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Research Article

Advanced development of nuclear power as a factor in ensuring sustainable development of humanity*

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Abstract

The future of nuclear power has been widely discussed by the scientific community and the public, which is explained by the high potential of peaceful nuclear technologies in providing mankind with affordable energy, preserving the climate, developing industry, medicine, science, and education. The materials of the study are devoted to assessing the impact of nuclear power on modern challenges and achieving indicators that are reflected in the Sustainable Development Goals. The paper uses the provisions of the intersystem interaction theory, system models for managing basic target indicators, methods of correlation, regression, autoregression analysis. The study confirmed the positive impact of nuclear power on the integral indicators of sustainable development. Considering the resource constraints, the preferred scenario for nuclear power development was substantiated, and its impact on achieving the integral indicators of the Sustainable Development Goals was assessed.

Keywords

nuclear power, advanced development scenario of nuclear power, sustainable development, Sustainable Development Goals

Introduction

Today, the world community views sustainable development as one of the most important long-term objectives achieving which requires joint solutions to be developed by representatives of humanity with respect to the extensive list of interdependent global challenges. Based on global evolution scenarios, the world's population is expected to grow to ten billion by 2050, this increase to be largely achieved at the expense of developing countries facing the problem of poverty. Currently, over two billion people are not provided in full with clean water, and basic medical and energy products, their quality of life being far from the living standards enjoyed by modern developed countries. As a result, along with developing the world economy, covering the growing demand for resources, preserving the environment, and supporting climate control, the world community needs to assess on a permanent basis the effect of the initiatives being developed and implemented on the interests of the global majority of the planet's population and those living in poor countries. Common approaches to assessing global challenges and developing ways to address these are reflected in the concept and structure of the Sustainable Development Goals (SDGs) adopted at the UN Sustainable Development Summit in 2015.

The role of nuclear power (NP) in the long-term evolution of civilization has been extensively discussed to

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date in scientific community and media and is analyzed in detail in publications by Rosatom State Corporation (Rosatom State Corporation. Sustainable Development). The development of peaceful atom technologies, along with exploration of space, automation and robotics, genetic engineering, and the increase in the share of renewable energy sources (RES), is considered as one of the global initiatives (projects) capable to influence significantly the situation in many national economies and humanity as a whole (Podchufarov et al. 2021). The results of this study are devoted to assessing the effect the share of nuclear power has on the SDG achievement depending on the predicted scenarios for transforming the world energy balance structure by 2050 and providing rationale for the highest-priority scenario.

Literature overview

At the current stage of human development, the concept of sustainable development has led to new opportunities emerging for addressing global challenges. In recent decades, studies in this field have been widely presented in papers by Russian and foreign authors. Most studies treat sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, as formulated in 1987 in a report called “Our Common Future” from the World Commission on Environment and Development (A/RES/70/1 2015). The modern debate on sustainable development dates back to the report entitled “Limits of Growth” delivered to the Club of Rome by D.H. and D.L. Meadows which emphasized the need for a balanced approach to human development that took into account environmental constraints (Brief overview of reports to the Club of Rome). As part of the scientific discussion on the proposed principles, there has been an extensive array of investigation results presented which are devoted to the analysis of the prerequisites for the sustainable development concept, and the provisions of the Millennium Development Goals (MDGs) and the SDGs adopted at the 2015 UN Summit (Shi et al. 2009; Nemtsev 2015).

The results of investigations on the approaches to assessing the sustainable development targets based on integral indices have been discussed extensively. The most common of these are the Human Development Index (HDI), the Happy Planet Index (HPI), the Sustainable Development Goals Index (SDG Index), and the Sustainable Development Index (SDI) (Dervis and Klugman 2011; O’Brien 2013; Hickel 2020). Depending on the methodology used, the indices are calculated based on dedicated sets of macroeconomic indicators and expert assessments.

Many studies on sustainable development analyze the relationship between the SDG indicators and forecast macroeconomic trends. Special attention is given to assessing the effect of the energy balance structure on the level of economic development, energy consumption, carbon emissions, industrial development, urbanization, and agriculture. In most cases, authors divide the effects of the energy impact into indicators for developed and developing countries, energy exporting countries, and energy-dependent countries (Goldemberg and Lucon 2009; Eregha and Mesagan 2017; Grachev 2018; Safdar et al. 2019).

In many cases, investigations are based on the system approach, theoretical assumptions on the interaction of systems, and the fundamentals of vector optimization and scenario analysis (Odum 2007; Podchufarov and Ponyatsky 2019). Correlation, regression and autoregression methods have been commonly used for handling statistical samples (Fischer 1993; Arzhenovskiy and Sinyavskaya 2018).

