Assessment of a Nuclear Energy System Based on the Integral Indicator of Sustainable Development

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Abstract. Ability of nuclear power to meet the requirements of sustainable development is a critical point for public acceptance of the energy technology and its further deployment. Sustainability of the nuclear energy systems (NES) based on once through nuclear fuel cycle (OTFC) with thermal reactors and UOX fuel on a large time horizon needs enhancement. The numerical indicator is introduced in the paper to assess a progress in nuclear energy systems development taking into account requirements of sustainable development. The indicator shows radical increase of the NES sustainability due to synergistic use of thermal and fast reactors with closed nuclear fuel cycle (CNFC). This effect can be gained within the country that has mastered the technologies of CNFC with thermal and fast reactors or in the system in which a user country receives services on CNFC from a supplying country. It is noted that the model needs further development in order to agree on the significance of advances in technology and institutional development.

Key Words: Sustainability Indicator, Fast Reactors, Closed Fuel Cycle.

1. Introduction

Within the framework of the IAEA international project INPRO the methodology of sustainable development of a nuclear energy system (NES) was developed based on the general UN concept of sustainable development [1]. The methodology defines basic principles and requirements for assessment of the NES sustainability in separate areas of economics, nuclear safety, resources, radioactive waste management, non-proliferation, physical protection, and infrastructure. However, a method of the overall assessment of a NES from the standpoint of sustainable development that would aggregate all subject areas of the assessment was not developed. Meanwhile, the idea of a harmonious combination of economic, social, environmental, and institutional dimensions forms the basis of the UN concept of sustainable development as a new objective reality of social development.

Without an integral evaluation, the criterion of the NES sustainability becomes ambiguous making impossible a comparative evaluation of sustainability of NESs with different reactor fleets and installations of the nuclear fuel cycle. Below an approach to determination of a quantitative aggregated indicator of the NES sustainability is discussed.

2. Calculation Procedure

Almost all NESs currently in operation in the world use mastered technologies of thermal reactors and open nuclear fuel cycle. These are systems that meet existing requirements of the regulation authorities, ensuring a guaranteed energy supply at affordable prices. At the same time, need for improvement of the systems was clearly expressed by public and politics at the beginning of the century in order to provide a new technological and institutional framework for safe, cost-competitive, large-scaled nuclear energy with practically unlimited fuel resources and reliably closed channels of nuclear weapons proliferation. In fact, requirements of sustainable development of the nuclear industry were formulated in general terms, which were subsequently detailed in the INPRO methodology [1]. The main provisions of this methodology served as a guide for development of the integral index of NES sustainability.

Calculation of the indicator of the NES sustainability defined in the paper requires a lot of information, including data on reactor and fuel cycle technologies and installations, strategies and development scenarios in the energy sector, possible options for international cooperation in the field of nuclear energy. The goals of sustainable development in each of the subject areas of assessment were set forth in INPRO methodology in the form of basic principles [1]. They are very similar to the targets adopted in the "Generation IV» international project [2] and to the objectives for the future nuclear power set in many other major studies. Development of innovative technologies and infrastructure, strengthening of international cooperation are mechanisms for achieving these sustainable goals of the NES assessment.

Achieving the NES sustainability goals is a complex long-term task. Approaches to modelling of the process are explored in the INPRO collaborative project "Roadmaps for a transition to a globally sustainable NESs" [3]. The way to a globally sustainable NESs is considered in this project as a gradual process with important intermediate objectives ‘key developments’. The authors of the paper suggest express numerically the degree of closeness of a key event to the final sustainability target. Achievement of key developments should be associated with the implementation of specific programmes, requiring, as a rule, a lot of manpower and financial resources.

Currently, there are many publications on the forecasts of the nuclear power deployment in various countries, the expected cost of the programmes in the nuclear energy sectors, the results of monitoring of the public attitude, etc. Based on the data it is possible to estimate how much of a percentage of the full program provides reaching of a certain key event. The numerical values that express these estimates should be considered as a selection from a fairly wide interval, in which, as we should expect, may lie the real indicator of the development component of the NES at a given time. The authors believe that this approach is sufficient in order to see the majour trends in the NES sustainability assessment on a large time horizon.

The initial stage of the sustainability programmes implementation includes construction and operation of nuclear power plants and related NFC infrastructure that meets current regulation requirements for nuclear power (*see FIG. 1*). Many countries have already passed this way others are just beginning to implement the relevant programmes.

