Long-term Stochastic Forecasting of the Nuclear Energy Global Market

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Keywords

stochastic forecasting; nuclear energy market; NPP installed capacity; NPP construction; NPP decommissioning; natural and enriched uranium; uranium isotope separation work; Monte-Carlo method; variance

DOI: 10.17323/1995-459X.2015.2.58.71

Citation: Kharitonov V., Kurelchuk U., Masterov S. (2015) Long-term Stochastic Forecasting of the Nuclear Energy Global Market. *Foresight-Russia*, vol. 9, no 2, pp. 58–71. DOI: 10.17323/1995-459x.2015.2.58.71.

As a result of a number of catastrophic events in the nuclear energy sector, the increasing attention paid to the industry has acquired an undesirable and negative nuance. At the same time, this key economic industry — with high innovation potential — has achieved significant progress in making energy production more efficient and reducing production costs.

The authors of this article set out their own model to assess the future state of the nuclear energy market and present the results of their calculations of the expected volumes up to 2035, with several significant implications for policy changes in this sphere.

Strategic forecasting is critical both for global and local nuclear energy markets and even certain players in the industry. The nuclear energy market is characterised by high levels of persistence due to the long time-frames required for designing, constructing and operating nuclear power plants (NPP) which can take up to 100 years or more. In this article the nuclear energy market refers to the network of interrelated networks characterised in terms of physical volumes of several interrelated markets, such as:

- the construction and decommissioning of NPPs (expressed as the number of reactors or their electricity capacity in GW);
- natural and enriched uranium (in tons, tU);
- uranium enrichment services (in separative work units, SWU).

The main players in these markets are governments, state-owned and private companies, and international corporations. They are all interested in minimizing the risks in making decisions in technological, economic and political issues. One of the tools used to reduce these risks is regular publications by several international organizations and major energy companies containing industry development forecasts and the contributions of nuclear energy to the structure of the fuel and energy sector (FES) in certain countries, regions and the world as a whole. The most authoritative of these sources include the International Atomic Energy Agency (IAEA) [IAEA, 2014a, 2014b], the World Nuclear Association (WNA) [WNA, 2013, *Emsley*, 2013], the International Energy Agency (IEA) [IEA, 2012, 2014], the US Department of Energy (DOE) [DOE, 2014], the European Atomic

Energy Community (EURATOM) [European Commission, 2012], Ux Consulting Company, LLC (USA) [Ux Consulting, 2013; *Carter*, 2014], the Energy Research Institute (ERI) of the Russian Academy of Sciences (RAS) [ERI RAS, 2013], and the two energy companies ExxonMobil [Exxon Mobil, 2013] and British Petroleum [BP, 2013]. The regular reviews and development forecasts of the global energy market published by these organizations make a significant contribution to global debates on the future prospects of the industry.

The overwhelming majority of publications are based on so-called 'scenario approaches' to long-term forecasting, with a 20–30 year horizon. There are three main types of scenarios: pessimistic, moderate and optimistic (or, using the WNA's terminology, *lower, reference* and *upper*). The scenarios outlined in the forecasts of international organizations [IAEA, 2014a, 2014b; WNA, 2013; *Emsley*, 2013; IEA, 2012, 2014; DOE, 2014; European Commission, 2012; Ux Consulting, 2013; *Carter*, 2014; ERI RAS, 2013; Exxon Mobil, 2013; BP, 2013] are based on an analysis of the energy strategies of particular governments (both those with operational NPPs and those planning to construct NPPs) and take into account the economic development trends of these countries and the world overall. Virtually all forecasts show significant discrepancies between the three types of scenarios after 2020. Forecasts in 2013–2014 point to a lower growth in nuclear energy compared with earlier forecasts in 2011 (see for example, [WNA, 2011, 2013]). The pessimistic scenario reflects the political consequences of the incident at the Fukushima NPP, with construction plans reduced in developing countries and several reactors shut down in developed countries. The WNA's moderate scenario from 2013 assumes growth in the capacity of NPPs from 364 GW in 2011 to 574 GW in 2030, an increase of roughly 60%. The optimistic scenario anticipates the completion of established NPP construction projects in all countries and the extended operation of existing plants. The capacity of NPPs will grow by a factor of 1.9 to 700 GW.

Some of the discrepancies in the nuclear energy development scenarios by the aforementioned organizations and companies are largely linked to their attitudes towards 'green energy' (solar, wind, etc.) and the greenhouse effect from the use of hydrocarbon-based fuel, with virtually none of these forecasts offering any serious alternative to nuclear energy. Only the authors of the study by NIKIET (the Research and Development Institute of Power Engineering) [*Avrorin et al.*, 2012], which had a forecasting horizon up to the year 2100, pointed to the possibility and viability of starting the construction of next-generation fast-neutron reactors in the period up to 2030, which are capable of increasing the nuclear energy resource base by 100–200 times. However, the lifecycle of NPPs and the development of new reactors mean that replacing generations of equipment is extremely time-consuming in this sphere. This is shown in particular by the deferred construction (until after 2035) of commercial 4th generation reactors and nuclear energy systems with a closed fuel cycle, which are being developed as part of the GIF-IV and INPRO international projects [OECD, 2013, 2014; IAEA, 2011, 2014c].

It should be noted that all of the forecasts mentioned above, like our own model, are based on the assumption that there will be no level 6 or 7 accidents (according to the International Nuclear Event Scale, or INES) globally in the period up to 2040. If there are, new moratoria on NPPs will follow, together with the postponement and cancellation of new projects and even the partial refusal to continue operating existing units.

Nuclear energy market participants formulate forecasts of their opportunities and risks based on assessing the dispersion (or 5% and 95% quantiles) of supply and demand on the global market. According to the aims and strategies of market players, their risks may call for market requirements to be overestimated or underestimated. Therefore, in contrast with the widely used scenario approach [IAEA, 2014a, 2014b; WNA, 2013; *Emsley,* 2013; IEA, 2012, 2014; DOE, 2014; European Commission, 2012; Ux Consulting, 2013; *Carter,* 2014; ERI RAS, 2013], there is a need for tools which can set dispersions of expected tendencies and analyse arbitrary cross-sections of the nuclear energy market structure, vary the initial parameters and, in doing so, systematically measure the risks of a particular scenario materializing. Some studies [*Runte,* 2013; *Schneider et al.*, 2012; *Andrianova et al.*, 2008, 2011] have attempted a probabilistic analysis of expected industry development trends. *Runte* [2013] gives statistical data on the dispersal of certain dynamic NPP construction parameters (time frames, capacity, capital outlay, estimated cost of electricity, etc.) without forecasting more general processes: probabilistic nuclear energy development scenarios and the industry's requirements in terms of nuclear fuel cycle services. *Schneider et al.* [2012] look at the question of statistically measuring the cost of operating a reactor. *Andrianova et al.* [2008, 2011] outlined the development of the DESAE computer software, which uses a stochastic method to search for the minimum functions required to build a specific scenario, but without taking into account the dispersion of results. The authors of these two studies also pay particular attention to the possible structure of the industry, including various types of reactors (thermal-neutron and fast-neutron) and different fuel cycles.

