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Research Article

Nuclear perspectives at exhausting trends of traditional energy resources*

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Abstract

For the first time the analytical relationship was established between the nuclear energy generation worldwide and supply of NPPs with natural uranium, as conventional resources are expected to deplete by the end of this century. Forecast results include the dynamics of a potential increased shortage of conventional energy resources, such as hydrocarbon fuels (coal, oil, natural gas) and natural uranium, in the course of time due to a growing energy demand (at the rate of 1 to 2% per year), on the one hand, and the depletion of nonrenewable resources, on the other hand. The forecast is based on the current geological data on extractable hydrocarbon and uranium resources, and a mathematical model for the dynamics of nonrenewable resources production. The forecast shows that, with the present-day paradigm of handling the produced conventional energy sources, the reserves of these will be significantly depleted by the end of this century, and their production peaks are expected to be reached by the mid-century. In the event of state-of-art NPP designs, the dynamics of the installed capacity will follow the dynamics of the natural uranium depletion, and the NPP contribution to the supply of energy for the needs of humankind will go down while increasing at the same time the total shortage of conventional energy sources. By 2100, however, the contribution of nuclear power (based on thermal neutrons) to primary sources may reach 10%, since hydrocarbons will be depleted at a higher rate than uranium. Meanwhile, this amount of nuclear energy will be negligible, as compared to the demand for primary energy, after the 2040s even at the smallest possible rate of growth in demand (1%/year). A growing spread between the increasing energy demand and the decreasing supply of exhaustible conventional energy resources necessitates the evolution of nuclear fuel breeding (breeding of ^{239}Pu from ^{238}U and, possibly, ^{233}U from ^{232}Th) no later than the 2030s.

Keywords

Nuclear energy, fuel burn-up, natural uranium, nonrenewable conventional energy resources, hydrocarbons, production dynamics, production rate, production peak, nuclear breeders.

Introduction

Sustainable supply of energy resources is one of the major criteria for the sustained long-term development of power industry (White Book of Nuclear Energy 2001, Avrorin et al. 2012, Kharitonov 2014, INPRO Methodology 2014). The evolution of civilization is accompanied by a steady growth in the production of energy resources and metals playing a key role as the "drivers of technologies and the advancement". Till the present day, conventional hydrocar-

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bon fuels (coal, oil and natural gas) account for nearly 90% of the energy consumed by humankind, including production of metals (Velikhov et al. 2010, Kontorovich et al. 2014, Laverov 2011). At the same time, the geological estimates of conventional fossil resources are very limited which, naturally, draws attention to the dynamics of their depletion and to the prospects of energy technologies, including nuclear power. The paper presents the current geological data on the energy potential of hydrocarbon fuels and natural uranium and their global production dynamics. Based on these data and a mathematical model taking into account the mass balance between the extracted and in-situ fossil energy resources, an analytical forecast was prepared for the depletion dynamics of conventional energy resources. It was shown to which extent the natural uranium production can limit the evolution of nuclear power in this century, and how the spread between the growing energy demand and the declining supply of conventional energy resources is expected to aggravate. One of the possible ways to mitigate the potential shortage of conventional energy resources, expected to grow rapidly after the 2040s, is intensive development of nuclear fuel breeding, e.g. breeding of ^{239}Pu and, possibly, ^{233}U from such primary nuclides as ^{238}U and ^{232}Th, with the energy potential to last for thousands of years.

Interrelation between nuclear energy generation and natural uranium consumption

An important energy and economic characteristics of nuclear fuel is the so-called fuel *burn-up factor* (also known as specific energy yield) defined as the thermal energy produced from burning a unit mass of nuclear fuel (with the given isotopic composition) throughout the period of its use in the reactor (Kharitonov 2014, Sinev 1987). The fuel burn-up fraction B is normally expressed in megawatt-days (of thermal energy) per kg of fuel (MW·day/kg or GW·day/t). The time the fuel stays in the reactor (and the burn-up factor) is limited primarily by two factors: a lower concentration of fissionable isotopes and accumulation of fission products. The burn-up factor is associated with the need for the reactor regular fueling, i.e. the reactor demand for enriched fuel, the uranium isotope separation work and natural uranium. The higher the burn-up factor, the lower the number of reactor outages for refueling and the more the NPP earns from electricity sales. Effective thermal-neutron power reactors have a burn-up factor of 40 to 50 GW·day/t. To improve the cost efficiency of reactors, new fuel types are developed with a higher burn-up factor (up to 70-80 GW·day/t).

