NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 10(2): 131–137
DOI 10.3897/nucet.10.130485

Research Article

Forecasting the cost and volume of uranium mining for different world nuclear energy development scenarios*

Ulugbek T. Mirkhusanov[1], Dariya Yu. Semenova[1], Vladimir V. Kharitonov[1]

1 *MEPhI, 31 Kashirskoye sh., 115409 Moscow, Russia*

Corresponding author: Dariya Yu. Semenova (dysemenova@bk.ru)

Academic editor: Yury Kazansky ♦ **Received** 10 December 2023 ♦ **Accepted** 25 June 2024 ♦ **Published** 5 July 2024

Citation: Mirkhusanov UT, Semenova DYu, Kharitonov VV (2024) Forecasting the cost and volume of uranium mining for different world nuclear energy development scenarios. Nuclear Energy and Technology 10(2): 131–137. https://doi.org/10.3897/nucet.10.130485

Abstract

The paper presents a new analytical methodology for predicting the volume and cost of natural uranium production depending on uranium resources and scenarios for the development of traditional nuclear energy. The proposed methodology is based on a mathematical model of the dynamic process of exhaustion of fossil resources previously developed at MEPhI and uses the parameters of the explored mass of the fossil resource, the annual volume of production and the set rate of production growth. The three parameters known at the beginning of forecasting make it possible to describe the change in the resource base over time and solve a number of economic problems related to the extraction of valuable minerals. The paper provides forecasts of the NPP's demand for natural uranium, depending on the scenarios for the development of global nuclear energy developed by the World Nuclear Association (WNA), uranium resources and volumes of its production with different costs for 2021–2022. It is shown that at a low rate (1.8%/year) of the installed capacity of nuclear power plants, uranium resources will last for more than a century, but the contribution of nuclear energy to electricity production will continuously decrease from the current 10%. Under high scenarios for the development of nuclear energy (>5%/year), which is possible under the conditions of intensification of the "green energy transition", the peak of uranium production may occur before the middle of this century. Based on these data, forecasts of the dynamics of uranium exhaustion and annual production volumes at fields with different costs are presented until the second half of this century, depending on the initial production growth rates determined by the scenario of nuclear energy development.

Keywords

natural uranium, cost of uranium mining, nuclear energy development scenario, uranium production

Introduction

It will be no exaggeration to say (following the authors Velihov et al. 2010; Simonov 2010) that the history of human civilization is the history of continuous competition for all types of resources. There is currently a tough competition observed for hydrocarbon sources of energy and for technology metals the resources of which have turned out to be highly limited. Hydrocarbon fuel covers 100% of humankind's demand for primary energy sources. And, as noted in Ivanov et al. 2004, oil is the "most mass weapon of destruction" since all other types of weapons do not work without oil. Numerous "carbon-free power" scenarios based on solar panels, wind turbines and energy storage devices have come to face an acute issue of "critical materials", such as nickel, cobalt, copper, lithium and rare earths the resources of which are limited and around which global tensions grow (World Energy Transitions Outlook 2022;

---

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2024, n. 1, pp. 119–131.

Kondratiev 2022; Mansurov and Ptitsyn 2022). The Critical Materials Institute was established under the US Department of Energy, and the Critical Raw Materials project was launched by the European Commission (World Energy Transitions Outlook 2022). The possibility for the limited resources of conventional minerals to affect the evolution of civilization was shown in the Roman Club reports (Meadows et al. 2007), a contentious debate about which have led, in the long run, to the sustainable development concept (United Nations 2023). Specifically, it follows from reports Meadows et al. 2007 that the sustainable development of the "Golden Billion" countries, which have their mineral resources practically exhausted, will be accompanied by a fierce battle for the resources available so far in developing countries. Recent events illustrate this forecast as graphically as possible. It has been growingly frequently that the sustainable energy development is associated with nuclear power (Rosatom State Atomic Energy Corporation 2023). New reports from the World Nuclear Association (WNA) (The World Nuclear Supply Chain 2023; World Nuclear Performance Report 2023; The Nuclear Fuel Report 2023) underline that the expansion of nuclear power is needed for achieving the global climate-related objectives with the zero-contamination level, energy security and sustainable development. Energy security for an extended period of time can be called one of the key criteria for the long-term sustainable evolution of power industry (The White Paper on Nuclear Energy 2020). From this point of view, renewable sources of electricity are unrivalled. At the same time, the unique capabilities of nuclear breeding based on fast neutron reactors make it possible to ensure the evolution of nuclear power for more than a thousand years. However, no rapid evolution of nuclear power based on fast neutrons has occurred. It looks like a noticeable contribution of fast reactors to electricity generation worldwide is expected to manifest itself not earlier than the second half of this century. And the evolution of sustainable nuclear power based on thermal reactors is expected to face an issue of limited conventional resources of uranium (Ivanov et al. 2004; Kharitonov et al. 2019; The White Paper on Nuclear Energy 2020; The Nuclear Fuel Report 2023). The purpose of this study is therefore to evaluate the influence of scenarios for the evolution of conventional nuclear power on the depletion rate and the mining cost of natural uranium against the background of the hydrocarbon depletion.

