# Modeling the optimal economic structure

# of a global deploying nuclear power

# system with fast and thermal reactors

# in a partially closed nuclear fuel cycle

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**Abstract**

The objective of this work is to model a global nuclear energy system deployment with fast and thermal reactors in a partially closed fuel cycle and find the global NES structure that is optimal from the point of view of economic criteria. The tool for the NES simulation used in the study is the software package MESSAGE distributed by the IAEA. The technologies with economic characteristics confirmed by the existing operational experience were candidates that could be included into the modelled NES: thermal neutron reactors with a full load of uranium oxide fuel (UOX), thermal neutron reactors with a partial load of mixed uranium-plutonium fuel (MOX) in a once-through and partially closed NFC, and fast neutron reactors with MOX fuel in a closed NFC. The results of the study show that in the conditions of lower capital costs of thermal neutron reactors compared to fast reactors, low prices for natural uranium and low cost of spent nuclear fuel (SNF) storage, the development of a global NES based on a once-through NFC with thermal reactors and uranium fuel will dominate until the 70s of this century. However, increase in the price of natural uranium associated with the system growth and increase in the costs of fuel management at the final stage of the once-through NFC, leads to an economically justified commissioning of fast reactors and partially closed NFC. The paper identifies the factors that most significantly affect the structure of the global system optimized for economic criteria.

* 1. INTRODUCTION

One of the most challenging sustainability requirements for a two-component nuclear energy system (NES) based on thermal (LWR) and fast neutron (FR) reactors operating in a partially closed NFC is the requirement to generate electricity at a competitive market price. The main reason for the difficulties consists in the fact that according to the forecast, construction of fast neutron reactors and development of the closed nuclear fuel cycle (CNFC) infrastructure will require higher investment costs as compared to the costs for construction of thermal reactors with a once-through nuclear fuel cycle (ONFC). At the same time, some aspects of the closed nuclear fuel cycle, which may manifest themselves in the long-term planning horizon, may have a positive impact on the NES economics. The aim of the study presented in this paper is to simulate a global developing nuclear energy system with fast and thermal reactors in a partially closed fuel cycle over a long time interval and to search for the global system structure that could be optimal in terms of its economic criteria.

* 1. General problem statement and simulation tools

In the scenario identification and the analysis of investigation results, the use was made of the approach developed under the IAEA INPRO international project [1] in the GAINS cooperation project (GAINS Framework) [2]. The key points of this approach are:

* use of an internationally agreed methodology for assessing nuclear energy systems in terms of their sustainability criteria [3];
* application of the tools disseminated by the IAEA for NES modeling;
* analysis of scenarios based on the agreed metrics (indicators);
* focus on the global nuclear power development plotlines elaborated by acknowledged international energy agencies with estimates of long-term demand for nuclear energy;
* use of the data on reactors and fuel cycles compiled in the INPRO project and other published materials.

**2.1. Optimization software package MESSAGE**

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) is a universal environment for energy planning, it is designed to elaborate and assess the alternative development strategies of the energy sector in the countries and regions on the basis of optimization of reduced costs of NES design and construction [4]. At the beginning of the 2000-s, the IAEA INPRO Section and Planning and Economics Studies Section (PESS) started their joint activities on expansion of MESSAGE code feasibilities to model NESs together with the components that are based on innovative nuclear power technologies: innovative reactors, NFC fuel reprocessing plants and other closed NFC facilities [5].

TheMESSAGE code is a dynamic optimization model used for mid-term and long-term energy supply planning, for the analysis of energy policy and generation of energy development scenarios. The code backbone consists in the technical description of the system under modeling. Nuclear power technologies are defined by their inputs and outputs, by their efficiency and complex interactions of various production patterns. The so-called energy chains are constructed in the model, where the raw and nuclear material flows from one chain link to another, where it is transformed and finally provides electricity and heat generation. The investment demands can be distributed over the facility construction time and can be divided into various categories.

