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ДИНАМИКА РАЗВИТИЯ АТОМНОЙ ЭНЕРГЕТИКИ В МИРЕ

Л. О. СУШКЕВИЧ[1)]***, А. Н. ШАВЕЛЬ***[1)]***, С. С. МИХАЙЛОВ***[1)]

[1)]*Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Беларусь*

На основе официальных статистических данных международных организаций в сфере энергетики (Международное агентство по атомной энергии, Международное энергетическое агентство) проведен анализ динамики развития и современного состояния атомной энергетики в мире. С использованием ретроспективного метода предложена периодизация развития отрасли и дана характеристика выделенным этапам. С помощью математико-статистических оценок, сравнительно-географического и картографического методов получена современная картина развития атомной энергетики в мире в страновом разрезе. Показано постепенное устойчивое сокращение удельного веса атомной генерации в общемировом объеме выработки электроэнергии, что происходит в результате сворачивания темпов развития данного сектора энергетики в странах Западной Европы и Японии на фоне атомофобных настроений правительств и местного населения. Однако отмечено, что продолжается активное развитие атомной энергетики в Азиатско-Тихоокеанском регионе, что подтверждается интенсивным строительством ядерных энергоблоков в Китае и Индии, а также перспективами появления новых стран на мировой карте производства атомной энергии (Беларусь, ОАЭ, Бангладеш, Египет, Турция). В условиях необходимости снижения выбросов углерода в атмосферу, а также исчерпаемости запасов углеводородного топлива и их удорожания на мировом рынке для многих стран атомная энергетика может стать единственным источником устойчивой электрогенерации в ближайшей перспективе, что позволит отрасли вернуть утраченные позиции на мировом энергетическом рынке.

Ключевые слова: мировая энергетика; производство электроэнергии; атомная электростанция; АЭС; ядерный реактор; добыча урана; динамика развития; особенности размещения.

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Авторы:
Лилия Олеговна Сушкевич – кандидат географических наук; заведующий кафедрой экономической и социальной географии факультета географии и геоинформатики.
Алексей Николаевич Шавель – старший преподаватель кафедры экономической и социальной географии факультета географии и геоинформатики.
Сергей Сергеевич Михайлов – преподаватель-стажер кафедры почвоведения и геоинформационных систем факультета географии и геоинформатики.

Authors:
Liliya O. Sushkevich, PhD (geography); head of the department of economic and social geography, faculty of geography and geoinformatics.
zhigalsk.geo1@mail.ru
https://orcid.org/0000-0002-5313-0170
Aliaksei N. Shavel', senior lecturer at the department of economic and social geography, faculty of geography and geoinformatics.
alexxxshavel@gmail.com
https://orcid.org/0000-0002-3542-9259
Siargei S. Mikhailau, trainee lecturer at the department of soil science and geographic information systems, faculty of geography and geoinformatics.
mikhailauss@bsu.by

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DYNAMICS AND SPATIAL FEATURES OF THE DEVELOPMENT OF NUCLEAR ENERGY IN THE WORLD

L. O. SUSHKEVICH[a], *A. N. SHAVEL'*[a], *S. S. MIKHAILAU*[a]

[a]*Belarusian State University, 4 Niezaliezhnasci Avenue, Minsk 220030, Belarus*
Corresponding author: A. N. Shavel' (alexxxshavel@gmail.com)

The comprehensive analysis of the dynamics of development and the current state of nuclear energy production in the world was carried out based on the official statistics of international organisations in the energy sector (International Atomic Energy Agency, International Energy Agency). Using the retrospective method, the authors propose a periodisation of the development of the industry and give a description of the identified stages. On the basis of mathematical and statistical estimates, comparative geographic and cartographic approaches has been obtained a modern picture of the development of nuclear energy in the world in the country context. The analysis showed a gradual steady reduction in the share of nuclear generation in the global volume of electricity generation, which is taking place against the backdrop of curtailing the development of this energy sector in Western Europe and Japan against the backdrop of atomophobic sentiments of governments and the local population. However, the active development of nuclear energy in the Asia-Pacific region continues, which is confirmed by the intensive construction of nuclear power units in China and India as well as the prospects for the emergence of new countries on the world map of nuclear energy production (Belarus, United Arab Emirates, Bangladesh, Egypt, Turkey). In the context of the need to reduce carbon emissions into the atmosphere and the depletion of hydrocarbon fuel reserves, coupled with their rise in prices on the world market, for many countries nuclear energy may become the only source of sustainable power generation in the short term, which will allow the industry to regain its lost positions in the global energy market.

Keywords: world energy; electricity generation; nuclear power plant; NPP; nuclear reactor; uranium mining; development dynamics; location features.

Introduction

Energy is the basic sector of the economy of any country: the development of the entire economic complex depends on the level of development and efficiency of functioning of energy production. Considering the significant continuing differentiation of the countries of the world in terms of the level of socio-economic development, the situation in the energy sector of the states also varies greatly. This leads to the fact that there is an excess of electricity production in some countries, and in others – its shortage.

The state of the electric power industry in the countries is determined by the level of economic development, the availability and provision of states with fuel and energy resources, their investment opportunities and energy infrastructure development. According to the uneven distribution of fossil fuels, which is the basis for generating thermal energy, many countries are forced to purchase significant amounts of energy resources, which increases their energy dependence on supplier countries. In this case, the most likely alternative to fossil fuels is the use of renewable energy sources and the development of nuclear energy.

And if the development of renewable energy in the world is given priority in the context of the concept of a low-carbon economy and net-zero emissions, then in relation to nuclear energy there is an ambiguous situation associated with atomophobia and fears about possible accidents at nuclear power plants (NPPs), as well as for the time being still unresolved problem of integrated processing, storage and disposal of spent nuclear fuel.

Currently, multidirectional trends are observed in the development of nuclear energy in the world, when some countries increase the production of electricity at NPPs through the construction of new power units, while others, on the contrary, curtail the activities of already functioning facilities. This is largely due to the reasons outlined above, but still, the desire to reduce energy dependence on hydrocarbon fuel suppliers, reduce energy operation costs and greenhouse gas emissions encourage many countries to build nuclear power units and develop nuclear energy. This fact requires both rethinking and evaluation of spatial differences in the processes under consideration, which determines the relevance of this study.

The purpose of the study is to identify spatial-temporal features of the development of nuclear energy in the world. The object of the study was the global nuclear power industry cutaway by country, and the subject of the study was the development trends and spatial features of the location of NPPs in the world.

State of knowledge of the issue and research methodology

Scientific interest in nuclear energy production in the modern world is determined by a new round of its development through the coverage of countries that were not previously involved in the production of electricity at NPPs. However, in many European countries there has been a steady trend towards the shutdown of existing

reactors, and the lack of projects for the construction of new NPPs in the region is leading to a restructuring of the geographical picture of the location of nuclear power in the modern world. Therefore, the main attention to the industry is riveted in countries where the industry is developing most dynamically.

In the scientific literature, there is traditionally a consistently high interest in the economic and geographical study of nuclear energy. The most accessible scientific publications on this topic are prepared by Russian scientists. The main content of their research is devoted to an overview of certain aspects of the development and deployment of nuclear energy in the world. These are, for example, the works of S. Ju. Modnikova [1], E. O. Shorohova [2], T. A. Zhuchkova [3]. Traditionally, Russian authors pay attention to the geopolitical and economic aspects of the positioning of the Russian Federation in the global nuclear energy market: S. S. Alabjan and V. V. Rogov [4], S. Z. Zhiznin and V. M. Timokhov [5; 6]. Some studies (M. I. Romanov [7], V. V. Ivanter, V. V. Semikashev [8], A. B. Sekacheva [9], V. V. Petushkova [10]) are devoted to the study of the development of nuclear energy in certain countries of the world. E. L. Loginov studied the trends in the world's nuclear energy in the post-crisis period for the industry after the accident at the NPP «Fukushima-1» and predicted the strengthening of the role of Russia's nuclear energy complex in the global and national markets [11]. A comprehensive analysis of the world nuclear power industry with a forecast up to 2050 is presented in the B. I. Nigmatulin's article [12].