Operation of a nuclear reactor with the thermal power Q (W or GW) and the installed electric capacity $W = \mathrm{h}Q$ (W or GW), at the (gross) efficiency h and the installed capacity utilization factor (ICUF), requires the following annual average quantity of fuel (enriched uranium product):

$$P = Q/B = \mathrm{ICUF}\cdot W/\,\mathrm{h}B. \tag{1}$$

So, with $W = 1000$ MW, h = 1/3, ICUF = 0.85, and B = 40 GW·day/t, we get the enriched uranium demand of P » 23 tU/year per reactor.

In the process of uranium enrichment (isotope separation), the separation facility at the enrichment plant receives natural uranium referred to as the primary raw material (or Feed) with the consumption rate F (t/year) and the concentration c = 0.7115% ^{235}U (by weight) (in the form of uranium hexafluoride UF_6). The isotope separation results in two uranium streams: Enriched Uranium Product (extraction) with the consumption rate P (t/year) and the concentration $x > c$, and Depleted Uranium or Tails with the consumption rate D (t/year) and the concentration $y < c$. Since the balance of masses is achieved for the total uranium quantity and for ^{235}U prior to and after the separation, the following interrelation of the three uranium streams (flows) is obtained with different concentrations of ^{235}U (Kharitonov 2014, Sinev 1987, Borisevitch et al. 2005, World Nuclear Association):

$$F = P(x - y)/(c - y),\ D = P(x - c)/(c - y) \tag{2}$$

Hence, the production of 1 MT of enriched uranium (P = 1 MT) with the assay x = 4.4% (for a typical PWR reactor) and the typical content of ^{235}U in tails (y = 0.2%) requires F » 8.2 MT of natural uranium, with $D = F - P$ » 7.2 t of depleted uranium (tails) formed. Therefore, the annual reactor fuel makeup of P » 23 tU/year requires some 189 t of natural uranium to be mined annually.

In 2016, according to WNA (World Nuclear Association), the NPPs worldwide (as of 01.01.2017, 447 reactors with the installed capacity of 391 GW in 31 countries) produced $E = 2.49\cdot10^{12}$ kW·h of electricity, which accounted for 10.6% of the total electricity generation globally. The annual natural uranium demand for the NNPs in operation was F = 63.4 kg. With the worldwide-average fuel burn-up factor assumed to be B = 40 GW·day/tU and the NPP efficiency h = 1/3, the global demand for enriched uranium product in 2016 was $P = E/\,\mathrm{h}B$ » 7.8 kgU/year, which gives the relation F/P = 8.1 (nearly the same as in the example above).

Therefore, a MT of natural uranium may be roughly assumed to produce some E/F » 40 GW·h of nuclear electricity or about $q = E/\mathrm{h}F$ » 424 TJ of thermal energy (1 TJ = 10^{12} J). This value (q » 424 GJ/kg) may be referred to as "effective caloric capacity of natural uranium" in current nuclear reactors which is approximately 10 thousand times as high as the caloric capacity of oil (about 42 MJ/kg). With the ^{235}U contained in 1 kg of natural uranium burnt completely, the heat release would be q_5 » 570 GJ, which exceeds the "effective caloric capacity" due to incomplete combustion of ^{235}U in the reactor not compensated by additional combustion of the plutonium accumulated in the fuel (during the reactor operation). So, the annual production of thermal energy by conventional (present-day) NPPs worldwide, Q, (or of electricity, E =

hQ) may be related to the annual production, F, of natural uranium in the given year t using a simple expression:

$$Q(t) = q(t)F(t), \tag{3}$$

which shows that a decrease in the natural uranium production in time (due to the depletion of conventional resources) will lead to lower nuclear electricity generation as well. With the progress of NPP design and nuclear fuel cycle upgrading, the “effective caloric capacity” value of natural uranium may grow in time due to the growing fuel burn-up factor and use of MOX fuel and other technologies. However, we are interested in the dynamics of conventional nuclear power and its capability to meet the global demand for primary energy sources, with regard for their depletion, including uranium depletion.

