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Article

Households' Energy Autonomy: Risks or Benefits for a State?

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Abstract: The purpose of this study is to determine the impact of households' energy autonomy on a country's energy independence level, to identify prospects and risks. To assess the economic efficiency of households' energy autonomy, the study used a modeling method based on maximizing the net present value, determining the average notional cost of energy efficiency and the level of energy independence in 20 countries. Based on the analysis of the volumes of electricity consumption by households in the studied countries for the period 2000–2018, it was revealed that in developed and developing countries there is an increase in this indicator. Diagnostics of the investment attractiveness of the installation and operation of energy systems for households makes it possible to determine the boundaries of a possible increase in the level of their energy autonomy. The scientific novelty of the research is represented by the proposed methodological approach, which makes it possible to assess the level of energy dependence of countries, possible deviations, and an increase in households' energy autonomy in relation to the risk limit of energy dependence. The proposed methodological approach allowed the authors to prove the positive impact of increasing households' energy autonomy for most developed countries. The most positive effect is characteristic of the leading countries in fossil energy market.

Keywords: deviation; energy dependence; energy efficiency management; energy saving; cost; risk limit

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1. Introduction

In the modern world, the main factor in the economic development of any country is energy, the efficiency of which determines the level and rate of improvement in population welfare [1]. Each country chooses its own way of developing the energy sector, which depends both on the availability of natural resources (coal, oil, natural gas) and on the level of well-being of the population. The formation of an energy-efficient model of economic development of countries is a fundamental problem of the global level, which is of a systemic nature and significantly determines the key parameters of energy independence. A reliable and uninterrupted supply of electrical energy is essential for the functioning of any economy. As the economy grows, the demand for electricity increases in line with population growth, industrialization, and income [2].

New technologies contribute to the economical use of energy in households, which leads to greater household independence. Digitalization and automation processes are bringing smart home systems to interact with power systems. Automated systems for managing energy consumption of a household are considered in the context of the transition to smart home and a grid based on contractual energy supply and a scenario of variable payment for electricity [3]. In addition to the development of energy-producing technologies, it is planned to introduce new energy service technologies based on the concept of "smart" power grids [4]. The concept of universal intelligent machines is especially popular to improve the efficiency of services provided to households in the context of information management [5]. Along with this, an important direction is to reduce the costs for the transportation of electricity by optimizing the design of district heating networks [6]. It is energy that today acts as the initiator of the progress of the world economy and occupies one of the first places, performing a key function in the economic, political, and social life of any state [7]. Decentralized energy production offers households significant potential to support the achievement of climate goals [8]. Therefore, this study is aimed at identifying the benefits and risks for countries with different levels of economic development and is valuable in the context of determining the possibilities of influencing the level of households' energy autonomy in the context of the global energy transition.

Households are both producers and consumers in the energy market. Decentralized energy production is becoming a subject of increased relevance, but at the same time, it also signifies an uncertainty in the event of disruptions in the distribution of autonomous energy systems. Energy supply companies, communities, and small businesses and households have access to the energy market today. Thus, increasing the level of energy autonomy of households provides an opportunity for homeowners to function in the energy market. At the same time, the motivational aspects for both households and a state have not been sufficiently studied, including their mutual benefits and risks in the event of an unsuccessful proliferation of autonomous energy systems and the ongoing liberalization of the energy market. This study aims to fill this gap by examining the mutual effects for households and a state in relation to their opportunities and threats. All this contributed to the formation of the goal of this study, which is to determine the impact of households' energy autonomy on the level of energy independence of a state, to identify prospects and risks.

The scientific novelty of the research is represented by the proposed methodological approach, which makes it possible to assess the level of energy dependence of countries, possible deviations, and an increase in households' energy autonomy in relation to the risk limit of energy dependence. This study is based on a methodological approach to modeling the maximization of net present value, which allows identifying the average notional costs of energy efficiency and the level of energy independence in the 20 countries studied. This made it possible to shape their overall dynamics until 2030. Using this methodology, it has been determined that independent energy systems have clear advantages. Decentralized energy systems are emerging against the backdrop of the population's tendency towards energy consumption, and therefore energy autonomy is the main motive for investing in local renewable energy sources.

The approach proposed in the study involves the formation of a set of predictive indicators of the impact of households' energy autonomy on the level of energy independence of the studied developed and developing countries. The motivation for the study is to determine the equality of opportunities for energy autonomy of households in countries with different income levels. In the end, government support for household energy autonomy can be energy efficient, but it can also best benefit higher-income households and thereby contribute to increasing inequality in society.

To achieve this goal, research tasks were formed, which determined the structure of this study:

- identifying the possibility of changing the level of energy autonomy of households and analyzing the volumes of electricity consumption in the studied countries for the period 2000–2018;
- determination of households' energy autonomy based on the level of energy savings in a country and the notional cost of 1% of energy savings for households;
- analysis and comparison of the impact of households' energy autonomy on the level of energy saving in the studied countries.

2. Literature Review

The concept of planning sustainable energy systems is viewed as multi-criteria decision analysis. However, in most of the previous studies, the impact of energy production technologies on public and private sectors has been considered separately. Sustainable planning of energy systems and their components should include both options for possible influence when making decisions within the framework of a multi-criteria decision analysis [9].

The use of information intervention to stimulate energy saving of residents is attracting more and more attention. However, the effect of different information content and intervention strategies remains controversial. In addition, there are not enough studies that assess (using a field experiment) the effectiveness of individual information interventions in motivating energy conservation in urban households. Of the four separate communication strategies, only environmental feedback and cost-benefit feedback had a significant incentive effect on household energy savings, while the impact of regulatory information and information on environmental education was negligible. The energy-saving effect of feedback on environmental contributions was more significant than the effect of feedback on costs and benefits, regardless of whether individual or joint activities were implemented, while the energy-saving effect of environmental education information was negligible [10–12].

It is critical to achieve the carbon emissions reductions set out in the EU 2050 targets, limiting energy consumption [6]. The transition of households to efficient energy consumption in the residential sector proved to be quite difficult, while one of the factors contributing to the regression was determined by human behavior in the field of energy consumption [13,14]. More traditional methods are being used (information campaigns and feedback) to stimulate households to change their behavior. However, these measures tend to be of a short-term nature, as they ignore the underlying causes of such practices [15]. A more efficient solution is a practice-oriented design, where innovative technologies are created jointly with a user. In addition, the emergence and use of automated technologies allow practitioners to act independently of a user. However, the success of automation also depends on understanding the home practice system, the needs and skills of a user who represents a household [16,17].

