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The state of the Russian fuel and energy complex and development paths in the context of the fourth energy transition

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Abstract
Global electricity production is increasing as a result of population growth, technological development and the demand for electricity by people and industry in the context of the energy crisis. Accelerated electrification has become the main energy transition trend in the final use of energy resources. In response to the climate challenges of the green agenda, the global energy industry has embarked on the fourth energy transition, focusing on prioritizing renewable energy generation. The countries of the world are faced with the most urgent tasks: accumulation and reservation of generated energy for further distribution, and balanced planning of the location of energy generation facilities, taking into account territorial features, economic needs and other factors, taking into account the normalised cost of a unit of energy obtained from renewable and non-renewable sources. The review used the research results of Russian and foreign scientists, including the authors of the study. The world energy system and the Russian energy system are considered in terms of the cost of energy by type of sources.
Keywords: world energy, fuel and energy complex of Russia, fourth energy transition, fossil energy sources, renewable energy sources.

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俄罗斯燃料和能源综合体的现状以及在第四次能源转型条件下的发展途径

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简介
随着世界人口的增长、技术的发展以及人口和工业在能源危机下对电力的需求，全球发电量不断增加。在能源资源的最终消费方面，加速电气化已成为能源转型的主要趋势。为了应对绿色议程中的气候挑战，全球能源行业已经开始了第四次能源转型，重点是优先利用可再生能源发电。世界各国正面临着最紧迫的任务：积累和保留所产生的能源，以便进一步分配；根据地域特点、经济需求和其他因素，均衡规划能源生产设施的布局，同时考虑到从可再生和不可再生资源中获取能源的单位标准化成本。综述采用了俄罗斯和外国科学家（包括本研究报告的作者）的研究成果。从各类能源成本的角度对世界能源系统和俄罗斯能源系统进行了研究。
关键词： 世界能源、俄罗斯燃料和能源综合体、第四次能源转型、化石能源、可再生能源。

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Introduction

Global electricity generation reached 29,925 TWh in 2023, an increase of 2.5% from 2022, demonstrating that the global energy system is becoming more electrified to meet the needs of a rapidly growing global population (Figure 1).

Fig. 2 shows the structure of global electricity generation by energy source for the period 1990 to 2022. The graph shows that the world's leading electricity generation is still thermal power plants fired by coal and gas.

By consistently implementing the green agenda, the world's countries produced a total of 4,748 TWh[1]. of energy from renewable sources in 2023, 13% more than in 2022. This level of generation was almost entirely provided by wind and solar energy, accounting for 74% of all additional clean electricity generated, and in the EU countries, 60% of the electricity produced was based on renewable energy sources[2].

Table 1 shows data on consumption, production and demand for electric energy of the unified energy system of Russia for 2019-2025 (forecast). Energy production is given by energy production sources. The ratio shows that the Russian energy system follows global trends: the largest amount of energy is produced by thermal power plants, followed by nuclear and hydroelectric power plants, and the list is completed by energy from renewable sources.

In the case of surplus production, the problem of storing the electricity produced arises. It should be remembered that since 1991 the Russian Federation has had a federal law on energy saving[3], which has many local regulations and helps to save energy wisely and preserve nature in general.

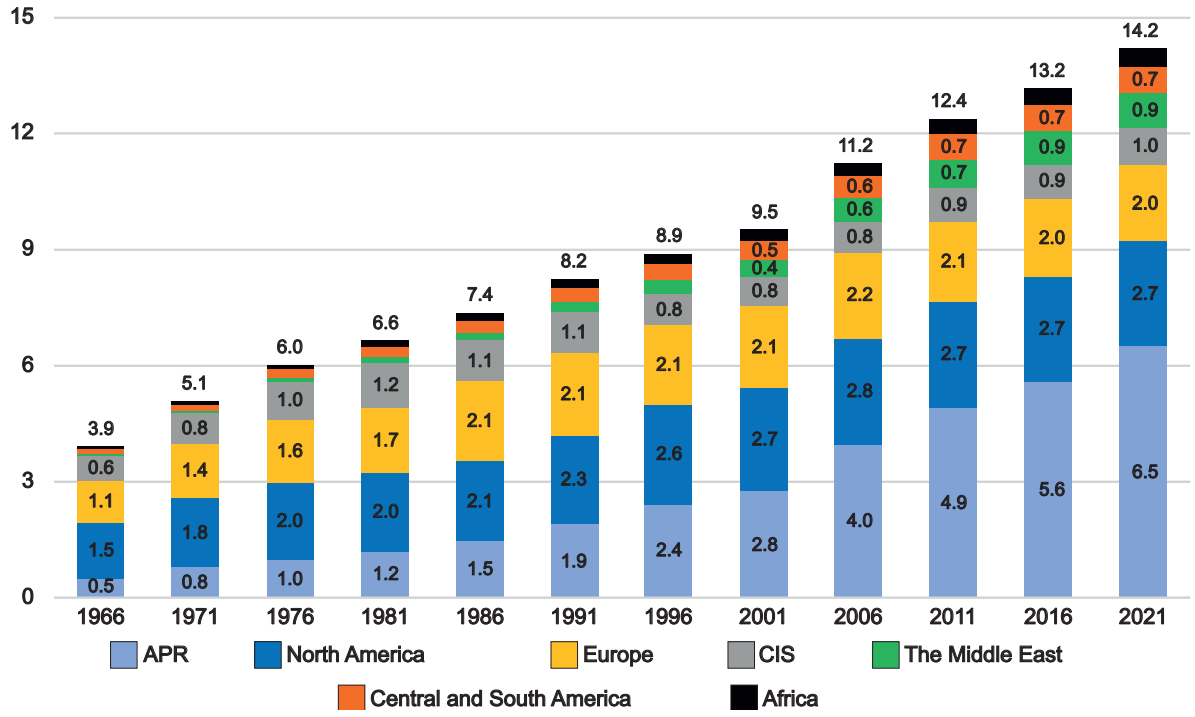
The main reason for using alternative energy sources is global warming caused by the use of fossil fuels. The depletion of energy resources, oil crises and the rising cost of energy production have forced the world to look for alternative energy sources.

Driven by changes in energy policy, the world is entering the fourth stage of the energy transition towards the widespread use of renewable energy sources and the displacement of fossil fuels. The development of renewable energy was spurred by the global energy crisis, which ended the long era of cheap fuel. In 1973, the world identified two ways out of the energy crisis[4]:

– intensive development of energy saving and energy conservation technologies, use of secondary energy resources;
– use of renewable energy sources.