In contrast with these approaches, our long-term global nuclear energy market forecasting method (with a 20–25 year horizon) is based on stochastic modeling of power unit lifecycles and the physical relationship between their type and capacity and demand for nuclear fuel cycle services. Using official reports by the WNA, IAEA and other sources [IAEA, 2012, 2014a, 2014b, 2014d; WNA, 2011, 2013; *Emsley*, 2013; IEA, 2012, 2014; DOE, 2014; *Schneider et al.*, 2013; *Sholly*, 2013], we created a database covering all types of operational thermal-neutron nuclear reactors and those under construction (or planned), with the majority falling under the second category, as generation III or III+ reactors. The model does not take into account 4th generation closed-cycle breeder reactors, as this type of reactor is not expected to be commissioned commercially until 2035 at the earliest.

The model makes it possible to obtain probabilistic distributions of these market characteristics, which are critical when assessing the economic risks of various global players in the nuclear energy market. Our article outlines the main principles and some of the results from using this model: NPP capacity dynamics in certain regions and globally and NPP demand for natural and enriched uranium and for separative work. We will also show the likely volumes of new plant construction and spent reactor decommissioning markets in different regions.

Nuclear energy development probabilistic forecasting method

The nuclear energy market probabilistic forecasting model is shown in Fig. 1.

The *first stage* involves making a list of all existing, planned, and proposed NPP unit in different countries using data from the IAEA, WNA and other sources.

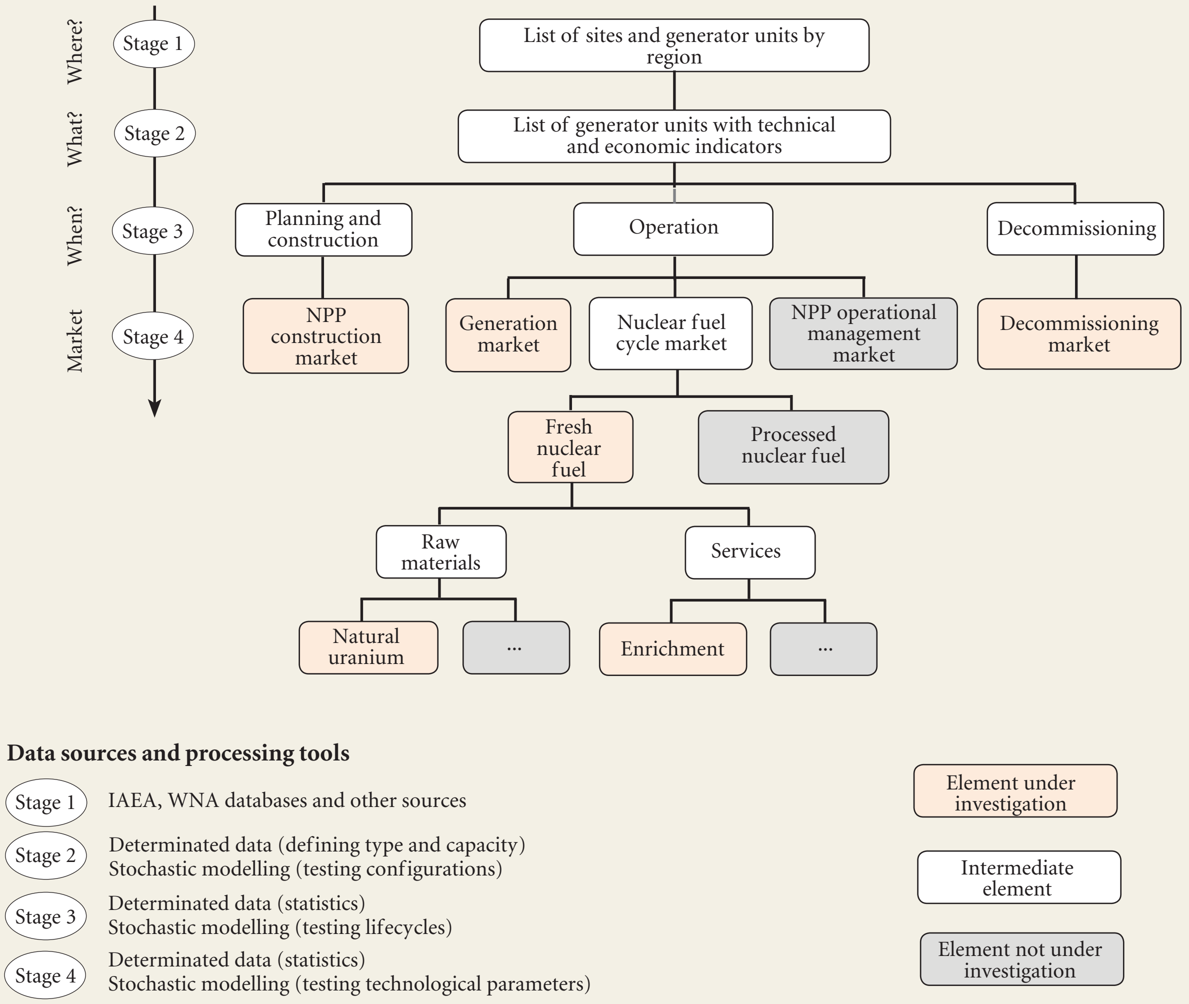
The *second stage* involves forming a database of the technical and economic performance for each NPP unit: the reactor type, its electricity and thermal capacity, average energy capacity factor (CF), fuel burnup, refueling enrichment, the mass and enrichment of the initial fuel loading, etc. Figures for planned to construction NPPs are modelled in the form of random values distributions based on existing designs.

The *third stage* takes into account and models the key temporal lifecycle parameters of power unit, such as start of construction, commercial operation and decommissioning dates. The planned lifecycle duration of generation III and III+ reactors under construction is generally at least 50–60 years.

The *fourth stage* (and subsequent stages) involves carrying out a probabilistic calculation of physical nuclear energy market volumes. The results can then be broken down according to certain criteria: by time, region, company, reactor type, etc.

