NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 9(1): 27–31
DOI 10.3897/nucet.9.100754

Research Article

The development options of nuclear power under carbon dioxide emissions constraints*

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Academic editor: Yury Korovin ♦ **Received** 1 March 2022 ♦ **Accepted** 17 November 2022 ♦ **Published** 8 March 2023

Citation: Marchenko OV, Solomin SV (2023) The development options of nuclear power under carbon dioxide emissions constraints. Nuclear Energy and Technology 9(1): 27–31. https://doi.org/10.3897/nucet.9.100754

Abstract

The aim of the work is forecasting the development of nuclear power in Russia and the world for the period up to 2050 under various scenarios of constraints on carbon dioxide emissions. A brief comparative analysis of the main characteristics of the forecasts of the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) has been carried out. Additionally, calculations were performed using the mathematical models of the world energy system GEM and GEM-Dyn developed at the ISEM SB RAS. The optimal ratio of nuclear and non-nuclear energy sources has been determined. It is shown that nuclear power, including nuclear power plants operating on a closed fuel cycle, along with renewable energy sources, is an effective technology that can solve the problem of reducing carbon dioxide emissions. Calculations have shown that in the sustainable development scenario, the capacity of nuclear power plants in Russia in the period from 2020 to 2050 can increase by 2.7 times, and their share in electricity generation can reach 21–25% in 2030 and 26–35% in 2050. The average annual growth rate (for 30 years) of the installed capacity of nuclear power plants in Russia in the sustainable development scenario is 3.1% compared to 2.7% for the world as a whole. In the GEM and GEM-Dyn calculations performed by the authors, the scale of nuclear energy use turned out to be about 30% higher than in the scenarios of the International Energy Agency due to more conservative estimates of the opportunities for improving the performance of renewable energy sources and taking into account the need to back-up their capacity.

Keywords

Nuclear industry, nuclear power plants, environmental restrictions, efficiency, energy model, forecast

Introduction

In recent years, many politicians and scientists have been talking about the need to combat global warming. They argue in this regard that measures to combat climate change are urgent, since the consequences of such a change may be worse than previously expected (Global Warming 2019).

The 2015 Paris Climate Accords have set a benchmark to limit global temperature rise to "well below 2 °C", and ideally to 1.5 °C above pre-industrial levels. Achieving this goal will require a profound transformation of the global energy sector. Since the combustion of fossil fuels increases greenhouse gas emissions, their further use should be limited (Future of solar photovoltaic 2019, Gielen et al. 2019, Hansen et al. 2019).

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2022, n. 2, pp. 5–14.

One of the most effective means of reducing the greenhouse gas emissions, primarily carbon dioxide (CO_2), is the further development of the nuclear industry (Belyaev et al. 2002, Murogov and Ponomarev-Stepnoy 2005, Zrodnikov 2010, Belyaev et al. 2011, Adamov et al. 2012, Kagramanyan et al. 2013, Marchenko and Solomin 2015, Adamov et al. 2021). However, its share in the world's total electricity generation has declined from 17% in 2000 to about 10% in 2020, despite the increased power and efficiency of modern reactors (World Energy Oulook 2021). This trend is largely driven by political factors.

The purpose of this work is to predict the development of the nuclear industry in Russia and the world for the period up to 2050. The authors consider various scenarios for limiting carbon dioxide emissions, some characteristics of the forecasts of international organizations and the results of calculating the prospects for the development of the energy sector using static (Belyaev et al. 2002, 2011, Kagramanyan et al. 2013) and dynamic (Filippov and Lebedev 2003, Marchenko and Solomin 2015) models of the global energy system developed at the ISEM SB RAS.

Mathematical models of the global energy system

The mathematical description of the problem of determining the optimal technological structure of the global energy system in a static (quasi-dynamic) formulation is as follows: it is necessary to find the minimum of the objective function

$$Z = \sum_r \sum_j c_{rj} x_{rj}, \qquad (1)$$

where c_{rj} is the unit reduced cost, x_{rj} is the installed capacity; indices r and j denote the sets of regions (model nodes) $R=\{1,\ldots, r_u\}$ and energy technologies $J=\{1,\ldots j_u\}$, respectively.

The minimum of the objective function can be found subject to the following constraints: meeting the specified energy needs and peak power as well as balancing the production and consumption of primary, secondary and final energy, financial, environmental and other restrictions. Among the electricity generation technologies, the model describes base and peak power plants using fossil fuels and hydrogen, NPPs with thermal and fast reactors, hydraulic power plants (HPPs), solar power plants (SPPs), wind power plants (WPPs) and geothermal power plants (GeoPPs).