Scenarios of nuclear power evolution

Based on different scenarios, global production of electricity will grow until 2050, the growth rate to be not less than 2%/year. With nuclear generation of electricity growing at a rate of not less than 2%/year, as is the case in recent decades, the contribution of nuclear power to global electricity production will go down. According to the scenario from the International Energy Agency (IEA) published in October 2022 (World Energy Outlook 2022), nuclear generation of electricity will grow until 2040, with a growth rate of about 1.8%/year, while electricity generation by wind and solar power plants will increase at a rate of 9% to 12% per year (Fig. 1). At the same time, the share of nuclear electricity generation will decline from 10% in 2020 to 9% in 2040.

The WNA reports identify three global scenarios, that is, low-rate, base-rate, and high-rate scenarios (The Nuclear Fuel Report 2023). The installed capacity of NPPs is expected to grow until 2040 at a rate of 1.6%/year (low-rate scenario), 3.6%/year (base-rate scenario), and 5.4%/year (high-rate scenario) at the expense of the East Asian countries for the most part. Accordingly, the reactor demand for fuel and natural uranium will grow. Given the trends for the growth in the installed capacity utilization factor (ICUF) and for the increase in the reactor life, and the fuel enrichment and burnup (with an invariable dump depth of 0.22%), the NPP demand for natural uranium is expected to grow at a rate of 1.8%/year (low-rate scenario), 4.1%/year (base-rate scenario) and 6.0%/year (high-rate scenario). Thus, the demand for natural uranium will practically double and reach 130 thousand tons per year (kt/year) by 2040 for the base-rate scenario, and will triple to reach 183 kt/year in the event of the high-rate scenario.

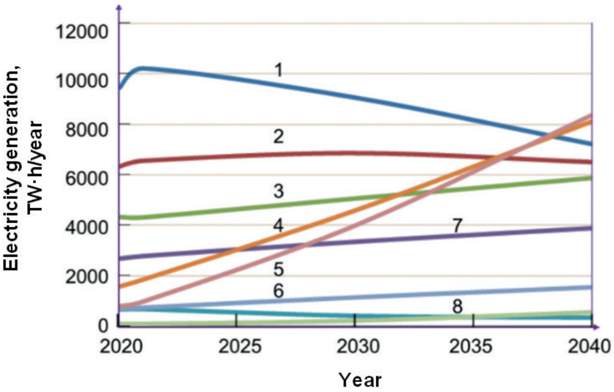

Figure 1. Electricity generation forecasts for different energy sources up to 2040 (World Energy Outlook 2022): 1 – coal, 2 – gas, 3 – hydropower, 4 – wind, 5 – solar PV, 6 – bioenergy, 7 – nuclear, 8 – other RES and oil.

Natural uranium resources and cost

In accordance with the IAEA classification of uranium resources, the core criterion is the probable cost of uranium mining (The Nuclear Fuel Report 2023; The Nuclear Fuel Report 2023; Uranium 2022: Resources, Production and Demand 2023; Zhivov et al. 2012). Four price categories of uranium production cost have been used since 2009: < 40 $/kgU, < 80 $/kgU, < 130 $/kgU, and < 260 $/kgU. As follows from Table 1, the uranium resources extracted by conventional methods (in the cost category of below 260 $/kgU) amount to below 8 Mt. For the entire period of commercial uranium production (before 2020), some 3.2 Mt of uranium were extracted (Table 2), which is 40% of the resources remaining in place.

