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Research Article

Elaboration of approach to nuclear energy systems assessment by criterion of sustainable development*

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Abstract

The paper describes the approach to the assessment of nuclear energy systems based on the integral indicator characterizing the level of their sustainability and results of comparative assessment of several nuclear energy system options incorporating different combinations of nuclear reactors and nuclear fuel cycle facilities. The nuclear energy systems are characterized by achievement of certain key events pertaining to the following six subject areas: economic performance, safety, availability of resources, waste handling, non-proliferation and public support. Achievement of certain key events is examined within the time interval until 2100, while the key events per se are assessed according to their contribution in the achievement of sustainable development goals. It was demonstrated that nuclear energy systems based on the once-through nuclear fuel cycle with thermal reactors and uranium oxide fuel do not score high according to the integral sustainable development indicator even in the case when the issue of isolation of spent nuclear fuel in geological formation is resolved. Gradual replacement of part of thermal reactors with fast reactors and closing the nuclear fuel cycle results in the achievement of evaluated characteristics in many subject areas, which are close to maximum requirements of sustainable development, and in the significant enhancement of the sustainability indicator.

Keywords

Nuclear energy system, sustainable development, closed nuclear fuel cycle, fast reactors.

Introduction

Methodology was developed within the framework of the INPRO international project implemented by the IAEA (IAEA 2008) which allows determining on the basis of the UN sustainable development concept the goals of enhancement of sustainability of nuclear energy system (NES) within the subject areas significantly affecting this assessment: economic performance, nuclear safety, availability of resources, radioactive waste management, physical protection of nuclear facilities and infrastructure. It has to be noted that the method for general assessment of the NES from the viewpoint of sustainable development as the unified process including the above listed subject areas is not yet developed. Meanwhile, it is specifically the idea of achievement of harmonious combination of economic performance, social sphere, environmental issues and institutional structure, which forms the basis of the concept in question as the new objective reality of social development.

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Expediency of development of the method for integral assessment of NES using unified quantitative indicator of sustainable development without which the concept itself becomes ambiguous and comparative assessment of NES with different configurations of inventory of nuclear reactors becomes impossible was discussed by numerous meetings of the IAEA/INPRO. The authors of the present study who participated in these discussions suggest the approach to the determination of aggregated sustainable development indicator.

Calculation methodology

Practically all NES currently operated in the world utilize well developed technologies of thermal nuclear reactors and once-through nuclear fuel cycle. These systems comply with existing requirements of oversight agencies, ensure guaranteed electric power supply under acceptable prices and are positively accepted by the majority of population. At the same time, one cannot regard these systems as reaching perfection. The task of development of technological and institutional basis of safe, economically competitive large-scale nuclear power with practically unlimited availability of fuel resources and securely barred channels of proliferation of nuclear weapons was designated at the very beginning of this century. Requirements of sustainable development of nuclear industry were substantially formulated in general terms, which were later specified in details in the INPRO methodology developed at the IAEA (IAEA 2008). The main provisions of the methodology under discussion here served as the guidance in the development of the methodology of calculation of integral indicator of NES sustainability. Substantially similar approach to the development of advanced nuclear reactors is accepted as well in the Generation IV international project (GEN-IV 2015) which evidences the objective character of requirements imposed on the NES as pertains to the sustainability enhancement issues.

Development of technologies and infrastructure, expansion of cooperation are the mechanisms for complex enhancement of NES characteristics within the six subject areas addressed in the present study: economic performance, nuclear safety, availability of resources, waste handling, non-proliferation and public acceptance. Calculation of the NES sustainable development indicator required large volume of information on nuclear reactor and nuclear fuel cycle technologies, on the composition of reactor types and nuclear fuel cycle infrastructure, on the strategy and scenarios of development of power generation sector, on possible options of international cooperation within the sphere of nuclear power generation.