With the growth of the Earth's population and its need for electrical energy, the development of industry in countries around the world, a related problem of accumulation and storage of produced energy has arisen. The use of energy

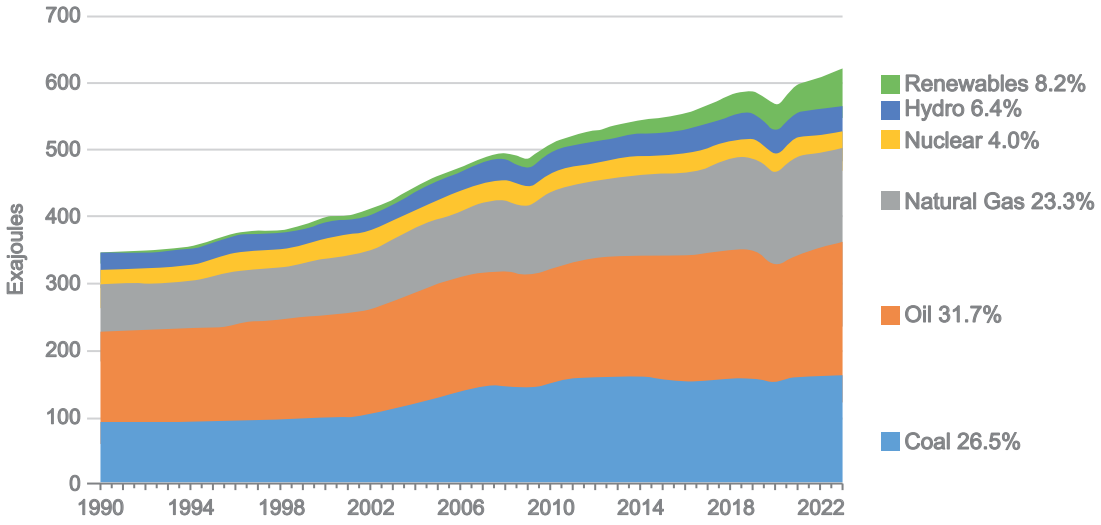
Fig. 1. Dynamics of world energy consumption for 1966–2022



Source: Statistical review of world energy. 2022, June. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.

[1] Statistical review of world energy. Energy Institute releases, 2024. https://dieselnet.com/news/2024/06energyreview.php.
[2] https://energy.hse.ru/Wiie.
[3] 'On Energy Saving and Energy Efficiency Improvement and on Amendments to Certain Legislative Acts of the Russian Federation' (as amended). SPS 'Consultant +'. https://www.consultant.ru/document/cons_doc_LAW_93978.
[4] Trends in the development of renewable energy sources in Russia and the world. http://www.bumprom.ru/im/files/305_fname.pdf.

Fig. 2. World electricity production, 1990–2022 (% by energy source)



Source: Statistical review of world energy. Energy Institute releases, 2024. https://dieselnet.com/news/2024/06energyreview.php.

storage systems (ESS) is an integrated solution for the accumulation of electrical energy, its conversion and further use [Mazurov, 2017]. At present, there are no technical solutions and energy storage devices that can be used on the scale required by energy-intensive companies. However, these companies should be most interested in such solutions, as increasing energy efficiency is one of the factors in reducing production costs, which ultimately leads to an increase in net profit[5].

It is worth mentioning another underestimated source of energy production - biomass. In economically developed Europe, according to IAEA data for 2019, the share of completely non-green sources - bioenergy and waste - in the total volume of primary resources used is 8%, which is not small[6]. Russian analysts have calculated: 'Renewable energy sources currently provide about 15% of the world's primary energy consumption, but 13% is hydropower and biomass. The share of new types of renewable energy sources is only 2%'[7].

These statistics are somewhat at odds with what is generally known, but biomass has a chance of taking a certain share of energy production, although it is not a clean source.

The purpose of this study is to determine the optimal source or complex of sources for electricity production in the country in the context of the global energy transition, based on the analysis of the following factors:

- the life cycle characteristics of energy production from different sources;
- electricity demand of population and industry;
- territorial population density [Mokshin, Reut, 2023];
- life cycle characteristics of energy production from various sources;
- standardised costs of produced energy by type of fuel and energy.

The subject of the study is the unified energy system of Russia.

It is assumed that in the near future, i.e. up to 2050 and beyond, priority will be given to the production of energy from renewable sources. One of its main advantages will be its cost.

1. Methodology, sources

To achieve the stated goal of this study, it is necessary to conduct an analysis of the current state and prospects for the development of energy in the world and Russia, the stages of the life cycles of energy production from various sources, the impact on the safety of the population and the environment, the cost of the produced kilowatt-hour of electricity.

A multi-factor analysis of the cost of generating electricity from different sources may include the following indicators:

- economic: investment and operating costs (fixed and variable). For instance, renewable energy plants have virtually no variable costs thanks to their free sources. In contrast, fuel costs account for up to 80% or more

[5] Report on the functioning of the unified energy system of Russia in 2023 (based on operational data). https://www.so-s.ru/fileadmin/files/company/reports/disclosure/2024/ups_rep2023.pdf.
[6] Report on the functioning of the unified energy system of Russia in 2023 (based on operational data). https://www.so-s.ru/fi leadmin/files/company/reports/disclosure/2024/ups_rep2023.pdf.
[7] Renewables alone won't keep you clean. https://atomicexpert.com/res_will_be_used_more_widely.

Table 1
Electricity balance of Russia's unified energy system, demand and consumption volumes, 2019–2025

Name	Measurement unit	Forecast						
		2019	2020	2021	2022	2023	2024	2025
Energy consumption	bn kWh	1032.8	1050.3	1081.5	1071.5	1081.3	1093.8	1097.2
Including pumped storage cost	bn kWh	2.71	2.71	2.71	2.71	2.71	2.71	2.71
Export	bn kWh	11.63	11.68	11.82	11.85	11.98	11.98	11.08
Import	bn kWh	1.19	1.11	1.11	1.11	1.11	1.11	1.11
Electricity demand	bn kWh	1042.9	1060.6	1071.8	1081.9	1091.9	1104.4	1107.8
Total electricity generation	bn kWh	1042.9	1060.6	1071.8	1081.9	1091.9	1104.4	1107.8
Hydroelectric power station	bn kWh	153.5	170.5	170.5	170.6	170.7	170.8	170.8
Nuclear power station	bn kWh	202.8	198.5	199.8	197.2	196.5	201.3	198.9
Thermal power station	bn kWh	685.12	687.33	695.3	706.2	715.4	722.2	727.99
Hydropower, hydroelectric power	bn kWh	1.58	4.35	6.14	7.9	9.21	10.12	10.12
Total installed capacity	MW	236 828	235 879	234 320	235 400	237 031	237 246	235 803
Hydroelectric power station	MW	45 304	45 394	45 475	45 525	45 576	45 591	45 598
Nuclear power station	MW	30 282	29 282	29 432	29 432	30 632	30 832	29 382
Thermal power station	MW	15 8840	157 866	155 175	155 518	155 401	155 401	155 401
Hydropower, hydroelectric power	MW	2401.5	3336.6	4237.4	4924.4	5422.1	5422.1	5422.1
Number of hours of installed capacity								
Nuclear power station	Hour/year	6697	6777	6789	6700	6414	6529	6768
Thermal power station	Hour/year	4313	4354	4481	4541	4604	4647	4685
Hydropower, hydroelectric power	Hour/year	656	1302	1448	1605	1698	1867	1867

Source: Scheme and programme for the development of the unified energy system of Russia for 2019-2025. http://gost.gtsever.ru/cgi-bin/ecat/ecat.cgi?b=2&pid=1&i=4293727666&pr=1.

of the total operating costs of thermal power plants (TPPs) [Degtyarev et al., 2016].

