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JEVONSON PARADOX, ENERGY SECURITY EFFECT AND DEVELOPING COUNTRIES INDUSTRIALIZATION EFFECT AS DRIVERS OF COAL INDUSTRY GROWTH

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This article examines the growth of the coal industry in the 21st century. Despite the development of diverse energy sources, including renewable ones, coal remains a key energy resource in the global energy mix, accounting for more than a third of the energy balance. This phenomenon is partly due to the Jevons paradox (rebound effect), which, however, cannot explain new surge in coal production, consumption, and trade (reaching a record in 2024), including in countries that have consistently reduced coal production and consumption over recent decades (the United States and Europe), given the absence of radical technological change. The article argues that energy security effect and developing countries industrial-ization effect are no less important factors in the coal industry's growth than the rebound effect.

Keywords: *coal industry, rebound effect, Jevons paradox, energy security, industrialization.*

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Introduction. In 2024, the coal industry reached new historical records:

– coal production amounted to 9.15 billion tons[1];

– global demand for coal amounted to about 8.8 billion tons, which is 1,5 % more than in 2023[2];

– world coal trade exceeded 1,5 billion tons[3], while "during the 21st century, international coal trade volume has increased nearly every year averaging an annual growth rate of 4 %, which is higher than the rates for demand or production"[4];

– commercial banks from Asia, the US and Europe have invested more than $130 billion in the coal industry[5].

At the individual company level, there is also growing interest in the coal industry: in 2023, 19 of the top 40 mining companies derive some revenue from coal (in 2022, this number was only 11) and for the first time since 2010, coal became the largest source of revenue for the top 40 mining companies, increasing from 23 % to 28 %[6].

[1] Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 5. – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).
[2] Global coal demand to remain on a plateau in 2025 and 2026 // International Energy Agency. – URL: https://www.iea.org/energy-system/fossil-fuels/coal (date of access: 01.11.2025).
[3] Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 6. – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).
[4] Ibid. – P. 6.
[5] Finance, Investment and Insurance – Backing Coal Responsibly // FutureCoal. – URL: https://www.future-coal.org/fund-fair-fund-equal-chairman-open-letter-press-release/ (date of access: 01.11.2025).
[6] Mine 2023. The era of reinvention // PwC. – 48 p. – P. 23. – URL: https://www.pwc.com/gx/en/issues/tla/content/PwC-Mine-Report-2023.pdf (date of access: 01.11.2025).

The global trend of coal industry growth has significant regional differences: in 2024, "rising consumption in China, India, Indonesia and other emerging economies is greater than the offset declines in advanced economies in Europe, North America and northeast Asia"[1]. China is the undisputed leader in the coal industry among countries: "It accounts for 56 % of global coal consumption – almost 30 % more than the rest of the world combined. One of every three tons of coal consumed globally is used in Chinese power plants, making China and its power sector the largest single driver of global coal demand"[2]. It is China's position that is currently decisive in the future development of the global coal industry.

Results and its discussion. The continued existence of coal as the primary energy resource for hundreds of years is partly explained by the Jevons paradox (or rebound effect), which was first described back in 1865 [1]. In its most general form, this paradox can be described as follows: as technological progress progresses, the marginal efficiency of resource use increases, which leads to an increase in the overall demand for it and the volume of its consumption in kind. "It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth" [1], – wrote W. Jevons. Jevons's conclusions were based on the example of England, where steam coal-fired engines designed by J. Watt were first used, the efficiency of which significantly exceeded previous models, which led to the spread of coal-fired engines in virtually all industries and the growth of the coal industry.

In the 1980s, D. Khazzum [2] and L. Brooks [3] again proved the validity of the Jevons paradox, significantly expanding the understanding of the mechanism of this phenomenon. G. Saunders called this hypothesis the Khazzoom-Brookes postulate [4], showing the diversity of internal effects (the direct rebound effect – increasing energy efficiency makes energy consumption relatively cheaper than it stimulates its growth; the income effect – increasing energy efficiency increases real income and leads to accelerated economic growth, which, in turn, leads to an increase in energy consumption) and the limitations of application in the neoclassical growth model (at the microeconomic level, increasing energy efficiency usually leads to a decrease in energy consumption, but at the macroeconomic level, overall energy consumption will grow) [4].