Contemporary research examines psychological barriers to reducing energy demand in the context of introducing energy-efficient technologies in households and discusses ways to overcome them. At the same time, behavioral approaches to overcoming these limitations are discussed, namely:

- an emphasis on the public choice of "green" technologies, simplification and optimization of this choice;
- reframing benefits;
- changing the time structure of costs and benefits;
- emphasis on the symbolic attributes of new technologies [18];
- behavior change aimed to reduce energy consumption in households [19].

Depending on the level of income, groups of households can be distinguished that react differently to fluctuations in energy prices in residential buildings. At the same time, energy poor households mainly belong to the group of households with the highest elasticity. Income insecurity does not necessarily mean fuel poverty [20]. At the same time, fluctuations in the development of energy companies are possible [21], which also affects the motivation for energy autonomy of households. However, subsidies, which cover a significant portion of total investment, play a significant role in household energy decision-making. Depending on their design, support measures can best benefit certain groups in society and thus can increase inequality. The potential distributional impact of investment subsidies is determined by a combination of targeted technologies and their costs, household income, support intensity, subsidy structure constraints, and additional measures [22].

For developing countries in the energy sector, electricity is not predominant. Biofuels and kerosene are the most common fuels used in the daily life of people in developing countries. The transition from these fuels to more modern forms of energy is already taking place in the 21st century. The government has a great influence on household energy consumption, and different governments have different priorities. For example, a government can subsidize up to 90% of the final electricity for households, thereby significantly increasing energy consumption, which has negative consequences for sustainable development. Effective strategies to reduce energy consumption represent individually tailored information and feedback from users, as well as a clear statement of goals by decision makers for both developed and developing countries [23,24].

Although there is a high level of knowledge about reducing energy demand, scattered information needs to be integrated to develop a combined and inclusive approach to managing energy demand in households. The knowledge gathered will inform decision makers who are involved in the design of residential buildings, energy consumption of households, and planning for sustainable communities to identify activities that can be implemented in a given locality [25–28].

Households' green energy production can make a positive contribution to a state's energy supply, increasing the environmental friendliness of the energy complex, ensuring the transition to the use of renewable energy sources, and reducing the use of fossil fuels [29,30]. At the same time, the pace of development of the private renewable energy sector is not sufficient to make a significant contribution to the achievement of indicators of national plans and programs [31,32]. The main reasons are doubts about the financial feasibility of such projects, requiring state support, and insufficient incomes of a country's population, which do not allow accumulating funds for investment in renewables, along with the high cost of credit resources. In this regard, the main direction for further development of private power plants using renewable energy sources is to strengthen financial state support for such projects [33]. However, with the development of a renewable energy sector, another problem is gradually being identified, which will worsen over time. Namely, an increase in renewable energy volumes at existing high rates of the "green" tariff can lead to a gradual increase in electricity prices, since the compensation for increased "green" tariffs occurs due to an increase in average prices for electricity, obtained from both traditional and from renewable sources. A situation arises when the growth in the production of "green" energy is paid for through the mechanism of increased prices by all energy consumers, and only a few can earn on increased tariffs [34–36]. Further expansion of a renewable energy sector with relatively high "green" tariffs can lead to social problems generated by the stratification of the population in terms of income based on the production of "green" electricity [37–39]. Taking into account the multidirectionality of modern research and the obtained results of the impact of households' energy autonomy, there is a need to develop methods for assessing the efficiency and permissible limits of households' energy autonomy in the context of a country's energy security. Therefore, this study is aimed at identifying possible threats and benefits of increasing households' energy autonomy in countries of different levels. For this, the authors have developed a methodological approach to assessing the impact of households' energy autonomy on the level of energy dependence of the studied developed countries.

3. Materials and Methods

To assess the economic efficiency of households' energy autonomy, the study used a model that maximizes the net present value and the level of energy independence of countries. Therefore, for the study, countries were selected that met certain criteria: the level of GDP per capita, and the second factor was the energy intensity of GDP (Figure 1). These criteria were the main ones for including countries in the study since energy autonomy requires a study of the equality of opportunities for households in countries with different income levels. A key prerequisite for this is that energy autonomy of households can be supported by a state and be quite effective, but at the same time it can be more beneficial for households with higher incomes, which may increase inequality. Besides, countries representing different regions of the world were included in the sample.

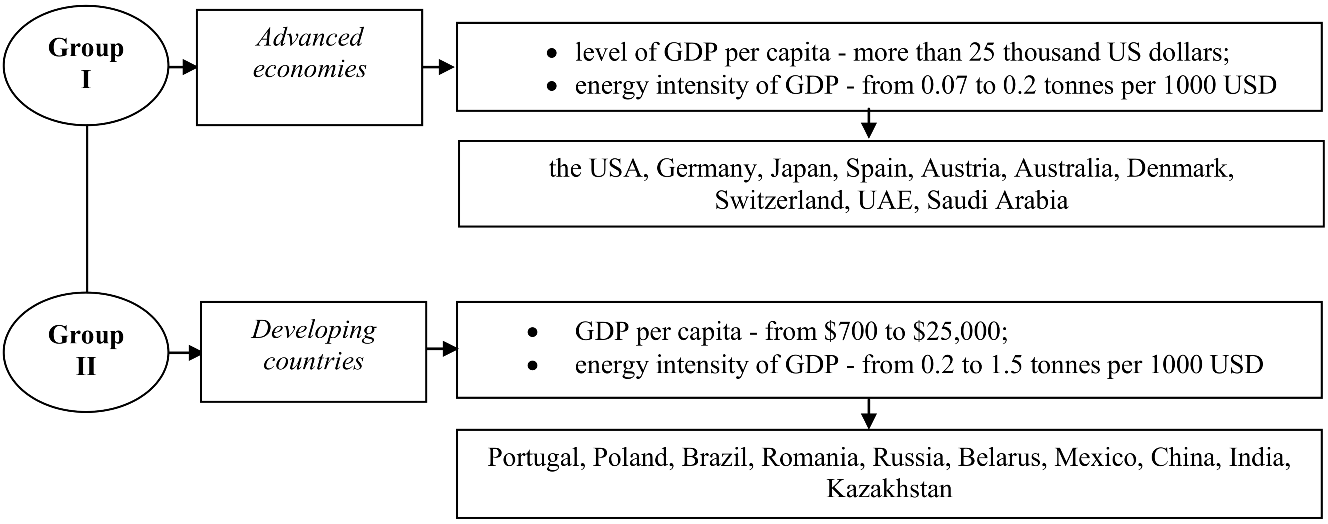

Figure 1. Distribution of the studied countries by groups. Source: generated by the authors.