- equipment disposal: The equipment disposal process for renewable energy generation facilities has been developed from a technical perspective, and can be launched within a short period of time (Dzedik et al., 2023).
- installed capacity utilisation factor (ICUF): for thermal power plants, this figure is 80–90%, which is four times higher than for renewable energy power plants. The ICUF for wind and solar power plants can vary widely depending on geography and natural conditions [Degtyarev et al., 2016].
- estimated service life;
- construction and commissioning costs;
- location area and choice of specific type of power plant, etc.

Therefore, the characteristics of each type of power plant should be taken into account when planning the country's energy system.

In order to achieve the objective of this study, the authors also relied on data obtained from studies of the global energy industry and the Russian fuel and energy complex conducted by other scientists. The life cycles of energy production from various sources were compared: renewable and non-renewable (see Appendix 1).

The analysis revealed the pros and cons of renewable and non-renewable energy sources. In order to implement a mechanism to support renewable energy sources in Russia, legislation was passed to establish maximum value

indicators for renewable energy generating facilities, as well as target indicators for the input volumes of each type of facility up to 2035, and the degree of localisation[8]. Countries around the world have also adopted legislation on the use of renewable energy sources for energy generation. One important feature is the standardised cost per unit of energy for making decisions about the construction of specific types of power plant in specific areas, alongside other conditions.

Analysts from the Energy Research Institute (ERI) of the Russian Academy of Sciences conducted a comprehensive study (Makarov et al., 2024) on the current state and future development of Russia's fuel and energy sector. The study led to the following conclusion: 'Over the next 25 years, renewable energy sources and fossil fuels will be complementary rather than competing elements in most countries' energy systems.'

The ERI RAS study used a set of economic and mathematical models, with economic and demographic indicators and energy balances serving as the research tools. Calculations were based on various forecasting methods, including econometric analysis, cluster analysis techniques, optimisation, simulation and multi-criteria modelling. One of the issues identified by the ERI RAS study was the lack of a comprehensive approach to comparing the cost of producing a unit of energy from renewable energy sources and fossil fuels.

Researchers from the Institute of Energy Research of the Russian Academy of Sciences concluded that 'annual increases in electricity consumption will increasingly be provided by renewable energy sources, particularly due to their growing economic efficiency. By 2050, almost all the world's increased electricity consumption will come from wind and solar generation, with the shares of renewable energy sources and nuclear energy reaching 57–70% each (compared to 38% in 2021). Together with fossil fuels, these sources will form a complementary part of the future energy system' [Kulagin et al., 2024].

The final cost of switching to carbon-free energy sources depends on various factors, including the region's location, the availability of energy resources, import capabilities, demand levels and dynamics, solvency, economic sustainability, requirements for a sustainable electricity supply and the ability to synchronise with neighbouring regions' energy systems.

The increased use of gas and coal as reserve fuels in the electricity generation industry is expected to make their prices more volatile. The era of inter-fuel competition has arrived, with liquefied gas, ammonia and methanol set to grow in use for sea transport, electricity and gas, and for biofuels in road transport. Meanwhile, the transportation of passengers and goods by rail uses electricity or diesel-powered locomotive engines.

Clearly, as electricity consumption in Russia grows, the predicted indexation of regulated electricity tariffs will also increase: by 9% from 1 December 2022, by 6% from 1 July 2024, and by 5% from 1 July 2025. In certain regions of the Russian Federation, however, other tariffs may be established by the Government of the Russian Federation or FAS Russia[9].

The speed at which each country achieves the climate goals of the green agenda will be determined by its ability to offset the costs that would result from choosing a comprehensive solution to the energy supply problem associated with increasing the share of renewable energy sources.

2. Nuclear power

The use of nuclear energy for industrial purposes began in Russia in 1954 and is regulated by the federal law 'On the Use of Nuclear Energy'[10]. Nuclear power plants were commissioned in the UK and the US in 1956 and 1957. Thus, from the mid-20th century onwards, industrial energy production began at nuclear power plants around the world.

At the beginning of 2024, the share of nuclear energy in the world remained unchanged at 9% of the total energy generated[11]. In 2023, nuclear power accounted for almost 23% of Europe's total electricity generation[12], making it the largest source. This was driven by new nuclear power units coming online in Europe, China and the United States, as well as the restart of Takahama units 1 and 2 in Japan.

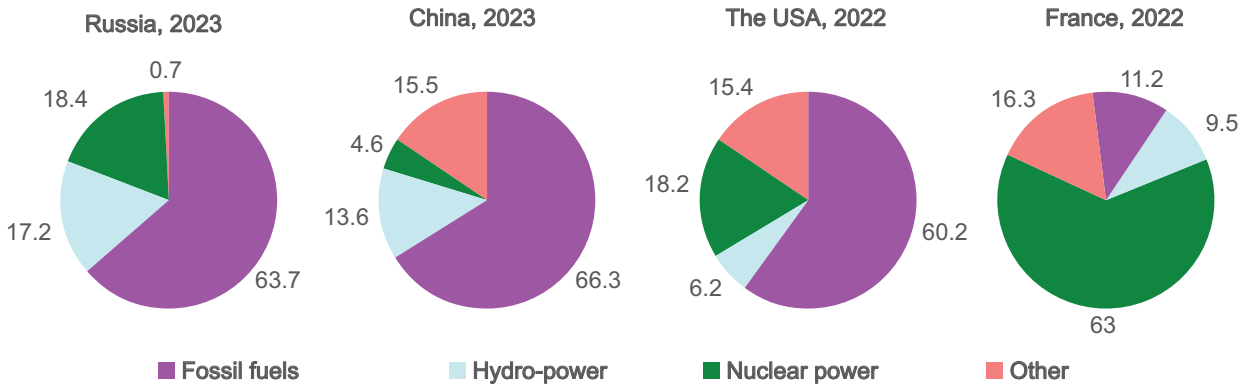
The life cycle of nuclear power plant units includes the following stages: placement; design; construction; operation; and decommissioning (Alshraideh & Engovatov, 2023). At each stage, certain risks arise that are associated with objective and subjective factors, which must be linked to the NPP's life cycle. The service life of an NPP is 45 years, with periodic certification required after 30 years of operation.