Achieving the goals of systematic enhancement of NES characteristics within several subject areas is a complex long-term task. On international level the ways for obtaining solution of this task are discussed in the INPRO Project "Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems" (ROADMAPS). Transition to NES satisfying the requirements of sustainable development is addressed in the project as the phased process where important intermediate tasks (key events) acting as the indicators of NES development are singled out. Expediency of determination in each of the subject areas of metrics characterizing closeness of the NES condition forecasted during each of the roadmap phases to the final goals of enhancement of sustainability accepted to be equal to 100% implementation of the complete program. The idea of integral assessment of the level of sustainable NES development in time amounts to the aggregation of metrics within separate subject areas.

Achieving key events is associated with implementation of specific programs requiring, as a rule, significant expenditures of labor and financial resources. There exist separate publications on the expected expenditures for implementation of these programs and other data serving as the input information for assessment of the significance of solution of intermediate tasks relative to the final goal of development of the NES fully complying with requirements of sustainable development. Issues of enhancement of NES sustainability referring to one or several subject areas are examined in different studies (Egorov et al. 2012, Egorov et al. 2013, Klimenko and Mironovich 2016). Qualitative assessment of NES is presented for a certain time moment in the area in question. However, as of today, quantitative assessment of the indicator of sustainable development of the system examined in dynamics during the time interval until the end of the century and allowing tracing variation of efficiency indicators with time, is not available.

The developed option of the metrics characterizing NES sustainability in the subject areas based on numerical values of the contributions of different key events in the achievement of final goals of sustainable development within these areas is discussed in the present study. Due to the incompleteness of information on the issue in question the approach under discussion must be regarded as the first approximation to the solution of the assigned task. Nevertheless, sensitivity analysis demonstrated stability of the obtained results on the assessment of integral indicator of NES sustainability within wide range of variation of numerical values of indicators of key events under the condition of keeping the unchanged order of sequence and relative significance of these events. Conclusion was formulated based on these premises that even with high enough uncertainty in the evaluation of numerical values of key events integral indicator of NES sustainability ensures the possibility of analysis of main trends of NES development during the extended time horizon.

Naturally, the starting point of any program of enhancement of the level of indicators of NES performance is the fulfillment of the requirements existing in the industry (Fig. 1). Nuclear power generation using well developed technologies and adequate regulatory and institutional basis can be regarded as NES of the first level of sustainable development.

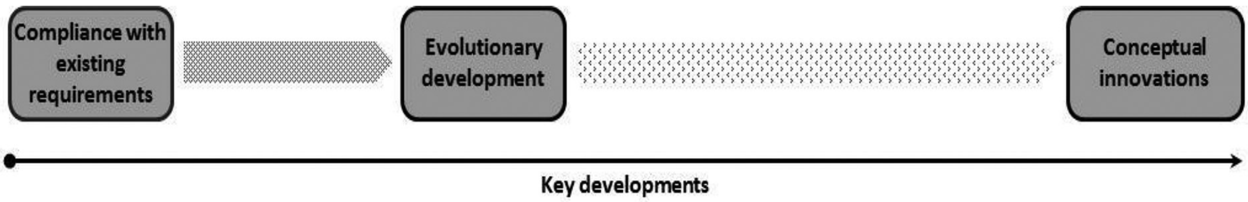

Figure 1. The phases for achieving sustainability of NES.

System including innovative components developed and implemented based on evolution approach can be assigned to the second level. Systems directed towards the radical renovation of technological and institutional platform of nuclear power generation refer to the third level.

Key events and fractions in percent showing the measure of implementation of complete program of sustainable development when these key events are achieved are determined for the subject areas significantly affecting the NES assessment examined in the present study.