St. Lange et al. note: "The literature on the rebound phenomenon has grown significantly over the last decade. However, the field is characterized by diverse and ambiguous definitions and by substantial discrepancies in empirical estimates and policy proposals" [5, p. 1]. By summarizing the results of previous studies, these authors were able to demonstrate the complexity of the rebound effect mechanism at different economic levels and over different time periods. The results of their research are graphically depicted in Figure 1, where: "Four stacked analytical levels at which the rebound effect can be measured are distinguished. At each level, several rebound mechanisms, which are represented by the arrows, cause an increase in energy consumption. The respective types of mechanisms are categorized into short-run and long-run mechanisms. The connecting lines between the levels indicate that the rebound effect at a lower level is part of the rebound effect at a higher level" [5, p. 6].

In the context of this study, St. Lange's work is important because, by consistently generalizing all the results of research into the Jevons paradox (rebound effect), the authors once again confirm the validity and practical applicability of this theory. Of particular interest are also the results of the study of the rebound effect. Brockway et al. [6]: "They find much higher effects (backfire) for China than the other two, which suggests that producer-sided economies are more rebound-prone" [5, p. 3].

[1] Global coal demand to remain on a plateau in 2025 and 2026 // International Energy Agency. – URL: https://www.iea.org/energy-system/fossil-fuels/coal (date of access: 01.11.2025).
[2] Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 4. – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).