Table 1. Global uranium resources (kt) with different cost of production as of 2021 (The Nuclear Fuel Report 2023)

Production cost	Reasonably assured resources (RAR)	Inferred resources (IR)	Recoverable resources (RAR+IR)
<$40/kgU	457	319	776
<$80/kgU	1211	780	1991
<$130/kgU	3815	2264	6079
<$260/kgU	4688	3229	7917

It also follows from Table 2 that the current capacities of uranium producers are used at 65% (49.36 kt/year are mined, the annual capacity being 76.2 kt/year). The countries with the biggest uranium production capacities in operation are Kazakhstan (38% of the global capacity), Canada (22%), and Namibia (12%). It is important to note that the major suppliers of natural uranium for the world market are countries with no domestically deployed NPPs, and the major uranium consumers are the "Golden Billion" countries with practically no domestic uranium reserves (Fig. 2). It is only Canada that covers in full its own nuclear power demand for uranium at the expense of domestic uranium production. In accordance with the development level of nuclear power, the countries with the highest uranium demand are the USA (about 18 ktU/year), China (11.3), France (8.8), Russia (6.3), and South Korea (4.1).

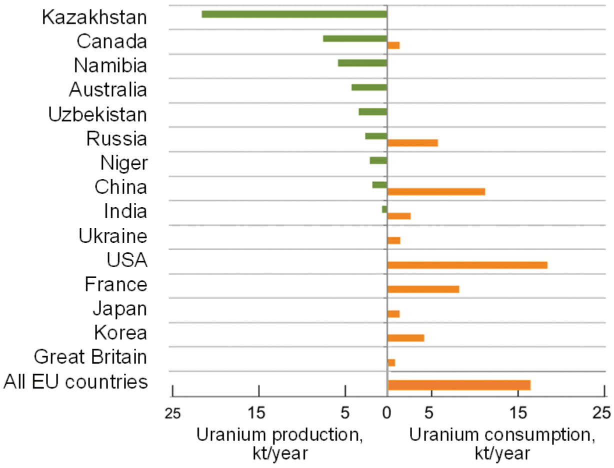

Figure 2. Production and consumption of natural uranium (kt/year) by countries in 2022 (The Nuclear Fuel Report 2023).

Depletion model for recoverable resources

A MEPhI paper of Kharitonov et al. 2019 proposes a new mathematical model for the dynamic depletion process of recoverable resources as the existing modification of the model proposed in 1956 by M. King Hubbert who forecast the oil production peak in the USA in 1972. The new model is based on the balance of the masses of recoverable and in-place resources and uses three initial parameters (as of the forecast start time): explored mass of the recoverable resource (recovered by traditional methods), M_0, (tons), annual output, G_0, (t/year), and preset production growth rate, k_0, (1/year). For example, the initial uranium production growth rate, k_0, is defined by the nuclear power evolution strategy and reflects the existing trends in the change of demand for the recoverable resource in question and the earlier production investments.

According to the MEPhI model, the dynamics of annual production, $G(t)$, in year $t>0$ (as from the forecast start time) is described by the analytical expression

$$G(t) = G_0 \frac{(2+\theta)^2 \exp(T)}{(\exp(T)+1+\theta)^2}. \tag{1}$$

Table 2. Resources and production of uranium in the cost category of below 260 $/kgU by countries of the world as of 2022 (The Nuclear Fuel Report 2023)

Country	Uranium resources in 2021 *R*, kt	Uranium production in 2022 *P*, kt/year	Capacity in 2022 kt/year	Cumulative uranium production for 1945–2022 *Q*, kt	Uranium demand, kt/year
Australia	1960	4.55	6.81	241	-
Kazakhstan	875	21.23	29.06	350	-
Canada	865	7.35	16.54	554	1.48
Russia	657	2.51	3.10	378*+91	6.28
Namibia	510	5.61	8.90	159	-
Niger	468	2.02	2.02	157	-
South Africa	445	0.20	0.77	166	0.28
Brazil	277	-	-	-	0.34
China	245	1.70	1.92	54	11.3
India	221	0.60	0.61	-	1.41
Ukraine	185	0.10	1.65	25	1.57
Uzbekistan	131	3.30	3.50	77	-
USA	112	0.075	-	378	18.05
Others	967	0.11	0.34	557**	24.94***
Total	**7918**	**49.36**	**76.20**	**3185**	**65.65**

* Sum (prior to 1991): Russia, Kazakhstan, Uzbekistan, and Ukraine. From 1992 onwards, the figures are shown individually for all countries.
** Including Germany (220 kt), the Czech Republic (112 kt), and France (76 kt).
*** Including the EU demand of 15.58 kt/year.