Depletion model for nonrenewable resources

The model of the dynamics in the depletion of a limited resource was proposed by K. Hubbert in 1956 (Hubbert 1956, Kharitonov et al. 2016, Sverdrup et al. 2012) (see Kharitonov et al. 2016 for detailed description). He showed that, for any given geographical region, e.g. a mineral deposit or the entire planet, the diagram of the production rate $G(t)$ for the given resource for the time t is expected to be bell-shaped (Fig. 1).

The production initially grows rapidly, then reaches the peak (maximum), G_M, at a certain time point, T_M, and decreases thereafter down till complete depletion of the resource. In 1972 the oil production peak was reached in the USA. Hubbert’s prediction was verified in a general context, whereafter his work won a broad recognition. The drawbacks of the Hubbert model include the symmetry of the curve $G(t)$ and its divergence with the current

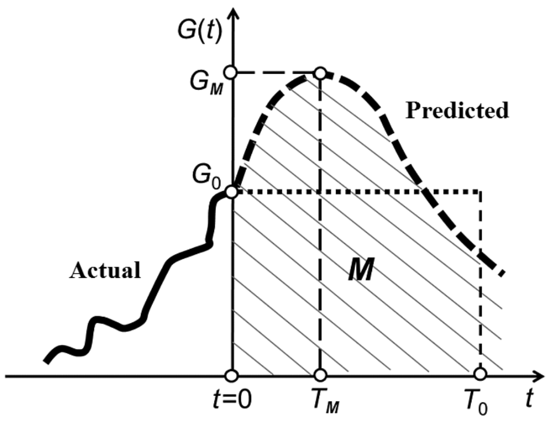

Figure 1. Forecast production dynamics of a nonrenewable resource with the known initial production level G_0 and in-situ resource amount M, based on the MEPhI model. $T_0 = M/G_0$ is the total depletion period with the constant annual production level G_0 (“R/P-ratio”).

production value with an intense volatility of historical data (Kharitonov 2014, Kharitonov et al. 2016). Therefore, the authors use a MEPhI-developed model (Kharitonov 2014, Kharitonov et al. 2016, Kharitonov et al. 2012). The current time point from which the forecast is to be done shall be selected as the reference time $t = 0$. The past period (production history) corresponds to the negative values of $t < 0$, and the future period (the forecast period) corresponds to the positive values of $t > 0$. We shall define the total quantity of the given in-situ resource as M. The MEPhI model includes three assumptions for the smoothened (trend) characteristics of production:

– equation of the material balance for the in-situ resource of $M(t\ {}^3\ 0)$

$$M = \int_0^\infty G(t)dt\ ; \tag{4}$$

– the production variation rate dG/dt is proportional to the production level $G(t)$, that is

$$dG/dt = k(t)\times G(t), \tag{5}$$

where the factor $k(t)$ is the trend production rate (1/year) depending on time, $k(t)$ being occasionally referred to as the resource utilization efficiency or the effectiveness of economy, since the larger is $k(t)$, the higher the production growth rate with the same production level);

– the production rate decreases linearly over the forecast period:

$$k(t) = k_0(1 - t/T_M), \tag{6}$$

where k_0 is the rate value at the initial stage of the forecast period ($t = 0$) and not at the beginning of the resource development as in the Hubbert model. It is important to note that the production rate k_0 at the beginning of the forecast period reflects the existing demand for the mineral resource in question and the investments in future production. As a result, an analytical expression was obtained for the resource production dynamics shaped as a Gaussian curve shown to the right of $t = 0$ on Fig. 1):

$$G(t\ {}^3\ 0) = G_M \exp[k_0T_M(1 - t/T_M)^2/2]. \tag{7}$$

The maximum (peak) annual production rate G_M is related to the initial production level $G_0 = G(t = 0)$, the initial production rate k_0 and the production peak achievement period T_M in the expressions:

$$G_M = G_0 \exp(k_0T_M/2) \text{ or } T_M = 2\times k_0^{-1}\ln(G_M/G_0). \tag{8}$$