The key and most sensitive stage of the modeling is the third stage, which is linked to defining the temporal lifecycle parameters of NPP units (stage 3). The stated project time frames are practically never executed to the letter, so the method is based on probabilistic modelling of the duration of key stages of NPP lifecycle and several nuclear fuel cycle parameters. The most important stages of the lifecycle of each power unit [*Runte*, 2013; *Sholly*, 2012; IAEA, 2012] are modelled in the form of an event tree (Fig. 2). The 'yes' – 'no' branch probability depends on the region where construction is taking place, the time since the forecast was compiled, and the integrity of input data. The calculation also takes into account the fact that for each region in which a NPP is located the branch probabilities

Fig. 1. **Nuclear energy market probabilistic forecasting model diagram**



Data sources and processing tools

Stage 1 IAEA, WNA databases and other sources

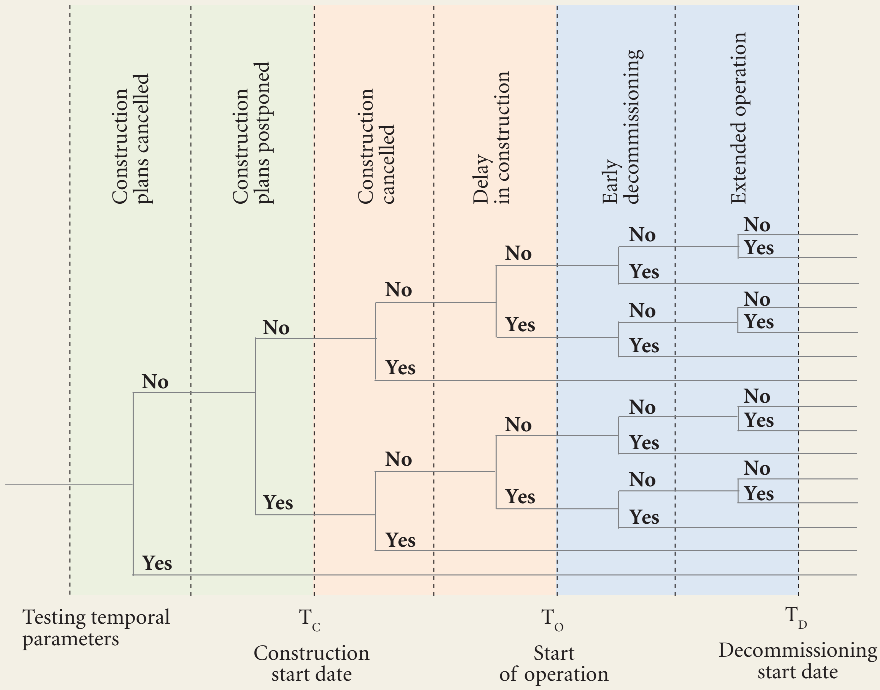
Stage 2 Determinated data (defining type and capacity)
Stochastic modelling (testing configurations)

Stage 3 Determinated data (statistics)
Stochastic modelling (testing lifecycles)

Stage 4 Determinated data (statistics)
Stochastic modelling (testing technological parameters)

Source: compiled by the authors.

Fig. 2. **Power unit lifecycle temporal characteristics modelling diagram**



Source: compiled by the authors.

linked to planning the commissioning of new units correlate with one another in the same way as they do when units are decommissioned. Thus, for each branch of the tree, unique sets of random distributions of temporal power unit parameters are generated, where T_C is the probability distribution of the construction start date, T_O is the start of operation, and T_D is the start of decommissioning. The probability values of the temporal parameters are modelled using uniform and PERT distributions [*Davis*, 2008]. Since temporal power unit lifecycle parameters are dependent values ($T_O = f(T_C)$; $T_D = f(T_O)$), their probability distributions are consecutively defined, taking into account the duration of construction t_C and the duration of operation t_O:

$$T_C \rightarrow T_O = T_C + t_C \rightarrow T_D = T_O + t_O \qquad (1)$$

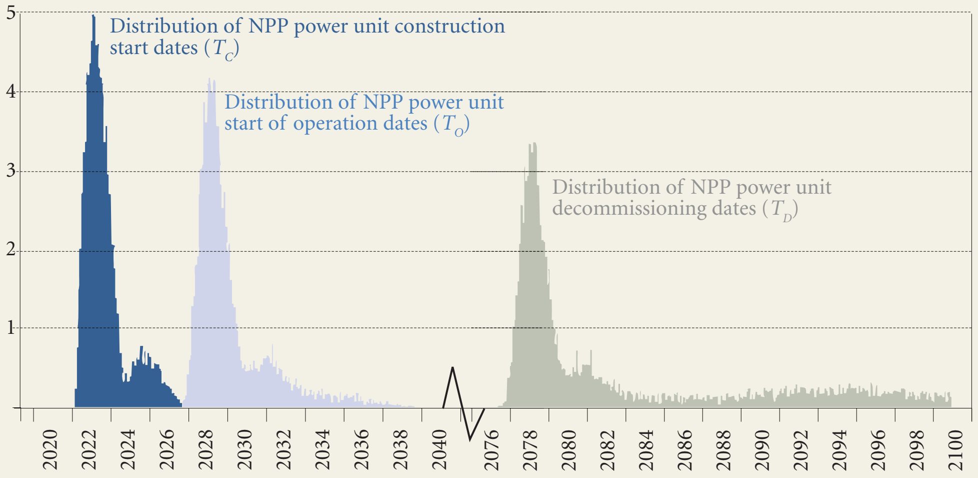
Probability distribution parameters are formulated on the basis of statistical, design and forecast data for the various types of nuclear reactors [IAEA, 2012, 2014a, 2014b, 2014d; WNA, WNA, 2013; *Emsley*, 2013; IEA, 2012, 2014; DOE, 2014; *Schneider et al.*, 2013; *Sholly*, 2013]. They take into account assessments of their reliability. As a result, the form of certain probability distributions (for instance, the minimum, maximum and mode values for the PERT distribution) are selected taking into account the location, time and specific characteristics of a particular power unit.

The result from modeling the temporal parameters of a single power unit's lifecycle can be presented in the form of a frequency histogram (Fig. 3).

The structure of the global nuclear energy industry can be modeled using the Monte Carlo method by reproducing the lifecycles and technical and economic performance of each specific power unit. The relations between the different random events is taken into account by the correlation coefficients and the introduction of stochastic control parameters, both in geographic and in temporal measurements. Using a correlations shows that decisions about building, extending or prematurely ceasing the operations of a NPP power unit are not made arbitrarily, but are influenced by developmental tendencies in the nuclear energy sector in a particular country, region or the world in a given time period. The correlation coefficient can serve as one of the control parameters of the model alongside distribution parameters reflecting the level of reliability of the input data, different technological and regional characteristics, scientific and technological progress in reactor construction, and other characteristics.

This theoretical model makes it possible, in principle, to take into account the impact of factors such as major accidents, economic crises, political decisions, as well as improvements in NPP construction and operation technologies, uranium enrichment, and nuclear fuel production.

Fig. 3. **Frequency distribution of NPP power unit lifecycle temporal characteristics** (%)



Source: authors' calculations based on data from [WNA, 2013].