Here, $\theta = k_0T_0 = k_0M_0/G_0$ is the dimensionless parameter that characterizes the raw material depletion rate; $T_0=M_0/G_0$ is the depletion period of the raw material resource, M_0, in the event of stable annual production, G_0, (referred to in foreign literature as “Reserves-to-Production” or “R/P ratio”); and $T=(k_0+2/T_0)t$ is the dimensionless parameter that characterizes the forecast time. According to (1), with $k_0>0$, the diagram of $G(t)$ is bell-shaped: the production grows initially at a rate of k_0, and then the production rate, $k=(dG/dt)/G$, slows down and becomes equal to zero ($k=0$) at a certain time point, t_M, as the mineral production reaches the peak, G_M:

$$G_M = G_0 \frac{(2+\theta)^2}{4(1+\theta)}; \; t_M = \frac{\theta}{k_0\,(2+\theta)} \ln(1+\theta). \qquad (2)$$

The annual production decreases thereafter due to the further depletion of the resource. The model suggests that there will be no new deposits in future. If otherwise, the resource amount needs to be changed for a new value at this point. That is, the model takes into account long-term trends rather than short-term production declines and increases due to all kinds of current circumstances. For Kazakhstan, for instance, as shown in Table 2, we have that M_0=875 ktU and G_0=21.23 ktU/year, and the depletion period is then T_0=41. With the production growth rate being k_0=2%/year, we shall have that $\theta = k_0T_0$=0.82 and that the production peak is G_M=23.2 kt/year and occurs in $t_M \approx 9$ years. For Canada, the initial production rate being the same, we shall have that T_0=118 years, θ =2.35, G_M=10.4 kt/year, and $t_M \approx 33$ years.

To illustrate how the resource depletion model can be used, Fig. 3 presents the results of calculating the global dynamics of oil, gas and uranium production the initial data for which are provided in Tables 1–3. According to different forecasts, the global demand for hydrocarbon fuel will grow at a rate of not more than 1%/year. Therefore, k_0=1%/year has been assumed to be the initial oil and gas production rate. The uranium production forecast uses three WNA scenarios (The Nuclear Fuel Report 2023) and the “stagnation scenario” (k_0=0) as the initial growth rates, and the world NPP demand for natural uranium in 2022 as the initial production level (G_0=62 kt/year). As follows from Fig. 3a, the existing traditional recoverable energy resources (gas and oil) are not enough for the long-term development of power industry not only with the known resources but also with doubled resources and based on a very moderate scenario with the initial annual increase rate of only 1%/year.

The doubled oil and gas resources (dashed lines in Fig. 3a) do not change the trend essentially while simply postponing the production peak by two decades into the future. This means that the “Green Energy transition” from

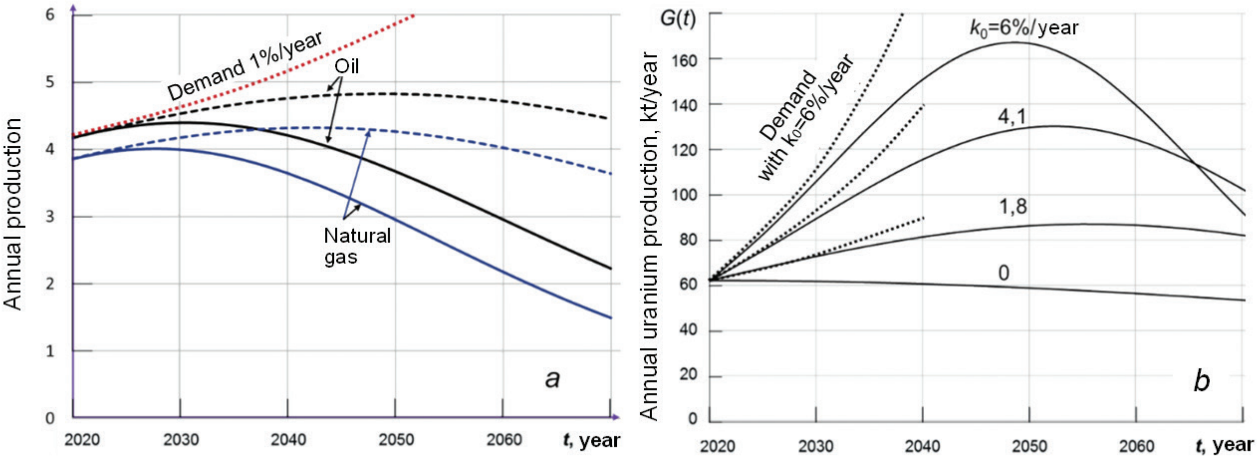

Figure 3. Dynamics of the annual oil and natural gas production worldwide (10^9 t/year and 10^{12} m^3/year respectively) with the initial rate of production growth rate being k_0=1%/year with initial data shown in Table 3 (**a**), and the annual uranium production for different evolution scenarios of nuclear power based on thermal reactors (**b**). The dashed lines in (a) are for the doubled oil and natural gas resources, and the dotted lines are for the oil demand with a rate of 1%/year (**a**) and the uranium demand according to three WNA-23 scenarios (The Nuclear Fuel Report 2023) (b).