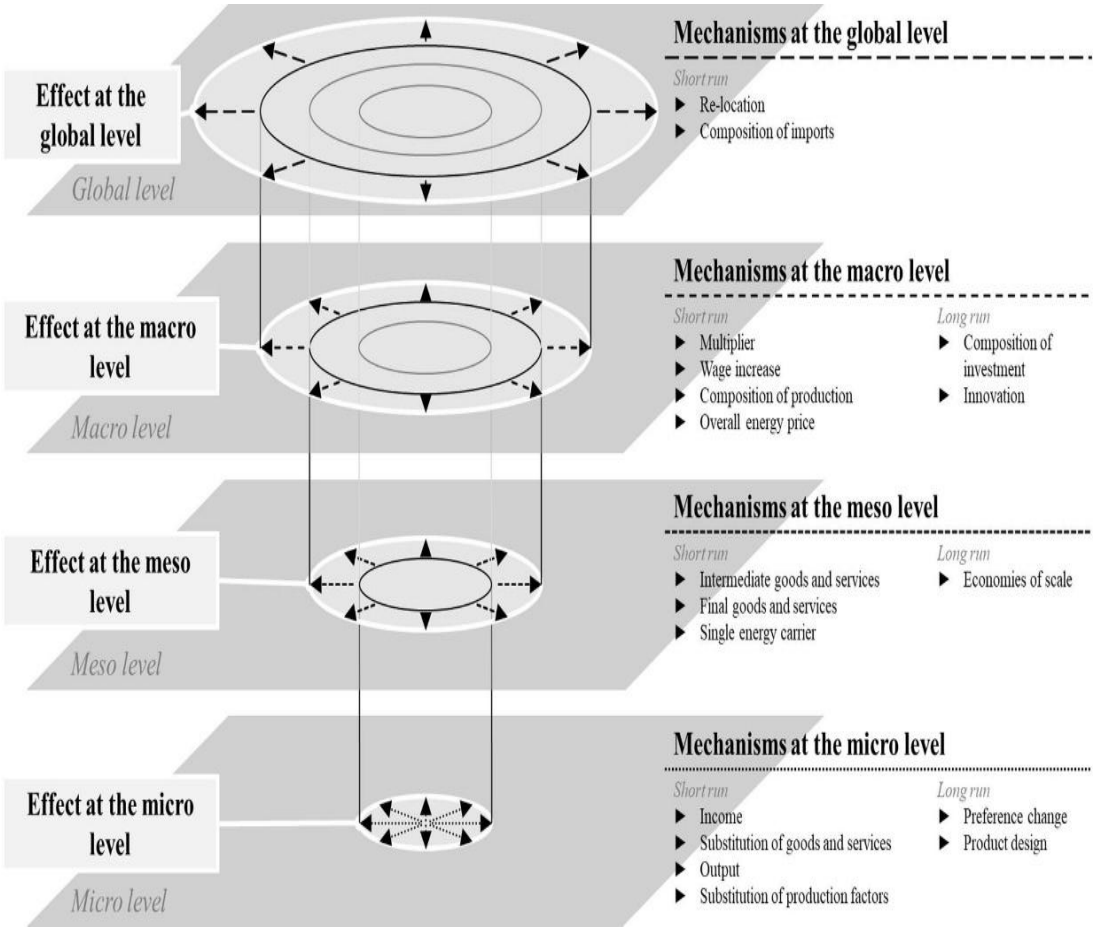

Figure 1 – Rebound effects and mechanisms at different economic levels and time frames
Sourse: [5, p. 6].

Thus, in the future, we will proceed from the fact that one of the most important factors in the growth of the coal industry over several hundred years has been and remains the increase in the marginal efficiency of coal as an energy fuel in line with technological progress (the Jevons paradox or rebound effect). An important condition for the practical applicability of this theory is the geological abundance of coal: "The success of coal in the primary energy mix is due to the fact that it is abundant, cheap, and most often a domestic resource" [7].

However, the Jevons paradox cannot explain the recent trends in the global coal industry, namely the high rates of growth in coal production, consumption and trade in recent years in the absence of a radical technological leap.

As noted, the coal industry's growth is driven primarily by Asian countries, primarily China. Figure 2 shows global coal consumption by country (region).

However, in 2024 and 2025, coal consumption is expected to increase even in countries that have been consistently reducing it over the past decades. In particular, the United States and the European Union: – "coal demand in the United States is estimated to have increased by 10 % in the first half of 2025, driven by strong electricity demand and higher natural gas prices, which prompted some electricity generation to shift from gas to coal"[1];

[1] Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 4-5. – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).

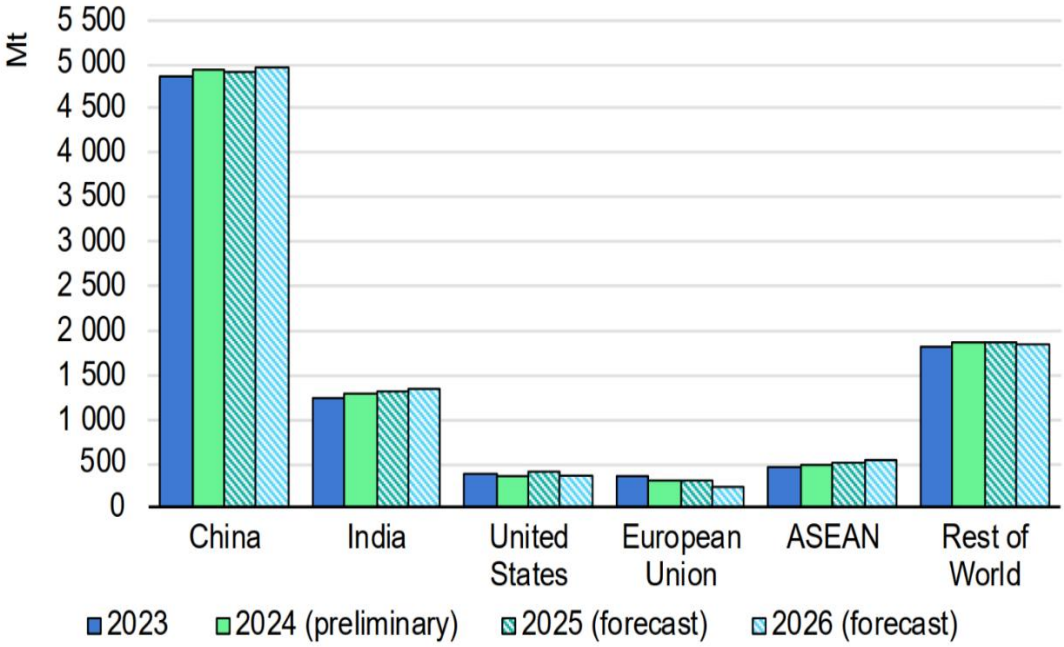

Figure 2 – Global coal consumption, 2023–2026 (2025–2026 forecast)
Sourse: [1].