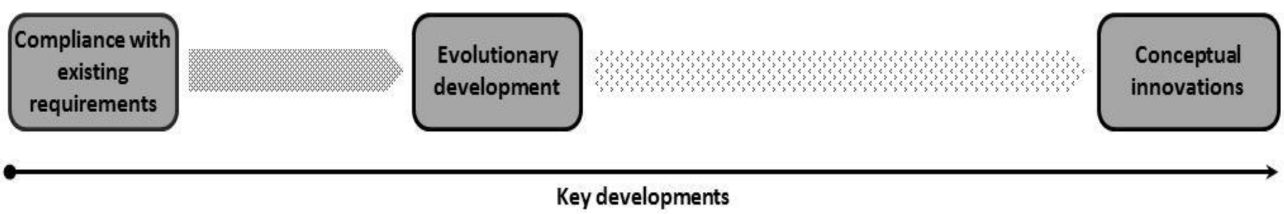

FIG. 1. The phases for achieving sustainability of NES

The second stage can include key developments related to creation of the innovative components of NESs within the evolutionary approach. Key developments related to creation of the radically new technological and institutional platform should make the third and final phase of achieving the NES sustainability objectives.

The key developments and a percentage of their contribution to the implementation of the full programme providing the NES sustainability accepted by authors for various subject areas as follows:

- Safety
  - compliance with current regulation requirements and the IAEA recommendations - 60%;
  - compliance with the requirements for the Generation 3+ reactors (the use of passive safety systems, the presence of containment and a melt trap, grace period until human intervention is necessary increased relative to existing facilities, calculated frequency of a major release of radioactivity $<10^{-6}$ per unit-year, etc. [1,4]) - 80%;
  - compliance with the requirements for the Generation 4 reactors (passive automatic reactor shutdown systems, probability of core damage less than for the Gen 3+ reactors, no need for relocation or evacuation measures outside the plant site, etc. [1,5,6]) - 90%;
  - deterministic exclusion of severe accidents [7] - 100%.
- Economics
  - increased cost of electricity on the phase of innovative technologies introduction - 20%;
  - cost comparable with wind, sun, etc.being used for ensuring energy security, diversification of energy sources or decreasing environmental impact - 40%;
  - cost at the level of the average in the electricity market - 80%;
  - best economic performance in the energy sector - 100%.
- Resources
  - once-trough NFC with less than 1% of natural uranium utilization – 0%;
  - use of depleted uranium or single cycle of plutonium - 20%;
  - NES of thermal and fast reactors with multiple recycling of plutonium - 80%;
  - full use of the energy potential of all fissile material - 100%.
- Waste management
  - reactor spent fuel storage of spent nuclear fuel - 0%;
  - centralized long-term storage of spent nuclear fuel - 40%;
  - final geological disposal of spent nuclear fuel - 80%;
  - disposal of waste without plutonium and minor actinides in it [8] - 100%.
- Proliferation resistance
  - not all states' commitments, obligations and policies regarding non-proliferation and its implementation are adequate to fulfill international standards - 0%;
  - states' policy meets international standards, provides a low attractiveness of nuclear materials and nuclear technologies, ensure difficulty of carrying out acts of sabotage, and conditions for it concurrent detection [1] - 40%;
  - providing balance of the production and consumption of fissile material in the NFC - 100%.
- Public and governmental attitude
  - lack of public and governmental support - 0%;
  - debate on the role of nuclear power and ways for its development- 20%;
  - positive attitude of the majority of population and government - 40%;
  - full support of the government and the population - 100%.

Indicator of the NES sustainability $f_l\ (t_R)$ for all the NES components in the subject area l for time period t_R is calculated by summing of percentage of contribution to the implementation of the full sustainability programme achieved at the given key development:

$$f_l(t_R) = \sum_i x_{li}(t_R) \cdot \frac{N_i(t_R)}{N_{ЯЭС}(t_R)}, \tag{1}$$

where x_{li} (t_R) - the percentage of contribution to the implementation of the full sustainability programme achieved at the given key development for *i* - component of the NES in the subject area *l* for the time period t_r;

N_i (t_R) - installed electric power of *i* - the component of the NES in the time period t_r;

N_{NES} (t_R) - installed electric capacity of the entire NPS in the time period t_r.