Table 3. Proven resources and annual production of oil and natural gas by countries of the world for 2020*(BP-2021) (Statistical Review of World Energy 2021)

Countries	Oil			Natural gas		
	Resource M, 10^9 t	Production G, 10^9 t/year	Depletion period $T_0=M/G$, years	Resource M, 10^{12} m^3	Production G, 10^{12} m^3/year	Depletion period $T_0=M/G$, years
USA+Canada	8.2 + 27.1 = 35.3	0.965	36.6	12.6 + 2.4 = 15.0	1.080	13.9
Western Europe	1.8	0.167	10.8	3.2	0.219	14.6
Russia	14.8	0.524	28.2	37.4	0.638	58.6
Middle East	113.2	1.297	87.3	75.8	0.687	110.4
World total	**244.4**	**4.165**	**58.7**	**188.1**	**3.854**	**48.8**

*After 70 years of publishing statistical overviews, BP stopped to publish data on hydrocarbon resources.

hydrocarbons to RES has been caused not so by the CO_2 and climate issues as by exhaustion of conventional deposits.

It follows from Fig. 3b that low-rate scenarios of nuclear power evolution ($k_0 \leq 2\%$/year) lead to the uranium resources to suffice for more than a century but its contribution to electricity generation will decrease continuously from the current 10%. With high-rate scenarios of nuclear power evolution, the uranium production peak will occur by the middle of this century. It is possible to make up for the continuously growing shortage of uranium (the difference between demand and supply=production) for some time at the expense of secondary resources (e.g., REMIX and MOX fuel) which require reprocessing of spent fuel (SNF). However, development of commercial SNF reprocessing is a more practicable option for fast rather than for thermal reactors. There are potential nonconventional sources of uranium, e.g., seawater. At the same time, even if the cost of uranium extraction from water at a level of 400 to 500 \$/kgU, as shown in literature, is altogether achievable, it will be evidently only through integrated extraction of different chemical elements due to the extremely low concentration of uranium in seawater.

Dynamics of the uranium production cost

Uranium production cost, unlike uranium market price, is a more stable quantity while uranium market prices are highly volatile due to varying several-fold under the influence of either the demand growth expectations or following the volatility of prices for oil, gas and other energy sources. Thus, in 2007, on the eve of the world economic crisis of 2008–2009, the uranium prices reached the historical peak of 345 \$/kgU (133 \$/lbU_3O_8). There was another price peak (148 \$/kgU) observed in 2011, just before the Fukushima nuclear accident in Japan, after which the market prices dropped to reach the minimum of 57 \$/kgU (22 \$/lbU_3O_8) in 2017. At the same time, there have been no major changes in the uranium production technology, output or cost. In a longer term, however, due to the exhaustion of cheap deposits and development of more remote (expensive) deposits with the use of more advanced (and expensive) technologies, the cost of uranium production will grow to affect inevitably the market prices. Accordingly, forecasting the uranium production cost is fundamental to identifying the trends for the change in the market prices for natural uranium and, therefore, for the NPP electricity cost fuel component.

The cost of different deposits varies in the limits of $C_0 \leq C \leq C_M$ where the minimum cost is $C_0 \approx 16$ \$/kgU (Karatau, Kazakhstan (Uranium 2022: Resources, Production and Demand 2023; Uranium Production Cost Study 2021), and the maximum cost is C_M=260 \$/kgU (the IAEA classification). Presently, the most expensive uranium (in the cost category of below 215 \$/kgU) is produced for domestic consumption in India, China and Pakistan ((Uranium 2022: Resources, Production and Demand 2023; Uranium Production Cost Study 2021). For modeling, however, one needs to have the entire range of production cost. The price category of C_M=260 \$/kgU, if added to the initial data, contributes insignificantly to the actual uranium production balance.