- Safety area:
  – Compliance with existing national regulations and IAEA recommendations – 60%;
  – Compliance with requirements imposed on nuclear reactors of generation 3+: probability of vast discharge of radioactivity in atmosphere < 10^{-6}, application of passive safety systems, availability of containment and melt trap, possibility of safe shutdown within 72 hours from the moment of initiation of the accident, etc. (IAEA 20081, Goldberg and Rosner 2011) – 80 %;
  – Compliance with requirements imposed on reactor technologies of generation 4: probability of damage of reactor core – not more than that for reactors of generation 3+, exclusion of the necessity of resettlement of population in case of accidents, availability of passive automatic reactor shutdown systems, etc. (OECD 2014, IRSN 2012) – 90%;
  – Deterministic exclusion of severe accidents (White Book of Nuclear Power 2001) – 100%.
- In the area of economic performance:
  – Acceptable values of indicators during the phase of innovative technologies – 20%;
  – In the group of energy sources (wind, sun, etc.) with high cost of electricity included in the system for diversification of energy sources and ensuring energy and environmental security – 40%;
  – At the level of average indicator values for the electricity market – 80%;
  – The best economic performance within the energy generation sector – 100%.
- Area of resources:
  – Once-through nuclear fuel cycle with thermal reactors when less than 1% of natural uranium is utilized for production of electricity – 0%;
  – Inclusion of depleted or regenerated uranium in the fuel cycle, once-through plutonium recycling in thermal reactors – 20%;
  – Two-component system of thermal and fast breeder reactors with repetitive plutonium recycle – 80%;
  – Use of complete energy potential of all fissionable materials – 100%.
- Area of waste handling:
  – On-site storage of spent nuclear fuel – 0%;
  – Centralized long-term storage of spent nuclear fuel – 40%;
  – Final geological disposal of spent nuclear fuel – 80%;
  – Final disposal of wastes with extraction of plutonium and minor actinides (Ponomarev-Stepnoy 2016) – 100%.
- Area of non-proliferation:
  – Not all state liabilities, agreements and policy with regard to non-proliferation of fissionable materials are in correspondence with international norms – 0%;
  – State policy corresponds to international norms, low attractiveness of nuclear materials and nuclear technologies, difficulty to organize diversions, possibility of early detection of diversions are ensured (IAEA 2008, White Book of Nuclear Power 2001) – 40%;
  – The previous item is fulfilled and balance of production and consumption of nuclear materials within the nuclear fuel cycle is ensured – 100%.
- Area of public opinion and policy:
  – Absence of support by the majority of population and government – 0%;
  – Unstable support of nuclear power, significant scale of public discussions on the expedience of use of nuclear power – 20%;
  – Positive attitude of the majority of population and government – 40%;
  – Full support by the population and government – 100%.

Indicator of NES sustainable development $f_l(t_R)$ within subject area l for time interval t_R is calculated by adding up the fractions of implementation of tasks of sustainable development for key events for all the components included in the NES:

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

where $x_{li}(t_R)$ is the measure of sustainability of i-th component of the NES as pertains to the achieved key event within the subject area l for time interval t_R; $N_i(t_R)$ is the installed electric capacity of i-th NES component on the t_R; $N_{\text{NES}}(t_R)$ is the installed electric capacity of the whole NES on the t_R.

Integral indicator of sustainable development of the NES $SI(t_R)$ is calculated by summing up values of indicators of NES sustainable development for all subject areas $f_l(t_R)$:

$$SI(t_R) = \sum_{l}^{L=6} f_l(t_R) \cdot w_l(t_R), \quad (2)$$

where $w_l(t_R)$ is the weight factor determining significance of the subject area l on the t_R; L is the number of subject areas (L = 6).

$$\sum_{l=1}^{L} w_l = 1. \quad (3)$$

Similar weight factors (w_l = 1/6) are assigned to all subject areas in order to demonstrate the result achieved by the NES sustainability parameter without giving preference to this or that subject area. Examination of behavior of numerical sustainability indicator was conducted for the following three time intervals t_R: t_1 – [2015 – 2034]; t_2 – [2035 – 2054]; t_3 – [2055 – 2100].

At present the model is implemented using MS Excel electronic tables where necessary data on the NES conditions are entered for the time intervals under examination.

Nuclear energy systems under examination

Four options of development of nuclear energy system installed capacity of which reaches 150 GW(e) by the end of the century are simulated. Growth rate of capacities corresponds on the average to commissioning of 1.5 GW(e) per year taking into account replacement of decommissioned capacities. Issues of assessment of the system are examined taking into consideration the general requirements of sustainable development without correlation with specific conditions existing in this or that country. Measure of implementation of the program of sustainable development is determined in percent for each option in all subject areas (Fig. 2).