However, the share of nuclear generation worldwide remains below the level of 2000 (9.1% versus 16.6%) [Alshraideh & Engovatov, 2023]. This is due to the consequences of the disaster at the Fukushima-1 nuclear power plant, which has prevented the share of nuclear generation in Japan from returning to the 2010 level (7.6% versus 25.3%), as well as the delayed commissioning of nuclear reactors in developed countries[13].

First-generation Russian NPPs had significant shortcomings: an absence of a hermetic reactor compartment

[8] Report on the operation of the Unified Energy System of Russia in 2023 https://www.so-s.ru/fileadmin/files/company/reports/disclosure/2024/ups_rep2023.pdf.
[9] Forecast of the energy system of Russia for the period 2023–2028. https://conomy.ru/analysis/articles/1020.
[10] The latest revision of the Federal Law of 21 November 1995 No. 170-FZ 'On the Use of Atomic Energy'. https://www.consultant.ru/document/cons_doc_LAW_8450/?ysclid=m7t2gbjfa0327720229.
[11] Nuclear generation accounts for more than 9% of the world's energy production. https://www.atomic-energy.ru/news/2024/05/16/145868.
[12] For the first time, wind power in Europe has overtaken gas-fired power plants. https://www.vedomosti.ru/esg/reports/news/2024/02/07/1019064-vetroenergetika-v-evrope-vpervie-operedila-gazovie-elektrostantsii.
[13] Nuclear generation accounts for more than 9% of the world's energy production. https://www.atomic-energy.ru/news/2024/05/16/145868.

Fig. 3. Electricity generation in selected countries by energy source, 2023



Source: The electric power industry in Russia and other countries worldwide. https://refru.ru/power7.html#g3.

shell, use of the biblock principle, a conservative design service life of approximately 30 years, and, most importantly, no consideration or allowance for the decommissioning stage. Currently, Russia is launching projects to build NPPs of the fourth generation.

Russia's first (and currently only) floating nuclear power plant, the Akademik Lomonosov, began commercial operation in May 2020. It generates power from two 35 MW small modular reactors (SMRs). Other SMRs are currently being constructed or licensed in Argentina, Canada, China, Russia, the United States and South Korea.

Russia is the first country in the world to implement fourth-generation nuclear reactor technologies. A fast reactor and a closed nuclear fuel cycle will be built at the nuclear power plant. After reprocessing, irradiated fuel will be used to produce fresh fuel again. This will make the recycling system virtually autonomous and independent of external energy supplies. Rosatom is building the innovative BREST-OD-300 nuclear reactor as part of the Breakthrough project in the city of Seversk in the Tomsk Region. It is expected to generate its first electricity in 2028–2029.

The prospects for the development of global nuclear energy are impressive. As of May 2024, there are 416 operating reactors worldwide with a total net capacity of 374.6 GW. In addition, 59 power units with a total net capacity of 61.6 GW are under construction, 40 of which are in China, India, Turkey and Egypt[14]. In 2022, nuclear power plants were included in the EU taxonomy, which ranks energy sectors based on their contribution to sustainable development. Japan is calling for new-generation reactors to be constructed to replace decommissioned capacity. Another advantage of nuclear power plants is that they do not require long lines and can be used as an uninterruptible power supply for important industrial facilities, seaports and defence facilities.

Rosatom has begun construction of five low-power nuclear power plants in the Arctic, an area of strategic interest to several countries.

Given the promising development prospects, it is important to acknowledge the associated challenges in the construction and operation of nuclear power plants, including the high costs, lengthy construction periods, complexities, and high costs of waste disposal and decommissioning [Putilov & Mokshin, 2023].

In the coming years, Russia will begin the practical implementation of new-generation nuclear power plant (NPP) projects with small- to medium-capacity reactors (300–700 MW). These projects are promising for regions where the use of traditional organic energy sources is difficult or impossible. In Russia, these include the Far North, Chukotka, Kamchatka and the Far East. Preliminary designs for small and medium-capacity NPP units featuring SVBR-75/100, VVER-600 and SVBR-600 reactors have been finalised.

Figure 3 illustrates the proportion of electricity generated by different sources in Russia, China, the United States and France in 2023[15].

Despite the global green agenda, gas, oil and coal currently provide the bulk of electricity generation in the leading fossil fuel producing countries of Russia, the USA and China.

The Russian government has approved the General Scheme for the Placement of Electric Power Facilities up to 2042[16]. The plan prioritises increasing energy generation at nuclear power plants from 18.9% to 24%, and at solar and wind power plants from 0.8% to 3.3%, while reducing the share of thermal power plants from 62.7% to 57.4%. Currently, most of the energy generated in the country comes from fossil fuels, followed by wind and solar power.

[14] Id..
[15] Electric power industry in Russia and around the world. https://refru.ru/power7.html#g3.
[16] Decree of the Government of the Russian Federation dated 12/30/2024 No. 4153-r "On Approval of the General Layout of Electric Power Facilities until 2042". http://government.ru/dep_news/53923/.

3. Energy from renewable sources

In 2023, a world record was set for electricity production from renewable energy sources when the proportion of electricity generated from renewable sources increased from 29% to 30% of the total. South and Central America recorded the highest contribution of renewable energy sources at 72%. Primary energy use from renewable sources accounted for 8.2% of the total, or 14.6% including hydropower[17].

The largest proportion of solar and wind power plants in the total electricity generation mix is found in European countries: Denmark (61%), Lithuania (50.9%) and Greece (43.9%). The world leaders in terms of the capacity generated from renewable energy sources are China, the USA, Brazil, India and Germany, accounting for around 58.4% of the global total[18].

In 2023, electricity production in the Unified Electric Power System of Russia amounted to 1,149.984 billion kWh. Of this, 217.697 billion kWh (18.9%) was produced at nuclear power plants, 202.618 billion kWh (17.6%) at hydroelectric and pumped-storage power plants, 720.662 billion kWh (62.7%) at thermal power plants and 9.006 billion kWh (0.8%) at solar and wind power plants[19]. In 2023, electricity generation at Russian renewable energy enterprises was twice the level of 2020. Wind power plants produced 3.4 billion kWh and solar power plants produced 2.4 billion kWh, making them the leading producers of renewable energy in the country. Meanwhile, geothermal, biogas, biomass and wastewater energy plants produced 0.39 billion kWh[20].