Sufficient attention has been paid to the development of nuclear energy in China in recent years. The authors of the studies (Zhang Xiaoping, Lu Dadao, Chen Mingxing, Gao Shanshan, Wu Aiping [13]) emphasise its high importance for the country and the world community, considering the international climate change agenda, the need to strengthen national energy security and increase the competitiveness of industrial production. On the basis of a comprehensive assessment of trade flows between countries associated with the operation of nuclear energy, the authors identified the competitive advantages of the industry for the existing nuclear powers. Based on the results of a comprehensive assessment of competitiveness in the nuclear power industry, the authors identified countries with the highest values of the indicator (USA, Russia, Canada, France and China), which occupy a leading position in ensuring the construction of new NPPs. In addition, the study predicts an increase in the role of the Asia-Pacific region, which in the future may become the center of nuclear energy production in the world.

The interest in the geography of nuclear energy among other scientists from far abroad does not subside. Among recent works, it can be highlighted the study of the coexistence of nuclear technology with society, and the benefits, problems and social transformations generated by this phenomenon, prepared by B. Alexis-Martin and T. Davies [14], as well as geographical studies devoted to the justification of sites for NPPs in Ghana (E. B. Agyekum, F. Amjad, F. Aslam, A. Ali [15]) and Canada (R. Almalki, J. Piwowar, J. Siemer [16]) and etc.

Belarusian researchers make their contribution to the development of modern ideas about the development of nuclear energy in the world as a whole and in Belarus in particular. It is worth noting the work of a team of authors headed by V. M. Tsilibina [17] devoted to the study of the energy efficiency of the Belarusian economy and including an analysis of the role of the Belarusian NPP (BelNPP) in raising the level of the country's socio-economic development. T. G. Zorina are being developed issues of integration of the BelNPP into the Belarusian energy system [18]. B. I. Popov's research is being carried out in the field of the formation of a comprehensive tariff policy for energy resources in the context of the commissioning of the BelNPP [19].

The methodological aspects of the study were determined by traditional approaches to the study of the global industry. On the basis of open data from international organisations in the energy sector (International Energy Agency (IEA), International Atomic Energy Agency (IAEA)) was compiled a statistical database characterising the development of nuclear energy both around the world and in the context of individual states.

A retrospective analysis of the history of nuclear energy production in the world according to the dynamics of its main indicators made it possible to periodise the development of the industry. On the basis of mapping of statistical indicators characterising the nuclear power industry in the context of the countries of the world using the *ArcGIS* software package were determined its spatial features of the location and development.

Results and discussion

Trends in the development of the electric power industry in the world and the role of nuclear energy. The end of the 20th and the beginning of the 21st centuries were characterised by a significant increase in electricity consumption in the world (fig. 1), which was associated with the intensive development of industry in developing countries, a further increase in electricity consumption in developed countries and the gradual replacement of the use of fossil fuels by renewable electricity. During the period 1990–2020, the volume of electricity consumption in the world increased by 2.29 times (from 10.9 to 24.9 PW · h). Per capita electricity consumption over the period under review increased to a much lesser extent (by 1.56 times) from 2.06 to 2.31 MW · h per person per year, which was associated with 1.47 times increase of the world population. The highest growth rates of energy consumption were observed in the 2000s before the global financial crisis of 2008. However, in 2000–2010 the whole growth rate of energy consumption was 1.4 times.

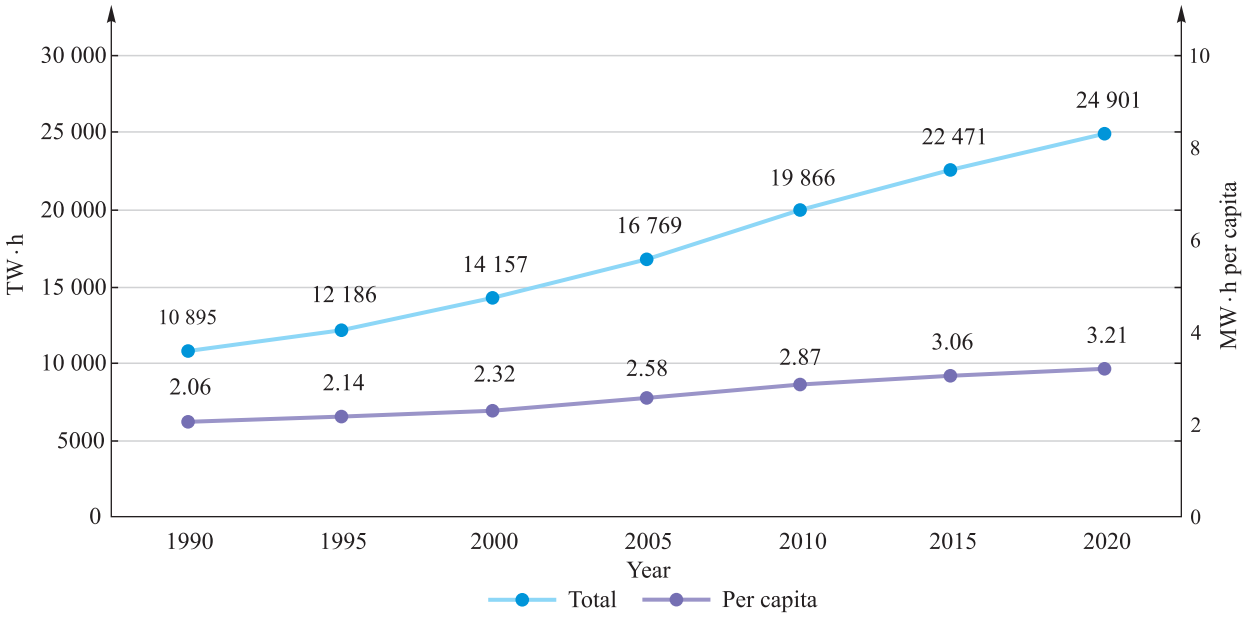

Fig. 1. Dynamics of electricity consumption in the world total (TW · h) and per capita (MW · h per capita) in 1990–2020 (compiled by the authors according to the IEA data)

The developed countries of the world had low growth rates of energy consumption in 1990–2020 (in the USA – 1.44 times, Japan – 1.17 times, Europe – 1.22 times), but developing countries at that time showed a grandiose growth (China – 12.4 times, Indonesia – 9.1 times, Turkey – 6 times, India – 5.5 times, Saudi Arabia – 5.5 times, Brazil – 2.5 times)[1].

However, as mentioned above, the level of development of the electric power industry in the countries of the world varies greatly. Among the indicators that characterise these disproportions, one can pay attention to electricity consumption per capita (fig. 2) – the most important macroeconomic indicator that demonstrates the degree to which the population is provided with electricity. The level of electricity consumption in a country depends on its availability, market demand, tariffs, breadth of electricity use and other factors.

In 2020 world average value of this indicator was 3.21 MW · h per person per year. At the forefront are such countries as Iceland, Norway, Bahrain, Qatar, Kuwait, Finland, Canada, where consumption is more than 15 MW · h per person. In addition to them, the USA, Sweden, the countries of Western Europe, Gulf states and Australia are distinguished by significant volumes of electricity consumption. The lowest indicators of electricity consumption are typical for the countries of Africa, overpopulated South Asia and individual countries of Latin America.

Another important indicator is the electricity intensity of GDP, which reflects the ratio between the consumption of electricity and the volume of the country's GDP. This indicator, along with the energy intensity of GDP, characterises the energy efficiency of the economy in the country. The value of this indicator depends on many factors, including the level of industrial development, the degree of electrification of production processes, transport infrastructure and the domestic sector, the structure of the economy, etc. In accordance with the provisions of the concept of sustainable development in order to achieve maximum energy efficiency of the economy it is necessary to maintain a balance electricity and energy conservation. Therefore, the value of the GDP electricity intensity indicator should simultaneously correspond to the possibilities of economic growth and ensure the rational use of energy resources. As practice shows in contrast to the energy intensity of GDP, high values of the electricity intensity of GDP are observed in highly developed countries and low values – in developing countries (fig. 3). This is due to the fact that electricity is a universal type of energy that can be easily and quickly transmitted over long distances, and thereby satisfy the need for timeliness, reliability and quality of the supplied energy.

The global value of this indicator in 2020 was 187 kW · h per 1000 US dollars. The highest value of this indicator is in Iceland – 971 kW · h per 1000 US dollars, Bhutan – 532, Bahrain – 441, Tajikistan – 429, Kyrgyzstan – 414 kW · h per 1000 US dollars. The lowest value is in most African countries (Sierra Leone – 9 kW · h per 1000 US dollars, Chad – 8 kW · h per 1000 US dollars), which indicates the low power supply of countries and the still weak use of electricity in production. The surplus of electricity production in a number of countries makes it possible to actively develop energy-intensive industries (for example, electric steelmaking, smelting of non-ferrous metals such as aluminum, magnesium, titanium, refining of non-ferrous metals, etc.).