To determine the level of costs for the transition to autonomous systems in households, a modeling method was used. Based on the formed investment projects to increase the level of households' energy autonomy, an assessment was carried out, and the average notional cost of 1% of energy savings for the autonomous systems under study was determined.

The modeling is based on the assumption that there is an effective amount of investment for the use of each autonomous energy system by a household. Based on econometric diagnostics of the obtained results of modeling, the study analyzed the interdependence of energy saving and energy efficiency of households' autonomous energy systems, namely, the corresponding volume of investments. In this case, the following dependence is assumed:

$$\varphi_\tau(\Delta HS_{aut}) = hs_{0\tau}^{autin} + hs_{1\tau}^{autin}\Delta HS_{aut} \tag{1}$$

where HS_{aut}—the level of energy savings of a household as a result of introducing an autonomous energy system (%);

τ—investment option index according to autonomous system of using renewable energy sources, $\tau = \overline{1.5}$;

$\varphi_\tau(\Delta HS_{aut})$ —the amount of power generation for the investment option τ;

$hs_{0\tau}^{autin}, hs_{1\tau}^{autin}$—parameters of the econometric model for the investment option τ on the implementation of an autonomous energy system.

Based on the proposed methodological approach to the construction of investment projects for the introduction of autonomous energy systems by households, the authors determined the expected value of the energy saving volumes function $\varphi_\tau(\Delta HS_{aut})$ of random variable ΔHS_{aut} with a distribution density $f(\Delta HS_{aut})$. Wherein $f(\Delta HS_{aut})$ has the following value:

$$f(\Delta HS_{aut}) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\Delta HS_{aut} - \mathrm{EVS})^2}{2\sigma^2}} \tag{2}$$

where EVS_{res}—the expected value of saving a certain energy resource;

σ—the level of its possible mean deviation.

In this case, the expected value for the energy saving function has the form:

$$ME[\varphi_\tau(\Delta HS_{aut})] = \int_{-\infty}^{+\infty} \varphi_\tau(\Delta HS_{aut}) f(\Delta HS_{aut}) d\Delta HS_{aut} \tag{3}$$

Based on the substitution within the integration and replacement of certain mathematical models, the equation takes the following form:

$$\begin{aligned} ME[\varphi_\tau(\Delta HS_{aut})] = & \int_0^5 \left(hs_{0\tau}^{autin} + hs_{1\tau}^{autin}\Delta HS_{aut}\right)\cdot\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut} \\ & = \frac{hs_{0\tau}^{autin}}{\sigma\sqrt{2\pi}}\int_0^5 e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut} \\ & +\frac{hs_{1\tau}^{autin}}{\sigma\sqrt{2\pi}}\int_0^5 \Delta HS_{aut}e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut} \\ & = hs_{0\tau}^{autin}\left[\varphi\left(\frac{5-EVS_{res}}{\sigma}\right)+\varphi\left(\frac{EVS_{res}}{\sigma}\right)\right] \\ & +\frac{hs_{1\tau}^{autin}}{\sigma\sqrt{2\pi}}\int_0^5 \Delta HS_{aut}e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut} \end{aligned} \quad (4)$$

where $\varphi\ (y)$—integral Laplace function taking into account the parameter y.

In order to determine the integral $\frac{1}{\sigma\sqrt{2\pi}}\int_0^5 \Delta HS_{aut}e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut}$ it is assumed that $x = \frac{\Delta HS_{aut}-EVS_{res}}{\sigma}$ and x is accepted as a new variable. As a result $\Delta HS_{aut} = x\sigma + EVS_{res}$. Wherein $d\Delta HS_{aut} = \sigma dx$. By replacing the variables, one can get:

$$\begin{aligned} & \frac{1}{\sigma\sqrt{2\pi}}\int_0^5 \Delta HS_{aut}e^{-\frac{(\Delta HS_{aut}-EVS_{res})^2}{2\sigma^2}}d\Delta HS_{aut} = \frac{\sigma}{\sigma\sqrt{2\pi}}\int_{-EVS_{res}/\sigma}^{(5-EVS_{res})/\sigma}(\mathrm{x}\sigma + EVS_{res})e^{\frac{x^2}{2}}d\mathrm{x} = \\ & \frac{\sigma}{\sqrt{2\pi}}\int_{-EVS_{res}/\sigma}^{(5-EVS_{res})/\sigma}\mathrm{x}\sigma e^{\frac{x^2}{2}}d\mathrm{x} + \frac{EVS_{res}}{\sqrt{2\pi}}\int_{-EVS_{res}/\sigma}^{(5-EVS_{res})/\sigma}e^{\frac{x^2}{2}}d\mathrm{x} = \\ & \frac{\sigma}{\sqrt{2\pi}}\int_{-\frac{EVS_{res}}{\sigma}}^{\frac{(5-EVS_{res})}{\sigma}}e^{\frac{x^2}{2}}d\left(-\frac{x^2}{2}\right)+EVS_{res}\left[\varphi\left(\frac{5-EVS_{res}}{\sigma}\right)+\varphi\left(\frac{EVS_{res}}{\sigma}\right)\right] = \frac{\sigma}{\sqrt{2\pi}}\left[e^{-\frac{EVS_{res}{}^2}{2\sigma^2}} - \right. \\ & \left. e^{-\frac{(5-EVS_{res})^2}{2\sigma^2}}\right] + EVS_{res}\left[\varphi\left(\frac{5-EVS_{res}}{\sigma}\right)+\varphi\left(\frac{EVS_{res}}{\sigma}\right)\right] \end{aligned} \quad (5)$$