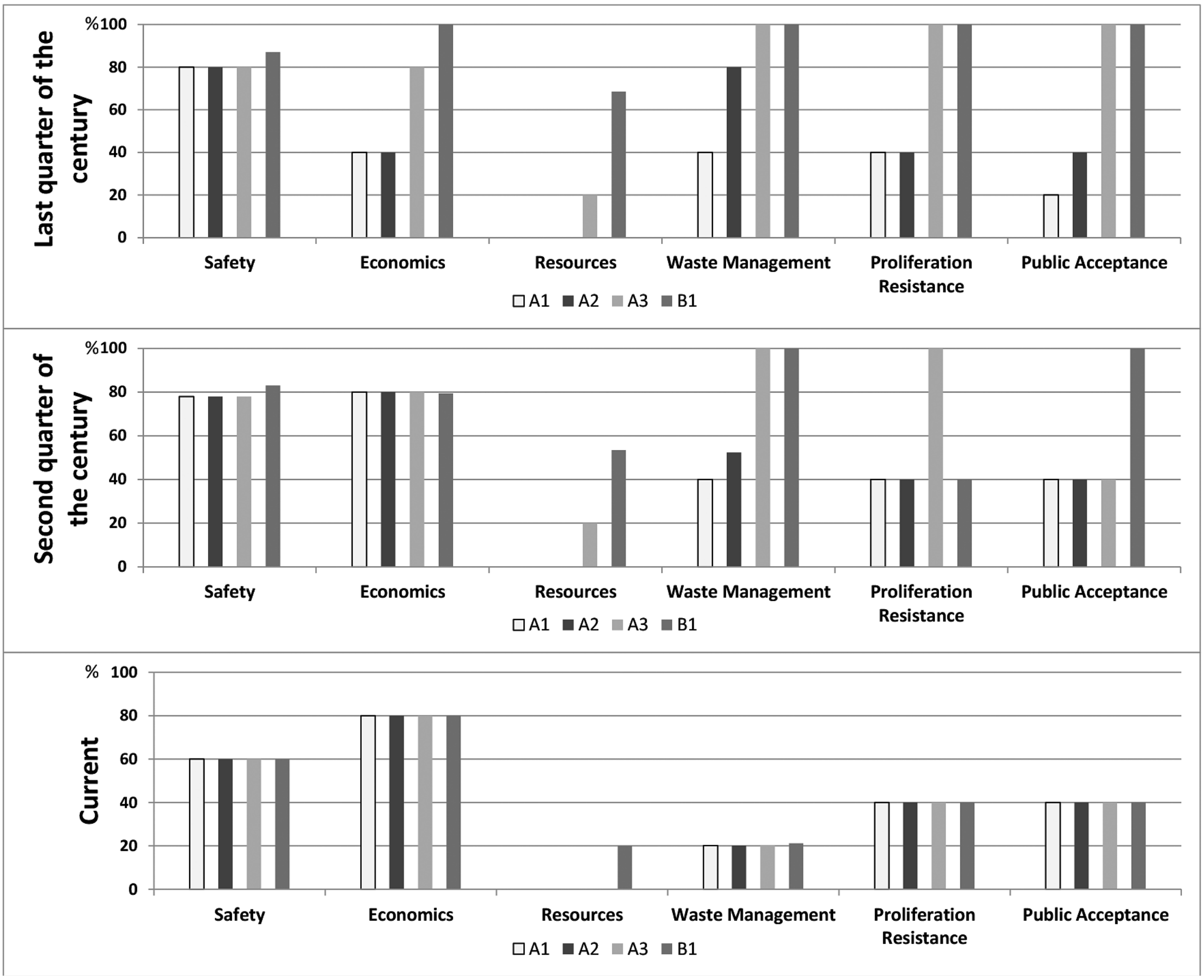

Figure 2. The long term evolution of the NES sustainability programme implementation.

