Research Article

Economic Assessment of Russian Nuclear Strategies on the Basis of Fast Breeder Reactors

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The paper assesses the economic risk caused by the delay in commissioning innovative nuclear power plants with fast breeder reactors in Russia. The risk is quantitatively measured by the excessive costs for energy development and the possibility of implementing the considered variants that differ in power consumption, technical and economic indices of the reactors, and constraints on CO₂ emissions. The probability distribution functions of economic losses for different strategies of nuclear energy development are constructed.

1. Introduction

Investigation of long-term perspectives of world development shows that nuclear energy is the most efficient means for decreasing CO₂ emissions [1]. Fast breeder reactors (FBR) should be applied also due to depletion of economically efficient uranium-235 resources [1–5]. The closed fuel cycle will allow using the additional fissile material, that is, plutonium received from uranium-238 isotope (99.3% in natural uranium), while now only natural fissile material-uranium-235 (0.7% in natural uranium), is used. Thus it will allow increasing the nuclear fuel reserves that will be sufficient throughout thousands of years.

In February 2010 the Government of Russia approved the Federal Target Program until 2020 designed to bring a new technology platform for the nuclear power industry based on fast reactors with a closed fuel cycle [6]. The paper aims to assess the economic risk caused by the delay in the large-scale commissioning of nuclear power plants with fast breeder reactors in Russia.

In order to consider the relations of different energy sources among themselves and with the environment the energy sector should be treated as a whole system. The paper considers the nuclear power industry as part of the energy sector in Russia that, in turn, is analyzed in background of the world energy sector development. This is justified by the fact

that the cost of energy resources in Russia, including uranium (and correspondingly the fuel component of energy cost), is determined not only by the costs for their production but also by the world market prices.

2. Method

Future conditions of energy development are characterized by high uncertainty that usually is considered on the basis of a scenario approach [7–14]. We formulated two scenarios of constraints on CO₂ emissions (soft and strict), three scenarios of power consumption (low, medium, and high), and four scenarios of technological development of the nuclear energy, which in total makes up 24 calculation variants. The calculations were performed using the global energy model (GEM) [1, 12–14].

The GEM model belongs to a class of mathematical models that are based on the “bottom-up” approach and is intended for determination of an optimal technological structure of the world energy system with specified energy demands. The model describes the world energy system as a set of interconnected processes of primary energy resources extraction or production, their transformation into secondary energy carriers and final energy. In the model the world energy system is represented by several interconnected

regional energy systems with distinguishing the following regions: North America, Europe, Japan and Korea, Australia and New Zealand, Russia, countries of the former Soviet Union, Latin America, Middle East and North Africa, the rest of Africa, China, and South and Southeast Asia.

The GEM model sequentially optimises the regional energy structure and the interregional fuel exchange for the years 2025, 2050, 2075, and 2100 with further transfer of the obtained structure as an initial one for the coming 25-year period.

The model contains a description of several hundred energy technologies, including two types of nuclear power plants: power plants with thermal neutron reactors that use uranium-235 as a fuel and power plants with fast neutron reactors (breeders) that use uranium-238 (as an additive to the main fuel—plutonium).

Each technology j for the region r is characterised by the specific costs on product output— c_{rj} , the specific consumption of resources and the outputs of products and harmful substances, and the constraints on minimum and maximum scales of utilisation. The yearly production of technologies (x_{rj}) is the optimised variables of the model.

The specific costs for each type of technological installations were calculated by the formula

$$c_{rj} = (a_k K_{rj} + S_{rj}) \frac{\gamma}{h_{rj}}, \quad (1)$$

where

$$a_k = \frac{p}{[1 - (1 + p)^{-T_{rj}}]}. \quad (2)$$

Here K_{rj} represent specific investments, US\$/kW; S_{rj} represent specific constant operating costs, US\$/(kW/year); p represent a discount rate, 1/year; T_{rj} represent service life of technological installation, years, h_{rj} represent annual number of utilisation hours, $\gamma = 278 \text{ kW/h/GJ}$.

The objective function of the model is the discounted total expenditures (investments and operating costs) on regional energy systems (for the whole technological chain) and the interregional transport of energy carriers for the 25-year period. The technological structure of the world energy system can be represented mathematically in the following form: determine the minimum of the objective function:

$$z = \sum_r \sum_j c_{rj} x_{rj} \quad (3)$$

subject to technological, economic, and environmental constraints described in detail in the works [1, 14].

The scenarios of technological development differ in the time of commissioning fast breeder reactors, which is modeled by the specified constraints. We consider the following scenarios for commissioning fast breeder reactors: (1) the basic scenario that implies large-scale development of fast breeder reactors under the most favorable conditions; (2) “Scenario-20” that implies a delay in commissioning fast breeder reactors of approximately 20 years as compared to

the basic scenario, (3) “Scenario-40”—a 40-year delay; (4) scenario “without FBR.”

The fast breeder reactors have the best technical and economic indices in the basic scenario (2700 \$/kW in 2025 and 2500 \$/kW in 2100 (in present-day dollars (US dollars for economic assessment is used through the article))) and the worst indices in “Scenario-40” (4400 \$/kW and 4000 \$/kW, resp.). Technical and economic indices of nuclear power plants and levels of power consumption were varied only for Russia. For the other regions of the world these data were taken as the average or most probable set of values.