The substitution of (7) and (8) into balance relation (4) gives the interdependence of the critical production parameters k_0, T_M and G_M that define the production dynamics with the in-situ recoverable resource amount M:

$$M = G_MT_M\text{r(e)}. \tag{9}$$

Here, we introduce the dimensionless parameter e and the dimensionless function r(e) of the form (Kharitonov 2014)

$$\varepsilon = \sqrt{\frac{k_0 T_M}{2}} = \sqrt{\ln\frac{G_M}{G_0}};\quad \rho(\varepsilon) = \sqrt{\pi}\,\frac{1+\Phi(\varepsilon)}{2\varepsilon};\quad \Phi(\varepsilon) = \frac{2}{\sqrt{\pi}}\int_0^{\varepsilon}\exp(-z^2)dz. \qquad (10)$$

F(e) is referred to as the Laplace function or the probabilities integral. This function grows monotonously from zero to unity with e increasing from zero to ¥.

Practical use of this model, the key results for which are presented by expressions (7) – (10), require three quantities to be known: the latest actual value of the annual production, G_0, being initial for the prediction; the amount of the in-situ (at the time the forecast period starts) recoverable resources (reserves) of the fossil fuel, *M*, and one of the parameters k_0 or G_M. We shall consider both options (referred to as K and G respectively).

Option К could be used when one knows (or there has been defined) the initial production rate k_0, i.e. the quantities *M*, G_0 and k_0 are known. If no initial production rate (as of the time of the forecast period beginning) is defined, it can be estimated by averaging for a number of years preceding the forecast, taking into account the production volatility. Based on the known quantities k_0, *M* and G_0, the dimensionless complex $k_0 M/G_0$ is defined and the dimensionless parameter e is calculated from the transcendent equation:

$$k_0 M / G_0 = \rho_k(\varepsilon);$$
$$\rho_k(\varepsilon) = 2\rho(\varepsilon)\cdot\varepsilon^2\exp(\varepsilon^2) = \sqrt{\pi}\left(1+\Phi(\varepsilon)\right)\cdot\varepsilon\cdot\exp(\varepsilon^2), \qquad (11)$$

and then the sought-after production peak parameters are calculated:

$$G_M = G_0\exp(\mathrm{e}^2);\ T_M = 2\mathrm{e}^2/k_0. \qquad (12)$$

Option G could be used when we know the limit for the production peak value G_M (e.g. for technological, economic or geological reasons or due to the demand and so on), i.e. the value e = $(\ln(G_M/G_0))^{1/2}$ is known. Other calculated parameters k_0 and T_M, characterizing the production dynamics forecast, are calculated using the formulas:

$$T_M = M/(G_M \mathrm{r}(\mathrm{e}));\ k_0 = 2\mathrm{e}^2/T_M. \qquad (13)$$

When we know the relation of the expected production peak G_M to the latest actual value of the annual production $G_0 < G_M$, we could calculate the value e, and then, at the known value *M*, we could initially calculate the production peak occurrence time T_M from the forecast start, and then calculate the initial forecast production rate k_0.

Forecast of the depletion dynamics of conventional uranium resources and nuclear electricity generation

According to WNA, G_0 = 62 ktU was produced in 2016, which is slightly less than the NPP demand of 63.4 ktU/year (World Nuclear Association). Since 1990, the uranium production was behind the NPP demand. The uranium short supply was compensated by inventories and other secondary sources which have decreased considerably as of today (Kharitonov 2014, World Nuclear Association, Kharitonov et al. 2016, Uranium 2016). In 2016 the known recoverable natural uranium resources with a cost of less than USD 260 kgU amounted to about 7.6 MMT (million MT), which, together with the remaining inventories (about 0.2-0.54 MMT (Kharitonov 2014, Uranium 2016) give the upper estimate of *M* » 8.1 MMT. Meanwhile 61% of the conventional natural uranium resources are concentrated in four countries: Australia (31%), Kazakhstan (12%), Russia (9%) and Canada (9%) (Kharitonov 2014, World Nuclear Association, Uranium 2016, Zhivov et al. 2012, Tarkhanov 2012).