Option A1 corresponds to extensive development of nuclear power in the countries, which are not planning the closing of the nuclear fuel cycle and postponing resolution of the issue associated with accumulation of spent nuclear fuel. NES A1 consists of thermal reactors of PWR type loaded with uranium oxide fuel operated within once-through nuclear fuel cycle. Increase of capacities is achieved due to the commissioning of advanced reactors of the above type. Spent nuclear fuel from such reactors is transferred to the on-site spent fuel storage facility and, after cooling the SNF down, it is transferred to the centralized dry spent nuclear fuel facility. There are no significant changes introduced in the applied technologies. International cooperation is limited by the services provided by the external market during the initial phase of the nuclear fuel cycle.

It was accepted based on the analysis of available papers that boundary conditions for this option vary during the second half of the century. It is expected that the forecasted growth of prices of natural uranium and costs of SNF storage will lead to the deterioration of economic indicators and, in accordance with the approach to the assessment of the measure of implementation of the program of sustainable development described in the previous section, will reduce the rating of the option in the area of economic performance from 80 to 40% (see Fig. 2).

Forecasting as related to the public attitude towards this of that NES option represents an exceptionally difficult task and is characterized with high uncertainty. Uncontrolled accumulation of SNF and plutonium contained in this fuel in the conditions of absence of clear plans of SNF handling raise already as of today public uneasiness and protests. Authors of the present study admit that such public sentiments will increase in the future especially in the case if the possibility of safe and economically acceptable solution of the problem of accumulation of SNF will be demonstrated. Therefore, assumption is accepted for option A1 that public support will be lost during the last quarter of the century (see Fig. 2).

Option A2 differs from option A1 as refers to handling spent nuclear fuel: during the second half of the century all countries implementing the option in question gradually introduce into operation facilities for final geological isolation of SNF or send SNF to the centers for their geological isolation created on the basis of international cooperation. It is assumed within the framework of the present study that achievement of the key event in question will allow mitigating acuteness of the problem of public acceptance of this option. This is, possibly, a fairly optimistic assumption, since disposal of plutonium and minor actinides requires convincing substantiation of environmental safety of SNF isolation objects during thousands of years and, during the latest period, this requires, besides the above, substantiation of safety according to criteria of non-proliferation of fissionable materials. Nevertheless, the accepted assumption allows estimating the maximum potential of the once-through nuclear fuel cycle in case of implementation of its final stage in the country.

Option A3. In this option as well as in option A1 the strategy of use of nuclear energy is based on the principle of minimization of nuclear fuel cycle infrastructure, but, however, it is assumed in this case that countries implementing Option A3 work in close cooperation with countries-suppliers of reactor technologies and nuclear fuel cycle services including services on SNF recovery for subsequent processing and use. Results of such policy must significantly impact the assessment of potential of the option with regard to the implementation of the program of sustainable development (Fig. 1).

Option B1 represents the two-component system consisting of thermal and fast breeder reactors with developed infrastructure of closed nuclear fuel cycle, which is currently comprehensively investigated in Russia (Ponomarev-Stepnoy 2016, Kagramanyan et al. 2015) and in France (Le Mer 2013). Thermal reactors are partially operated with uranium oxide fuel and partially on mixed uranium-plutonium fuel (MOX-fuel). In Option B1 commissioning of sodium-cooled fast breeder reactors and advanced thermal reactors with partial use of MOX-fuel is implemented starting from the year 2030. Thermal and fast reactors with characteristics improved with regard to a number of performance indicators are commissioned during the second half of the century (White Book of Nuclear Power 2001). It is assumed that Options A3 and B1 are implemented on the legislation basis allowing the possibility of provision and reception of the whole spectrum of nuclear fuel cycle services.

Results and discussion

Results of calculation of the indicator of NES sustainable development using formula (1) are presented in Fig. 3. The suggested dynamic approach to the assessment of index of NES sustainable development supplements the conventional methodologies of comparison of NES options on the basis of methods of discrete analysis of solutions (for example, Kviatkovskii et al. 2017, Andrianov et al. 2014, Kuznetsov et al. 2014, Schwenk-Ferrero and Andrianov 2017, Schwenk-Ferrero and Andrianov 2017a, Kuznetsov et al. 2015, Andrianov et al. 2017).