We impose two types of constraints on CO₂ emissions: soft and strict ones. Based on the scenarios of sustainable development [1, 11, 13], we set limits on CO₂ emissions for the world as a whole (33–50 Gt in 2050 and 30–55 Gt in 2100) (the higher value corresponds to the scenario with soft environmental constraints, and the smaller value to the scenario with strict environmental constraints). The limits for Russia are 2–2.5 Gt until 2050 and 1.8–2 Gt until 2100.

3. Results and Discussion

Optimization calculations of the technological structure of the energy sector in the world and in Russia until 2100 were made for all the formed variants on the GEM. The scale of nuclear energy development in Russia that is determined as a result of optimization is presented in Table 1 (the lower values of the capacity range correspond to the soft constraints on CO₂ emissions, the higher values—to the strict constraints). In all the variants the construction of nuclear power plants with fast breeder reactors is economically efficient.

The delay in commissioning fast breeder reactors that is modeled by the constraints and the degradation of their technical and economic indices increases the costs for energy development (Table 2). This is explained by the fact that more efficient nuclear power plants with fast breeder reactors are replaced by nuclear power plants with thermal reactors (because of the switch to more and more expensive uranium, especially in the second half of the 21st century), hydrogen power plants, or renewable energy sources required to reduce CO₂ emissions.

The results of mathematical modeling are applied to determine the economic losses caused by delay in breeder reactor commissioning. The unified monetary value of each variant is obtained by addition of the costs (the cost difference) to the corresponding discount factors and their reduction to one time period (2012), taking account of extra expenditures for research, design efforts, and infrastructure creation (nuclear fuel cycle plants).

Possibility of implementing the variants was estimated based on the subjective probabilities. We assumed that the world and Russian energy would develop to a great extent based on the past trends. Therefore, low power consumption is more probable than medium and high ones (their probability is 50, 30, and 20%, resp.), and soft emission constraints are more probable than strict ones (their probability is 80 and 20%).

TABLE 1: Scales of nuclear energy development (installed capacity) in Russia, GW.

Years	Basic		Scenarios “Scenario-20”		“Scenario-40”	
	TR*	FBR**	TR	FBR	TR	FBR
Low power consumption						
2025	28–31	1–7	28–31	0	28–31	0
2050	45–50	21–23	45–50	8–10	45–50	0
2075	30–35	55–57	30–35	33–35	30–35	7–10
2100	8–10	100–109	8–10	64–70	8–10	24–26
Medium power consumption						
2025	32–34	9–11	32–34	0	32–34	0
2050	70–75	28–31	70–75	15–18	70–75	0
2075	35–41	70–77	35–41	55–60	35–41	15–21
2100	15–19	115–133	15–19	90–102	15–19	45–53
High power consumption						
2025	35–38	15–16	35–38	0	35–38	0
2050	75–82	50–54	75–82	25–30	75–82	0
2075	45–53	105–121	45–53	65–71	45–53	20–26
2100	20–30	140–170	20–30	100–127	20–30	55–60

* Thermal reactors, ** fast breeder reactors.

TABLE 2: Additional costs for energy development relative to the basic scenario, billion dollars per year.

Years	Scenarios		
	“Scenario-20”	“Scenario-40”	“Without FBR”
Low power consumption			
2025	0.2–3	0.2–3	0.2–3
2050	2–5	3–8	3–8
2075	10–12	21–22	25–26
2100	17–19	34–36	42–45
Medium power consumption			
2025	1–6	1–6	1–6
2050	3–7	11–16	11–16
2075	10–11	27–28	35–36
2100	16–17	35–39	52–57
High power consumption			
2025	6–11	6–11	6–11
2050	10–11	20–21	20–21
2075	25–26	48–49	58–59
2100	20–21	47–48	65–66

We constructed the probability distribution functions of economic losses (probability that the loss will be no less than the specified value) for different strategies of nuclear energy development on the basis of the indicated data (Figure 1).

4. Conclusion

The obtained results allow the following conclusions to be drawn:

FIGURE 1: Probability distribution of the economic losses caused by delay in scaled commissioning of breeder reactors: (a) “Scenario-20”, (b) “Scenario-40”, and (c): Scenario “without FBR”.

- (i) in Russia the commissioning of innovative nuclear power plants with breeder reactors is rational (earlier or later) for all the considered variants;
- (ii) the higher is the power consumption and the stricter is the environmental constraints, the larger is the economic loss caused by delay in commissioning nuclear power plants with breeder reactors;
- (iii) 20-year delay in commissioning nuclear power plants with breeder reactors is reasonable only in the case of expected low power consumption and absence of constraints on CO₂ emissions;

- (iv) 20-year delay in commissioning nuclear power plants with breeder reactors with a probability of 50% will result in the loss that will be no less than 10 billion dollars with a probability of 25%;
- (v) delay in commissioning nuclear power plants with breeder reactors of 40 years and more will result in the loss of 10–12 billion dollars with a probability of 50%;
- (vi) complete refusal to develop nuclear power plants with breeder reactors in Russia will cause the economic loss up to 40 billion dollars.

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