Forecasting the number and capacity of NPPs

The database for the proposed model uses data and forecasts from the IAEA's Power Reactor Information System, the WNA, and other sources as of the end of 2013. It covers roughly 1,100 power reactors, of which 434 are operational in 31 countries (which are home to two–thirds of the Earth's population) and 72 are under construction in 14 countries. Alongside these, more than 600 reactors in almost 40 countries are at the development or planning stage for construction by 2030. Many of these are in China (almost 250 reactors), India (70), other Asian (117) and European countries excluding Russia (up to 60).

The annual t installed electricity capacity $W(t)$ of all operational NPP units, grouped together under the symbol Ω (geographic position, technical, economic or other parameters), is the sum of the capacity of each j reactor in this group:

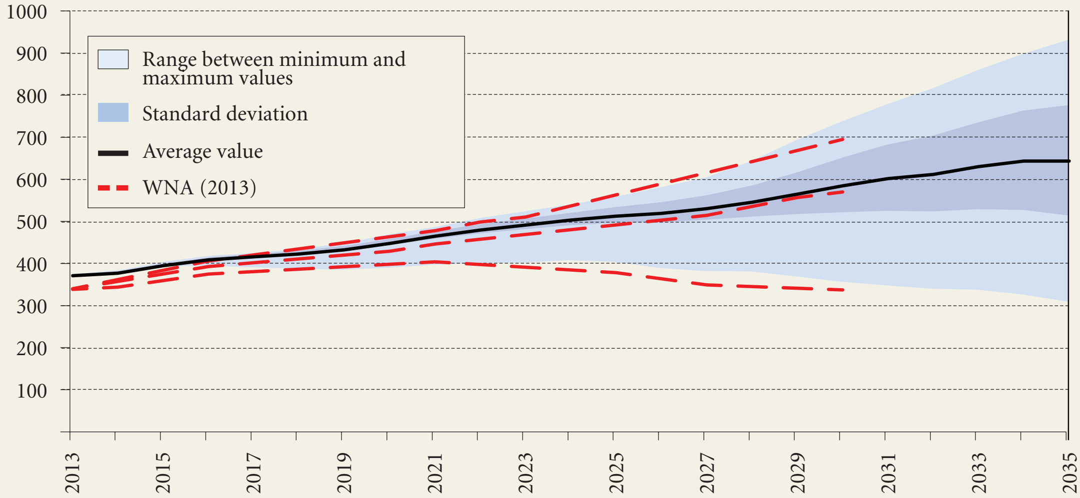
$$W_{\Omega}(t) = \sum_{j} W_{\Omega j}(t) \cdot [\eta(t - T_{O,j}) - \eta(t - T_{D,j})] \qquad (2)$$

The expression in brackets is equal to zero over the entire temporal interval, except the period during which the unit is operated from $t = T_{O,j}$ to $T_{D,j}$; $W_{\Omega j}(t)$ is the installed electrical capacity of unit-j; and $\eta(t)$ is the Heaviside function, or the unit step function, which is zero for negative values in the argument and one for positive. When building the forecast, the time at which commercial operation of each reactor starts T_O is calculated by adding the construction duration t_c to the construction start date T_C, and the date on which operation ends T_D is obtained by adding the service life t_0 to T_O (1).

Thus, in the formula (2) above the start date $T_{O,j}$ and end date $T_{D,j}$ for commercial operation of unit-j assume random values according to the probability distribution within bounded intervals, in line with the method described above. The reproduction of the lifecycle (stages and technical and economic performance) of each power unit, including even those that do not yet exist, and where necessary their type, class and capacity, gives the annual t distribution of the installed electrical capacity of NPPs $W(t)$ in the segment under consideration Ω over the period up to 2035 (Fig. 4).

Under the baseline variant, the average installed NPP capacity globally will grow at a rate of roughly 2.5% per year, as also shown in the WNA's moderate scenario [IAEA, 2014a], and the minimum and maximum values are in line with the pessimistic and optimistic scenarios. At the start of 2014, the installed capacity of the world's NPPs was 374 GW (in Russia, roughly 25 GW with 34 reactors). The proximity of the model's results to the WNA's scenarios confirms the validity of selecting the frequency distributions of key events on the reactors' 'life tree'.

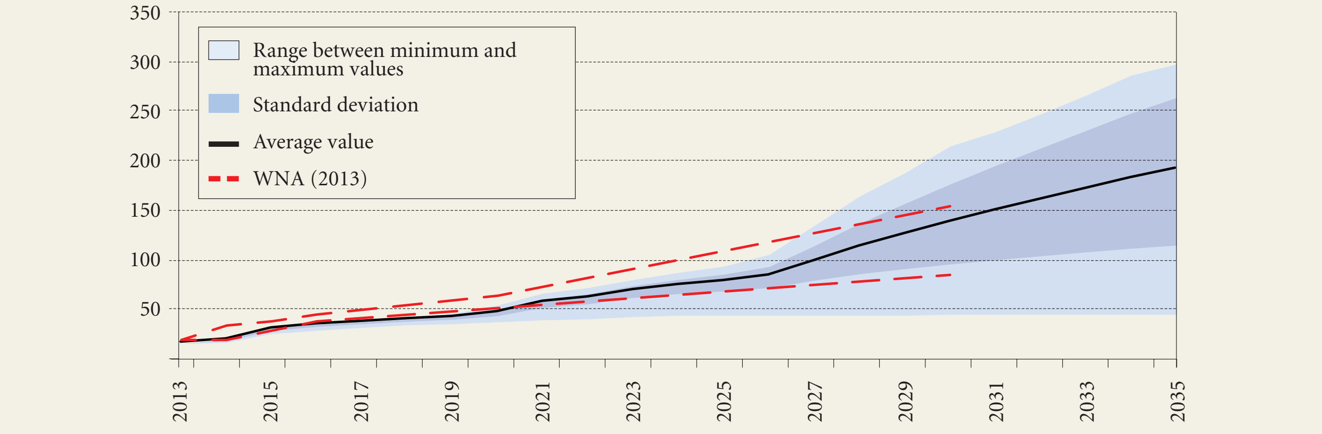
Fig. 4. **Installed NPP capacity dynamics globally** (*GW*)*



* The average value (solid line), band showing one standard deviation, and the maximum and minimum values of the model with 5,000 iterations (trajectories) are shown. The dotted lines represent the three WNA scenarios.

Source: authors' calculations based on data from [WNA, 2013].

Fig. 5. **Installed NPP capacity dynamics in China** (*GW*)



Source: authors' calculations based on data from [WNA, 2013].