– "in the European Union, in the first quarter of 2025, we estimate coal demand growth of around 5 %. … In Germany, the largest coal consumer in the European Union, we estimate that coal power generation increased by 11 % in the first half of 2025"[2].

China will invest a total of US$248 billion in the coal sector between 2022 and 2024. India has committed over $1 billion to coal gasification projects by 2025. The United States has planned $625 million in investments in the modernization and upgrading of coal-fired power plants in the fall of 2025[3].

Another factor in the growth of the coal industry, no less important than the Jevons paradox, is energy security. Energy security is understood as "a state of assured and consistent availability of energy sources like fossil fuels, renewables, and nuclear energy to satisfy the energy needs of the nation or region" [8, p. 2]. Electricity availability should be understood as both the ability to access energy resources (extraction or import) and their affordability.

There is no universal solution to energy security issues. Each country determines its optimal energy balance based on its available mineral reserves, its own structural policies, and the global energy market situation. Aydin et al. argue: "If the energy security risk is too high, instead of long-term R&D investments that will reduce the country's energy intensity, it may increase the use of fossil fuels to ensure energy stability in the short term. On the other hand, a relatively lower security risk may enable the economy to reduce energy intensity in the long term through R&D investments" [9, p. 500]. Coal is one of the most stable energy sources, which national economies turn to every time a crisis occurs.

Despite the decarbonization efforts declared by most countries, coal remains the primary fuel in the global energy sector. Coal is a cost-effective and reliable energy source, as it leads the

[1] Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 11 – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).
[2] Ibid. – P. 9.
[3] Finance, Investment and Insurance – Backing Coal Responsibly // FutureCoal. – URL: https://www.future-coal.org/fund-fair-fund-equal-chairman-open-letter-press-release/ (date of access: 01.11.2025).

energy trilemma: energy security, availability, and reliability. Due to its abundance, cost-effectiveness, and developed infrastructure, coal remains a key energy resource in many countries.

Assessing the economic effectiveness of energy security is twofold. On the one hand, "if history is a guide, then we should not expect many interventions in these policy areas to come close to maximizing net economic benefits" [10]. Indeed, the primary objective criterion for successful energy security is the physical availability of electricity, even if its price is higher. On the other hand, the unaffordability of electricity, especially in the long term, can become a serious threat to energy security.

Coal is an energy resource that meets two availability criteria: it is geologically abundant and its cost, including extraction and other costs, is relatively low. Despite rising coal prices due to mine closures and reduced investment, coal remains far more cost-competitive than any other fuel source.

During the peak of the energy crisis in 2022, thermal coal prices soared above $400[1] (which even exceeded the price of coking coal). However, by the end of 2023, coal prices had declined again, remaining only slightly above pre-crisis levels. Thus, coal affordability had been restored. The observed price peak during the energy crisis, driven in part by the stock market, demonstrates the continued critical role of coal as an energy resource.

The main, and virtually the only, factors driving the possible reduction of the coal industry are decarbonization and the emergence of a "green economy". Most often, scientific and political rhetoric about the need to reduce the coal industry is based on environmental reasons. Economic factors remain ignored. According to the World Energy Agency: "Global electricity demand increased by 4,3 % in 2024, a step change from the 2,5 % growth seen in 2023. The average pace of electricity demand growth from 2010 to 2023 was 2,7 %, double the rate of total energy demand growth over the same period. Electrification picked up across sectors, raising electricity demand in most major economies in 2024. China accounted for the largest share of electricity consumption growth, but increases were seen globally". Almost all regions saw an acceleration in the rate of electricity consumption growth in 2024 compared with the annual average from 2012 to 2022. Globally, electricity consumption increased by 1080 TWh, nearly two times the annual average of the past decade"[2]. Such high rates of growth in global energy consumption can only be achieved by utilizing all energy sources available to humanity at the current technological level. The steady growth of global electricity consumption (and given increasing digitalization and the growing global population, there is no reason to assume it will stop, much less decline) suggests that, in the absence of radically new and fundamentally more cost-effective electricity generation technologies, the coal industry will continue to grow (even if its relative share in the energy balance declines amid the growth of alternative energy sources).