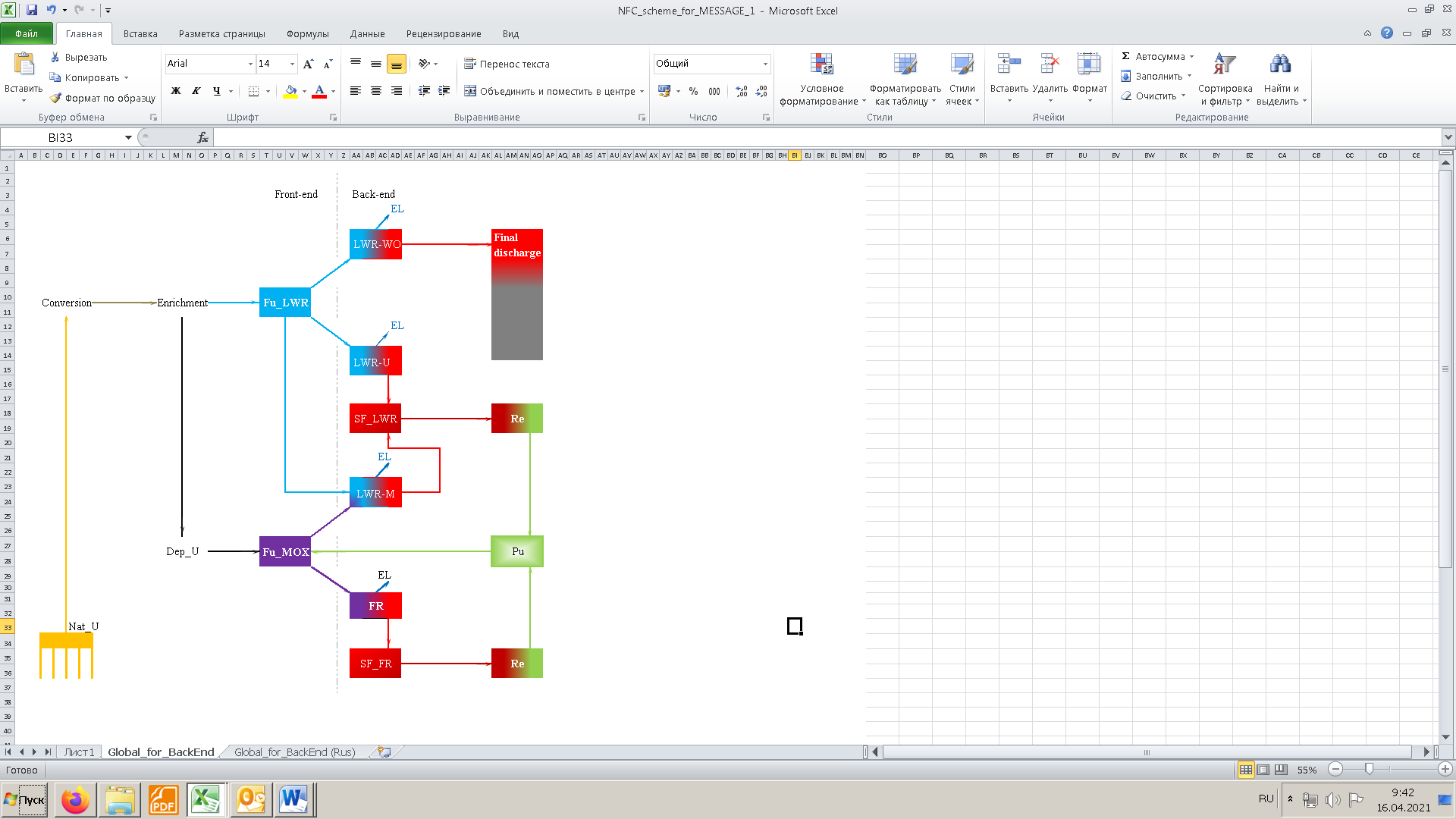
In the scenario economic study aimed at determining the global NES structure, there is no need for detailed representation of design specific features and specifications of reactors and their fuel cycles. To perform the study like this with the use of the MESSAGE software package, it is necessary to know:

* boundary conditions (global nuclear energy demand forecast, natural uranium resources and prices, etc.);
* candidates for integration into the NES structure (types of NFC reactors and facilities);
* routes of fuel movement between the NES elements;
* technical and economic parameters of each NES link.