Integrated indicator of the NES sustainability *SI* (t_R) is defined by the following equation:

$$SI(t_R) = \sum_l^{L=6} f_l(t_R) \cdot w_l(t_R), \tag{2}$$

where - f_l (t_R) is defined by equation (1);

w_l (t_R) - weight factor for the subject area *l* in the time period t_r;

L - the total number of subject areas (*L* = 6).

$$\sum_{l=1}^{L} w_l = 1, \tag{3}$$

In this study, identical weights (w_l = 1/6) are assigned to all subject areas. Three time intervals t_r are defined: t_1 - from 2015 to 2034, t_2 - from 2035 to 2054, t_3 - from 2055 to 2100. Currently, the model is implemented using MS Excel spreadsheets with the necessary data arranged in the related formats.

3. Nuclear energy systems under consideration

Four options for the deployment of a NES of total installed capacity 150 GW(e) by the end of the century are simulated. The rate of capacity growth corresponds to an average input of 1.5 GW(e) per year, taking into account the replacement of retired capacities. The general requirements of the NES sustainability are applied to the NES options without reference to the particular conditions of a country.

The option A1 corresponds to the extensive deployment of nuclear power without solving the issues related to the accumulation of spent nuclear fuel and plutonium therein. The NES of the option consists of PWR reactors with uranium oxide fuel operating in a once-trough NFC. Capacity grows due to introduction of advanced reactors of the same type. Unloaded SNF is cooled down in the reactor pools and then in a centralized wet or dry storages. International cooperation is limited to the front end nuclear fuel services of the global market.

Option A2 differs from the option A1 only in the approach to the spent nuclear fuel management. It is assumed that in the second half of the century the country which implements this option commissions the objects of final geological isolation of SNF or sends SNF to the international centers for SNF geological isolation.

The strategy of nuclear power use in the option A3 is based on the principle of the nuclear fuel cycle infrastructure minimization. It is assumed that countries, which implement this option, closely cooperate with the supplier of the reactor technology and nuclear fuel cycle services, including services on taking back of SNF for further reprocessing and reuse of fissile materials.

Option B1 presents a two-component system consisting of thermal and fast reactors with a closed fuel infrastructure cycle, investigated in detail at the present time in Russia [8] and France [9]. Thermal reactors operate partly with the uranium-oxide fuel, partly with a mixed uranium-plutonium (MOX) fuel. Input of fast reactors and advanced light water reactors with partial use of MOX fuel begins from 2030. In the second half of the century fast reactors on the new technological platform with radically improved system characteristics [7] are included into the B1 option. It is assumed that the countries implementing B1 option has a technical, institutional and legislative basis for providing wide spectrum of the nuclear fuel cycle services while countries implementing option A3 has a basis for receiving these services.

For each option the percentage of contribution achieved at the given key development to the implementation of the full sustainability programme is defined in all areas of evaluation. These values can be considered as a partial sustainability indicator in a specific area of assessment. The vision on the long term evolution of the NES sustainability programme implementation assessed in the study for three intervals of the century is illustrated in *FIG. 2*.