[1]Energy statistics data browser // International Energy Agency : website. URL: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser (date of access: 02.05.2023).

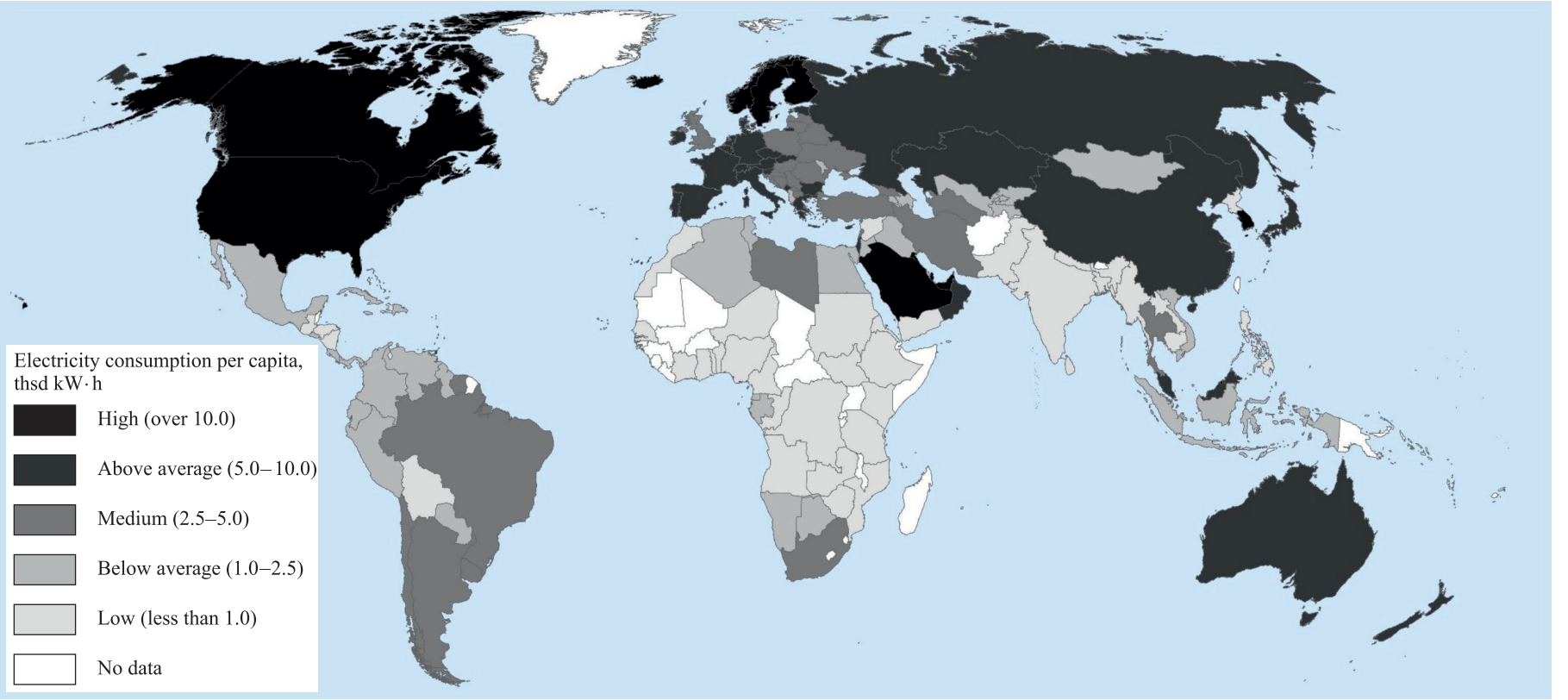

Fig. 2. Electricity consumption per capita by countries in 2020
(compiled by the authors according to the IEA data)

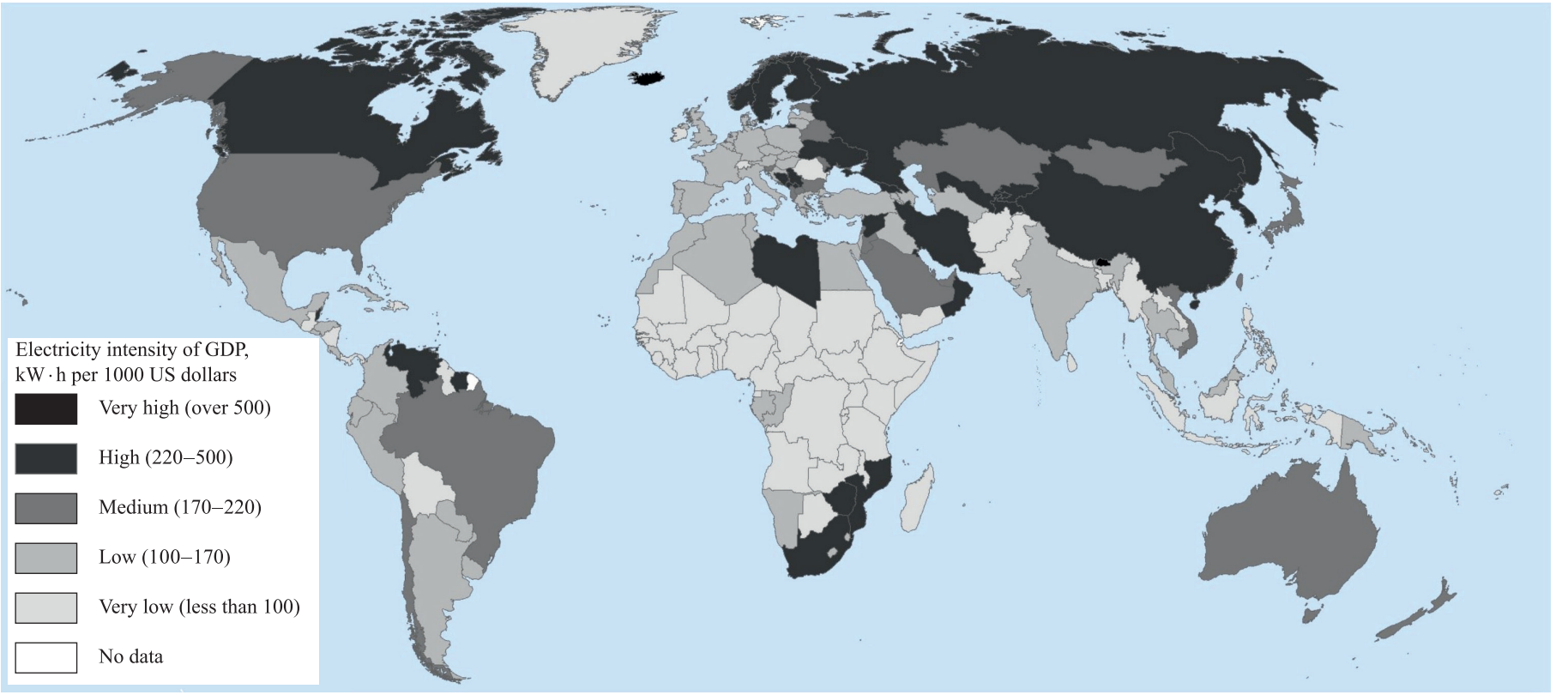

Fig. 3. Electricity intensity of GDP by countries in 2020
(compiled by the authors according to the IEA data)

Periodisation of the development of nuclear energy in the world. Nuclear power, which has been developed since the beginning of the second half of the 20th century, is currently one of the most important subsector of the world energy.

The «atomisation» of the world's electric power industry took place gradually, since only a limited number of countries in the world possessed the necessary technologies and their growth was rather slow. The maximum growth rates of nuclear energy were observed in the 1970s and the first half of the 1980s. After major nuclear accidents at the NPP «Three Mile Island» (1979), Chernobyl NPP (1986) and NPP «Fukushima-1» (2011), the development of nuclear energy was drastically slowed down. But in recent years the nuclear industry has gradually begun to recover, which manifested both in the construction of new facilities and in the expansion of its geographical representation.

A retrospective analysis of the development of nuclear energy in the world allows us to periodise its development, highlighting the following stages:

- pioneering development of nuclear energy (first-built reactors) (1954–1961);
- widespread use of nuclear energy (1962–1970);
- mass development and intensification of nuclear energy (1971–1985);
- deceleration of the development and curtailment of nuclear energy (1986–2008);
- limited renovation of the nuclear power industry (2009 – present).