Technologies used to generate clean energy are developing rapidly. For instance, Russian scientists have developed a compact hydroelectric unit that can generate electricity for remote northern regions such as Yakutia. This device is essentially a turbine with a built-in pump that is powered by the flow of water.

Many remote settlements in northern Russia do not have a central power supply, so electricity is generated by expensive diesel power stations. To solve this problem, scientists have developed a mini hydroelectric power plant that produces energy in a more environmentally friendly and cost-effective way. It is a hydro turbine with a built-in hydraulic pump that operates using the flow of the river.

The natural potential of hydro, nuclear, solar and wind energy is significant and practically inexhaustible. In Russia, the state programme supporting renewable energy has been extended until 2035, receiving funding of around 350 billion rubles. In the future, using renewable energy sources will greatly reduce coal and gas consumption in the country's and the world's energy balances.

Compared to fossil fuel-based energy generation, the cost of producing electricity from renewable energy sources is trending downwards. An increase in the proportion of renewable energy in the energy system will lead to higher system costs for fossil fuel-based energy. The speed at which countries achieve the goals of the green agenda will largely be determined by governments' willingness to strike a reasonable balance in the cost of electricity from different sources. According to International Energy Agency forecasts, renewable energy sources are expected to surpass coal power by 2025. By 2026, renewable energy and nuclear energy together are predicted to account for nearly half of the world's electricity generation [Plautz, 2024].

4. Solar energy

In 2023, China was the world leader in solar and wind power generation, producing 486.1 billion kWh of wind and solar power. The United States followed with 226.9 billion kWh, ahead of Germany (66.5 billion kWh), India (56.2 billion kWh) and Brazil (36.8 billion kWh) [21].

In 2023, the total share of renewable energy in EU countries increased to 44%[22]. European countries are therefore increasing their production of electricity from renewable energy sources in order to achieve the goal of zero emissions by 2050.

The first solar panels were offered on the market by Americans in 1956. By 1967, the USSR had launched the Soyuz-1 spacecraft into space — the first manned spacecraft to feature solar panels. In the context of countries' global transition to sustainable energy sources, wind and solar energy are becoming especially relevant. The economic efficiency of each energy source depends on a number of factors and is an important indicator.

5. Wind energy

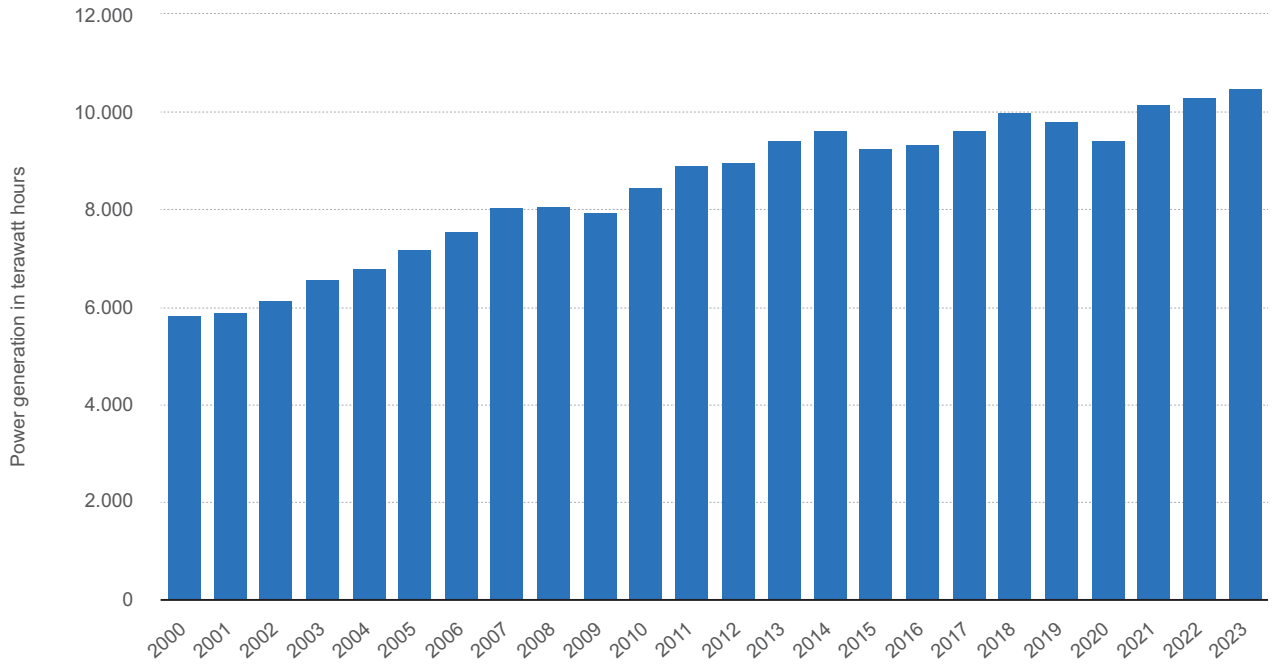
In 2023, the total capacity of commissioned wind turbines (WTs) worldwide was 116,616 MW, a 50% increase on 2022. This was the highest commissioning volume on record and exceeded 100 thousand MW for the first time.

The top five global markets for new installations in 2023 were China, the United States, Brazil, Germany and India. Notably, India returned to the top group after a long absence.

As of the beginning of 2024, Russia's share of renewable energy sources in total electricity generation was only 1.1%.[23]However, wind power plants have enormous growth potential, partly due to the low cost of energy production compared to other sources, including renewable energy sources and fossil fuels.

[17] The world set a new annual record for electricity production from renewable energy sources in 2023. https://qazaqgreen.com/news/world/2122/.
[18] https://energy.hse.ru/Wiie.
[19] Order of the Government of the Russian Federation, dated 30 December 2024, No. 4153-R… http://government.ru/dep_news/53923/.
[20] Alternative energy in Russia. https://www.tadviser.ru/index.php.
[21] For the first time, wind power in Europe will overtake gas-fired power plants in 2023. https://www.vedomosti.ru/esg/reports/news/2024/02/07/1019064-vetroenergetika-v-evrope-vpervie-operedila-gazovie-elektrostantsii.
[22] Id.
[23] Wind power in Europe in 2023... https://www.vedomosti.ru/esg/reports/news/2024/02/07/1019064-vetroenergetika-v-evrope-vpervie-operedila-gazovie-elektrostantsii.