To forecast the energy generation by conventional NPPs, we use expression (3) with *q* = 424 GW/kg, where the time dependence of the demand for natural uranium is defined by expression (7). The parameters G_M and t_M in

Table 1. Production dynamics parameters for conventional energy resources in the 21st century based on the proposed model. Sources: initial data (*M*, G_0, k_0) from WNA (World Nuclear Association) and British Petroleum (BP Statistical Review of World Energy 2017, BP Energy Outlook 2017); depletion dynamics parameters (resources and annual production in energy units, ε, G_M, T_M) calculated by the authors.

Production parameter*	Coal	Oil	Gas	Uranium**	Total
Resource *M*, thou EJ	23.4	10.4	7.3	3.4	44.5
Production in 2016, G_0, EJ/year	153	206	138	26.9	524
Initial rate in 2017, k_0, %/year	2.5	1.1	2.4	2.5	
Depletion period T_0="R/P-ratio", years	153	51	53	128	84
Dimensionless parameter ε	0.724	0.193	0.377	0.664	0.38
Production peak G_M, EJ/year	259	214	159	42	604
Peak achievement period T_M, years	42	7	12	35	16
Peak production year	2059	2024	2029	2052	2033

* The assumed relations between measurement units: 1 toe = 41868 MJ; 1 equiv. barrel = $6.12\cdot10^9$ J; average caloric capacity of coal 20.5 MJ/kg; average caloric capacity of natural gas 39 MJ/m^3; effective caloric capacity of natural uranium 424 GJ/kg.

** The uranium resource determined with regard for then stock reserves of 0.5 Mt; annual operating NPP demand for natural uranium used instead annual production this expression are calculated for option K (11) and (12) with G_0 º F_0=63.4 ktU/year and the global nuclear power trend development rate of k_0 » 2.5%/year, as shown by WNA (2017). For the assumed initial data, as follows from Table 1 and Fig. 2, the nuclear energy generation peak Q_M » 42 EJ/year for thermal reactors of modern design is expected to be reached in the mid-century (T_M » 35 years, that is, in 2052). Accordingly, the nuclear electricity generation and natural uranium production peaks will be E_M » $3.89 \cdot 10^{12}$ kW·h/year and G_M » 99 ktU/year, which is 56% higher than the similar quantities in 2016. By the end of this century, the supply of natural uranium from conventional sources and the respective nuclear energy generation will be 1.5 times lower than in 2016.

The higher the nuclear power development rate at the beginning of the forecast period, the higher the nuclear energy generation peak (and the supply » uranium production peak) and the steeper the subsequent production decline (see Fig. 2), i.e. the faster the resource are depleted. In the “low-rate scenario” for the development of global nuclear power with the initial rate of k_0 = 0.5%/year, the generation of conventional nuclear energy will be 38% lower at the end of the century than in 2016. If nonconventional uranium resources (with a higher production cost), which are twice as large as the current resources, are utilized, the nuclear energy generation is also expected to double by the end of the century (see Fig. 2). In this case, the natural uranium resources will be sufficient for thermal-neutron reactors of the current type operating more than a century. Even then the contribution of nuclear power to meet the growing demand for primary energy, will decrease (from today’s low contribution of about 5.1%).

To compare, Fig. 3 shows the depletion curves for conventional coal, oil and gas resources calculated based on the formulas (7), (11) and (12) in energy units that characterize the amount of thermal energy released from the complete combustion of produced hydrocarbon fuels. It does not take into account the mutual effects from production of different energy resources.

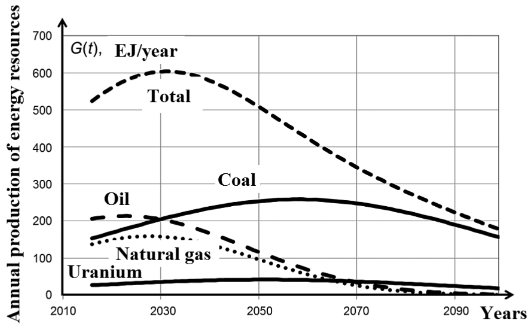

Figure 3. Forecast dynamics in the annual production of conventional energy resources (coal, oil, gas and uranium) worldwide in energy units (EJ/year = 10^{18} J/year)

As follows from Table 1, containing initial data (M, G_0 and k_0) and estimated production dynamics parameters (ε, G_M, T_M), as well as in Fig. 3, the conventional energy resources will be significantly depleted by the end of this century at the existing technological and production capabilities. And the production peaks for conventional energy sources are expected to occur in the mid-century.