We shall express the uranium production cost dynamics as the most common function, $g(C,t)$, that describes the annual uranium output (kg/year) for all deposits with a production cost of not more than C (\$/kgU) in year t as from the forecast start. That is, value $g(C,t)$ is the cumulative annual output for all deposits in a cost range from the smallest cost to C, quantity C varying between the minimum value and the maximum value as determined above. The initial form of this function (with t=0) is known to be $g(C,t=0) \equiv g_0(C)$ and is shown in Fig. 4b (the heavy line plotted based on data in Uranium Production Cost Study 2021 with the total output being $g_0(C_M)$=49.4 kt/year (Table 2). To forecast the uranium production cost dynamics in accordance with the nonrenewable resource depletion model presented above, one needs to know two more functional relationships, that is, of resources $m(C,t)$ and initial annual production rates, k_0I, with the uranium production cost. Function $m(C,t)$ describes the uranium resource (kt) in the cost category not higher than C (in a range from the minimum cost to C) in year t. Quantity $m(C,t)$ is the total (cumulative) uranium resource left by time point t as from the forecast start for all deposits with the production cost in a range from the minimum cost to C. At the forecast start time ($t=0$), this function is known as $m(C,t=0) \equiv m_0(C)$ and is shown in Fig. 4a. The points on curve $m_0(C)$ correspond to the data in Table 1. The results of the uranium production calculation using formula (1) shown in Fig. 3b take into account all deposits, that is, $G(t)=g(C_M, t)$ and $M_0=m_0(C_M)$.

Having such initial data as $m_0(C)$, $g_0(C)$ and k_0I, and using expression (1), we find the sought solution for the dynamics of uranium production with a different cost in the following form

$$g(C,t) = g_0\,(C)\,\frac{(2+\theta)^2 \exp(T)}{\left[\exp(T)+1+\theta\right]^2}. \qquad (3)$$

Here, dimensionless groups $\theta(C)$ and $T(C)$, which depend on the uranium production cost, are determined by the following expressions:

$$\theta(C) = \frac{k_0\,(C)\,m_0\,(C)}{g_0(C)};\; T(C) = \left(1+\frac{2}{\theta(C)}\right) k_0\,(C)\cdot \mathrm{t}. \quad (4)$$

The time-dependent change in the balance of in-place resources, m(C, t), with the cost of production in a range between the minimum cost and C is determined by the following expression

$$m(C,t) = m_0(C) - \int_{t=0}^{t} g(C,t)dt = m_0(C)\,\frac{2+\theta}{\exp(T)+1+\theta}. (5)$$

Therefore, since the initial functions of the resource, $m_0(C)$, and of the output, $g_0(C)$, are known (see Fig. 4 and Tables 1, 2), also known are functions $\theta(C)$ and $T(C)$

determined based on formulas (4), so, accordingly, the sought relationship $g(C,t)$ between the uranium output and cost (Fig. 4b) and the balance of the in-place resource (Fig. 4a) at different time points are also known. In the low production cost range (C<120 $/kgU), as can be seen, the uranium resources have the highest rate of decrease over time since it is cheap deposits that are developed first. The uranium output, as follows from Figs 4b, 5, will grow initially in accordance with the initial rate and, then, after the peak is reached, will go down with time due to cheap uranium resources to be first to deplete. Thus, the uranium production peak for cheap deposits (less than 40 $/kgU) is expected to occur in 10 years, while production will decrease by nearly twice in the middle of the century, as compared with 2022, with the initial rate of about 4%/year. Production at expensive deposits will grow until the middle of this century to decline thereafter, as expected, equally rapidly.

The results presented in Figs 4, 5 have been obtained for the same initial rate (4.1%/year). One can reasonably assume that the higher is the price of the demand (market price), as compared with the current production cost, (i.e., the higher is the expected gain), the greater is the intensity of the deposit development, while the production rate is smaller with the demand price being close to the production cost. The dashed lines in Fig. 5 show how much production changes at low-cost deposits.