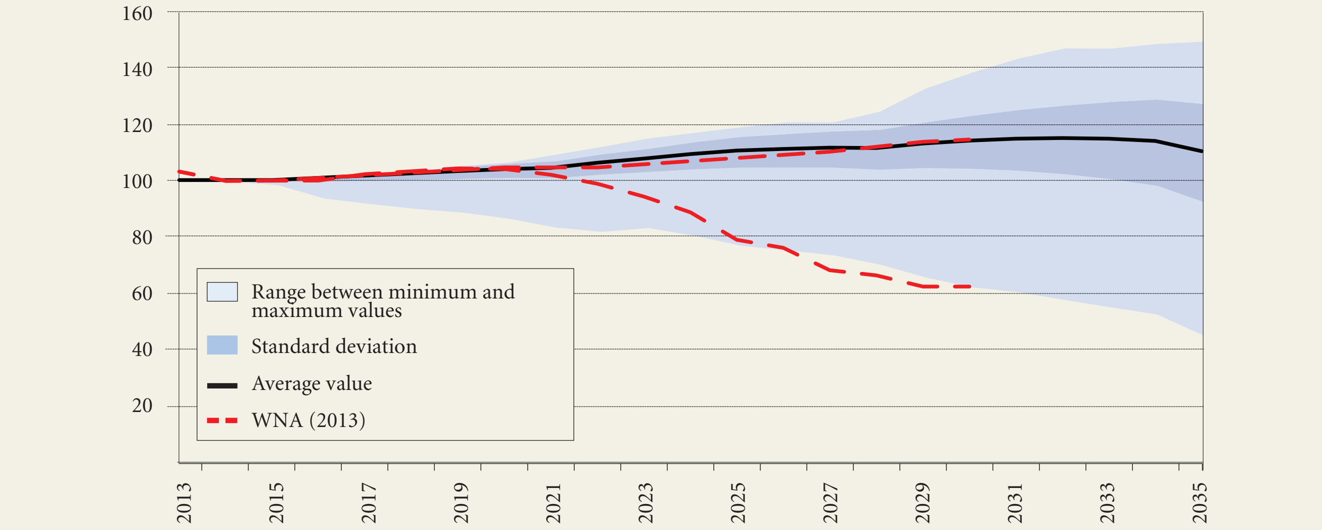
We forecast growth of roughly 11% in the Chinese nuclear energy industry (Fig. 5). By 2035, the number of reactors in the country will be almost double the number in the US (Fig. 6), the largest nuclear power in the world with an installed NPP capacity of roughly 100 GW and 103 reactors as of the end of 2013. For such a developed national industry, low growth is probable (0.6% per annum): there is even the possibility of a reduction in its total nuclear capacity by 2035.

Our calculations show that uncertainty significantly increases as the distance from the forecast starting point (2013) grows, in a similar as observed in the IAEA and WNA scenarios (Figs. 4–6). At the same time, the distribution dispersion is still acceptable in 2035. The increased uncertainty in the forecast is not a methodological defect: rather it is a measure of the uncertainty present in national nuclear energy development programmes. An annual review of the forecast that takes into account any newly commissioned or decommissioned reactors will make it possible to adapt the model to the industry's changing nature.

Forecasting NPP demand for fuel and uranium enrichment services

Forecasts of installed NPP capacity dynamics make it possible to assess the level of demand for nuclear fuel and uranium enrichment services. A particular power unit's annual fuel consumption depends on the thermal capacity of the reactor Q (GW),

Fig. 6. **Installed NPP capacity dynamics in the US** (*GW*)



Source: authors' calculations based on data from [WNA, 2013].

the fuel burnup B (GW·day/tU), and the capacity factor (CF). The mass of uranium M_f in the fuel to be fed in to a reactor (t/year) is defined by the widely accepted formula [*Kharitonov*, 2014; *Sinev*, 1987]:

$$M_j(t) = \frac{Q_j \cdot КИУМ_j(t) \cdot 365}{B_j(t)} \qquad (3)$$

Currently, the average global NPP capacity factor is 0.75. The CF of some reactors is as high as 0.93. Fuel burnup is roughly 40–50 GW·day/tU, showing an upward trend to 60–80 GW·day/tU. Annual demand $P(t)$ for enriched uranium is defined as the sum of mass M_{Ok} for the initial fuel loading of commissioned reactors and mass M_j of the refueling for operational reactors:

$$\begin{aligned} P(t) = {} & \textstyle\sum_{\Omega k} M_{ok}[\eta(t - T_{Ok} + 1) - \eta(t - T_{Ok})] + \\ & \textstyle\sum_{\Omega j} M_j[\eta\big(t - T_{Oj}\big) - \eta\big(t - T_{Dj}\big)]. \end{aligned} \qquad (4)$$

Indices j and k take into account all types of reactors operating in year t and those commissioned the following year, as demand for fuel for initial loading arises roughly one year prior to commencing the commercial operation of a reactor. Purchases of fuel for this purpose are done in advance, so a lag of two years is applied when calculating market demand for enriched uranium. Likewise, when calculating capacity, the addition in formula (4) is done for all reactors in the database or for any particular group of interest Ω.

To obtain value P of the enriched fuel x (mass concentration of uranium-235 in the fuel) at the isotope fractionation plant, natural uranium with a concentration of c=0.77% in value F is needed, forming depleted uranium with concentration y in value D [*Kharitonov*, 2014; *Sinev*, 1987]:

$$F = P\frac{x - y}{c - y}; \quad D = F - P \qquad (5)$$

The uranium enrichment process is known to characterize *separative work R*, expressed in the same units as uranium spending (t/year etc.):

$$R = P\Phi(x) + D\Phi(y) — F\Phi(c), \qquad (6)$$

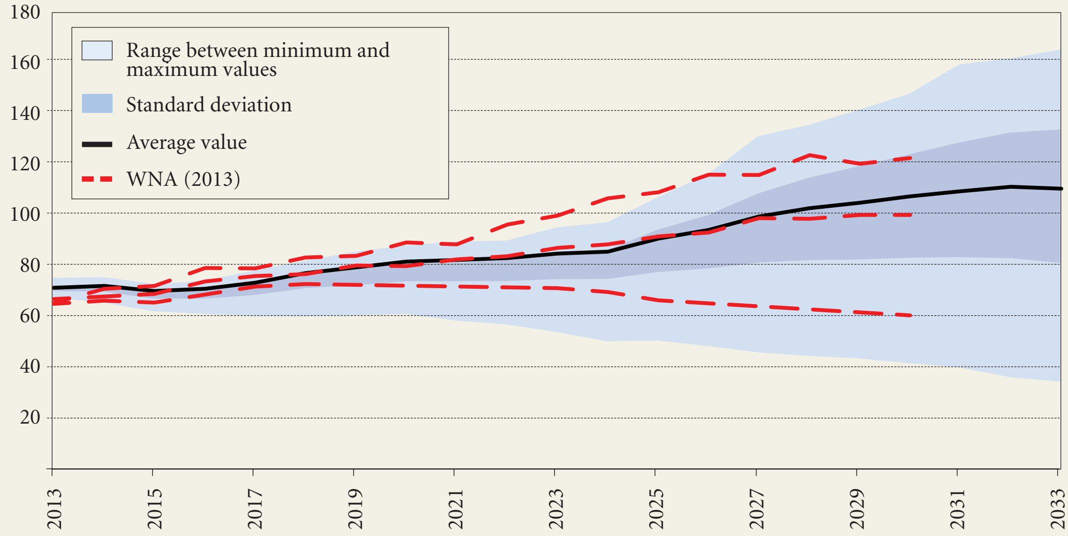
representing the difference between the 'values' of the obtained products P and D and the raw material input (feed) F. 1 kg of separative work is called a separative work unit (SWU). Separative work, like separative potential $\Phi(x)=(2x\text{-}1)\ln[x/(1\text{-}x)]$, characterizes the state of the gas mixture irrespective of the actual method used to separate the isotopes [*Borisevich et al.*, 2005].