The static model describes the nuclear industry on the assumption that at each time interval the energy structure changes completely (all the existing technologies will be decommissioned and replaced with new ones or completely reconstructed). The continuous development of the nuclear industry is described by the dynamic model, which, when moving to a new time interval, takes into account the existing structure of energy technologies in the regions, timing of the decommissioning of facilities, differences in the service life as well as dynamics of technical and economic indicators of the technologies. The objective function of the problem in the dynamic formulation is written as:

$$Z = \sum_t \sum_r \sum_j c_{trj} x_{trj} \ \forall\ t \in T,\ \forall\ r \in R,\ \forall\ j \in J. \qquad (2)$$

Here, as before, c_{trj} is the specific reduced cost, x_{trj} is the installed capacity, and the index t refers to the time intervals t_u, into which the entire considered period $T=\{1,\ldots,t_u\}$ is divided. In addition to the constraints of the static model, the solution of the problem must satisfy the conditions of continuity at the boundaries of the time intervals. As the experience of applying these two modifications of the global energy system model has shown, when considering a time period of several decades (as in the case of this work, up to 2050), the calculated structures at the end of the period differ insignificantly.

The models in these formulations are described in most detail in (Belyaev et al. 2002) and (Filippov and Lebedev 2003). The model in the quasi-dynamic formulation (1) is called GEM (Global Energy Model), the model in the dynamic formulation (2) is GEM-Dyn.

Global and Russian nuclear industry development scenarios

Table 1 shows the values of global carbon dioxide emissions in the scenarios proposed by the International Energy Agency (IEA). In Scenario 1 (STEPS, or the declared policy scenario), the emissions are approximately constant and remain at the current level (34 Gt/year), in Scenario 2 (APS, or the announced promises scenario), the emissions gradually decrease to 21 Gt/year by 2050, in Scenario 3 (SDS, or sustainable development scenario), they decrease up to 8 Gt/year. Scenario 4 (NZE, or zero-emissions scenario) will completely stop the emissions by 2050 (World Energy Oulook 2021). The last scenario appears to have no chance of being implemented and is considered only for the sake of completeness.

The International Renewable Energy Agency (IRENA) proposed the following two emission scenarios: (1) inertial (35 Gt in 2030 and 33.1 Gt in 2050) and (2) REMAp (24.9 Gt in 2030 and 9.8 Gt) (Future of solar photovoltaic 2019). The first scenario is similar to the STEPS scenario of the IEA; the second one is similar to the SDS sustainable development scenario (see Table 1).

Table 1. Current and predicted carbon dioxide emissions, Gt CO_2/year

	Scenarios	Years				
		2010	2020	2030	2040	2050
1	STEPS	32.3	34.2	36.3	35.3	33.9
2	APS	32.3	34.2	33.6	26.7	20.7
3	SDS	32.3	34.2	28.5	16.4	8.2
4	NZE	32.3	34.2	21.1	6.3	0.0

Table 2 shows the specific capital investments for the main electricity generation technologies in the IEA scenarios (upper part of the table), and Table 3 for illustrative purposes presents the results of calculating the cost of electricity (discounted costs of electricity generation) and ranking technologies according to this criterion, taking into account the uncertainty of both technical and economic indicators and the location of the energy source.

Table 2. Specific capital investments for key technologies, $/kW

	2030			2050		
	Europe / USA	**India / China**	**Russia**	**Europe / USA**	**India / China**	**Russia**
IEA Model (2021)						
NPP	4800/5100	2800	–	4500	2500/2800	–
SPP (PVC)	510/640	340/380	–	370/440	260/330	–
WPP	1390/1280	990/1160	–	1391/1200	960/1090	–
Coal	2000/2100	1200/800	–	2000/2100	1200/800	–
Gas	1000	700/560	–	1000	700/560	–
GEM Model (2022)						
NPP (thermal)	4800	3000	3200	4500	3200	3500
NPP (FR)	5200	5000	3600	5000	4700	3500
SPP (PVC)	850	750	1000	750	500	800
WPP	1300	1050	1100	1200	1000	1000
HPP	4100/3950	2500/2400	2500	4100/3950	2800/2700	2600
Coal	1500	1250	1400	1450	1200	1350
Gas	1000	900	1050	1000	900	1100

Table 3. Ranking key technologies by electricity cost in 2050

Energy source	**Rank**	**Discounted cost of electricity, cent/kW×h**	
		2030	**2050**
SPP	1	2.0–4.5	1.5–4.0
WPP	2	3.0–5.5	3.0–4.5
NPP	3	6.5–12.0	6.0–11.5
HPP	4	6.0–12.0	7.0–12.0
Gas	5	6.0–12.0	12.5–13.5
Coal	6	6.5–14.0	12.5–14.0

Specific investments are the most important indicators that affect the economic efficiency of the energy source. In addition, the cost of fuel plays an important role and, for renewable energy sources, climatic and meteorological conditions determine the installed capacity utilization factor.