During the period of pioneering development of nuclear energy (1954–1961), 19 nuclear reactors were put into operation (on the average of 2.5 reactor plants per year). Only Russia (USSR), the USA, United Kingdom and France possessed the technologies for creating nuclear reactors (fig. 4), which limited the geography of the distribution of NPPs [20]. The average capacity of the commissioned power units was less than 100 MW.

At the stage of widespread use of nuclear energy (1962–1970), 75 reactors were launched (on the average of 8.5 reactors per year). The average capacity of the introduced power units amounted to just over 200 MW. In 1970 NPPs operated in 15 states [20].

During the period of mass development and intensification of the industry (1971–1985), a total of 334 nuclear reactors were commissioned (on the average of almost 21 reactors per year). At that time the energy crisis contributed to the intensification of the construction of NPPs, which led to an increase in the prices of fossil fuels [20]. The number of countries operating nuclear reactors has grown to 26, and the average unit capacity of power units commissioned has approached 1000 MW. During this period (in 1979), the first major accident in the nuclear industry occurred at the NPP «Three Mile Island» in the USA, which slightly slowed down the development of the industry (in 1979 only 8 reactor plants were put into operation).

The turning point in the development of nuclear energy in the world was the nuclear disaster at the Chernobyl NPP (1986) in the USSR, after which the construction of new power units in the world was almost completely curtailed for a certain time. At first, only power units were put into operation, which were in a fairly high degree of construction readiness, but at the same time, the construction of a number of power units was completely frozen.

The period that began after the tragedy at the Chernobyl NPP can be described as the stage of deceleration of the development and curtailment of nuclear energy (1986–2008). If in 1984 and 1985 34 nuclear reactors were put into operation, then already in 1986 – 23 reactors, and in 1991 – only 4 reactors [20]. The end of the period can be called 2008, when for the first time in the history of nuclear energy in the world not a single nuclear reactor was launched at NPPs. Although the intensification of the construction of NPPs began in 2007, and in subsequent years the number of nuclear reactors under construction has steadily grown (in 2010, the construction of 16 nuclear reactors was laid down).

The curtailment of the mass commissioning of new nuclear reactors is also associated with the cyclical development of the industry, which is called the «anti-nuclear trend» [11]. Its essence lies in the periodic reduction in the commissioning of nuclear energy capacities, which occurs due to the freezing of previously adopted programmes for the development of nuclear energy against the backdrop of major nuclear accidents. Against this background, many developed countries make decisions to terminate the operation of existing NPPs or refuse to build new ones (for example, Japan, Germany, Italy, Switzerland). At the same time, there is a group of countries that abandon plans for the further development of nuclear energy, subject to the tightening of safety parameters for the operation of NPPs.

The current stage of the limited renovation of the nuclear power industry (2009 – present) is characterised by an increasing interest in nuclear power generation not in traditional «nuclear» countries, but in countries that have not previously used the possibilities of generating electricity at NPPs. The number of countries in which NPPs are operating or being built has increased to 38 units. The annual commissioning of nuclear reactors has practically reached the value of 6 units per year. As of 2021, 56 reactors with a total capacity of 58.1 GW were under construction. Safer pressurised water reactors have appeared (for example, the Russian NPP-2006 project of generation 3+) with a nominal unit power of 1200–1400 MW and with the potential to increase up to 1600 MW.

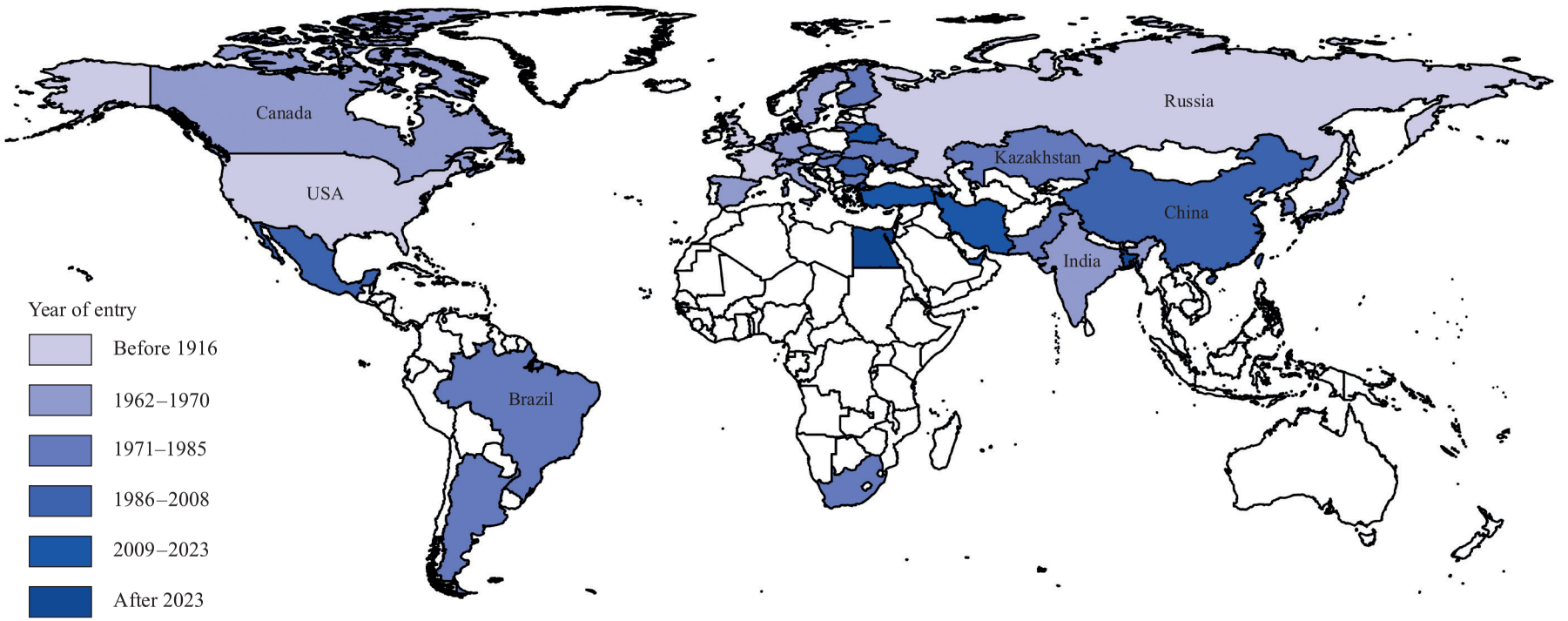

Fig. 4. Periods for countries to become nuclear power producers (compiled by the authors according to the IAEA[2] data)

[2]Country nuclear power profiles // International Atomic Energy Agency : website. URL: https://cnpp.iaea.org/pages/index.htm (date of access: 03.05.2023)

Development trends and spatial features of nuclear power production in the modern world. Despite the anti-nuclear public opinion, the production of electricity at NPPs in the world grew until 2007 inclusive. However, the global financial crisis of 2008 and then the accident at the NPP «Fukushima-1», led to a reduction in the production of nuclear electricity. This was due, among other things, to the shutdown of NPPs in Japan and some EU countries. Nuclear generation in 2020 accounts for 2674 TW · h, which is the fourth position in the global electricity balance after coal, natural gas and hydroelectric power plants (fig. 5).

The maximum share of nuclear generation in the global electrical balance was observed in the middle of 1990s – 17.5 %, after which it began to decline and in 2020 amounted to only 10.0 % of global electricity production.

However, despite the decline in the share of electricity generation in the world, nuclear power in the structure of world energy supply currently retains its significant role. This is due to the fact that nuclear energy is a unique technology that, despite existing risks, is able to provide a reliable, relatively inexpensive and environmentally responsible energy supply that is consistent with the leading concepts and strategies of global and national socio-economic development. Among such concepts stand out the concept of sustainable development, the concept of «green square», the concept of low-carbon economy, the concept of green economy, etc., which are interconnected with each other. They are based on key components that are influenced by the development of nuclear energy: the socio-economic sphere, energy, ecology and technology development. Nuclear energy provides enterprises with relatively cheap electricity and solves the acute issue of reducing greenhouse gas emissions into the atmosphere, which is why it is increasingly becoming the basis for the stability of energy markets, and hence the entire country's industry. The low share of the fuel component in the cost of nuclear generation, about 10–15 %, allows the consumer to predict prices for the entire life cycle, which is almost 100 years.