Thus, the expected value of household energy savings as a result of the introduction of an autonomous energy system will have the following form:

$$\begin{aligned} ME_\tau = ME\quad & [\varphi(\Delta HS_{aut})] \\ & = hs_{0\tau}^{autin}\left[\varphi\left(\frac{5-EVS_{res}}{\sigma}\right)+\varphi\left(\frac{EVS_{res}}{\sigma}\right)\right] \\ & ++hs_{1\tau}^{autin}\left\{EVS_{res}\left[\varphi\left(\frac{5-EVS_{res}}{\sigma}\right)\right]+\varphi\left(\frac{EVS_{res}}{\sigma}\right)\right. \\ & \left.+\frac{\sigma}{\sqrt{2\pi}}\left(e^{-\frac{EVS_{res}{}^2}{2\sigma^2}} - e^{-\frac{(5-EVS_{res})^2}{2\sigma^2}}\right)\right\} \end{aligned} \quad (6)$$

The proposed methodological approach to assessing the effectiveness of introducing an autonomous energy system by households allows:

- taking into account energy saving drivers;
- determining directions for increasing energy efficiency;
- promoting favorable investment support for the introduction of autonomous systems, which are to be implemented in households.

The study took into account autonomous energy supply systems, including all costs. It is assumed that the average life of the systems is twenty years since income and expenses during this period remain in the same ratio. Discounted cash flows allow for the overall expected life of the system. At the same time, the self-consumption rate assumes the production of electricity by installations that are autonomous in a household, divided by the total production of electricity by the system.

When predicting the efficiency of investments in autonomous energy systems by households, it is assumed that maintenance costs can be as low as 1% per year of investments [40]. In the period up to 2030, it is assumed that there are no tariffs for the introduction of new systems and the presence of income, taking into account the market price for the duration of the entire study period. Based on this, the profitability of the proposed investment in an autonomous energy system for a household was assessed.

Determining the economic value of introducing an autonomous energy system for a household involves defining the net present value (NPV_{haut}) in the studied period i:

$$NPV_{haut} = \sum_{i=1}^{n} \frac{CF_{hauti}}{(1+d)^i} - \sum_{i=0}^{n} \frac{\mathrm{Inv}_{haut}}{(1+d)^i} \quad (7)$$

When justifying the economic feasibility of introducing autonomous energy systems in households, the possible emergence of new technologies was also taken into account. At the same time, the study took into account a decrease in investments for households' autonomous systems in the period under review. Taking into account that the assessment was formed for a long period (20 years), it should be noted that there is some limit of the proposed methodological approach, namely, the emergence of innovative technologies in the formation of autonomous energy systems. This could result in a slight bias in the projected performance indicators in the context of economic benefits.

In order to determine the dependencies between such factors of energy independence of countries as GDP per capita, the volume of energy production per capita, the volume of energy imports per capita, regression equations were constructed as single cases of multiple relationships. Based on the formed dependencies, it is possible to determine the relationship between the factors under study. The following is the standardized form of the dependence of energy consumption per capita on indicators of energy resources impact on a country's economic development:

$$t_x = 0.68t_{x_1} + 0.14t_{x_2} + 0.04t_{x_3} + 0.81t_{x_4} + 0.35t_{x_5} - 0.18t_{x_6} \quad (8)$$

where t_{x_1}—the volume of energy resources production per capita (tons); t_{x_2}– energy resources imports (USD per capita); t_{x_3}—energy resources exports (USD per capita); t_{x_4}—energy intensity of GDP (tons per 1000 USD); t_{x_5}—GDP volume (USD per capita); t_{x_6}—the value of the import quota of energy resources (%).

Based on the integral coefficient of energy dependence, a forecast of indicators of energy dependence of the studied countries was compiled to assess the effect of an increase in the level of households' energy autonomy by 2030. A realistic (the level of autonomy will increase by 20%), optimistic (the level of autonomy will increase by 30%), and pessimistic (the level of autonomy will increase by 10%) scenarios were formed. The authors proposed the methodological approach to assessing the impact of risks of increasing households' energy autonomy based on such indicators as the probable deviation of the level of a country's energy dependence, as well as the determination of risk limits.

The integral coefficient of energy dependence of each of the studied countries is determined by the Equation:

$$IED = \sqrt{t_x} \quad (9)$$

Deviation of the level of energy dependence (Dev_{ed}) is determined by the Equation

$$Dev_{ed} = \sqrt{\sum_{i=1}^{n} (IED_i - Exp(IED)^2 \times p_i} \quad (10)$$

where IED_i—integral coefficient for optimistic, realistic, and pessimistic scenarios;

$Exp(IED)$—expected total cumulative coefficient of energy dependence of a country;

p_i—the probable value of the integral coefficient of a country's energy dependence according to the optimistic, realistic, and pessimistic scenarios.

The expected total integral coefficient of energy dependence of a country is determined by the Equation:

$$Exp(IED) = \sum_{i=1}^{\infty} IED_i \times p_i. \quad (11)$$

The risk limit of the level of energy autonomy of households in a country is determined by the Equation:

$$EAH_{rl} = \frac{Dev_{ed\ min}}{Exp(IED)} \quad (12)$$

Using the probable deviation of energy dependence and the risk limit, the authors analyzed the impact of changes in the energy market on changes in the energy security of the countries under study as a result of households' energy autonomy. The results were compared to determine future trends.

The initial data for the assessment given in the proposed methodological approach are shown in Table 1.

Table 1. Initial data for determining the risk limit of the level of energy autonomy of households.

Country	Energy Saving Level, %	Notional Cost of 1% of Energy Saving, USD	IED 10%	IED 20%	IED 30%
Australia	18	375	0.3039	0.2271	0.2135
Austria	10	474	0.7473	0.6639	0.5238
Belarus	8	736	1.1417	1.0040	0.8367
Brazil	12	525	0.9700	0.6800	0.6540
China	22	562	0.9329	0.7236	0.6587
Denmark	6	358	0.7511	0.6123	0.5498
Germany	12	421	0.7536	0.5283	0.4966
India	15	625	1.0496	0.8062	0.7632
Japan	13	384	0.4508	0.4069	0.3825
Kazakhstan	11	672	0.5476	0.4740	0.4332
Mexico	12	457	0.8768	0.7790	0.6543
Poland	6	598	0.7696	0.5972	0.5185
Portugal	5	589	0.7288	0.6475	0.5287
Romania	16	829	1.0367	0.9117	0.6598
Russia	15	680	0.4907	0.3576	0.3376
Saudi Arabia	21	459	0.4700	0.3786	0.3559
Spain	12	338	0.8269	0.6417	0.5543
Switzerland	7	295	0.5045	0.4554	0.4281
UAE	14	425	0.3701	0.3017	0.2836
USA	22	359	0.3703	0.2694	0.2532

Source: compiled by the authors based on statistical data [41].