The cost of electricity accumulates all the main technical and economic indicators of the energy source and is generally used for preliminary estimates and pairwise comparisons. The next approximation for evaluating economic efficiency is mathematical modeling, which takes into account the relationship of energy sources with each other and with the environment. This is especially important when considering renewable energy sources operating in an unmanaged mode, since they must be duplicated by other energy sources in order to provide uninterrupted electricity supply to consumers. In particular, in the GEM models, variables describing the renewable energy sources are included not only in energy balances but also in power balances with coefficients that take into account the insecurity of their generation.

In the period up to 2050, a sharp reduction is expected in the cost of solar power plants based on photovoltaic converters (PVCs). In this regard, nuclear and hydraulic power plants are inferior in terms of the cost of electricity to solar and wind power plants (SPPs and WPPs) (see Table 3).

Given these prerequisites, the global energy structure predicted in the IEA and IRENA scenarios assumes a radical increase in the role of renewable energy sources (RESs). In the REMAp scenario, the share of RESs in global electricity production increases to 86% by 2050. In the IEA scenarios, the same indicator ranges from 42% to 88%, and the share of NPPs decreases from 10% to 8–9% (Table 4). The maximum volume of world electricity production at NPPs in the IEA scenarios is 5.5 thousand TW×h/year (an increase over the current level for 30 years by a little more than 2 times, or about 2.4% per year).

Table 4. Electricity generation (thousand TW×h/year) and NPP share in electricity generation (%) in the IEA scenarios

	2020	**2030**	**2040**	**2050**
World, total	26.7	33.5–37.3	40.5–56.5	46.7–71.1
Including NPP	2.7	3.1–3.8	3.5–4.9	3.8–5.5
NPP share, %	10.1	9.3–10.1	8.7–9.4	7.7–8.1
Russia, total	1.1	1.3	1.4	1.5
Including NPP	0.2	0.2–0.3	0.3	0.3–0.4
NPP share, %	20.3	17.5–20.2	18.0–23.5	18.5–27.2

In this work, for the first three IEA scenarios (see Table 1), calculations were performed on the GEM and GEM-Dyn models with technology indicators from Table 2 (lower part of the table). Their results in comparison with similar results of IEA (WEM model) (World Energy Oulook 2021) are presented in Tables 5, 6.

Table 5. Electricity generation forecast in Russia, TW×h/year

Energy sources	**Years**						
	2020	**2030**			**2050**		
		Sc. 1	Sc. 2	Sc. 3	Sc. 1	Sc. 2	Sc. 3
IEA scenarios (2021)							
RES	195	236	236	332	432	432	867
Nuclear energy	216	219	219	254	275	275	409
Fossil fuel	646	798	798	666	780	780	232
Total	1057	1253	1253	1255	1488	1488	1508
Authors' scenarios (2020)							
RES	209	270	290	310	410	420	600
Nuclear energy	216	290	300	330	420	490	540
Hydrogen	0	0	0	20	0	50	130
Fossil fuel	639	850	760	540	820	640	290
Total	1064	1410	1350	1200	1650	1600	1560

Table 6. Share in electricity generation, %

Energy sources	**Years**						
	2020	**2030**			**2050**		
		Sc. 1	Sc. 2	Sc. 3	Sc. 1	Sc. 2	Sc. 3
IEA scenarios (2021)							
RES	18.5	18.8	18.8	26.5	29.0	29.0	57.5
Nuclear energy	20.4	17.5	17.5	20.2	18.5	18.5	27.1
Fossil fuel	61.1	63.7	63.7	53.1	52.4	52.4	15.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Authors' scenarios (2020)							
RES	19.6	19.1	21.5	25.8	24.8	26.3	38.5
Nuclear energy	20.3	20.6	22.2	27.5	25.5	30.6	34.6
Hydrogen	0.0	0.0	0.0	1.7	0.0	3.1	8.3
Fossil fuel	60.1	60.3	56.3	45.0	49.7	40.0	18.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