Fig. 4. Global coal-fired power generation, 2020–2023



Source: Coal-fired electricity production worldwide from 2000 to 2023. https://www.statista.com/statistics/1082201/coal-fired-electricity-generation-globally/

In late 2023, scientists and researchers from the Moscow Power Engineering Institute (MPEI) developed a hardware and software system to integrate renewable energy sources into traditional power systems[24]. This development comprises a microcontroller that controls converters at generating facilities based on renewable energy sources. The microcontroller implements an algorithm that simulates the operation of a synchronous generator with a specific level of inertia.

6. Water energy

In the structure of the world energy system, the share of hydropower in energy generation in 2023 amounted to between 14% and 18.4%, according to various estimates. This ranks second after energy generation from fossil sources, with a share approximately equal to that of solar energy generation.

However, global hydropower production is in decline. In the first half of 2023, there was an 8.5% historic decline in global hydropower production, and the six-month decline was greater than that recorded for an entire year over the past two decades. This is due to droughts caused by global warming resulting from the emission of greenhouse gases into the atmosphere from the processing of fossil fuels.

In this regard, the Russian Ministry of Energy prepared a decision in 2023 to support small hydropower facilities, which will enable the construction of an average of 70 MW of new small hydropower plants per year. According to the General Scheme for the Distribution of Electric Power Facilities, 17.6% of energy was obtained from hydroelectric and pumped-storage power plants in 2023. The prospective development of hydropower involves developing the hydro potential of the Siberian and Far Eastern regions, with a projected increase in the volume of hydroelectric power plants and the commissioning of new pumped-storage power plants to reach 7.756 million kW by 2042[25].

7. Coal-fired thermal power plants

Global coal-fired electricity generation has continued to increase steadily and peaked in 2023 (see Figure 4). In China, for example, coal-fired electricity generation accounted for over half of the global total in 2023, at 5,742 TWh.

It is expected that, by 2030, more than twenty EU countries will have phased out coal-fired generation. In line with the implementation of the green agenda, the global trend of decarbonising the electricity sector will continue.

Russia ranks second in the world for coal reserves, accounting for 15% of global reserves. However, coal is more expensive than gas in Russia and cannot be widely used in the domestic market. This is due to the lobbying

[24] Alternative energy in Russia. https://www.tadviser.ru/index.php.

[25] The Ministry of Energy plans to increase subsidies for building small hydroelectric power plants. https://itek.ru/news/minenergo-namereno-uvelichit-subsidii-na-stroitelstvo-malyh-ges/.

Table 2
Cost of building and operating the power plants needed to generate a given amount of electricity (17,613 GWh/year)

Power plant type	Investment costs (in millions of dollars)	The accumulated costs (investment and operating) over a given period of time					Share of investment costs in total structure over 25 years (%).
		5 years	10 years	15 years	20 years	25 years	
Conventional coal	3246	10767	12856	16945	20034	23123	15
Coal-based combined heat and power using coal gasification and carbon capture and storage.	15 609	19993	24377	28760	33144	37527	42
Conventional gas CHP	2119	6675	11231	15786	20342	24898	9
Gas: advanced CHP with carbon capture and storage.	4842	10493	16144	21795	27446	33098	15
Nuclear	12354	14435	16516	18597	20678	22754	54
GeoCHP	9533	10626	11718	12811	13904	14996	64
Biomass	19815	27650	35486	43321	51157	58992	34
Onshore wind	12713	13849	14985	16121	17257	18388	69
Offshore wind	34017	36028	38038	40049	42060	44070	77
Solar thermal	50893	54319	57700	61081	64462	67843	75
Solar PV	31148	32141	33134	34127	35120	36112	86
Hydro	11138	11407	11675	11944	12212	12481	89

Source: [Degtyarev et al., 2016].

policy of Gazprom in favour of its own interests. The cost of coal on the global energy market is significantly lower than that of oil and gas. Despite the oil and gas crisis observed worldwide in recent decades, coal continues to find its energy niche, particularly due to the attractive cost of generating a kilowatt-hour of energy at thermal power plants. The phase-out of coal will likely take several decades for the following reasons: coal is difficult to replace in industrial processes; coal-fired power plants are long-term assets with a design service life of at least 30–40 years; there are losses in the mining industry; workers are made unemployed; there is political lobbying of interests; and restructuring the industry and the economy is complex. Currently, emerging market countries account for 76.8% of global coal consumption, with China accounting for around 50%.

8. Gas power plants

Russia and the United States have traditionally held the leading position in global gas production for many years. Gas-fired power plants can be divided into two types: gas turbine and gas piston.

Gas turbine power stations are high-tech energy complexes that use coolant heated to a high temperature to generate heat and electricity. A gas turbine unit can have a capacity of several megawatts.

Depending on the installation method and design features, there are three main types of gas turbine station: stationary, mobile and mini-format. All installations require careful maintenance. While the systems pay for themselves in a short period of time, they are inferior to gas piston stations in terms of the cost of the energy generated.

Gas piston power plants (GPPPs) are widely used in industry and the municipal sector due to their high efficiency and ability to operate on various gases. This is an effective, environmentally friendly way of generating electricity in the face of high prices for traditional fuels and strict environmental standards. Although gas turbine power plants have high initial costs and depend on gas quality, their advantages make them an attractive choice for many industries.

In 2023, global electricity generation from gas reached a historical maximum of 6,634 TWh[26]. Currently, gas is the second most popular source of electricity after coal, with

[26] Gas-fired power generation reaches a historic high. https://globalenergyprize.org/ru/2024/05/10/jelektrogeneracija-iz-gaza-dostigla-istoricheskogo-maksimuma/.

a share of 35.5%, compared to 14.3% for hydroelectric power plants, 9.1% for nuclear power plants, 7.8% for wind generators, 5.5% for solar panels, and 10.8% for all other sources[27]. The world leaders in gas-fired power generation are the United States and China. In the near future, gas is expected to retain its primacy in the global energy balance, while the shares of coal and oil are predicted to decrease.

9. A comparison of the cost of generating a unit of electricity by energy type

The economic efficiency of energy production differs between power plants operating on fossil and renewable sources, and there are different approaches to determining this. The cost structures of the two types of plant differ fundamentally, and the economic efficiency of electricity production is essentially an integral indicator. Comparing the economic efficiency of energy obtained from renewable sources requires detailed consideration of the cost structure of each energy production method, taking projected energy resource prices into account. A group of Russian researchers studied the technical features of the life cycle of power plants operating on various sources, calculating the cost per unit of energy produced (see Table 2). The study resulted in the following conclusions [Degtyarev et al., 2016].