**2.2. Two-component global NES model with thermal and fast reactors**

The plants with the economic parameters confirmed by their operating experience have been considered as the NES candidates, namely: thermal neutron reactors with a full load of uranium oxide fuel (UOX), thermal neutron reactors with a partial load of mixed uranium-plutonium fuel (MOX) in a once-through and partially closed NFC, and fast neutron reactors with MOX fuel in a closed NFC. No doubt, this list does not exhaust the possible options for arranging a global NES, but it reflects the essential features of evolutionary nuclear power deployment.

Figure 1 demonstrates the NES scheme used in the work. It includes all the principal NFC components: natural uranium resources, conversion, enrichment, fuel fabrication, reactor fuel irradiation, spent fuel cooling and interim storage, spent fuel reprocessing, disposal, storage of the products separated after reprocessing and their further use as fuel for sodium fast reactors (SFR). The model assumes multiple use of plutonium separated from thermal LWR and FR fuel. Other separated products are stored and can be further used or disposed. The simulation time-step is equal to 1 year. The scheme shows the movement of principal material flows in the NFC model. Some parameters, for example, plutonium accumulation, are not calculated in detail in the model and can differ from the accurate calculation. They are corrected via the CYCLE code [6].



*Figure 1. Nuclear fuel cycle scheme in the MESSAGE model*

* 1. input data PreparATION

**3.1. The data for global nuclear power development model**

As a projection of global nuclear power deployment, the use was made of the scenario with a capacity growth up to 2500 GW (e) by the year 2100, developed under the IAEA GAINS project. The global NES is modelled within the time period from 2020 to 2100. At the same time, consideration is given to the background of reactors’ commissioning in terms of SNF accumulation and the time of commissioning of new power units. To eliminate the edge effects of modeling, the computation scheme was developed to the year of 2160, with the NES capacities remaining constant at the level of 2500 GW starting with the year 2100.

**3.2. Technical characteristics of the reactors**

Technical characteristics of light-water reactors (LWR) are given in Table1 [7, 8]. Two LWR types were considered: a conventional LWR option with a full load of uranium fuel and an LWR option with a partial load of mixed uranium-plutonium MOX fuel (LWR-M). Besides, it was assumed that in the conventional LWR option both an open NFC without SNF reprocessing but with its final disposal, and the option with SNF reprocessing are implemented. In the LWR-M option, SNF is also reprocessed with plutonium separation. These nuclear fuel cycles are schematically represented in Figure 1. The SNF holding time was assumed equal to 5 years for thermal reactors and 3 years for fast reactors. The life-time for the above-mentioned reactor types was assumed equal to 60 years.

TABLE 1. technical characteristics of the reactors

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | LWR with UOX fuel | LWR with MOX fuel | FR with MOX fuel |
| Capacity, GW (e) | 1.0 | 1.0 | 1.2 |
| Load factor | 0.8 | 0.8 | 0.85 |
| Efficiency | 0.33 | 0.33 | 0.43 |
| Burn-up, GW·day/t HM | 45 | 45 | 120 |
| Fuel residence time, EFPD | 1168 | 1168 | 1650 |
| Enrichment | 0.04 | 0,04 | - |
| Pu contents in the MOX core | - | 0,07 | 0.18 |
| Initial loading, t | 75 | 75 | 42 |
| Spoil dump | 0.003 | 0.003 | - |

**3.3. Economic parameters of reactors and nuclear fuel cycle**

Preparation of economic characteristics of reactors and nuclear fuel cycle for modeling is an extremely challenging task. The MESSAGE software package envisages an option to set economic parameters of the system under modeling on an annual basis; however, the problem consists in uncertainty pertaining to costs and prices within a long time period. Table 2 shows the economic parameters used in the reference case assumed for the study [8]. The effect of possible variations in these characteristics was determined in the input data sensitivity analysis.