Keeping the cost of uranium enrichment to a minimum allows for an optimal concentration y of uranium-235 in heaps ('enrichment tailings'), representing the relationship between the cost of natural uranium and separative work units. Currently, the optimal concentration of 'enrichment tailings' globally averages at roughly y≈0.22–0.25%. Over time, the price of natural uranium is expected to grow faster than the cost of separative work. This will entail a reduction in the optimal concentration of heaps to y≈0.15–0.18% or even lower. This uncertainty surrounding the y value causes additional dispersal in calculations of demand for natural uranium and separative work.

The demand of the global nuclear energy industry for natural uranium and isotope separative work will grow at a rate of 2–3% per year (Figs. 7–8). The dispersal of the calculation values characterizes the uncertainty risk: should the optimistic development scenario materialize in the nuclear energy industry, global demand for uranium enrichment services could surpass existing capacity at enrichment plants. Amid the stagnation in the industry, demand for natural uranium may be covered for a long time by stockpiled reserves (currently totalling 600 kt) with the inevitable landslide in uranium prices and closure of numerous extraction companies.

It is worth noting that roughly 40% of global uranium isotope separation production capacity is concentrated in Russia, all using the high-tech gas centrifuge method. Accordingly, Russia also accounts for roughly the same share (30–40%) of the global uranium enrichment services market.

Fig. 7. **Forecast of demand from the global nuclear energy industry for natural uranium** (*ktU/year*)



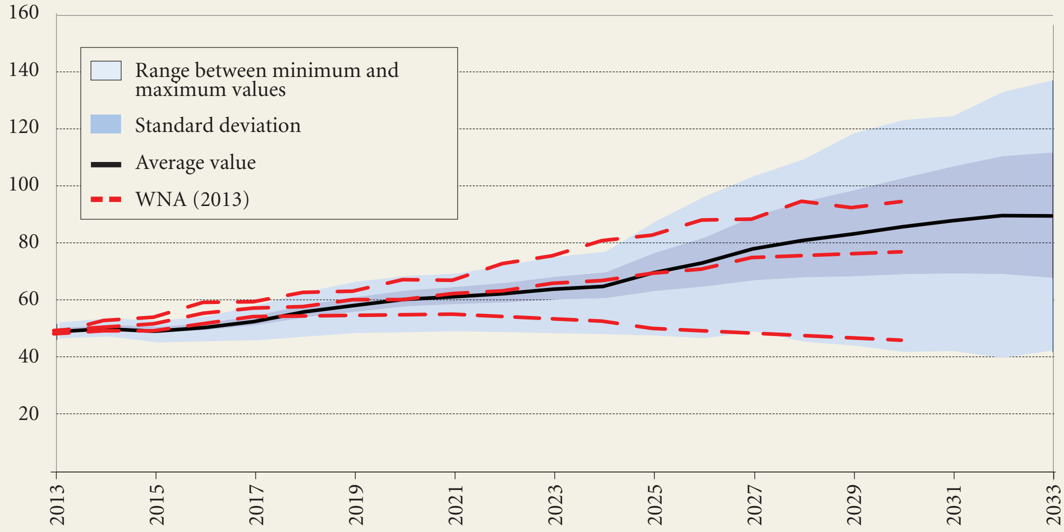
Source: authors' calculations based on data from [WNA, 2013].

Forecasting the size of the new NPP construction market

Nuclear power plants are among the most complex and high-tech facilities in industry. The construction and operation of a NPP are tied to numerous other sectors of the economy — construction, engineering, instrument-making, logistics, finance, insurance, science, education, etc. — and give rise to a significant multiplier effect on GDP dynamics [*Ivanter*, 2014]. On average, building a NPP takes 5 to 15 years and requires hundreds of thousands man-hours. Upon completing construction, the plant typically becomes a town- and structure-forming facility in a region for many decades. Forecasts of construction volumes in the industry help to appraise not only the prospects of local engineering, supply and construction markets, but also the markets of accompanying products and services. Below is a forecast of the new NPP construction market volume for the period 2015–2025, based on a database of reactors in various regions, compiled by the authors.

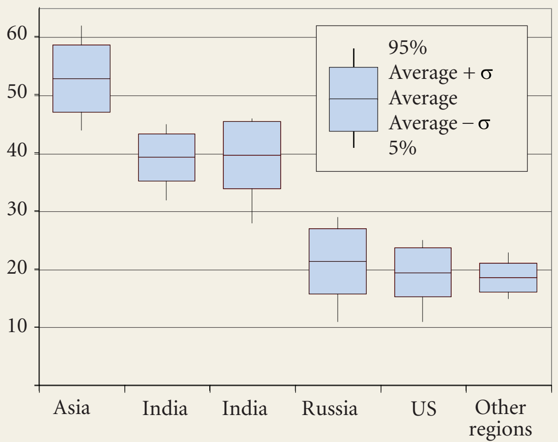
This study covers the following regions of the world and countries operating on the nuclear energy market: Russia, China, India, developed Asian economies, Japan and South Korea, other Asian states, Europe (excluding Russia), the US, and

Fig. 8. **Forecast demand from the global nuclear energy industry for uranium isotope separative work** (*millions of SWU/year*)



Source: authors' calculations based on data from [WNA, 2013].