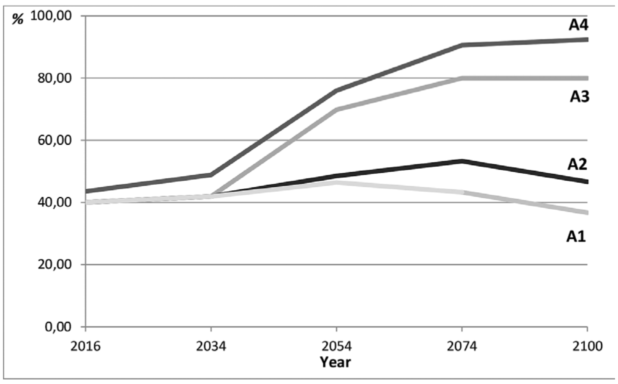

Figure 3. Calculated integral indicator of NES sustainability.

Indicator of sustainable development for Option A1 simulating NES with once-through nuclear fuel cycle grows approximately from the middle of the century due to the replacement of reactors of generations 2 and 3 with reactors of generation 3^{+} with improved safety characteristics, optimization of economic performance of use of nuclear fuel, construction of intermediate SNF storage facilities and implementation of other measures within the framework of evolution approach. However, these measures are becoming insufficient for stabilization of the indicator during the second half of the century in the case when factors of growth of price of natural uranium and costs of SNF handling, risks of proliferation of fissionable materials and reduction of public support of the option in question are realized.

Resolution of the issue of final geological disposal of spent nuclear fuel suggested in the present paper significantly enhances the sustainability indicator for Option A2 as compared to that for Option A1 during the second half of the century (Fig. 3). However, even optimistically appraising public attitude towards final disposal of SNF with highly radioactive wastes and fissionable materials contained in it absolute increase of the indicators of sustainable NES development for Option A2 is insignificant because of the presence of advancement to the goals of sustainable growth in other subject areas of the assessment: the potential of radical reduction of radiotoxicity of wastes during the foreseeable time horizon and of saving natural uranium resources is excluded while the need of implementation of costly measures for ensuring guarantees of non-proliferation of fissionable materials during final SNF disposal remains.

Higher level of sustainable development is achieved when the country pursuing once-through nuclear fuel cycle (Option A3) transports SNF to the country possessing infrastructure of the closed nuclear fuel cycle (Option B1) for its reprocessing and utilization of fissionable materials. Fast reactors utilizing plutonium (and, subsequently, minor actinides as well) extracted from reprocessed nuclear fuel of thermal reactors reduce the volumes of accumulated nuclear wastes and their radiotoxicity which significantly impacts sustainability parameters within the area of waste handling. Besides that, they allow cardinally expanding the base of fuel resources for nuclear power generation and developing capacities of the latter to any required scale. Both these factors are critical for the concept of sustainable development and are reflected in the assessment of sustainability parameter characterizing this development (see Fig. 1). Resolution of complex issues of both national and international legislation as well as substantiation of economic expediency are required for implementing promising Options A3 and B1.

Conclusion

The calculation method worked out in the present study and the model developed on its basis were applied for calculating the integral indicator of sustainable development for the preset forecasting time intervals for several alternative NES options following scenarios constructed until the end of the century. Comparative assessment of options of transition of nuclear power to sustainable development was obtained using the above instruments. It was demonstrated that NES on the basis of once-through nuclear fuel cycle with thermal reactors and uranium fuel is characterized with fairly low level of the indicator of sustainable development, and resolution of the issue of disposal of spent thermal reactor fuel by its final disposal in geological storage facilities does not resolve all problems of once-through nuclear fuel cycle according to sustainable development criteria. Introduction of fast reactors in the system and closing nuclear fuel cycle with plutonium recirculation in thermal and fast reactors results in significant increase of the indicator of sustainable development. Expansion of international cooperation during the final stage of nuclear fuel cycle for the option with utilization of fissionable materials from spent fuel delivered by user country to the supplier country possessing fast reactors and closed nuclear fuel cycle technologies makes significant contribution in sustainable development of both partner countries.

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