4. Results

To study the possibilities of changing the level of energy autonomy of households, the volumes of their electricity consumption in the studied countries for the period 2000–2018 were determined (Figure 2). It is electricity that is the main energy resource, based on which a household can increase its energy independence from a state based on renewables, including solar and wind energy.

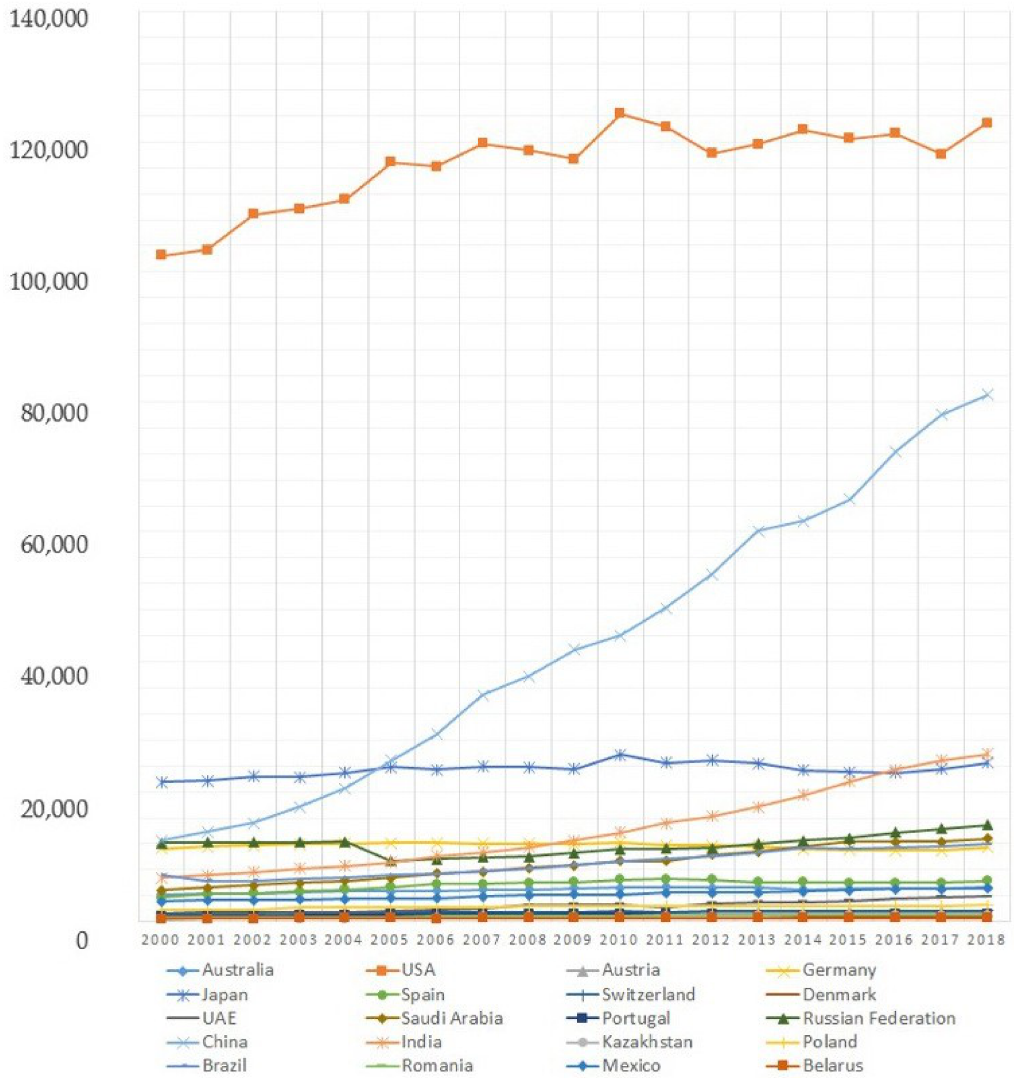

Figure 2. Final electricity consumption by households in the studied countries. Source: developed by the authors based on data [41].

Throughout the study period, the highest level of electricity consumption by households was recorded in the United States. It has grown by 22% compared to 2000. The most pronounced increase in the volume of electricity consumption by households is in China, where the indicator has increased almost seven times. A significant increase in the level of consumption is typical for India (about four times), the United Arab Emirates (3.5 times), and Kazakhstan (about three times). The lowest increase in consumption was recorded in Germany (6%) and Denmark (4%). In general, in all the studied countries, there is an increase in the volume of electricity consumption by households, resulting from the development of science and technology. The indicators do not depend on whether it is a developed or a developing country. At the same time, in each country, there are certain conditions for the introduction of the same technologies of renewable sources by households, the cost of equipment, conditions, and terms of operation. Taking into account all these determinants, the investment attractiveness of the installation and operation of autonomous energy systems for households has been assessed. The forecast is based on the assumption that 50% of households will gain energy independence. Based on this, factors for increasing the level of households' energy autonomy were determined on the basis of country's energy saving and the notional cost of 1% of households' energy saving (Figure 3).