TABLE 2. ECONOMIC CHARACTERISTICS OF REACTORS AND NFC ELEMENTS IN THE REFERENCE OPTION

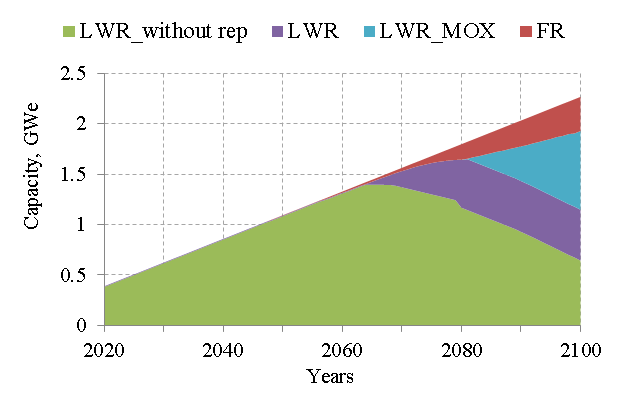
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | | NFC without SNF reprocessing | NFC with SNF reprocessing | | |
| LWR-UOX in once-though fuel cycle | LWR-UOX | LWR-MOX | FR-MOX |
| 2020-2100 | 2020-2100 | 2020-2100 | 2020-2100 |
| Capital cost, $/kW(e) | | 3500 | 3800 | 3900 | 4500 |
| Operation cost, $/kW y | | 54 | 54 | 54 | 54 |
| Conversion, $/kg U | | 17 | 17 | 17 | - |
| Natural uranium cost, $/kg | category a | 80 | 80 | 80 | 80 |
| category b | 300 | 300 | 300 | 300 |
| Enrichment, $/kg SWU | | 100 | 100 | 100 | - |
| Fuel fabrication, $/kg HM | | 300 | 300 | 600 | 1200 |
| SNF reprocessing, $/ kg HM | | - | 600 | 600 | 800 |
| Specific costs for SNF transport, interim storage and RW management, $/ kg HM | | 100 | 100 | 100 | 100 |
| Specific costs for SNF final disposal, $/ kg HM | | 300 | 100 | 100 | 100 |
| Specific costs of separated plutonium storage, $/kg | | – | 2000 | 2000 | 2000 |

The data on natural uranium resources (t) are taken from the Red Data Book [9]. They were presented as two categories of natural uranium cost. In the first category, natural uranium costs 80 $/kg, in the second one –300 $/kg. The amount of these categories is 5 mln t. and 35 mln t., respectively.

## results of modeliing scenarios and analysis of key economic criteria of the global two-component NES

**4.1. Energy production structure**

Figure 2 shows the structure of the installed capacities of different types of reactors in the global two-component NES consisting of thermal and fast reactors for the reference option, which was obtained using the MESSAGE software package. The optimization model shows that until the mid-2060s, thermal reactors with uranium fuel without SNF reprocessing will prevail in the structure of electricity generation in the global NES. This is due to the lower capital costs associated with the construction of thermal reactors compared to the construction of fast reactors, low prices for natural uranium and low cost of SNF interim storage. However, the run-out of cheap natural uranium and transition to the use of uranium with a higher price at the given pace of the global nuclear power deployment, as well as an increase in costs of the ONFC back-end, associated with the need to create SNF interim storage facilities and especially its final disposal, leads to a change in the electricity generation structure of the global NES. After the mid-2060s, thermal reactors without reprocessing their own SNF are gradually replaced with alternative innovative reactor technologies with SNF reprocessing.



*Figure 2. Global nuclear energy system capacity structure in the reference option*