In addition to macroeconomic effects from the development of nuclear energy, a positive impact is also observed for the region where it is located in the form of accelerating the pace of socio-economic development. Nuclear energy is a possible solution to the energy problem, because nuclear fuel has a huge energy intensity: 1 kg of uranium enriched to 4 %, with complete burnup, releases energy equivalent to burning about 100 t of high-quality coal or 60 t of oil [21]. There is also the possibility of reusing nuclear fuel. However, the uranium market is very specific and deserves separate consideration.

The nuclear fuel market has significant differences from the organic fuel market. It includes not only the extraction and transportation of raw materials to the place of consumption, but consists of a whole chain of sequentially repeating processes that make up the nuclear fuel cycle. It includes uranium mining, purification from impurities, enrichment, production of nuclear fuel and production of electricity based on it, soaking, long-term storage, processing and disposal of spent nuclear fuel.

The raw material basis of nuclear fuel is natural uranium. According to the data of World Nuclear Association, the world reserves of uranium in 2020 amounted to 6147.8 thsd t. They are characterised by uneven distribution. More than half (56.4 %) of all reserves are located in four countries: Australia (26.2 %), Kazakhstan (14.0 %), Canada (8.7 %) and Russia (7.5 %). Namibia (7.3 %), South Africa (5.2 %), Brazil (4.5 %), Niger (4.5 %) and China (4.0 %) also have large uranium reserves.

Uranium mining in the world has an unstable dynamic, which is associated with the cyclical development of nuclear energy and the instability of prices on the world market for this resource. In 1990, 42.0 thsd t of uranium ores were mined, but subsequently, until 2007, uranium mining was practically in the range of 30–40 thsd t per year. After that, a gradual increase in production began, the peak of which fell on 2016 (62.2 thsd t) and was associated with a decrease in prices for uranium raw materials. However, starting from 2017, uranium prices began to grow, therefore, subsequently, its production decreased significantly (by 1.3 times) and in 2020 amounted to 47.7 thsd t[3].

The main «players» in the uranium market are the countries in whose territory its main reserves are concentrated. The list of leading countries in uranium mining has been reshuffled (previously the United States, South Africa, Canada, France, Gabon were in the leading positions), and the geography of production has also expanded. In 2020, Kazakhstan ranked first in the world in terms of uranium production (annual production volume is 19.5 thsd t). It is followed by Australia (6.2 thsd t), Namibia (5.4 thsd t), Canada (3.9 thsd t), Uzbekistan (3.5 thsd t), Niger (3.0 thsd t), Russia (2.9 thsd t), China (1.9 thsd t).

The largest uranium mining companies in the world are «Kazatomprom» (Kazakhstan, 10.7 thsd t), «Orano» (France, 4.5 thsd t), «Uranium One» (Russia, 4.3 thsd t), «CGN» (China, 3.7 thsd t), «Navoi Mining» (Uzbekistan, 3.5 thsd t), «CNNC» (China, 3.3 thsd t), «BHP» (Australia, 3.3 thsd t), «Cameco» (Canada, 3.0 thsd t), «ARMZ» (Russia, 2.8 thsd t).

[3]World mineral statistics data [Electronic resource] // British Geological Survey : website. URL: https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS (date of access: 28.02.2023).

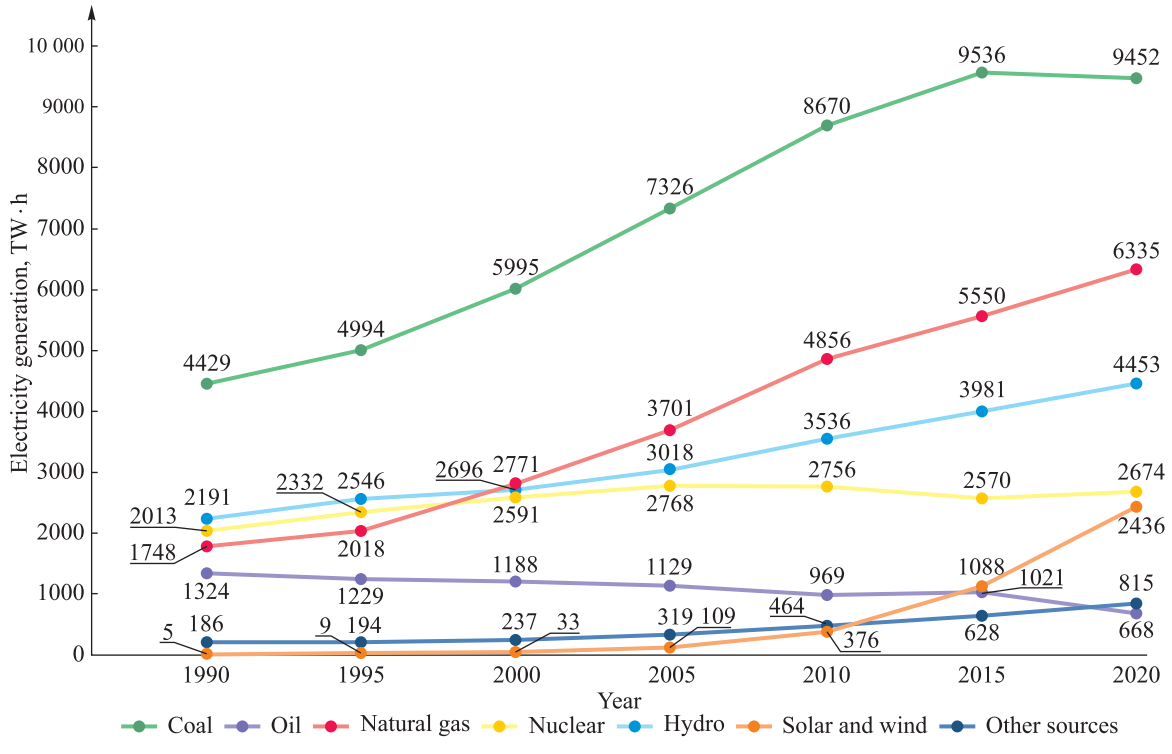

Fig. 5. Electricity generation by source in 1990–2020
(compiled by the authors according to the IEA data)

The development of the world natural uranium market is due to several fundamental factors. First, the increase in demand for uranium is associated with the restart of Japanese NPPs, as well as the commissioning of new power units in China, India, the Republic of Korea and other countries where there is no infrastructure component of the uranium raw material base. Secondly, the decline in uranium supply is due to the intensive development of existing deposits and the cost of developing new ones. Thirdly, there is a reduction in the involvement of secondary sources of uranium as the most liquid part of them is used. Fourth, there is an increase in long-term contracting. In addition, given the prospects for the commissioning of new nuclear power facilities until 2025, there is a need to develop new deposits with a higher cost, which will lead to a further increase in uranium prices [22].

The market for the production of direct nuclear fuel is segmented, which is due to the manufacture of nuclear fuel for specific types of reactors in accordance with standards. A limited number of companies are represented here, the largest of which are manufacturers of rods for «light water» reactors: «TVEL» (Russia), «Westinghouse» (USA), «Framatome-FBFC» (France); manufacturers of rods for «heavy water» reactors – «Cameco and GNF-Canada» (Canada), «DAE Nuclear Fuel Complex» (India). This situation characterises the high monopolisation of the nuclear fuel market.

In addition to the monopolisation of the nuclear fuel market, the limited number of countries possessing technologies for the development and construction of nuclear power units is indicative. This largely determines the geopolitical factor in relation to the cooperation of countries in the development of nuclear energy, which can be seen in the fig. 6. Traditional allies help their partners develop nuclear energy, and also get the opportunity to earn money on construction (capital investments in the construction of NPPs are among the highest in the energy industry) and create a positive international image for themselves. In relation to the availability of technologies and capabilities for the production of nuclear reactors and the construction of NPPs, the countries of the world can be divided into three groups:

- exporting countries of technologies in nuclear power engineering (France, Germany, Russia, USA, Republic of Korea). This group of countries is both the developer of their own nuclear reactors with the corresponding industrial facilities, and also exports their own nuclear technologies for the construction of NPPs abroad;
- self-sufficient countries (Canada, China, India, Japan, Sweden, United Kingdom). This group of countries are developers and manufacturers of their own nuclear reactors, but they have not exported their own nuclear technologies;
- importing countries of nuclear technologies (Turkey, Egypt, Brazil, etc.). This group of countries is represented by new members of the «club» of nuclear powers. They do not have NPP construction technologies and import them from the countries of the first group.