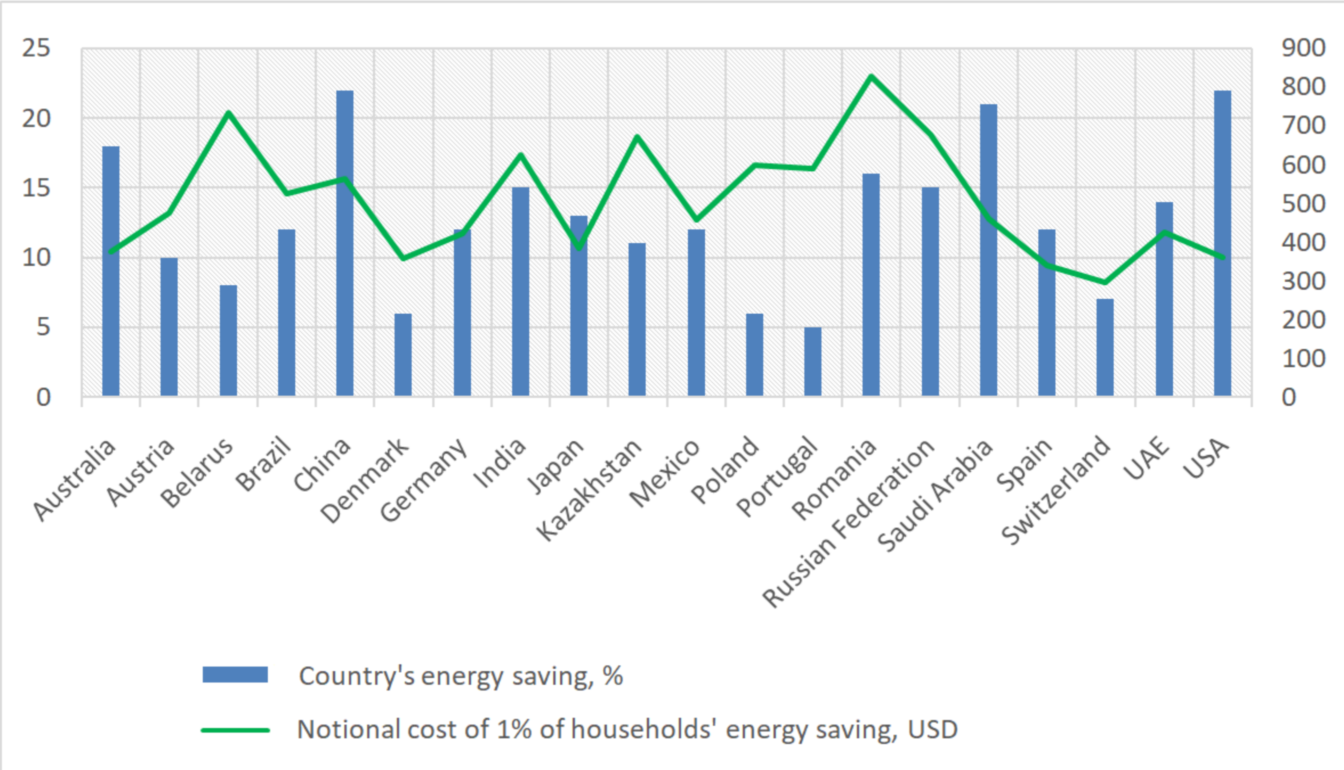

Figure 3. Motivational benchmarks for increasing state's and household's energy autonomy. Source: generated by the authors.

Households' energy autonomy is the most attractive in the USA, China, and Saudi Arabia, where a possible increase in the level of energy savings is expected by 21–22%. Most developed countries are characterized by the prospect of increasing energy savings above 10%, with the exception of Denmark and Switzerland. This is primarily due to the fact that Denmark and Switzerland already have a fairly high level of households' energy autonomy. Among developing countries, a high level of energy saving is possible in Russia, India, and Romania. This is due to the effective government policy in recent years to develop solar energy and to stimulate the introduction of renewable energy technologies in households. However, despite the prospects for a state, it is necessary to take into account households' interests as well. For example, the lowest notional cost of 1% energy savings for households was recorded in developed countries such as Switzerland, Spain, and Denmark, which is a consequence of effective government policies in previous years. The highest notional cost of energy savings for households is found in Romania, Belarus, Russia, and Kazakhstan. Given the prospect of benefits for Romania, the state should reconsider its strategic priorities and methods of stimulating household energy independence. In Belarus, there is a confrontation of state interests with households, expressed in a need for significant investments from households, which, as a result, affects the payback period and reduces investment attractiveness. For Russia and Kazakhstan, the main reason for this situation is the absence of an urgent need to motivate households since there is a priority of providing fossil energy resources.

Taking into account the opposition of the interests of a state and households, the forecast of energy dependence indicators was modeled (Index of country's energy dependence—IED) according to three scenarios, possible deviations (Dev_{ed}), and the impact of households' energy autonomy in relation to the risk limit of energy dependence of the studied countries (EAH_{rl}) until 2030. At the same time, three scenarios have been formed that imply an increase in the energy autonomy of households in a country by 10, 20, and 30% (Figure 4).

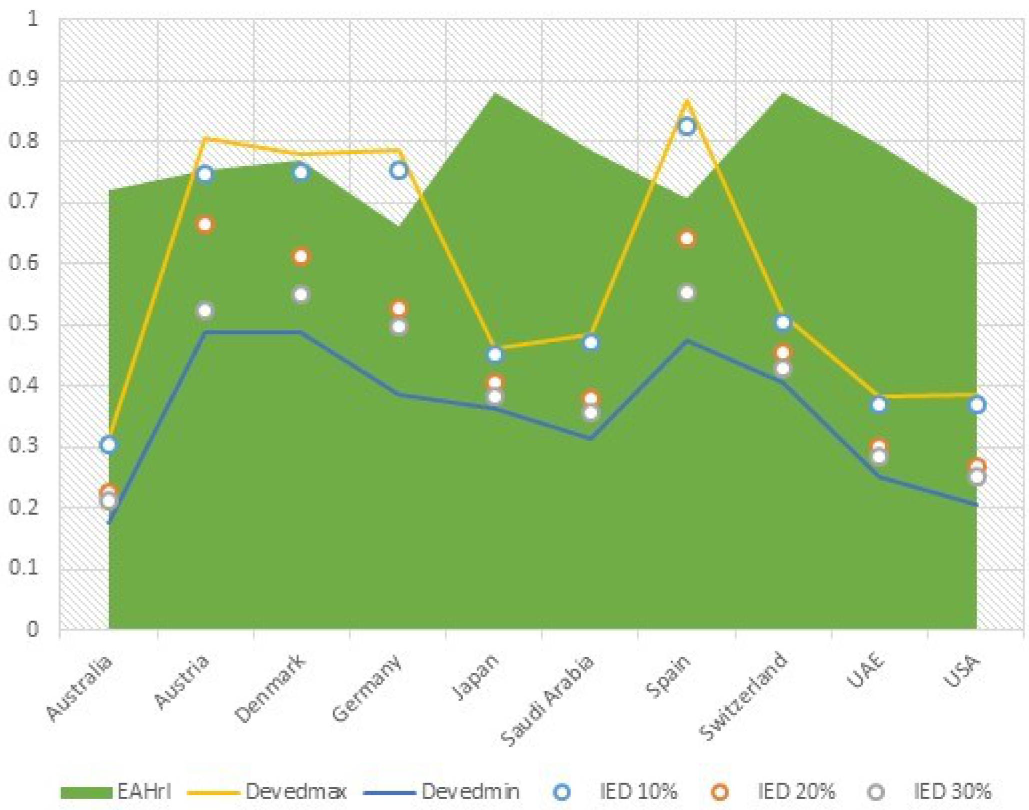

Figure 4. Forecast indicators of the impact of households' increasing energy autonomy on the level of energy dependence of the studied developed countries until 2030. Source: generated by the authors.