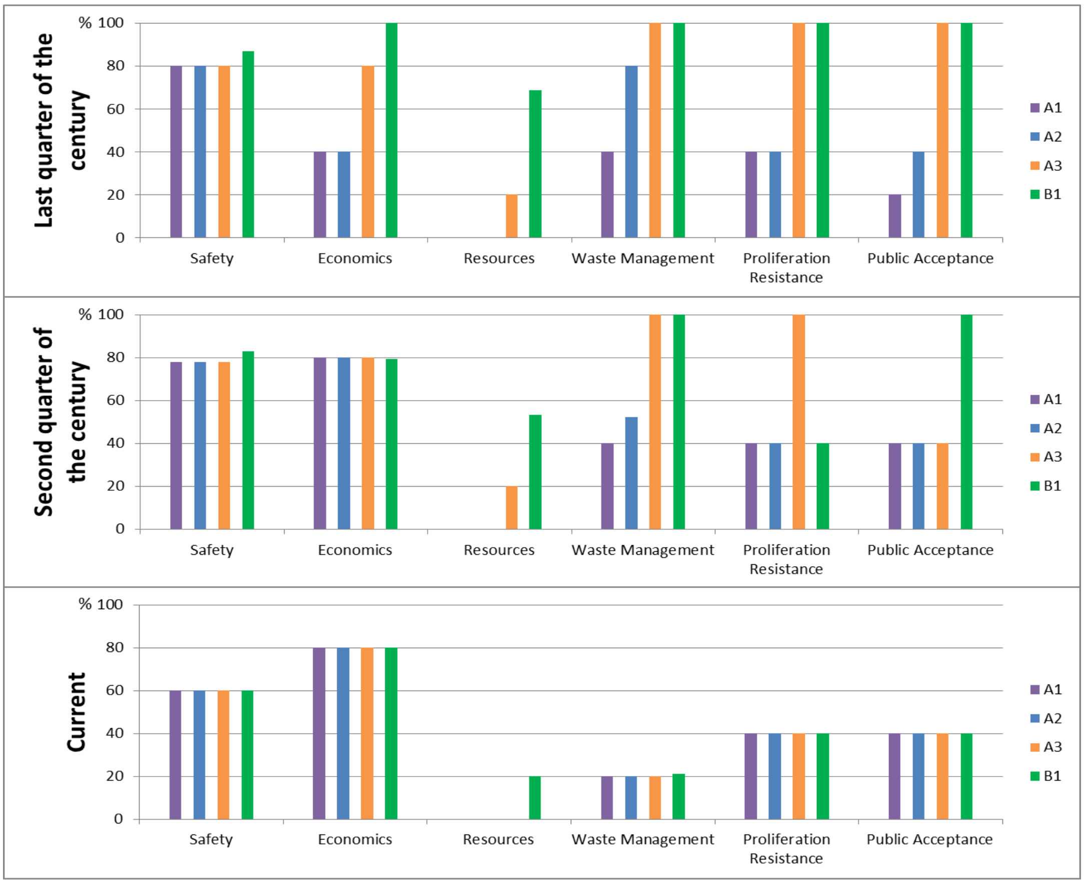

FIG. 2. The long term evolution of the NES sustainability programme implementation

The long term projections on the implementation of the NES sustainability programme were built in the study based on the analysis of numerous publications and discussions at the meetings of experts. Brief comments on the main features of the selected options, which seem to be important for the sustainability assessment, are given below.

As seen in Figure 2, the safety of NES in the options A1-A3 is rather high in the second part of the century due to gradual growth of the share of the Generation 3+ reactors with enhanced safety characteristics comparing to the thermal reactors of previous generations. Within accepted boundary conditions of the study for the scenarios development, Generation 4 reactors are commissioned only in the option B1. The integral effect on safety evaluation due to introduction of fast reactors with enhanced safety characteristics is not significant because the share of the reactors by scenario assumption is less than 40% of the NES and the accepted safety characteristics of the Generation 3+ thermal reactors by themselves are rather high.

The essential evolution of the economic characteristics is observed for the A1, A2 options and for the B1 option. It is important for the economic assessment of the A1 option that expected price of natural uranium and spent fuel storage costs in accordance with many publications will rise in the second half of the century. In the model used this led to deterioration of economic indicators of the NES in the A1, A2 options in the third quarter of the century. On the contrary, these trends, when modelled, result in a positive impact on the economy of the option B1.

The partial sustainability indicator for the resource area clearly reflects the established potential of the closed NFC in saving of natural uranium. The most significant effect in the natural uranium saving demonstrates the options B1. For this option the UOX fuel is substituted in an essential part by MOX fuel and by the UOX fuel with reprocessed uranium. In the option A3, according to accepted assumption, these types of fuel do not use and thus saving is less.

It should be noted that assessments in the areas under consideration partially influence each other. This is especially true for the areas of waste management, proliferation resistance and public acceptance. The uncontrolled accumulation of SNF and plutonium therein is assumed in the study to result in the rise of safety and proliferation risk, ecological concerns, and eventually in decreasing of public support for the option A1 in the second half of the century. Absence of a decision on or clear plans for SNF final disposal is already a matter of a public concern and protests. One can admit that these sentiments will increase in the future, especially if the safe and economically acceptable solution on the disposal of SNF and radioactive waste in other options of NES will be demonstrated.

The SNF final isolation implied in the option A2 will improve, comparing to the option A1, waste management, proliferation resistance of fissile materials in SNF, and social acceptability of this option. Nevertheless, the burial of SNF with plutonium and minor actinides therein requires convincing substantiation of environmental safety and proliferation resistance require justification of safety and proliferation resistant requirements for hundreds of thousands of years. NES of options A3 and B1 implie full use of plutonium and minor actinides for energy generation thus radically decreasing waste radiotoxicity and providing an opportunity for approaching the final objectives of waste management, proliferation resistance, and social acceptability of these options.

4. Results

The results of the calculation with the equation (1) of an integral indicator of the NES sustainability of the assessed options are presented in *FIG. 3*.