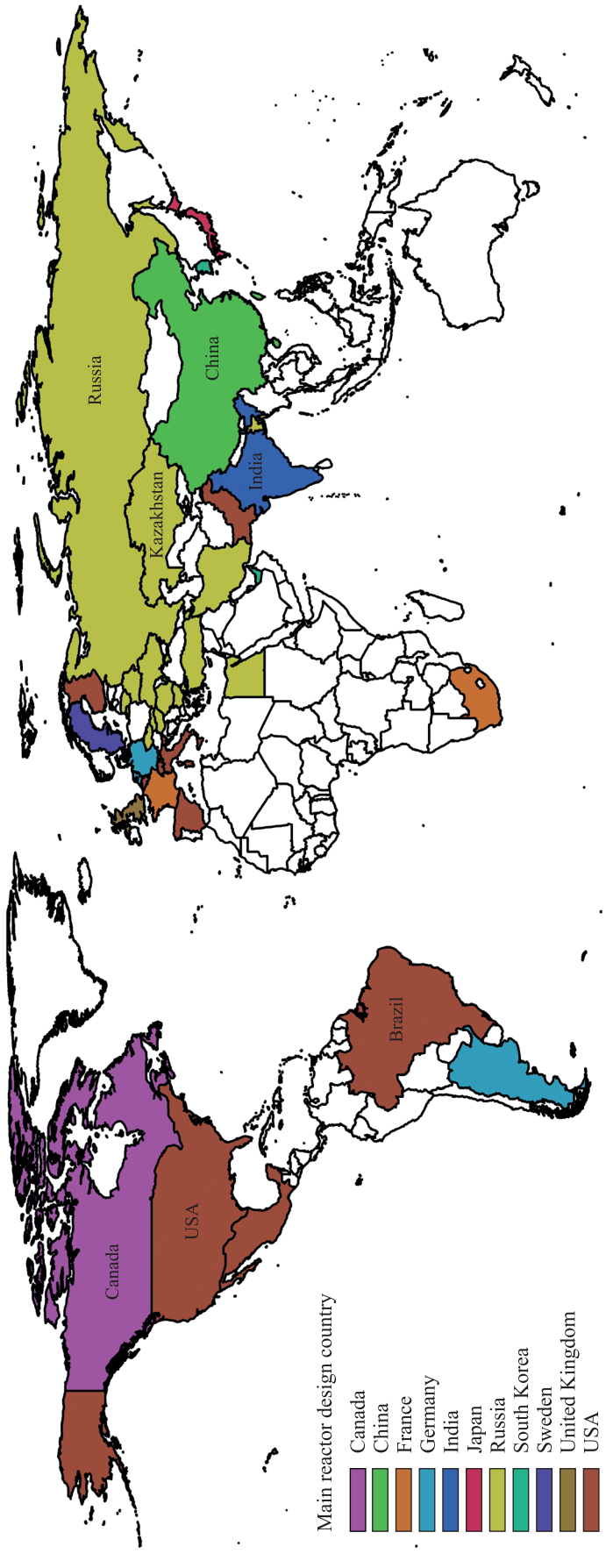

Fig. 6. Geographical pattern of the distribution of states with NPPs, depending on the dominant origin of reactor facilities (compiled by the authors according to the IAEA data)

The spread of nuclear energy in the macroregions of the world is uneven, which is associated with the availability of energy resources, technological development, growing demand for electricity and other factors. In the regional structure of electricity generation (fig. 7), the largest share of nuclear energy is observed in Europe (21.6 %), which is associated with the intensive development of the industry in past periods against the background of a shortage of its own fossil fuel resources. In addition, a high share of electricity generation is typical for North America (17.9 %) and the CIS countries (15.6 %). In other regions, the share of nuclear generation remains significantly below the global average.

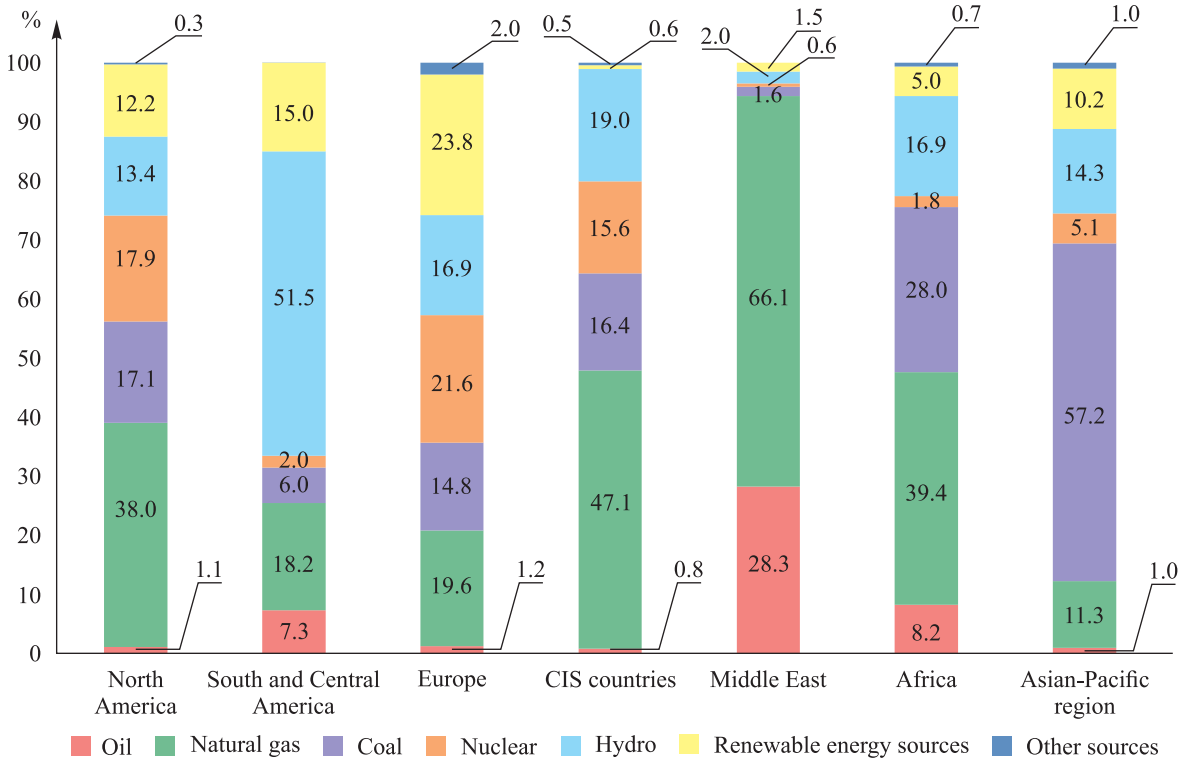

Fig. 7. Electricity generation by source in regions in 2020
(compiled by the authors according to the IEA data)

According to the dynamics of NPP development in macroregions they can be divided into three groups. The regions with the stabilisation of the development of nuclear energy include North America, where after the 2000s electricity production stabilised at 935 bln kW·h. The regions with a decrease in energy generation at NPPs include Europe, where for the period from 2004 (the maximum generation was recorded – 1122.7 bln kW·h) to 2020, there was a drop of 25.4 %. The remaining regions form the third group – with the growth of electricity production at NPPs (Africa, South and Central America, the Middle East, a group of CIS countries and the Asia-Pacific region).

At the country level the largest producers of nuclear energy in the world are the USA, China, France, Russia and the Republic of Korea (fig. 8). The first three countries account for more than half of all nuclear power generation, the first five – about 70 %, the first ten – about 85 %. This indicates a high level of concentration of nuclear power generation, but at the same time, the number of countries with NPPs has increased compared to 1990 from 28 to 33 units.

In total up to the beginning of 2021 there are 442 functioning nuclear reactors in the world (fig. 9). The USA has the largest fleet of nuclear reactors (93 units), followed by France (56 units), China (50 units), Russia (38 units), Japan (33 units). The vast majority of NPPs are located in the Northern Nemisphere and are concentrated mainly in developed countries. At the same time, it is worth noting the intensive development of nuclear energy in the states with which the prospects of this industry are associated – China, India and the Republic of Korea. In the Southern Hemisphere, NPPs operate only in Argentina, Brazil and South Africa. The only macroregion of the world where there is no nuclear power is Australia and Oceania.