For most developed countries, there is a positive impact of increased energy autonomy of households. This is manifested in the fact that in all three scenarios the index of energy independence is within the risk of possible deviations. Moreover, the lower the index of energy dependence in comparison with the risk limit, the more effectively households' autonomy is manifested. The most positive effect in this context is typical for Japan, Australia, UAE, the USA, and Saudi Arabia. At the same time, one should pay attention to the paradoxical situation, which consists in the fact that most of these countries are leaders in the fossil energy market. Although, at first glance, households' energy autonomy is not a priority for these states, increasing its level can contribute to the development of additional energy resources to increase the level of their development. Despite the sufficient level of energy independence, an increase in households' energy autonomy for Austria, Germany, and Spain can lead to an excess of the risk limit and negatively affect the energy efficiency of countries since they are characterized by a deviation that exceeds the level of risk limit of energy dependence.

By analogy, the assessment was carried out for developing countries (Figure 5).

The forecasted indicators confirm the effectiveness of expanding the household's energy autonomy in Russia, Kazakhstan, and practically in Portugal. This process can ensure the further development of these countries based on energy savings and the development of additional energy resources. Russia and Kazakhstan have an advantage in the context of the availability of fossil energy resources that provide for the needs of households, but at the same time harm the environment. Energy autonomy of households in these countries has both economic and sustainable effects. Romania and most other developing countries can get a positive effect only as a result of a total increase in the energy autonomy of households up to 30%. For Belarus and India, so far, the energy autonomy of households is not feasible, since the energy dependence of these countries increases due to a rather high cost of improving energy efficiency. At the same time, deviations of possible results have exorbitant values in relation to the risk limit, which indicates that these countries are not ready for such a transition.

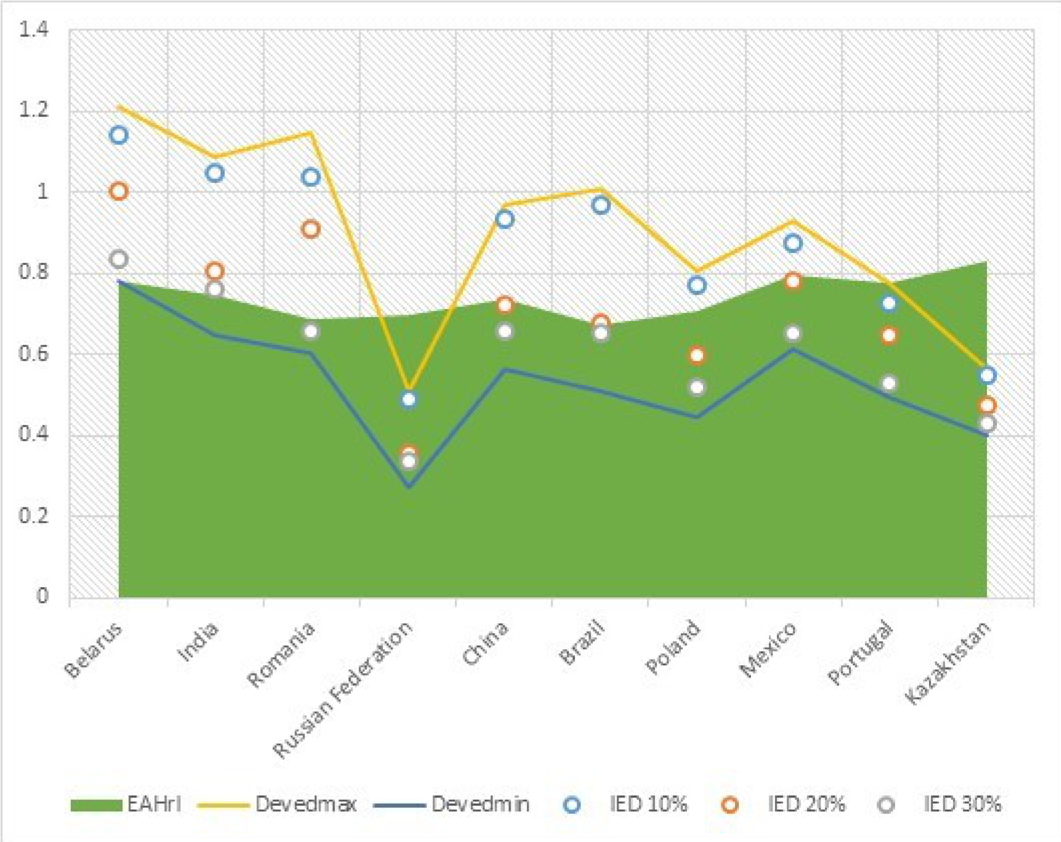

Figure 5. Forecast indicators of the impact of households' energy autonomy on the level of energy dependence of the studied developing countries until 2030. Source: generated by the authors.

For developed countries with a high level of energy independence and developing countries that own fossil energy resources, it is imperative to increase households' energy autonomy, which will mitigate the pressure on the environment. For developing countries, it is not advisable to prioritize this autonomy, since sufficient conditions have not been created for its successful and effective implementation.

5. Discussion

The household share is significant in global energy consumption, however, it is difficult to characterize it since consumer characteristics are determined by several factors, ranging from geographic location to the behavior of each of the users of a particular residential building. In addition, it is important to take into account the significant amount of energy used in this sector due to the use of traditional fuels and the implementation of modern energy policies [42]. Based on this specificity, the current study is relevant and can serve as a basis for further developments in this direction.