We note that the production peaks will occur ahead of the so-called depletion period $T_0 = M/G_0$ for the resource M with the current level of its production, G_0, referred to in foreign literature as “R/P-ratio” (Reserves-to-Production ratio).

It follows from the comparison of the curves in Fig. 3 that the current contribution of nuclear energy to supply of fuel for the needs of humankind slightly exceeds 5%. However, the contribution of nuclear energy (thermal neutron reactors) to primary sources may reach 10% by 2100 due to the fact that conventional hydrocarbons deplete faster than uranium.

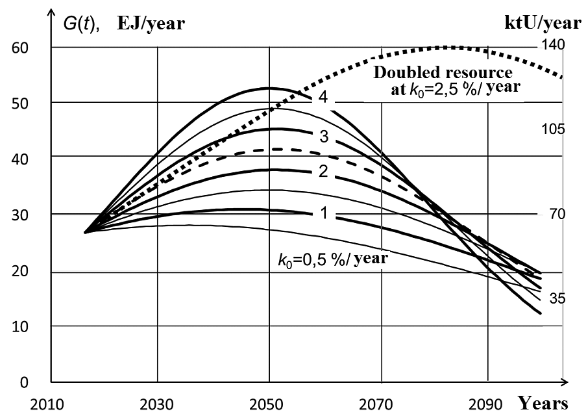

Figure 2. Forecast dynamics of annual nuclear electricity generation (EJ/year = 10^{18} J/year) and natural uranium supply (ktU/year) with different scenarios (initial rates) of the global nuclear power development and with 8.1 Mt of uranium resources (uranium production cost: up to 260 $/kg). The calculation based on formulas (3), (7), (11) and (12) with the initial parameters as of 2016 from Table 1. The dash line corresponds to k_0 = 2.5%/year; and the dotted line corresponds to the doubled natural uranium resource M = 16.2 Mt and k_0 = 2.5%/year.

Forecast short supply of conventional nonrenewable energy sources

In recent decades, thanks to the energy saving policy, the energy consumption worldwide has decreased practically by half to approximately 1.5%/year (BP Energy Outlook 2017). In the event of such energy consumption rate to continue till the end of the century, the annual energy consumption will increase by a factor of 3.5 by 2100 as compared to 2016 (Fig. 4). The demand will considerably exceed the production of conventional energy resources beginning in the 2030s, and the short supply at the end of the century will be thrice as great as the consumption of primary energy at present.

The short supply of conventional resources will not be noticeable prior to the 2040s with the growth in demand at a level of 1 %/year, while the shortage will increase rapidly in the second half of the 21st century. In conditions of the growing demand for primary energy at a rate of 2%/year and above, the short supply of conventional energy resources will be growing catastrophically in the next decade (Fig. 4).

What can partially compensate the forecast short supply of conventional primary energy resources (hydrocarbons and uranium)?

First, it is the development of nonconventional resources that needs both new technologies and increased investments (shale oil and natural gas, gas hydrates, uranium salts dissolved in ocean water, etc. (Laverov 2011). Assumingly the total resources of fossil fuel can be doubled thanks to nonconventional resources of hydrocarbons and uranium. As follows from Fig. 4, in this unlikely scenario of recoverable energy resources to double as well, the shortage is also inevitable but will start to manifest in a noticeable way somewhat later, in the 2050s (with low rates of the growth in demand at about 1%/year). In this scenario the contribution of nuclear energy (with doubled uranium resources) to primary nonrenewable sources will not exceed 10%.