From 2020 to 2065, the capacity structure includes a small share of thermal reactors with a capacity of ~ 6.8 GW with spent UOX fuel reprocessing, which is almost invisible in the figure. This component reflects the results of the activities aimed at developing reprocessing technologies for SNF from thermal reactors until 2020. With regard to the forecasts of the natural uranium cost, this strategy does not find economic incentives for deployment until the end of the 2060s, when an economically justified significant increase in the capacity of thermal reactors with SNF reprocessing is observed. By the year 2080, this NES component reaches a value of ~ 500 GW and then remains approximately at this level. Thermal reactors with partial loading of MOX fuel and full reprocessing of the total amount of SNF begin to be introduced into the structure of the global NES in 2080, with a subsequent annual increase in the capacity of these reactors by ~ 10%. Fast reactors are commissioned since the end of the 2040s with a capacity of about 3 GW, following thermal reactors with spent UOX fuel reprocessing, and remain at this level until the 2060s. Introduction of individual power units of fast reactors into the structure optimized according to economic criteria is explain4ed by the need to promptly use plutonium separated from thermal reactor SNF in order to eliminate the expenses associated with the high storage cost for this plutonium. In the time interval from 2060 to 2100, the capacity of fast reactors annually grows by ~ 13%, which is accounted for by an increase in the price of natural uranium and an increase in the cost of long-term storage of SNF in a once-through NFC. Despite the fact that until the middle of the century the capacities of the reactors with SNF reprocessing represent an insignificant part in the total electricity production, maturing of the technology for the NFC closure and gradual formation of the corresponding infrastructure is critical for rapid deployment of innovative reactors and the fuel cycle when the economic benefits of these technologies become evident.

The capabilities of the MESSAGE software package make it possible to obtain a vision of the global NES structure formation in time in terms of individual parameters of the system.

**4.2. Analysis of key economic criteria of the global two-component NES**

Figure 3 shows the total annual consumption of natural uranium according to two cost categories ([a], [b]) for the reference option of the global nuclear energy system model. It can be seen that the projected resources of natural uranium of the cheap category are running out by the middle of the century, and then uranium of the more expensive category will have to be used. The shape of the curve of the annual consumption of natural uranium resources is similar to the curve that reflects the commissioning of thermal reactor capacities. The graph shows two small peaks in consumption in 2020 and 2080. This is due to the increased, in comparison with the annual one, value of the first loads of fresh fuel of the newly commissioned thermal reactor power units. According to the scenario, the increase in electricity demand occurs after 2020, when new power units are added to the historically existing reactors. As, according to the assumptions made in the study, the service life of a reactor unit is 60 years, by 2080 it will be required to replace the power units that were commissioned in 2020, and again there will be an intensive consumption of natural uranium through the initial loading.

*Figure 3. Total natural uranium consumption*

From Figure 2 it follows that UOX fuel constitutes the main part of the NES needs. Therefore, the consumption of fresh UOX fuel to a large extent follows the schedule of thermal reactors’ commissioning. Starting from 2060, MOX fuel demand emerges, which reaches ~ 30% of the total annual fuel mass by 2100. The average annual growth in the amount of MOX fuel in the 2060 - 2100 segment is ~ 7%. Since 2080, the growth in fuel demand is determined by MOX fuel, while the demand for UOX fuel is decreased.

Figure 4 presents the demands for the total annual SNF reprocessing in the global NES.

*Figure 4. SNF reprocessing*

The figure shows that economically motivated SNF reprocessing at a significant scale begins in 2075. Prior to that, it is carried out within the framework of the programs for maturing of NFC closure technologies, and its incorporation into the system optimized in terms of reduced costs is determined by a decrease in the cost of separated plutonium storage. In the time interval after 2080, there is a significant increase in reprocessing volumes, from ~ 200 tonnes/year to ~ 5000 tonnes/year.

The estimates of the SNF accumulation in the global NES, obtained in the study with regard to the fuel cooled in the storage pools, interim storage and subject to final disposal, showed that almost the entire volume of accumulated SNF is determined by thermal reactors whose spent fuel is not reprocessed. In the period from 2020 to 2100, the amount of stored SNF from other types of reactors does not exceed 10%. The storage volume of SNF from fast reactors covers the smallest part of the entire SNF volume in the global NES. This is due to the small share of fast reactors in the system and recycling of spent fuel from these reactors.

In the mathematical model of the global NES implemented in the MESSAGE software package, plutonium is present in two categories: separated plutonium and plutonium contained in reactor SNF. The calculations show that separated plutonium is at the minimum level of the operating inventory for the initial and annual loading of reactors with MOX fuel. This is due to the high cost of plutonium storage assumed in the study ($ 2000/kg per year).