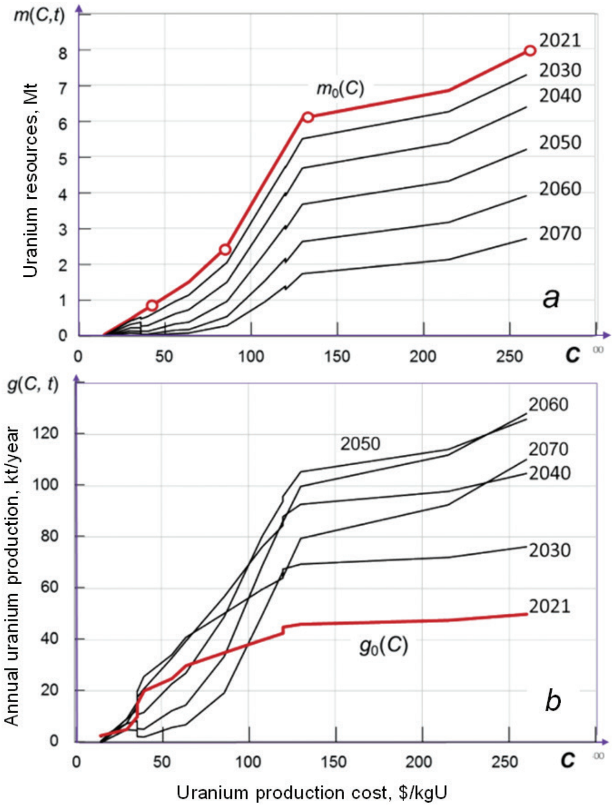

Figure 4. Influence of uranium production cost, C, ($/kgU) on time-dependent change in uranium resources, $m(C,t)$, (2021–2070), Mt U (**a**) and annual uranium production, $g(C, t)$, ktU/year (**b**), with the initial production growth rate of k_0=4.1%/year which corresponds to the WNA-23 base scenario (The Nuclear Fuel Report 2023). The initial data on the relationship of uranium production cost with uranium resources, $m_0(C)$, and annual output, $g_0(C)$, for the world deposits in 2021 ((The Nuclear Fuel Report 2023, Uranium Production Cost Study 2021) are shown by heavy lines in **a** and **b**. The points in **a** are for the WNA's 2021 data (The Nuclear Fuel Report 2023) for resources in 4 price categories of uranium deposits (see Table 1).

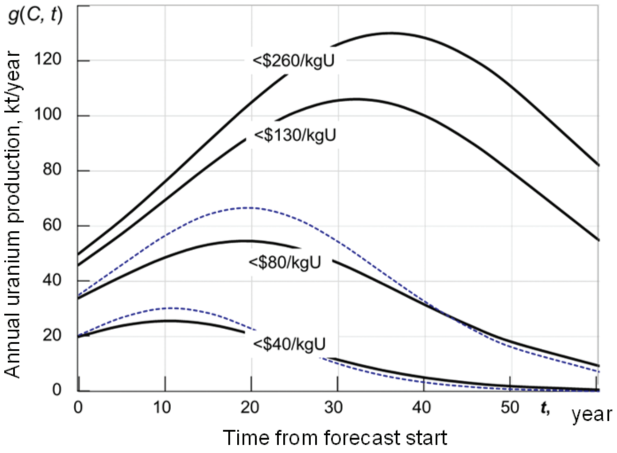

Figure 5. Dynamics of uranium production with different cost (initial rate of k_0=4.1%/year) which corresponds to the WNA-23 base scenario (The Nuclear Fuel Report 2023). The calculations are based on formulas (3) and (4) with the 2021 initial data (see Fig. 4). The dashed line is the dynamics of production for low-cost deposits with a higher initial rate (k_0=6.5%/year).

The results that justify the reliability of the proposed methodology, that is, the estimated depletion dynamics for different mineral resources, are presented in detail in Kharitonov et al. 2016.

Conclusion

Forecasting the cost of uranium production is fundamental to identifying the trends for the change in the market prices for natural uranium and, thus, for the fuel component of the nuclear electricity cost.

Based on the mineral resources depletion model developed by MEPhI, this paper shows for the first time how global annual uranium production changes over time depending on the cost of production with the predefined uranium resources and scenarios of the global nuclear power evolution (and with initial uranium production growth rates). The uranium production peak is expected to occur in 10 years for cheap deposits (below 40 $/kgU), while production will be half as small, as compared with 2022, by the middle of this century with the initial production growth rate being about 4%/year (the base scenario from the World Nuclear Association). For expensive deposits, production will increase until the middle of the century with the equally rapid decline in production thereafter. With low-rate scenarios of nuclear power evolution (less than 2%/year), conventional uranium resources in the production cost category of below 260 $/kgU will suffice for more than a century but its contribution to electricity generation will decrease continuously from the current 10%. With high-rate scenarios of nuclear power evolution, the uranium production peak is expected to be reached by the middle of this century.