1. Renewable energy power plants have a low capacity utilisation factor. While there are no variable costs, there are high costs at the investment stage of the project. Therefore, renewable energy power plants will be more economically advantageous over the course of their long service lives.
2. Investments in gas thermal power stations, even environmentally improved ones, remain the lowest.
3. Due to high variable operating costs, the total accumulated costs will exceed those of hydroelectric, geothermal, nuclear and onshore wind power plants within 5 to 15 years of the plant's commissioning date.
4. Over a period of 5 to 25 years, hydraulic, geothermal and nuclear power plants, as well as onshore wind farms, proved to be competitive in terms of investment and total costs.
5. Although modernised coal-fired power plants have average investment costs, they have a service life of more than 15 years and are therefore inferior to most other types of power plant.
6. It will be expensive to operate biomass, solar, offshore wind and solar thermal power plants over a 25-year horizon or longer.
7. Onshore wind farms have proven to be cheaper than nuclear power stations and advanced thermal power stations with a service life of five to ten years.

Thus, the price of electricity from renewable energy power plants is becoming competitive with that from technologically and environmentally improved fossil fuel power plants. Increased use of renewable energy sources with unstable generation in the electricity industry will lead to greater volatility in gas and coal prices, as well as an increased need for backup and storage systems. Researchers from the Institute of Energy Research of the Russian Academy of Sciences [Kulagin et al., 2024] calculated the cost price of a unit of energy and obtained the following results.

1. The average weighted cost of electricity production at solar power plants decreased from $0.43 to $0.08 per kWh between 2010 and 2022, and it is projected that costs will decrease by another 30% by 2050.

2. After costs at onshore wind power plants decreased from $0.11 to $0.07 per kWh between 2010 and 2022, a further 10% decrease is expected by 2050. At offshore wind power plants, costs decreased from $0.20 to $0.11 per kWh, and a further 30% decrease is projected.

3. The cost of electricity production at large hydroelectric power plants is one of the lowest among alternative energy sources, starting from $0.01/kWh in 2023. However, it is important to consider that the global potential for hydropower is limited and that the costs of small, medium, and micro hydroelectric power plants are high.

4. Nuclear power also has the potential to reduce production costs. However, in most countries, nuclear power plants are more expensive than gas and coal power stations for electricity generation. However, unlike renewable energy sources, nuclear power plants provide stable and uniform electricity generation.

The cost of coal and gas power plants tends to decrease due to increased plant efficiency, but this depends on the price of coal and gas supplies, which tend to increase. Consequently, electricity production from gas and coal will increase. In the second half of the forecast period, however, the absolute volumes generated at these power plants will decrease as their use in backup mode becomes more widespread due to the uneven generation of renewable energy.

According to the Renewable Energy Agency (IRENA), 81% of the renewable energy capacity added in 2023 was cheaper than fossil fuel alternatives. This provides a compelling business and investment case for tripling renewable energy capacity by 2030.

Power engineers around the world have observed a trend towards a reduction in the average weighted cost of electricity generated by the following types of renewable energy power plant that have been put into operation:

- solar photovoltaic energy - by 12%;
- onshore wind energy - by 3%;
- offshore wind energy - by 7%;
- concentrated solar energy - by 4%;
- hydropower - by 7%[28].

[27] Gas-fired power generation reaches a historic high. https://globalenergyprize.org/ru/2024/05/10/jelektrogeneracija-iz-gaza-dostigla-istoricheskogo-maksimuma/.
[28] Record growth has given renewable electricity a price advantage. https://www.irena.org/News/pressreleases/2024/Sep/Record-Growth-Drives-Cost-Advantage-of-Renewable-Power-RU.

Based on the research results presented, we can express the ratio of the levelled energy cost (LEC)[29], produced from various sources using the following formula:

$$LECfec > LECaps > LECwps. \quad (1)$$

Thus, the hypothesis put forward by the authors of this study has been confirmed.

The development of Russia's Unified Energy System has been approved until 2029, with the cost of building a new 15.7 GW generation capacity included[30]. Thermal power plants are set to remain the primary source of energy generation, accounting for an estimated 65% of the total planned output. A serious problem requiring an immediate solution is the energy deficit in Siberia, the Far East, and southern Russia.

The Russian Ministry of Energy's REA presented its report on the forecast for the development of global energy up to 2050[31], Alongside three proposed scenarios, the report noted concerns that have emerged to date.

Despite the many different scenarios for the development of world energy proposed by various researchers, some of their conclusions are in harmony with each other and seem quite definite. These include:

- The fourth energy transition will take place, and all the prerequisites for this have been established.
- The investments required to achieve the declared level of carbon neutrality by 2050 exceed the existing capabilities of the global economy.
- The share of electricity in global consumption will increase sharply.
- The role of hydrogen and modern types of biofuel will become especially important.
- The share of renewable energy will grow, but the need for traditional methods of electricity generation will remain.
- Due to the economic inexpediency of replacing traditional carbon energy sources with carbon-free ones, it is necessary to develop the absorption capacity of ecosystems and the relevant technologies.
- A decrease in the overall need for fossil hydrocarbon resources will lead to a reduction in world trade against the backdrop of stagnation in the global economy.

Consequently, until 2050, the world and Russia expect the energy sector to transform against the backdrop of the energy transition and a significant slowdown in the growth of primary energy consumption, which is associated with the general long-term forecast of a slowdown in global economic growth[32].

Conclusion

Research by Russian scientists has shown that, while green energy is low-cost and does not emit greenhouse gases, it is characterised by the instability of electricity production (dependency on wind speed, the need to find optimal locations for wind farms), and low levels of solar insolation in northern regions. The development of green energy should be supported by the state through targeted technical and economic policies, such as providing tax incentives and subsidising R&D.

Nuclear energy has a high energy density and relatively stable production. However, there are problems with the disposal of nuclear waste and the risk of accidents, as well as the high cost of constructing and operating nuclear power plants.

Against the backdrop of a significant slowdown in global economic growth and, accordingly, primary energy consumption, researchers have considered forecasts for the development of global energy until 2050 and have developed several scenarios. The increase in global electricity consumption will primarily be provided by renewable energy sources due to their growing economic efficiency. By 2050, almost all the increase in global electricity consumption will come from wind and solar generation [Kulagin et al., 2024]. The world is not only faced with the problem of generating green electricity, but also of storing, transmitting and distributing it, which requires serious research and the finding of solutions.

In the modern world, transport and heating systems depend on fossil fuels rather than electricity generation. It is impossible to completely reject oil, coal and gas at this stage. Fossil fuels will remain the most accessible energy source in the coming decades.

Ideally, digitalisation in countries' energy systems should focus on spreading smart grids and smart devices — electricity consumers that can also generate and distribute electricity in the network.