Fig. 9. **Number of new NPP units globally (excluding China) which are expected to start being built in 2015-2025**



Source: compiled by the authors.

other regions, including Canada, South American and African countries. The total installed capacity of NPPs W_Ω and the number of power units N_Ω which are going to start construction in the next decade in region Ω is calculated as follows:

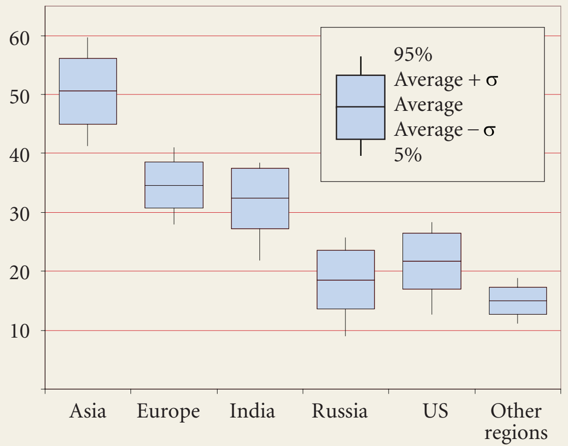
$$W_\Omega = \sum_{t=2015}^{2025} \sum_j W_{\Omega j} \cdot \delta(T_{Cj} - t); \quad N_\Omega = \sum_{t=2015}^{2025} \sum_j \delta(T_{Cj} - t). \qquad (7)$$

Where $\delta(t)$ is the delta function, which equals 0 everywhere, except t=0, where it equals 1. The number and capacity of the new reactors which are expected to start being built in 2015–2025 are relatively high in all regions examined: 17 and 53 reactors with a total capacity of 15 and 52 GW, respectively (Figs. 9–10).

Bearing in mind that the specific capital expenditure on construction of generation III and III+ reactors in various regions globally is currently 2,000–6,000 US dollars/kW [*Kharitonov*, 2014], the total investment in the industry could range from 34 to 370 billion US dollars between 2015 and 2025. The level of volatility on the market is confirmed by the dispersion analyses (Figs. 9–10).

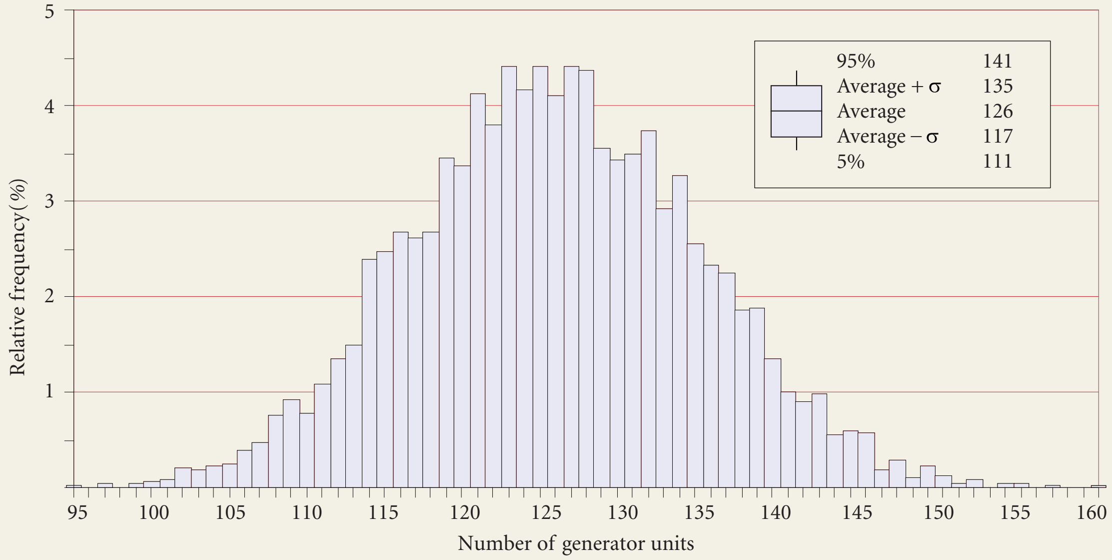
The forecast construction volumes for new NPPs in China significantly exceed those in other regions of the world (Fig. 11). The second group of countries after China with a high construction volume, referred to above as ‘other Asian states’, is at virtually the lowest limit of the Chinese market.

Fig. 10. **Installed capacity of new NPP units globally (excluding China) which are expected to start being built in 2015–2025** (*GW*)



Source: compiled by the authors.

Fig. 11. **Probability density distribution of the number of new NPP units in China which are due to start construction in 2015–2025**



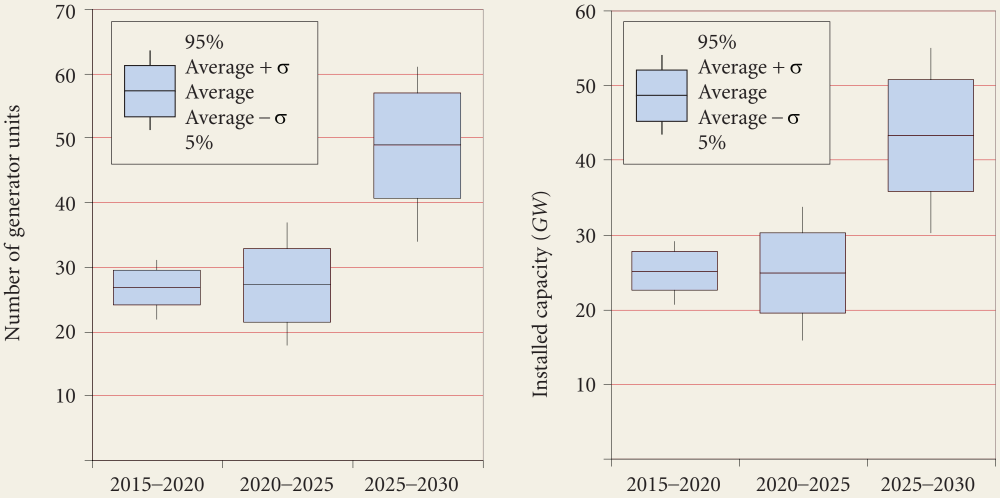
Source: compiled by the authors.

This method forms the basis for studying market prospects for NPP construction contractors. As an example, we will look at the expected export construction volume of Russian-designed reactors over the next three five-year periods: 2015–2020, 2020–2025 and 2025–2030 (Figs. 12, 13). In this case, the temporal interval changes and the condition 'Russian-designed reactor' is added to Ω in formula (7). Currently, Russia accounts for roughly 20% of the global NPP construction market.

The analysis shows that the variance of the share of Russian-designed power units exceeds the variance of the total number of reactors globally, and this in turn can be explained by the uncertainty in constructing Russian-designed power units affecting the instability of industry development parameters on a global scale. Existing capacity makes it possible to export from five Russian-designed NPP units in 2015–2020, and nine in 2025–2030. However, at present, the engineering infrastructure allows for only four reactors to be built per year.