At the same time, SNF of thermal reactors contains about 1% of plutonium. In MOX fuel of fast and thermal reactors, the plutonium content is more concentrated. Besides, the plutonium separated from MOX and UOX SNF is almost completely used for new MOX fuel, which is in line and does not conflict with the nuclear weapons non-proliferation requirements. On the contrary, the plutonium contained in thermal reactor SNF and is supposed to be ultimately disposed of together with this fuel, poses risks in the area of non-proliferation of nuclear weapons and environmental risks, which causes public and professional concern and creates significant uncertainties in the timeframe and cost of the final disposal of high-level waste in geological formations.

5. SENSITIVITY ANALYSIS

The study encompassed the analysis of sensitivity of the deployment rates for the considered in the research reactor types with the corresponding fuel cycles to variations in the parameters that most significantly affect the structure of the global system optimized according to economic criteria. These parameters include: discount rate, capital costs, natural uranium cost, fuel fabrication cost, fuel reprocessing cost, high-level waste (HLW) disposal cost, plutonium storage cost. For each parameter, a value corresponding to the reference option was set, and the range of its probable variations was expertly determined. The effect of the parameter variations within the selected range on the global NES structure was analyzed both by direct comparison of the change in the integral share of the technologies under consideration over the time interval from 2020 to 2100, and by calculating the relative sensitivity of the technology share to the changes in the system parameters in a particular year.

**5.1. Analysis of the effect of variations in the parameters of nuclear energy technologies on the global NES structure**

The value of the discount rate significantly affects the global NES structure variations with time. Decrease in the rate results in an earlier introduction of fast reactors into the NES structure and, as a consequence, to an increase in their share for the period from 2020 to 2100. So, with the decrease in the rate from the reference value of 8% to 5%, the average share of fast neutron reactors in the predicted interval increases 8-fold, and the share of thermal neutron reactors decreases accordingly. In general, the discount rate determines the choice between short-term and long-term economic goals: the higher the rate is, the more importance is attached to short-term benefits to the detriment of solving fundamental economic problems, such as cost-effective radioactive waste management and their final disposal. According to the authors, in the course of elaboration of a long-term strategy for a nuclear energy development as part of a sustainable energy, applicability of the discounted cost model is not sufficiently justified.

With the values of capital costs selected for the reference option (Table 2), the shares of the technologies under consideration for the period of 80 years from 2020 to 2100 were as follows: thermal reactors in an ONFC - 64%, thermal reactors in a CNFC - 15%, thermal reactors with a partial load of MOX fuel - 14%, fast neutron reactors with MOX fuel - 7%. The effect of parameter variations within the selected range on the global NES structure was analyzed within the framework of direct comparison of changes in the share of the technologies under discussion, both for the case of simultaneous variation in the parameters of all the reactor technologies considered, and for the case when the parameters varied individually for each group of technologies, i.e. with variations in the parameters of one reactor technology, with the parameters of other technologies remaining unchanged.

In the former case, with the capital costs of all the reactor technologies under consideration reduced by a quarter, the share of thermal reactors without reprocessing decreased 1.5 times, and the share of fast reactors and thermal reactors with a partial load of MOX fuel increased twice. With the capital costs of all technologies increased by a quarter, the share of thermal reactors increased only by 4%, whereas the share of fast reactors decreased by more than half. In the event of variation of the parameters for each group of technologies, the reduction of capital costs for thermal reactors without reprocessing, with fast reactors’ capital costs remaining unchanged, resulted in an increase in the share of thermal reactors by 50%. For fast reactors with a CNFC, a decrease in capital costs, with capital cost invariance for thermal reactors, has caused a dramatic (almost ten-fold) increase in the share of fast reactors. The results suggest that for fast neutron reactors, reduction in capital costs appears a more important factor than for thermal reactors.

The share of fast reactors in the structure of the global NES capacities is also more sensitive to natural uranium price rise and fuel fabrication cost. For example, the natural uranium price rise from $80/kg U to $120/kg U results in reduction in the share of thermal reactors without SNF reprocessing within the structure of nuclear capacities from 64% to 50%, i.e. by 14%, whereas the share of fast reactors, where the fuel does not depend on the natural uranium price, increases from 7% to 35%, i.e. by a factor of 5. The LWR fuel manufacturing cost reduction has little effect on their share in the global structure, whereas the share of fast reactors is much more sensitive to a decrease in the cost of manufacturing fuel for these reactors and increase by a factor of 4. Changes in the cost of SNF reprocessing and the cost of plutonium storage within the range of costs under discussion do not significantly affect distribution of the technologies considered in the NES structure.