The investigation results presented in literature encompass, among other things, the analysis of the NP relationships with MDGs and SDGs (Leontief 1997; Rogner 2010; Lee and Chiu 2011; Önder and Gündüz 2019; Pioro et al. 2019; Nigmatulin 2019; Podchufarov et al. 2022; Soloviev et al. 2022). As part of the major arguments in support of the NP development, the authors identify the availability of a stock of raw materials for manufacturing nuclear fuel, which are sufficient to provide humanity with energy for several thousand years, and net-zero carbon emissions from nuclear facilities at the stage of operation. The opportunities offered by advanced NP technologies, such as small nuclear generation, closed nuclear fuel cycle technologies, hydrogen nuclear power, and, in a longer term, thermonuclear and plasma technologies, define further arguments in support of the active NP development. Publications note the positive effect of NP on particular SDG indicators, including poverty eradication (SDG 1), public health (SDG 3), sustainable energy (SDG 7), economic growth (SDG 8), infrastructure development (SDG 9), reduction of inequalities (SDG 10), climate change (SDG 13), and development of international cooperation (SDG 17) (Rogner 2010; Pioro et al. 2019; Podchufarov et al. 2022). To justify the positive multiplicative effect of NP on the economic activity of related industries, many papers refer to the interindustry analysis theory by Leontyev 1997. As part of current issues requiring further study, the authors identify safeguards for ensuring on an unconditional basis the safety of nuclear facilities, compliance of the technologies used for radioactive waste disposal with the IAEA population and environmental protection standards, and relatively high capital costs of the nuclear facility construction, as compared with alternative low-carbon technologies (SDGs 7, 12). The authors consider these issues in connection with the NP effect on public health (SDG 3), and the state of land and water ecosystems (SDG 14, 15). In the context of the current geopolitical situation, there has been an intensive debate concerning the potential risks from illegal use of dual-purpose NP technologies (Rogner 2010; Nigmatulin 2019).

As part of the NP evolution constraints, investigators also note the inertial nature of the increase/decrease in the resource capabilities for the construction of nuclear power plants (NPP). According to an IEA report, more than 60% of the NPPs in the world are currently over 30 years old, and the number of NPPs in developed countries is expected to decrease by one third by 2030. By 2050, it is planned to decommission all reactors started before 1990, and with the NPP installed capacity planned to be increased to 2000 GW by the middle of the century, it would be necessary to build up to 50 new units annually, which is obviously infeasible (Mourogov 1997; IAEA-RDS-2/42 2022; Nuclear Power and Secure Energy Transitions 2022). Additionally, the development of NP is expected to be hindered by insufficient political and public support, lack of the required infrastructure, and shortage of skilled personnel (Kim 2009)].

In general, despite a great deal of work done to define the prerequisites, analyze the current state, assess the prospects for the SDG achievement, and identify the relationships of NP with particular SDG indicators, the potential for the integral effect of NP as a global initiative on the SDG set has been disclosed to date to a highly limited extent, which defines the urgency of further research in the field.

Methodology of investigation

The methodological basis for the study is formed by provisions of the systems interaction theory and interdisciplinary approaches to managing base targets, including the MCC approach. To estimate in an integrated manner the NP effect on the SDG achievement, the human (HDI) and sustainable development (SDI) indices were adopted as integral sustainable development indicators taking into account economic, social and environmental aspects. When calculating the SDI, apart from life expectancy, average/expected education time and income level indicators the HDI includes, components that characterize the CO_2 emissions and total resource consumption are taken into account (Hickel 2020). All components of the indices are calculated on a per capita basis. Total values are measured in a range of 0 to 1 (Sustainable Development Index 2021).

Twelve countries were selected for the study: eight developed countries (Great Britain, Germany, Spain, Canada, the USA, France, South Korea, Japan) and four developing countries (Brazil, India, China, Russia). The macroeconomic environment conditions, the share of NP in the energy balance structure, the reserves of natural resources, and national policies in the field of supporting the development or reduction of NP in the period from 1990 onwards were analyzed for each country. In 2022, the countries under consideration accounted for over 85% of the global nuclear generation and are characterized by medium and high income levels and non-uniform indicators of natural resource reserves. The paper uses statistical samples from the World Bank and IAEA PRIS databases, materials from the International Energy Agency (IEA), Bloomberg New Energy Finance (Bloomberg NEF), the Intergovernmental Panel on Climate Change (IPCC), and the SDI Project. The interdependence of NP, the HDI and SDI indices, and their components was investigated using correlation and regression analysis methods.

Findings

The effect of the share of nuclear generation in national energy balances on the components of the HDI and SDI indices was estimated using statistical samples formed based on information resources of leading international organizations and analytical agencies (Ritchie and Rosado 2021; Sustainable Development Index 2021; The World Bank 2021; IAEA-RDS-2/42 2022). Summarized trends in the dynamics of the indicators under investigation are presented in Table 1 (plotted by the authors based on the Sustainable Development Index Time Series and the IEA). The multidirectional trends for the change in the HDI and SDI indices (to a greater extent for developed countries, and to a smaller extent for developing countries), the positive dependence of the NP share and the dynamics of the SDI index for most countries and of the HDI index for Russia and China defined the initial prerequisites for analyzing the existing dependencies and quantifying the effect of NP on the integrated SDG indicators.