Since the major suppliers of natural uranium for the world market are countries with no domestically deployed NPPs, and the major uranium consumers are economically developed countries (“Golden Billion” countries) with practically no domestic uranium resources, one can expect competition to grow in the world uranium market with a potential for an increase in the event of NPP construction in uranium producing countries.

References

- Ivanov GA, Voloshin NP, Ganeev AS, Krupin FP, Kuzminyh SYu, Litvinov BV, Svaluhin AI, Shibarshov LI (2004) Explosive Deuterium Energy. VNIITF Publ., Snezhinsk, 288 pp. [ISBN 5-85165-443-0:300] [in Russian]
- Kharitonov VV, Kabashev KV, Malikov RR (2016) Long-term Exhaustion Trends of Traditional Energy Resources and Prospects for Nuclear Energy. MEPhI Publ., Moscow, 96 p. [in Russian]
- Kharitonov VV, Uljanin YuA, Sliva DE (2019) Analytical modeling of exhaustion dynamics of nonrenewable traditional energy resources. Vestnik MEPhI 8(4): 370–379. https://doi.org/10.1134/S2304487X19030076 [in Russian]
- Kondratiev VB (2022) The role of critical raw materials in conditions of economic uncertainty: the EU experience. Russian Mining Industry 4: 94–102. https://doi.org/10.30686/1609-9192-2022-4-94-102 [in Russian]
- Mansurov OA, Ptitsyn PB (2022) Critically Important Minerals and Materials for Industry 4.0: Production Features and Application Prospects in Global Markets. Analytical Report. CARD of Private Enterprise for Nuclear Industry Scientific Development “Science and Innovations” Publ., Moscow, 142 pp. [ISBN 978-5-498-00898-1] [in Russian]
- Meadows DH, Randers J, Meadows DL (2007) Limits of Growth. 30 Years Later. Akademkniga Publ., Moscow, 342 pp. [ISBN 978-5-94628-218-5] [in Russian]
- Simonov KV (2007) The Global Energy War. Series: Secrets of Modern Politics. Algoritm Publ., Moscow, 272 pp. [ISBN 978-5-9265-0496-2] [in Russian]
- Rosatom State Atomic Energy Corporation (2023) Sustainable Development. Rosatom State Atomic Energy Corporation: Official Website. [Available at:] https://rosatom.ru/sustainability/ [accessed Dec. 1, 2023] [in Russian]
- Statistical Review of World Energy 2021 (2021) Statistical Review of World Energy 2021. 70th edition. BP, 72 pp.
- The Nuclear Fuel Report (2023) Global Scenarios for Demand and Supply Availability 2023–2040. World Nuclear Association. Report No. 2023/003. September 2023, 258 pp. [ISBN: 978-0-9931019-9-1]
- The White Paper on Nuclear Energy (2020) Closed-loop NFC with Fast Reactors (gen. edit. Adamov E.O.). NIKIET Publ., Moscow, 502 pp. [ISBN: 978-5-98706-129-9] [in Russian]
- The World Nuclear Supply Chain 2023 (2023) World Nuclear Association. Report No. 2023/002, 165 pp. [ISBN: 978-0-9931019-8-4]
- Velihov EP, Gagarinskij AYu, Subbotin SA, Tsibulskij VF (2010) Energy in the Economy of the XXI Century. IzdAT Publ., Moscow, 176 pp. [ISBN 978-5-86656-246-6] [in Russian]
- World Energy Outlook 2022 (2022) International Energy Agency, 523 pp.
- World Energy Transitions Outlook (2022) World Energy Transitions Outlook 2022: 1.5°C Pathway (2022). IRENA, Abu Dhabi, 52 pp.
- World Nuclear Performance Report 2023 (2023) World Nuclear Association. Report No. 2023/001. July 2023, 62 pp.
- United Nations (2023) 17 Goals to Transform Our World. United Nations: Official Website. [Available at:] https://www.un.org/sustainabledevelopment [accessed Dec. 1, 2023]
- Uranium 2022: Resources, Production and Demand (2023) A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency. OECD NEA No. 7634, 568 pp.
- Uranium Production Cost Study (2021) UxC Special Report, 124 pp.
- Zhivov VL, Boitsov AV, Shumilin MV (2012) Uranium: Geology, Mining, Economics. Atomredmetzoloto. RIC VIMS Publ., Moscow, 304 pp. [ISBN 978-5-901837-80-1] [in Russian]