The issue of the effect of the ONFC back-end cost is important, but complicated for economic research. At-reactor and interim dry storage of SNF does not have a significant effect on the share of thermal neutron reactors without SNF reprocessing within the NES structure. However, construction of facilities for SNF final disposal in geological formations calls for implementation of severe measures in relation to environmental safety and non-proliferation of nuclear weapons, which can result in considerable rise in the cost component value. As can be expected, the deployment limits for thermal neutron reactors without SNF reprocessing can be defined not only by the natural uranium price, but also by the cost of safe final disposal of SNF, although the currently available information is insufficient for a quantitative economic assessment of the effect of the ONFC back-end on the prospects of this technology in the nuclear energy sustainable development.

**5.2. Relative sensitivity to system parameter variations**

In addition to the direct assessment of the share of the nuclear power technologies under consideration in terms of the variation of the NES key parameters over a long time interval, an approach used in the study was based on the calculation of relative sensitivity of the selected functional to the variation of the parameters on which this functional depends at specific points in time. The functional *F* in the problem in hand is the share of reactor technologies with global NES fuel cycles assumed in the study. Consideration was given to the same variables as those used in the direct assessment as the variable parameter: *Xn*: capital costs, natural uranium purchasing cost, the cost of fuel fabrication and reprocessing, SNF storage and disposal cost, plutonium storage cost. The relative sensitivity of the functional *F* to the parameter *Xn p* (*X1, X2,…, XN*) is the limit of the ratio *ΔF/ F* to *ΔXn/Xn* as *ΔXn/Xn* tends to zero [10]:

(1)

In accordance with formula (1), the sensitivity of the fast reactor technology in the CNFC to the NES parameters was analyzed. Figure 5 shows the results of this analysis for 2080. As can be seen in Figure 5, the share of fast reactors with the CNFC in the NES structure is most sensitive to the capital costs for the construction of these reactors. The developers of fast reactors have recently been able to approach the capital costs of thermal neutron reactors in terms of this indicator, and, as a result of fast reactor technology maturing, further convergence can be expected in the transition to their larger-scale integration into the NES. The research findings show that the key economic factor stimulating the commissioning of fast reactors within the framework of the existing and target prices for NFC technological process stages is the replacement of uranium fuel with plutonium one. However, this factor will be fully manifested only with the large-scale nuclear power deployment. With regard to the sustainability requirements, the NFC back-end objectives are growing in importance, but, as can be seen in Figure 5, the economic incentives for their solution are still too weak. In light of this, it is advisable to address multi-criteria methods to assess the prospects for the development of innovative technologies, where the development criteria are formulated not only in the area of economics, but also in nuclear safety, environmental preservation, non-proliferation of nuclear weapons and radioactive waste management.

*Figure 5. Relative sensitivity of the share of FR technology in the CNFC in the global NES structure to the key parameters of the model,* *dimensionless quantity*

1. CONCLUSION

The basic result of the research performed with regard to the economic prospects of fast neutron reactor deployment is the conclusion that, starting from 2020, fast neutron reactors are included in the optimal plan at a high cost of separated plutonium storage, and from 2060, an economically justified introduction of fast reactors to the NES takes place with a fairly significant growth in capacities, which is primarily accounted for by the expediency of replacing natural uranium rising in price. The maturing of NFC closure technology and gradual development of the relevant infrastructure is critical for the timely deployment of fast reactors and a closed NFC at a time when the economic benefits of this technology will become evident.

Although, with regard to the sustainability requirements, the NFC back-end objectives are growing in importance, the economic incentives for their solution are currently weak. There are grounds to believe that the current trends in developing nuclear energy as a sustainable energy will result in a change in this situation. It will allow the economic assessments of the prospects for fast neutron reactors to be brought closer to the multi-criteria assessments, where in addition to economic criteria, consideration is given to the criteria in the area of nuclear safety, preservation of the environment, non-proliferation of nuclear weapons and radioactive waste management.

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