Second, it can be the advancement of renewable resources (solar and wind energy) (REthinking Energy 2017, World Energy 2017, Energy [R] Evolution 2014, Aldo Vieira da Rosa 2005). According to (REthinking Energy 2017, World Energy 2017), the installed electric power of wind plants worldwide reached 416 GW in 2015 and that of solar power plants reached 219 GW, which, in total, is nearly twice as high as the power of worldwide NPPs (about 391 GW). However, it is difficult to substantiate the potential evolution of renewable energy at a scale exceeding several-fold the current level of the world's hydrocarbon-based power covering 90% of human demand.

Third, it is the evolution of nuclear power systems based on breeder reactors capable of nuclear fuel breeding (breeding of ^{239}Pu from ^{238}U and of, possibly, ^{233}U from ^{232}Th) no later than the 2030s. The energy potential of ^{238}U and ^{232}Th is dozens times higher than the potential of hydrocarbons. This, however, requires both technological and economic justification for the potential development rates of breeder-based nuclear power needing a closed fuel cycle, acceptable technologies of radioactive waste management and enriched uranium (and plutonium) for the initial breeder loading (Avrorin et al. 2012, Adamov et al. 2017, The Generation IV International Forum, Poplavsky 2011).

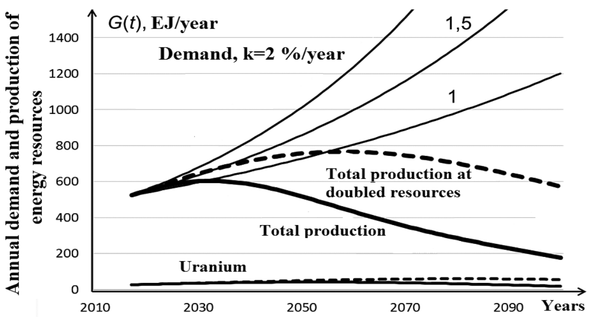

Figure 4. Forecast global demand for primary energy with different annual growth rates (1, 1.5 and 2%/year), and predicted total production of conventional energy resources and nuclear energy generation with the existing resources (Table 1) and doubled resources (dashed lines).

Conclusion

1. The paper presents quantitative results of forecast dynamics of nuclear energy generation (and supply of natural uranium) till the end of this century based on conventional thermal-neutron reactors and natural uranium sources. It presents forecasts for depletion of conventional hydrocarbons (coal, oil, natural gas) covering 90% of the current energy demand. The forecast is based on the present-day geological data on conventional energy resources and an analytical balance model for depletion of nonrenewable mineral resources developed by the authors.

2. It was shown that limited conventional resources of natural uranium (estimated at 8.1 MMT with production cost of up to USD 260 kgU, with regard for inventories) confine the contribution of nuclear energy to supply of fuels for human needs in this century to a level below 5-10%. The nonrenewable conventional energy sources will be largely depleted by the end of the century with the existing technological and economic production capabilities. Meanwhile the production peaks of conventional energy resources are expected to be reached by the mid-century.

3. A comparison of the growing demand for primary energy sources (at the growth rate of 1-2 %/year) against the production and depletion level of conventional energy resources has shown that the demand will be much in excess of the conventional energy resource production, beginning in the 2030s, while the short supply of energy resources will increase rapidly in the second half of the century exceeding by many times the supply of these. Assuming that the total resources of mineral fuel can be doubled thanks to conventional hydrocarbon and uranium resources, the short supply of these is inevitable in this case but it will start to manifest itself in a noticeable manner somewhat later, i.e. in the 2050s (with low rates of the growth in demand at about 1%/year). The contribution of conventional nuclear energy (with doubled uranium resources) to nonrenewable primary sources will not exceed 10% in this case as well.

4. The shortage of primary energy could be reduced, and contribution of nuclear energy to meet the humankind's energy demand could be increased through development of nuclear power systems based on breeder reactors capable of nuclear fuel breeding (breeding of ^{239}Pu from ^{238}U and, possibly, ^{233}U from ^{232}Th) no later than the 2030s. The energy potential of ^{238}U and ^{232}Th is dozens

times greater than the potential of hydrocarbons. This, however, requires both technological and economic justification for the potential evolution rates of the breeder-based nuclear power needing a closed fuel cycle, acceptable technologies of radioactive waste management and enriched uranium for the initial breeder loading, which is expected to be problematic due to depletion of conventional natural uranium resources.

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