Among all countries operating NPPs, only in nine of them, nuclear energy is the dominant energy source in the production of electrical energy (fig. 9): France (66.7 %), Slovakia (53.4 %), Ukraine (52.8 %), Hungary (46.0 %), Bulgaria (40.8 %), Belgium (38.7 %), Czech Republic (37.4 %), Slovenia (37.0 %), Fin-

land (33.9 %), Sweden (30.0 %). The share of NPPs in the electricity balance of countries is shown in fig. 9. Among the nuclear power countries, China stands out. Its peculiarity lies in the fact that a huge NPP capacity (47.5 GW) is concentrated here, and the country is in second place in the world in terms of nuclear energy generation. However, the share of NPPs in the structure of electricity generation is insignificant and amounts to only 4.9 %.

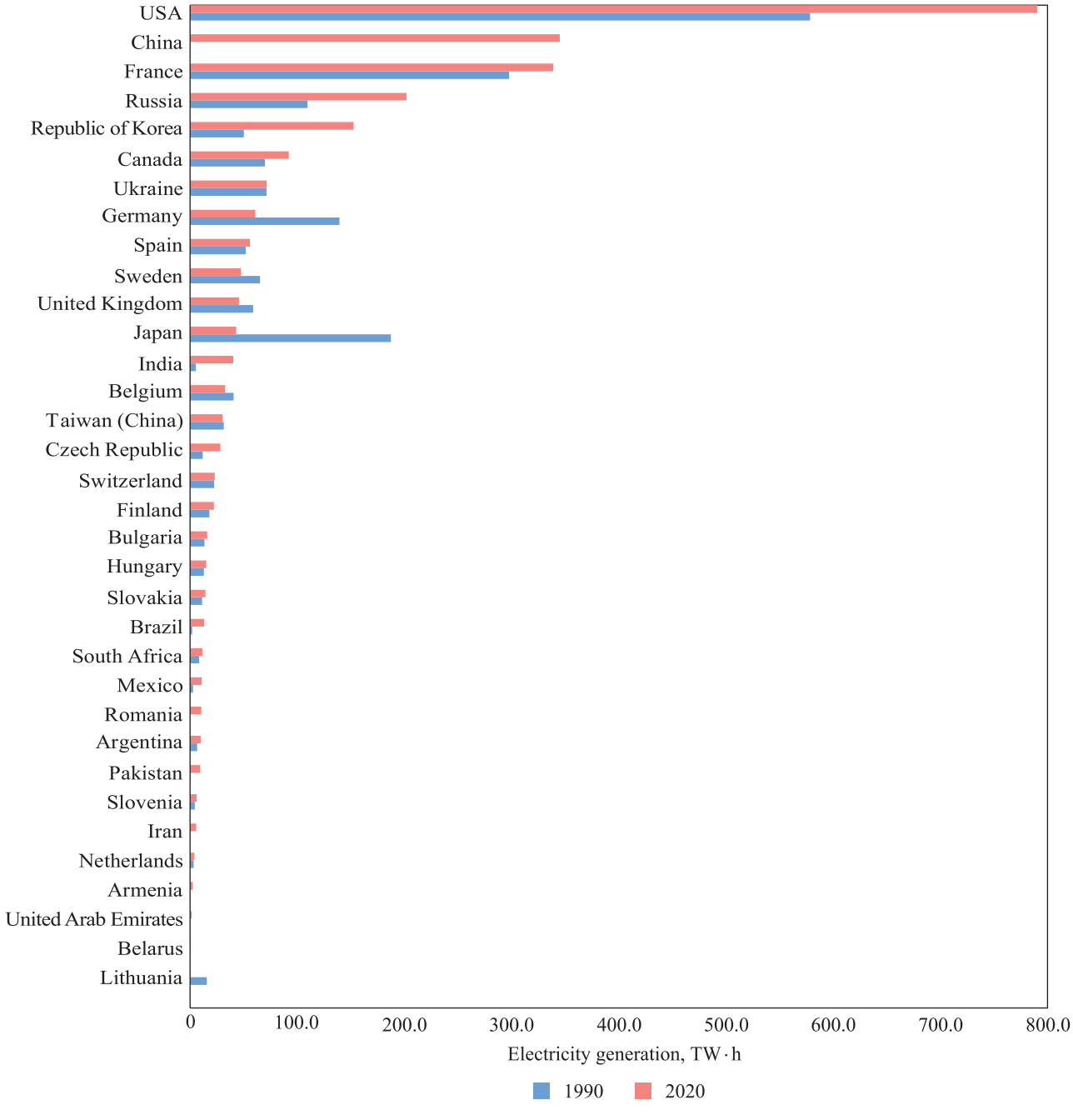

Fig. 8. Electricity generation at NPPs by countries in 1990 and 2020
(compiled by the authors according to the IAEA data)

Trends reflecting the dynamics of the role of nuclear energy in the countries of the world are shown in fig. 10. This map shows that in the highly developed countries of Western Europe, Japan, Sweden and Lithuania, there is a tendency to reduce electricity generation and the share of NPPs in the energy production structure. These trends are due to the refusal to use the nuclear industry in energy production and the transition to alternative energy sources (wind farms, solar power plants, etc.). In the South Africa, there is a slight decrease in electricity generation and the share of nuclear energy in total electricity generation, this is due to the modernisation of 2 nuclear reactors at the only NPP «Koeberg» in order to extend its operation life until 2050.

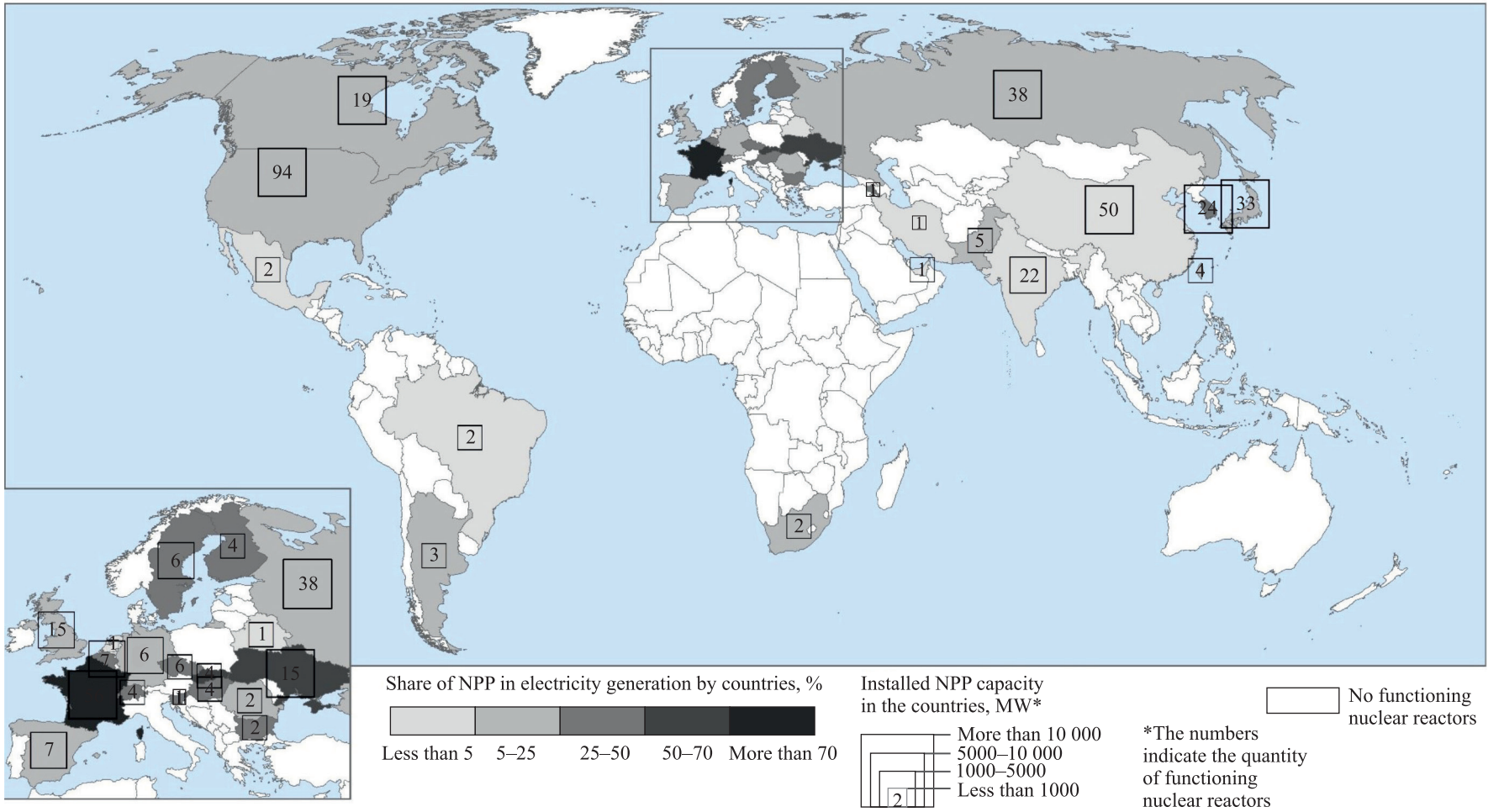

Fig. 9. Nuclear power development indicators by countries in 2020
(compiled by the authors according to the IAEA data)