Hecking's calculations showed that "a carbon price of 25–100 USD per tonne of CO2 would be needed to phase out coal in the power sector, depending on the technology and the world region, even assuming significant technological progress" [7]. According to Russian scientists, "to achieve zero global greenhouse gas emissions by 2050, it is necessary to increase the share of energy expenditure in global GDP from 8% to 25 % <…> by 2035" [11, p. 12]. Obviously, the described scenarios are not feasible at the current level of technology, which once again confirms the validity of forecasts for the further growth of the global coal industry.

J. Zhang and X.-f. Liu point out the lack of existing research analyzing the relationship between renewable energy sources and energy security: "Depending on the term of geopolitics, the influences of renewable energy on energy security remain to be explored. There are few studies regarding how developing countries integrate renewable energy technologies and

[1]Coal Mid-Year Update 2025 // International Energy Agency. – 29 p. – P. 9. – URL: https://www.iea.org/reports/coal-mid-year-update-2025 (date of access: 01.11.2025).

[2] Global Energy Review 2025. Electricity // International Energy Agency. – URL: https://www.iea.org/reports/global-energy-review-2025/electricity (date of access: 01.11.2025).

ensure energy security because studies that have been conducted have concentrated on the developed countries. Long-term sustainability and scalability of renewable energy technologies have not been given a lot of attention. Many times, studies assess short-term gains from the deployment of renewable energies, but there is a need to examine their potential for long-term energy security, with such considerations as energy storage and electric grids in mind. The economics of renewable energy have not been treated with enough attention. Although past studies are primarily concentrated on addressing technical issues, it is necessary to measure the economic effects of renewable energy implementation on the cost of an energy system, employment opportunities, and economic growth" [8, p. 3]. The economic analysis of the decarbonization trend and the emergence of a "green economy", and with it the prospects of the coal industry, is greatly complicated by the facts of their simulation, which are demonstrated in the works of S. Yu. Solodovnikov et al. [12; 13; 14; 15]. Such simulation may be caused by political struggle within the country, geopolitical clashes of interests at the level of countries, regions, and/or individual social groups, and other political-economic reasons.

The positive economic impact of developing renewable energy sources at the macro level can manifest itself in diversification of the energy balance and, consequently, increased national energy security. Diversification of the energy balance becomes especially relevant during periods of geopolitical instability. J. Zhang and X.-f. Liu share a similar opinion: "The wild swings in global energy markets are triggered by such geopolitical tensions as clashes over access to critical minerals, upheavals in trade routes to fossil fuels, and biased distribution of natural resources, which challenge fair access and development. Here, renewable energy is no longer positioned as a solution to the climate crisis but also as a strategic resource that can help reduce the risks of the supply chain and make energy more independent" [8, p. 1]. Some Russian scientists point this out: "The policy of Western European countries to expand the use of renewable energy resources is not driven by economic factors, but has the underlying motive of diversifying the fuel and energy balance of each individual state in order to limit the growth of dependence on imported energy resources, which is entirely logical" [11, p. 12]. Crawley also believes that the policy of developing renewable energy sources is supported throughout the world in order to mitigate barriers in the area of energy security [16].

However, the growing share of renewable energy sources also carries additional risks to energy security associated with the technical difficulties of ensuring the uninterrupted operation of a national energy system diversified by sources: "Renewable energy consumption can be used both positively and negatively in regards to energy security. Through the use of renewable energy technologies, the energy mix can be varied, and a single source can be eliminated. By utilizing the energy sources from the sun and the wind, countries will be able to produce their own clean energy and not rely on imported fossil fuels. Contrary, renewable energy sources bring forth transmission and grid stability challenges. It is necessary to adapt the grid infrastructure, energy storage solutions, and grid management systems for the integration of a large volume of variable renewable energy (VRE) into the grid. Deficiencies in these aspects could result in disturbances in the energy supplies, compromising energy security" [8, p. 2].

