth to 73% in 2014 from 54% in 1990), respectively, the share of renewable energy decreased.

For Russia, the energy efficiency indicator has a dynamics similar to the dynamics of GDP (energy consumption varied to a much lesser extent than GDP, and its ratio changed mainly due to changes in the numerator [Formatting Citation]. The share of energy from renewable energy sources in the total consumption is tiny (about 4%), practically does not vary and does not affect the dynamics of the studied indicator.

4. Conclusion
The production of energy from renewable sources is increasing in all countries, not only in the countries with the lack of fossil energy sources (Germany, India, China), but also in the USA and Russia. The performed analysis based on the available statistical data allows us to conclude that energy production from renewable sources in the countries is growing at different rates due to the level of state support.
The growth of energy consumption caused by the growth of the economy and the population is humped due to the introduction of energy-efficient technologies and due to an increase in the share of renewable energy. An increase in the renewable electricity output (% of total electricity output) decreases energy use per capita, controlling for GDP per capita in Germany, India and Russia. However, it is not the case for the USA and China for different reasons. Growth in the share of renewable sources in energy consumption and total factor productivity increases energy efficiency in terms of GDP per unit of energy used in Germany, India and Russia. This hypothesis is not supported for China and the USA.

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