The advantage of the proposed methodological toolkit is a set of predictive indicators of the impact of households' energy autonomy regarding the degree of energy independence of the studied developed and developing countries, which made it possible to form their trend until 2030. This study confirms that while government support for household autonomy is energy efficient, it provides the greatest benefits to higher income households and thus contributes to increasing inequality [43]. Subsidies do not help reduce energy poverty because of the low investment capacity of households in developing countries. To achieve a more even distribution of benefits when developing policies to increase households' energy autonomy, the current situation of low-income households and issues of energy availability should be taken into account [22]. Considering that the development and construction of a functional autonomous intelligent network require deep knowledge, high costs, and availability of opportunities to use modern technologies, as well as the fact that the first installations have been produced in highly developed countries, the study confirms the benefits of households' energy independence for these countries. Today, a significant proportion of autonomous energy systems for households in Europe have smart grid characteristics. Developing countries should use rich practical experience of other countries for the construction of modern equipment [44].

Based on the study, it is assumed that benefits for a state in the form of load switching and savings are possible, but taking into account the differences in socio-economic aspects. That being said, developing a strategy, in turn, can affect the net economic cost of energy and the total amount of energy that each household consumes [45].

The conducted research indicates that giving additional energy autonomy of households cannot be achieved solely by legislative and regulatory acts. Instead, it is necessary to form a motivational mechanism for homeowners towards the material benefits of more efficient energy use. In order to improve the energy efficiency of one's home, it is critical to provide appropriate, helpful guidance. At the same time, state policy at the level of developed and developing countries must take into account specific cultural and ethnic circumstances. Therefore, this study can be complemented by a study of the relationship between cultural values and household energy consumption [46]. Cultural differences are possible. For example, Japan and European countries show clear cultural differences that affect household energy consumption [23].

Based on the proposed methodological approach, it was determined that decentralized energy systems have clear advantages, but one of the main disadvantages is the lack of economic scale effect. Decentralized energy systems are developing in parallel with the trend towards the use of energy resources by the population. Energy autonomy is the main driving force behind investing in local renewable energies, according to many of these communities [47].

A limitation of the study is a certain degree of averaging of the initial indicators for assessing the level of energy independence of households since each of them has its own specifics and can establish different types of autonomous systems, as well as their integration. At the same time, a household can introduce the newly created autonomous system earlier than the period suggested in the study. This can affect the final results of deviations of the obtained indicators [48]. This study can also be expanded towards identifying potential opportunities for improving the quality of housing maintenance and modernization to increase the energy autonomy of households. In addition, there is a need to consider the possibilities of co-production with household participation, including opportunities for households to revise the parameters of tasks related to research and project implementation [49].

The results of the study confirm that energy consumption in the residential sector continues to increase, and there is reason to believe that these dynamics will continue in the future. In the conditions of the economic crisis, as well as within the framework of the current policy on environmental protection and energy saving, a significant number of households are forced to live in conditions of a decrease in income and an increase in electricity prices. In this regard, an increase in the number of energy-poor households is expected. In addition to the study, a regression model of panel shutdown can be used to experimentally diagnose the sensitivity of households to fluctuations in energy prices due to their flexibility [20]. Therefore, in the long term, this study should be aimed at identifying the factors that determine the demand for energy in the residential sector, while special attention is to be paid to the analysis of income distribution and household vulnerability to the impact of changes in energy prices. The study is relevant in terms of periodic discussions on energy efficiency and reducing energy dependence.

6. Conclusions

Based on the assessment and comparison of the volumes of electricity consumption by households in the studied countries for the period 2000–2018, the highest level of electricity consumption by households is characteristic of the United States. The highest rates of increase in electricity consumption by households among the studied countries were recorded in China, India, the United Arab Emirates, and Kazakhstan. At the same time, a low level of increase in consumed volumes is typical for Germany and Denmark. In all the countries studied, both developed and developing, there is an increase in the volume of electricity consumption by households, as a result of the development of scientific and technological progress.

Diagnostics of the investment attractiveness of the installation and operation of energy systems for households makes it possible to determine the boundaries of a possible increase in the level of their energy autonomy. The most indicative countries of households' energy autonomy are the United States, China, and Saudi Arabia. In most developed countries, there is a prospect of increasing energy savings above 10%. Among developing countries, a high level of energy saving is possible in Russia, India, and Romania based on effective government policies. A low level of notional cost of energy savings for households is typical for Switzerland, Spain, and Denmark. The highest notional cost of energy savings for households was recorded in Romania, Belarus, Russia, and Kazakhstan. Therefore, states should reconsider their strategic priorities and methods of stimulating household energy independence. A conflict of interests between a state and households has been identified, which manifests itself in the need for significant investment from households, which, as a result, affects the payback period and reduces the level of investment attractiveness. For countries rich in fossil fuels, the main reason for this situation is insufficient motivation of households.

The modeled indicators of a country's energy dependence for three scenarios, possible deviations, and determination of households' energy autonomy in relation to the risk limit of energy dependence demonstrate the positive impact of households' energy autonomy for most developed countries. The most positive effect in this context is characteristic of the leading countries in the fossil energy market. Despite the absence of a clear political priority of households' energy autonomy for these countries, an increase in its level can contribute to the development of additional energy resources to increase the level of development. Increasing households' energy autonomy for Austria, Germany, and Spain may lead to an excess of the risk limit and negatively affect the energy efficiency of countries. There is a positive economic and sustainable effect of increasing households' energy autonomy in Russia, Kazakhstan, and Portugal. For most developing countries, a positive effect is possible as a result of a total increase in household energy autonomy up to 30%. In Belarus and India, household energy autonomy is not sufficiently expedient. The reason for this is a rather high notional cost of improving energy efficiency, which affects the increase in the level of energy dependence. On the other hand, the exorbitant deviations of indicators in relation to the risk limit indicate an insufficient readiness of these countries for the energy transition.

For countries that have a high level of energy independence, households' energy autonomy is focused on effective sustainable development. An increase in households' energy autonomy in developing countries at the present stage is possible based on sufficient provision for its successful and effective implementation without threats to economic development.

The study is valuable in the context of determining the possibilities of influencing the energy autonomy of households, identifying the benefits and risks of taking measures in the process of transforming the global energy for countries with different economic statuses. In the long term, within the framework of this study, it is possible to analyze the determinants of energy consumption in the housing sector, namely, the significance of income and the vulnerability of households in relation to changes in energy tariffs.

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