A key technological, organizational, and economic feature of renewable energy is their inability to function without backup traditional energy sources, the most important of which is coal. Renewable energy sources can only be fully utilized if there is a stable supply of other energy sources (coal, gas, nuclear fuel). Therefore, another security risk for a national energy system with a high share of renewable energy is the availability of traditional energy sources. Moreover, the higher the share of renewable energy in a country's energy balance and the poorer its domestic carbon (or nuclear) fuel reserves, the greater the geopolitical risks to energy security.

Pang et al. warn about the risks of depletion of natural resources, which increase with the growth of renewable energy sources: "…diversifying energy sources is a good option, but policymakers should be careful while enhancing the share of renewable energy sources. Em-

bracing a mix of fossil fuels, renewables, nuclear energy, and emerging technologies like hydrogen can reduce dependence on finite resources and enhance resilience to supply disruptions. Although renewable energy sources can reduce energy security risks by diversifying the energy mix of economies, they can exacerbate the energy security risks by contributing to the depletion of natural resources. This is because the development of renewable energy projects requires fossil fuels, and renewable energy items are produced with scarce critical minerals" [17, p. 8]. The development of renewable energy sources stimulates the development of the mining industry, since it requires a large amount of diverse resources, including coal. In particular, the construction of renewable energy infrastructure requires steel and cement, the production of which is impossible without coal.

The transition to renewable energy sources is happening piecemeal, fragmented, and toward the diversification of national energy systems. A true guarantee of national energy security is not just a diversified but a well-balanced national energy system, which is extremely difficult (at least at the level of current technological development) without the use of such an accessible and sustainable energy resource as coal. In today's highly diversified global energy system, coal accounts for more than a third, serving as a guarantor of energy security. In more than 80 countries, coal plays a leading role in the power and heat supply[1].

Another factor driving the growth of the global coal industry is the industrialization of developing countries. Decarbonization and the "green economy" often obscure the objective economic reasons for the transformation of national energy systems. For example, many European countries were among the first to announce the abandonment of coal as an energy resource (France in 2005, Germany in 2019, etc.), citing a desire to reduce carbon dioxide emissions. At the same time, it should be remembered that in Europe, during the period of industrialization (first, second, and third waves), all the most favorable coal deposits have already been depleted, current mining involves costly underground mining, and the service life of coal-fired power plants is almost completely exhausted. Given this, coal production and/or imports may indeed be less profitable than, for example, nuclear energy in France or renewable energy sources in Germany, which has long been a technological leader in this field. In 2015, the UK ceased coal mining for purely economic reasons: expensive underground mining made coal uncompetitive. However, the situation could change radically depending on global market conditions, which in turn are strongly influenced by geopolitical developments (the energy security effect discussed earlier). This explains the current growth in coal consumption in Europe and the US in 2024.

The prospects for the development of the modern coal industry vary greatly across countries, depending on their starting points. Countries that have already industrialized and have a long history of coal development have significantly depleted their reserves, and their coal infrastructure requires modernization. Under these conditions, the development of new energy sources may indeed prove more feasible and cost-effective, especially if their current economic model is primarily service-based rather than industrial.

Developing countries, embarking on the path of industrialization (new industrialization), which requires high rates of growth in electricity consumption, find themselves in a completely different situation. Such countries are developing all available energy sources. Coal, as one of the most economical solutions, plays a critical role in the energy balance of such countries. This explains the growth in coal consumption in the countries of the Asia-Pacific region, which are thus solving the problem of rapidly increasing electricity production. According to EMBER analytics, in 2024, China will consume 30 % more electricity per capita than Europe; since 2000, this figure in China has increased by 569 %, while in Europe it has decreased by 7 %[2] (Figure 3).