The balance between fossil fuels and renewable energy sources in countries' energy systems is determined by many factors, including natural conditions, the availability of fossil resources, the possibility of synchronising energy systems with neighbouring states, pricing solutions that are acceptable to consumers, and the availability of established indicators for reducing emissions and developing the economy.

Currently, an effective option for generating electricity in a specific territory is a complementary model comprising different energy sources within a country's energy system, in a specific region, or even within a settlement. To achieve efficiency, it is worth considering combined-cycle power plants, taking into account the need for electricity linked to population growth and density, industrial and economic

[29] The levelised energy cost, or standardised cost, shows how much the objective function will change after a unit of this product is forced to be included in the optimal plan. If the product is profitable, the standardised cost will equal 0. https://www.sciencedirect.com/science/article/pii/S2352484723010569.

[30] The power system was planned. https://www.kommersant.ru/doc/6413256#:~:text=%D0%9D%D0%B0%20%D0%BD%D0%B0%D1%87%D0%B0%D0%BB%D0%BE%202023%20%D0%B3%D0%BE%D0%B4%D0%B0%20%D1%83%D1%81%D1%82%D0%B0%D0%BD%D0%BE%D0%B2%D0%BB%D0%B5%D0%BD%D0%BD%D0%B0%D1%8F,%D0%BE%D1%81%D1%82%D0%B0%D0%B2%D1%88%D0%B8%D0%B5%D1%81%D1%8F%201%2C9%25%20%E2%80.

[31] Scenarios for global energy development up to 2050. https://www.imemo.ru/files/File/ru/seminars/EnergyDialogue/2024/Drebentsov-26012024.pdf.

[32] Global economic growth is expected to slow to 2.4% in 2024. https://news.un.org/ru/story/2024/01/1448302.

Appendix 1
Life cycle comparison of renewable and non-renewable energy production facilities

Type of energy	Renewable sources of energy					Non-renewable sources	
	Wind	Nuclear	Solar	Water	Tides	Coal, gas, oil	Biomass
Advantages	The most promising source of energy. Ecologically clean. Conditionally renewable. Low operating and initial costs for energy production. Wind farms can be placed on wastelands and contaminated areas. Wind farms can help reduce unemployment in the regions where they operate.	It is a renewable source when operating in a closed fuel cycle. It has efficient fuel consumption. Environmentally friendly under strict operation. Low operating costs after start-up.	One of the promising energy sources. Environmentally friendly. Batteries do not require special maintenance. Reliability in operation. Easy installation of collectors	An ecologically clean source. Conditionally renewable. Hydroelectric power plants are highly efficient, with an efficiency rating of between 80 and 90%. The power plant can be stopped and started quickly. The system is proven and the operation of hydroelectric power plants is low-cost. The possibility of creating artificial lakes for the construction of hydroelectric power plants. Water resources are retained for agriculture	Ecologically clean source. Conditionally renewable	*Coal power plants:* Coal has a higher energy density than renewables. Of coal use, 72.8% is accounted for by electricity production, while 21.6% is used in industry. *Gas power plants:* Modern installations can be up to 45% efficient in electricity production. There is flexibility in the choice of fuel. Low emissions of harmful substances. They offer quick start-up and simple design. Economic efficiency.	Zero carbon emissions from biomass combustion. Lower emissions of sulphur dioxide, nitrogen oxides and carbon monoxide than fossil fuels
Disadvantages	Wind farms spoil the landscape. They are dependent on the weather and wind. Construction and maintenance are expensive. They occupy vast areas that could be used for agriculture. Turbine noise. They interfere with radio and television reception. Wind power plants are only 40% efficient.	There is a risk of man-made disasters in the event of accidents at nuclear power plants. There are also problems with spent fuel storage. High construction and decommissioning costs.	Technological obstacles: a large area is required for installation. Limited use: households, small farms and greenhouses. The source is inconsistent – it depends on the weather. The photovoltaic cells in the battery contain toxic elements. The daily solar radiation flux density is low.	Dependence on precipitation and the need to flood large areas and relocate people, which destroys the natural terrestrial habitat for plants and animals. The high cost of building hydroelectric power plants	Low profitability. Limited areas of use. Inconsistent energy generation.	*Coal-fired power plants:* depletion of global resources; environmental pollution from harmful emissions; the complexity and labour-intensive nature of coal extraction; and the high risk of accidents in mines resulting in human casualties. The phase-out of coal will take several decades. When burned, coal releases 2.2 times more carbon than natural gas. Methods of extracting fuel affect transportation needs and methane emissions. There are also losses of natural gas during transmission. *Gas power plants:* high initial costs; dependence on gas quality; need for regular maintenance; limited mobility; high noise level produced by turbine rotation (for turbine hydroelectric power plants)	Relatively low density of the raw materials makes them difficult to transport, store and dose. The high moisture content of the biomass makes it difficult to prepare for energy use. Raw materials have a low energy value. Some waste is only available seasonally.

Source: compiled by the authors based on the data from: [Tishchenko, 2018; Efimtseva et al., 2019; Spadaro et al., 2020; Buchnev, 2021]; Renewable energy sources. https://energy.hse.ru/Wiie; Krivonos A. (2023). Alternative energy sources: pros and cons. https://bezpeka-shop.com/blog/poleznye-sovety/alternativnye-istochniki-energii-plyusy-i-minusy/?srsltid=AfmBOormUIZKsWPUQgohZQVe9DX_UjPSnsMZCgMeLNYtEyxcoP9ndyDv; Bogmans K., Manji L.K. (2020). A greener future starts with the transition from coal to alternative energy sources. https://www.imf.org/ru/Blogs/Articles/2020/12/08/blog-a-greener-future-begins-with-a-shift-to-coal-alternatives; Advantages and disadvantages of gas piston power plants: what you need to know? https://aer-spb.ru/novosti/preimushchestva-i-nedostatki-gazoporshnevykh-elektrostantsiy-chto-nuzhno-znat/?ysclid=m5pmpdmna894702992; Gas turbine power plant (GTPP): what is it, advantages and disadvantages. https://gktex.ru/info/gazoturbinnaya-elektrostanciya/?ysclid=m5pnqmj94l73765493.

development, the natural landscape of the area and the efficient planning of power plant locations.

The authors of the study have stated that the global priority should be to use renewable energy sources for energy generation on a global scale. This hypothesis has not yet been justified, but it does fit organically into the development of the Russian fuel and energy complex. In Western countries and some EU countries, such as France, business interests are currently lobbying actively in favour of developing nuclear energy.

In summary, it can be confidently stated that the global energy sector will be heavily dependent on geopolitics, which will determine technology transfer possibilities, restrictions on trade flows, the ability to develop joint approaches to regulating foreign economic activity, and the overcoming of barriers to world trade.

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