The sustainability indicator for A1 option, which simulates NESs with open NFC, slowly grows to about the middle of the century due to the replacement of thermal reactors of second and third generations by thermal reactors of 3+ generation with improved safety, better economic performance, construction of intermediate storages of SNF and implementation of other measures within an evolutionary approach.

However, these measures are not sufficient to stabilize the indicator in the second half of the century because of assumed rise of natural uranium prices, costs of SNF management, risk of proliferation of increasing amounts of accumulated fissile materials, and public support reduction.

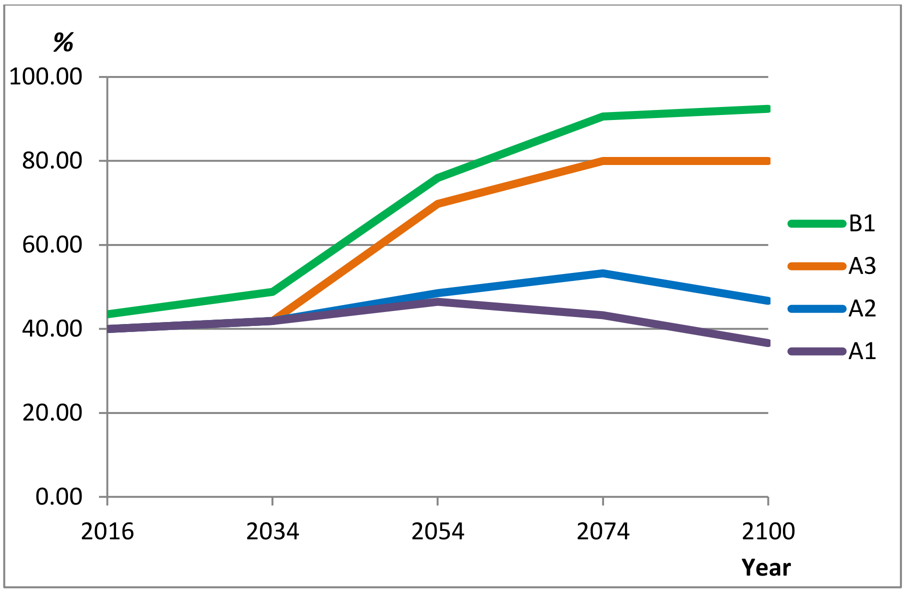

FIG. 3. Calculated integral indicator of NES sustainability

The assumption on the arrangement of the installation of the final geological isolation of SNF in the option A2 significantly increases the value of the integral sustainability indicator as compared to the option A1 in the second half of the century. However, even with an optimistic look at the public attitude towards spent fuel disposal containing high-level radioactive waste and fissile materials absolute growth of NES sustainability indicator in the option A2 is rather moderate. It is due to the lack of opportunities for advancement to the objectives of sustainable development in other subject areas of evaluation such as saving of natural uranium resources, reduction of the radiotoxicity of waste on the foreseeable horizon of time, preserving risks of proliferation of fissile materials.

The scenarios simulation shows that high level of the NES sustainability can be achieved when the country that use thermal reactors, sends SNF to the country that has the infrastructure of a closed NFC for processing of SNF and utilization of fissile materials (option A3). Complete utilization of reprocessed plutonium, minor actinides and uranium in a closed NFC with thermal and fast reactors in the option A3, B1 allows drastically cut the nuclear waste accumulation and their radiotoxicity, expand the resource base of nuclear power up to any required scale, reduce the cost of the nuclear fuel, enhance public support. All these factors are crucial for nuclear power sustainable development and eventually they determine the evaluation of the integral sustainability factor on a large time horizon.

5. Conclusions

The definition of the numerical indicator and the method of its calculation presented in the paper allows assess value of sustainability for the various options of the nuclear energy systems development and deployment. The approach is used for the calculation of the integral indicator of the sustainability for several NES options at time intervals up to the end of the century. Scenarios for four options with different configuration of the reactor fleet and installations of the nuclear fuel cycle are developed up to the end of the century taking into account expected technological and institutional innovations.

Application the calculation procedure with evaluation of the sustainability indicator has shown that using of the fundamental features of the fast reactors and closed cycle can drastically enhance the future NES sustainability. The scenarios indicate that demonstration and commissioning of these innovative technologies will take a lot of time implying a need for the transition to a two-component system based on closed nuclear fuel cycle with thermal and fast reactors with gradual increasing the share of fast reactors. If such a strategy is implemented in some technology holder countries then advanced framework of international cooperation at the back end of the nuclear fuel cycle will provide an opportunity to enhance the NES sustainability also in partner countries.

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