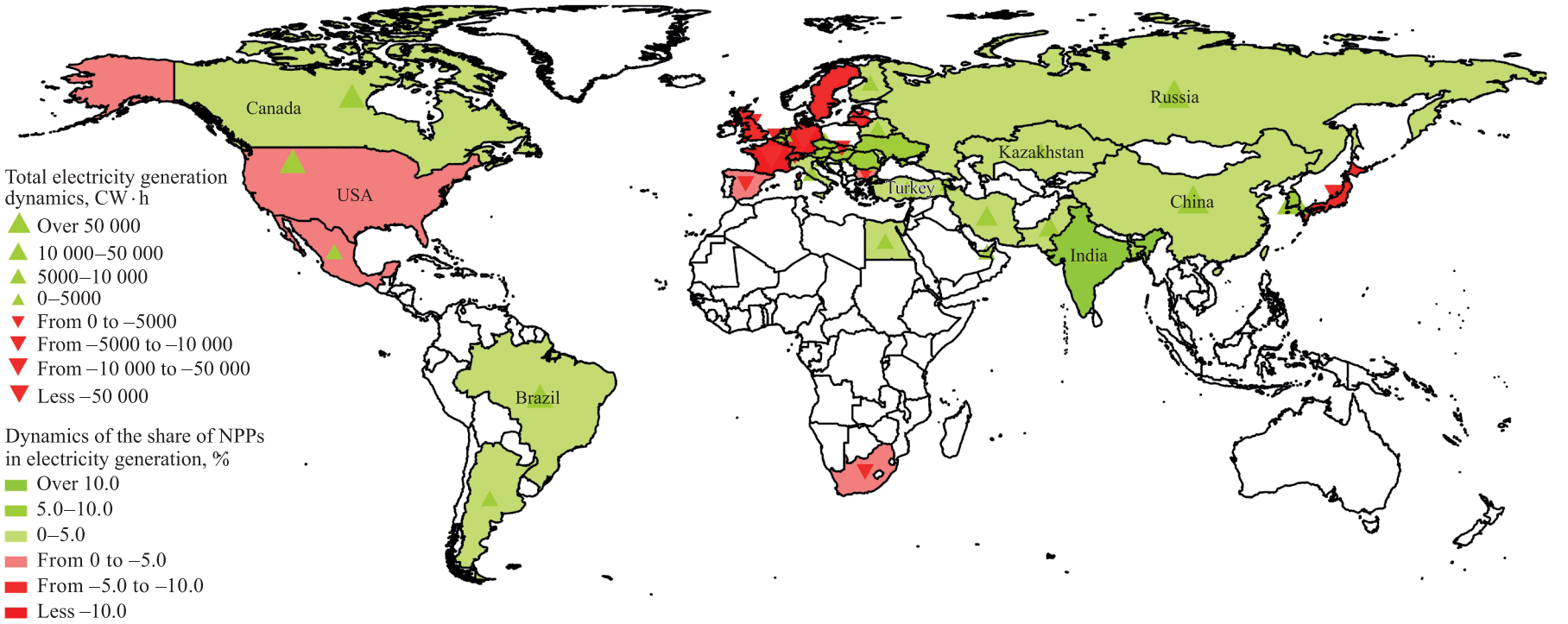

Fig. 10. Dynamics of nuclear power generation by countries in 2000–2020 (compiled by the authors according to the IAEA data)

Separately, it is worth highlighting a group of countries, including the USA, the Republic of Korea and Mexico, where there is a tendency to increase electricity generation, but at the same time, there is a decrease in the share of NPPs in the structure of its production, which is associated with a more significant increase in electricity generation from other sources.

In the third group of countries, there is a general trend towards an increase in electricity generation and the share of NPPs in the energy production structure. It is especially worth noting such countries as the China, Russia and India, where high rates of development of nuclear energy are observed.

The largest NPP in the world in terms of installed capacity according to IAEA data is «Kashiwazaki-Kariva» (Japan). It includes 7 reactors with a total capacity of 7965 MW, but after Fukushima disaster they are operational suspended. In second place is the South Korean NPP «Kori», which also consists of 7 reactors with a total capacity of 489 MW. It is the largest operating NPP in the world. In third place is Bruce NPP (Canada). The capacity of its 8 reactors is 6358 MW. The largest NPP in the post-Soviet space is the Zaporozhye NPP (Ukraine), which is currently temporarily stopped. It consists of 6 nuclear reactors with a total capacity of 5700 MW. The most powerful NPP in Russia is Leningrad – 4 nuclear reactors with a total capacity of 4017 MW.

At present, there is a certain kind of renaissance of nuclear energy. In 2020, 5 nuclear power units with a total capacity of 5521 MW were connected to the power grid, including the first power unit of the Belarusian NPP, construction of new power units began in China (3 units) and Turkey (1 unit). Currently, the largest number of nuclear reactors under construction is characteristic of China (18 units), India (7 units), Turkey (4 units). Three reactors are being built in the Russia, the Republic of Korea, and the United Arab Emirates. However, the depletion of hydrocarbon resources, the need to green the energy sector and the economic efficiency of NPPs (faster payback compared to thermal power plants) lead to an appeal to the development of nuclear energy. So, even after the accident at a NPP in Japan, a number of developed countries (USA, United Kingdom, France, Sweden), countries of Eastern Europe (Bulgaria, Hungary, Poland, Czech Republic), CIS countries (Armenia, Belarus, Kazakhstan, Ukraine), Asian countries (Bangladesh, Vietnam, Indonesia, India, Iran, China, the Republic of Korea, Taiwan, Turkey) confirmed their plans for the development of nuclear power, albeit with the condition of tightening the parameters for ensuring safe operation. In many of these countries, NPPs are being built, expanded or will be built. The largest program for the development of nuclear energy belongs to China, and India, Russia, the Republic of Korea, and others also have significant plans for nuclear energy.

Since 2020 Belarus has been among the atomic powers. The country attaches great importance to the development of nuclear energy, which should increase the energy security of the national economy. The installed capacity of the BelNPP, located in the northern part of the Grodno region near the town of Ostrovets and consisting of two power units, is 2400 MW. After the launch of the second power unit at maximum capacity, it is predicted that about 40 % of the electricity in the country will be generated at the expense of NPP. This will replace about 4.5 bln m^3 of natural gas and reduce carbon dioxide emissions into the atmosphere, which should bring both economic and environmental benefits not only for Belarus, but for the entire European region.

Conclusions

Thus, nuclear energy has established itself as a steadily developing industry that has firmly taken its place in the global electricity production. The modern image of nuclear energy is formed mainly by developed countries, followed by rapidly developing economies of the world (China, India, Republic of Korea). The Russia is emerging as a world leader in the export of nuclear technology and the construction of NPPs outside its territory.

The dynamics of the development of the world nuclear power industry is subject to cyclicality, like many other economic processes. However, the cause of crises in the industry, unlike other areas of the economy, are man-made disasters – accidents at NPPs that violate the global ecological balance and threaten the existence of the world community. This provokes a revision of national energy policies and adjustment of programs and plans for the development of the energy industry.

At the present stage, three trends can be distinguished in the prospects for the development of nuclear energy in countries:

- reducing the development of nuclear energy mainly in developed countries;
- continued development of nuclear energy in developed countries that are leaders in nuclear energy and possess nuclear technologies, and developing countries that are advanced in terms of economic growth;
- the emergence of new players, mainly among developing economies, seeking to ensure their energy security through nuclear energy.

In the future, the ratio of these trends will determine the level of development of the world nuclear energy.

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