[1]Coal Facts // FutureCoal. – URL: https://www.futurecoal.org/coal-facts/ (date of access: 01.11.2025).
[2]Data into action // Ember. – URL: https://ember-energy.org/ (date of access: 01.11.2025).

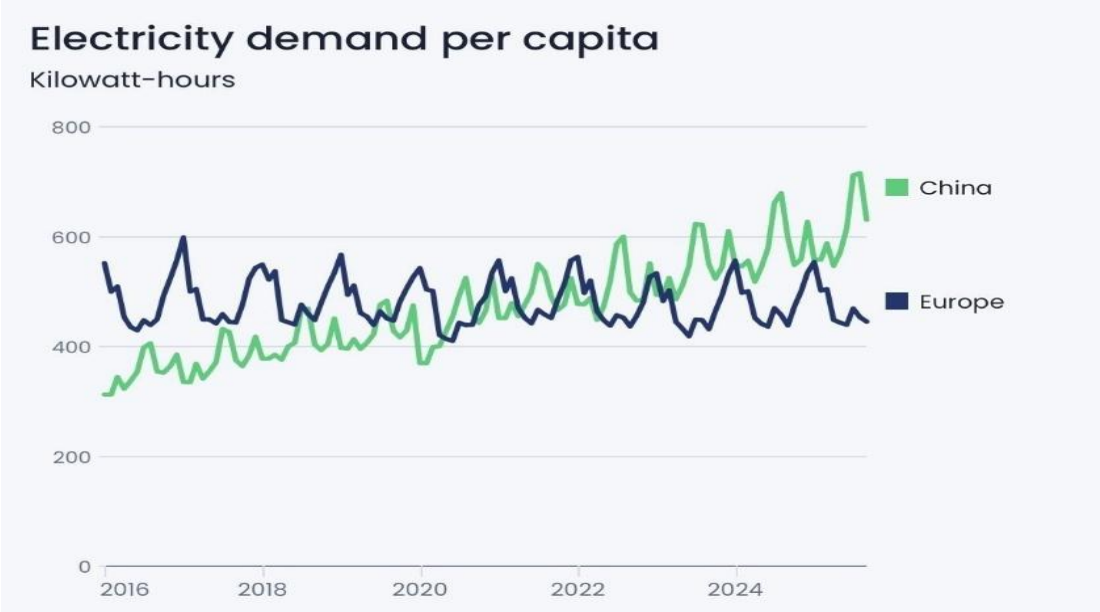

Figure 3 – Electricity demand per capita in China and Europe.
Source: [1].

For developing industrial countries, firstly, the issue of energy security is more important than environmental protection. Secondly, energy security can only be achieved by utilizing all available energy sources, especially the most cost-effective ones. In most cases, this resource will be coal. Moreover, for developing industrial countries, coal is also critical as a raw material needed in metallurgy, the chemical industry, and construction.

Conclusion. Despite the growing share of renewable energy sources in the global energy system, as in most national energy systems, coal consumption is also growing in volume terms. This phenomenon is partly explained by the Jevons paradox, according to which the increase in coal consumption occurs due to the declining marginal costs of elec-tricity generation as technology improves. However, given the absence of a radical techno-logical leap, the Jevons paradox cannot explain the trends in the global coal industry over the past few years, namely the high rates of growth in coal production, consumption and trade, including in countries that have been consistently reducing their coal industries for decades (USA, Europe).

In addition to the Jevons paradox, other factors in the growth of the global coal in-dustry include: energy security effect and the developing countries industrialization effect are prominent. While coal has lost its dominant role in the energy balances of some devel-oped countries, it retains its strategic importance in terms of energy security. The greater the geopolitical instability, the greater the likelihood of further expansion of coal's use as the most widespread and cost-effective fuel. For developing industrial countries, coal plays a critical role as the primary accessible source of energy to meet the high growth rates of electricity consumption, as well as a raw material needed in metallurgy, the chemical in-dustry, and construction.

Global coal reserves far exceed those of oil and gas, suggesting that coal, given its abundance and low cost, will remain an important energy resource in the long term.

[1]Data into action // Ember. – URL: https://ember-energy.org/ (date of access: 01.11.2025).

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