As the restrictions on carbon dioxide emissions tighten, the scale of development of the nuclear industry in general increases (in IEA Scenarios 1 and 2, it remains constant). According to the GEM and GEM-Dyn forecasts, the scale of use of nuclear energy in all the scenarios exceeds the IEA forecasts (by about 30% in the sustainable development scenario). This is due to the fact that the calculations include more conservative estimates of the reduction in specific capital investments in SPPs and WPPs, taking into account the need to duplicate their capacity with peak energy sources. At the same time, the calculations show the expediency of a partial transition of the nuclear industry to fast neutron reactors with a closed fuel cycle, which increases their resource base, the efficiency of nuclear fuel use, and makes it possible to solve some problems related to the disposal of radioactive waste. Nuclear power plants in Scenarios 2 and 3 prove to be useful for producing not only electricity but also hydrogen for peak power plants.

The share of NPPs in the total Russian electricity production predicted in the GEM models also significantly exceeds the estimates of the IEA (35% versus 27% in the scenario of sustainable development in 2050) and the forecasts in (Lagerev and Hanaeva 2021), according to which the share of NPPs will remain almost constant (slightly more than 20%) up to 2050.

The results of calculating the economic development of installed NPP capacities in the global and Russian energy sectors, which are optimal in terms of economic criteria, are shown in Figs 1, 2.

The average annual growth rate (over 30 years) of installed NPP capacities in Russia, according to the sustainable development scenario, is 3.1% compared to 2.7% for the world as a whole. In the considered scenarios, it will be economically optimal to increase the installed NPP capacities up to 56–72 GW by 2050 (an increase of 1.9–2.5 times compared to 2020).

It should be noted that the high growth rates of nuclear energy in Russia obtained as a result of calculations can hardly be realized, taking into account financial, political and other restrictions, but they reveal a trend in accordance with which it is expedient to develop nuclear energy in the coming decades.

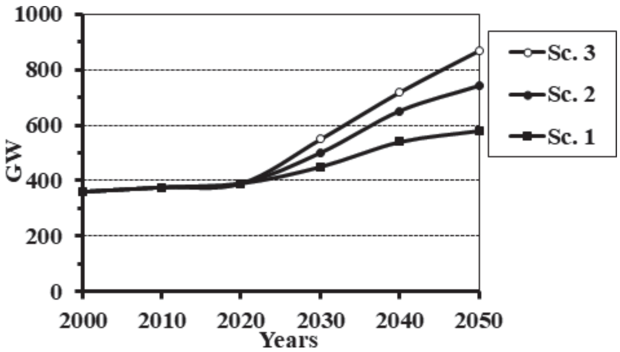

Figure 1. Installed NPP capacities (GW) in the world.

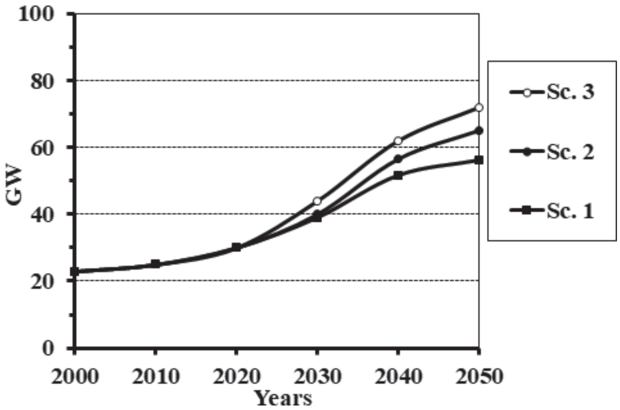

Figure 2. Installed NPP capacities (GW) in Russia.

Conclusions

1. The authors have conducted optimization calculations of the technological structure of the power industry in the world and Russia for different scenarios of restrictions on carbon dioxide emissions using the mathematical models GEM (Global Energy Model) and GEM-Dyn. The optimal ratio of nuclear and non-nuclear energy sources has been determined for the conditions of Russia.
2. It has been shown that nuclear power, including NPPs operating in a closed fuel cycle, along with renewable energy sources, is an effective technology that can solve the problem of reducing carbon dioxide emissions. In Russia, the share of NPPs in electricity generation may be 21–25% in 2030 and 26–35% in 2050.
3. In the GEM and GEM-Dyn calculations, the scale of nuclear energy use has turned out to be about 30% higher than in the scenarios of the International Energy Agency due to more conservative estimates of the opportunities for improving the performance of renewable energy sources and taking into account the need to duplicate their capacity.

Acknowledgements

The research was carried out under State Assignment Project (no. FWEU-2021-0001) of the Fundamental Research Program of Russian Federation 2021-2030.

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