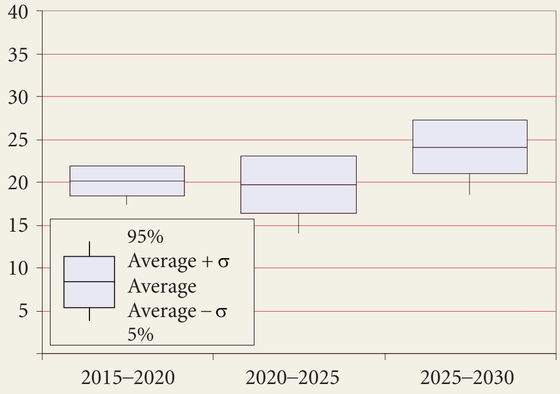
According to WNA analysts, the share of nuclear energy in EU countries over the coming decade could drop to critical levels due to the lack of internal development of next-generation reactors and restrictions on the construction of Russian-

Fig. 12. **Russian-designed NPP unit construction volumes in 2015-2030**



Source: compiled by the authors.

Fig. 13. **Share of Russian-designed NPPs in the total number of NPPs built globally** (%)



Source: compiled by the authors.

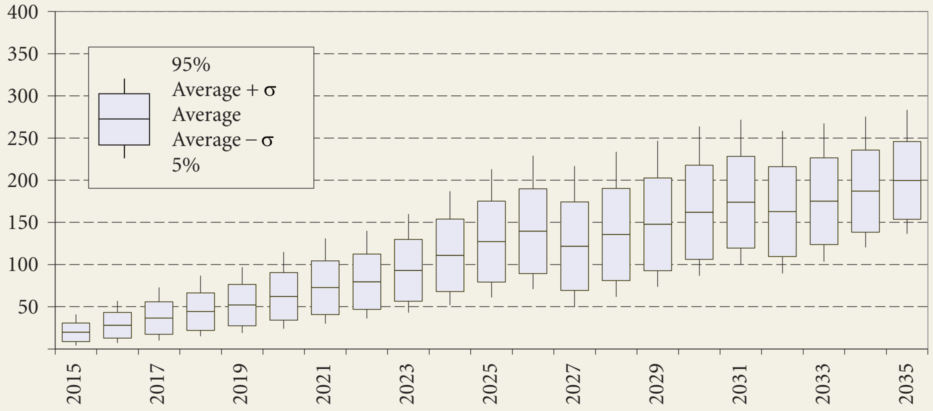
designed power units [*Tarlton*, 2014]. In those European countries where such restrictions do not exist, in our opinion the volume of power generation at NPPs will not suffer such a serious slump.

Forecasting NPP decommissioning

The planned service life of the majority of operational power reactors is 30–40 years. Life extension the service life of a NPP by 10–15 years is almost always considered economically advantageous and admissible from a safety perspective. This is primarily because of the low cost of electricity produced by NPPs which have already repaid its capital expenditure costs. The declared service life of generation III and III+ reactors does not generally fall below 60–80 years, meaning that these reactors will not be decommissioned under the temporal horizon that we have adopted up to 2035. The decommissioning process itself is a specific and labour-intensive procedure that last decades. Currently, the NPP decommissioning market is underdeveloped in the majority of regions, since demand for decommissioning services has been rare in recent years. However, in the medium term, a significant increase in the size of this market expected, due to ageing of the global NPP pull (Fig. 14). To calculate the retirement of power units on an accrual basis, we use a formula similar to (7), where in place of the construction start date used date T_D, and in place of the delta function $\delta(t)$ used a step function $\eta(t)$.

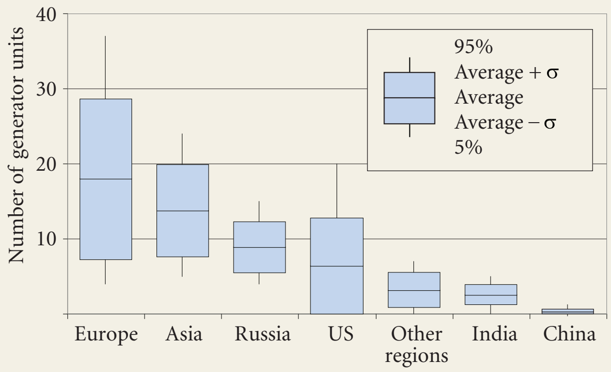
The high variety of our estimates is caused by inconsistent information about policies of several countries regarding whether to extend the service life of current reactors (Figs. 14–15). By 2035, over 200 power units with extended service

Fig. 14. **Number of power units which will cease operations (on a cumulative basis since 2015)**



Source: compiled by the authors.

Fig. 15. **NPP decommissioning volumes in various regions globally over the period 2015–2025**



Source: compiled by the authors.

lives are expected to be taken out of operation. Therefore, over the next decade, a capital-intensive NPP decommissioning market will start to form: this market will be extremely varied in terms of the distribution of its volumes between certain states and groups of countries (Fig. 15).

The most promising markets for NPP decommissioning services seem to be in Europe, where the largest number of reactors are in operation (over 160), and in Asia (excluding China) (Fig. 15). It is characteristic that the distribution forms differ significantly across regions: the possibility of extending the life of operational power units depends upon the type of reactor, technical capabilities and national strategies. In particular, in the US, despite the large number of operational reactors (roughly 100), the expected size of the NPP decommissioning market is proportionate to the Russian market but does not surpass the upper quantile of the latter.

In China, where the nuclear industry is relatively young, the number of spent NPPs is small. However, in regions with 'old' nuclear plants, companies will — by 2025 — have had time to accumulate experience in decommissioning NPPs and will be able to begin exporting their services to new markets.

Conclusions

This article presented the results of a forecast of expected global nuclear energy market volumes up to 2035 based on stochastic modeling, which makes it possible to analyse the economic risks of market players. The model's database included all types of existing, planned and built thermal-neutron generation III and III+ reactors. The model did not take into account 4th generation closed-cycle breeder reactors, as they are not expected to commence commercial operation until 2035 or later.

The data analysed confirm that over the next 20 years, the average annual growth in the global energy market will be roughly 2%. China, India and other Asian countries will see the highest market values in new NPP construction. The size of the industry in Russia is roughly on par with that in the US, but has a higher volatility. Meanwhile, the likely construction volumes for Russian-designed NPP units in the world by 2030 could increase both in absolute and relative terms.

This study has shown that the share of nuclear energy production from NPPs in EU countries over the coming decade risks dropping to critical levels due to the lack of internal development of next-generation nuclear reactors and the lack of quotas to construct equivalent Russian products. However, several European countries have projects to construct Russian reactors of the latest generation in place or at the planning stage.

Over the coming two decades, we expect to see growth in the number of spent reactors (increasing to 250). This will lead to the formation of a new science- and capital-intensive NPP decommissioning market. The largest volume is expected in Europe, the region with the oldest stock of nuclear reactors. In China, as in other countries with a young nuclear energy industry, the NPP decommissioning market is virtually non-existent.

The dynamics of launching new reactors (and stopping old ones) significantly impact on the status quo of regional natural and enriched uranium and uranium enrichment markets. In light of these tendencies, the current policies of several countries to diversify and allocate quotas for energy generation resources and equipment supplies may yet undergo significant revisions. F

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