Table 1. Dynamics of SDIs, HDIs and the NP share in countries under consideration

Country	Indicator	Trend	Country	Indicator	Trend
Brazil	SDI	Growth	China	SDI	Plateau
	HDI	Weak growth		HDI	Growth
	NP share	Growth		NP share	Strong growth
Great Britain	SDI	Weak decline	Russia	SDI	Plateau
	HDI	Growth		HDI	Weak growth
	NP share	Weak decline		NP share	Growth
Germany	SDI	Decline	USA	SDI	Decline
	HDI	Growth		HDI	Growth
	NP share	Decline		NP share	Weak growth
India	SDI	Growth	France	SDI	Weak decline
	HDI	Weak growth		HDI	Growth
	NP share	Growth		NP share	Weak growth
Spain	SDI	Decline	South Korea	SDI	Decline
	HDI	Growth		HDI	Weak growth
	NP share	Weak decline		NP share	Weak decline
Canada	SDI	Decline	Japan	SDI	Decline
	HDI	Growth		HDI	Growth
	NP share	Weak decline		NP share	Strong decline

The effect of NP on the HDI components is defined to a great extent by the HDI relationship with the dynamics of weighted average prices for energy sources. The dependencies of the population's incomes, life expectancy and education level the HDI includes on energy prices have been investigated in reasonable detail and are described in scientific literature (Lee and Chiu 2011; Evans 2016; Eregha and Mesagan 2017). As part of this study, an analysis was undertaken further for the effect of the energy resources cost on the population income level for different categories of countries (developed and developing): countries with their own energy resources and energy-dependent countries. For each of the categories, weighted average indicators of income level were calculated, and regression models of their dependence on weighted average energy prices were built. The results of considering the countries with domestic energy resources demonstrate a major positive effect of the price growth on the income level in developing countries ($\beta = 184.28$, $p < 0.05$) and a minor positive effect for developed countries ($\beta = 77.90$, $p < 0.05$); for energy-dependent countries, a strong negative effect has been demonstrated for developing countries ($\beta = -552.88$, $p < 0.05$) and a strong positive effect for developed countries ($\beta = 3333.91$, $p < 0.05$). The obtained results confirm the need for taking into account the effect of NP on the components of the indices under consideration in conditions of systemic changes, macroeconomic cycles and individual shocks.

As part of estimating the effect of NP on the HDI components, the least investigated area was associated with analyzing the dependencies between the share of nuclear generation, the level of CO_2 emissions and the total resources consumption that define the difference between the SDI and HDI indices, and their relationship with the SDI index components.

To address this problem, a correlation analysis was undertaken at the initial stage for the relationship between the indicators of the NP share in the energy balances of the countries under consideration and the respective SDI index values. To find out if the samples were homogeneous and if there were major differences between the categories of countries, an end-to-end panel regression was built based on 1990–2019 statistical samples, which links the analyzed time series with dummy variables corresponding to the categories of countries under consideration. Based on the estimates obtained for the statistical significance of the "developed/developing countries" variable, auxiliary indices were built for developed and developing countries based on the centering method and the time series values were adjusted, which made it possible to exclude trends other than related to the NP effect. The Pearson correlation coefficients calculated for the analyzed time series are 0.61 for Brazil, 0.67 for India, 0.53 for China, 0.38 for Russia, 0.45 for Great Britain, 0.60 for Germany, 0.70 for Spain, 0.45 for Canada, 0.58 for France, 0.72 for the USA, 0.62 for South Korea, and 0.53 for Japan. The obtained indicators of the strong relationship between the NP shares and the SDI values defined the next stage in analyzing the NP effect on the SDI components.

The choice of the time series analysis methods was justified using the Johansen cointegration test. No multiple cointegration vectors were found as the test result, which confirmed that it was possible to use vector autoregressive (VAR) models. In the process of their construction, statistical samples were checked for being stationary using the Augmented Dickey-Fuller Test, the Phillip-Perron Test, the Kwiatkowsi-Phillips-Schmidt-Shin Test, and the Breakpoint Unit Root Test. With deterministic (TS series) or stochastic (DS series) trends being present in the samples for particular countries, the respective time series were reduced to a stationary form by detrending method or by transition to first-order differences. The quality of the VAR models built for the twelve analyzed countries was checked by means of diagnostic tests for the normal error distribution (VAR Stability Condition Check), autocorrelation of the residuals (Autocorrelation LM Test) and heteroskedasticity of the residuals (White Heteroskedasticity Test).

A causality analysis by way of Granger causality tests made it possible to justify the existence of a major positive effect of the NP share on reduction of CO_2 emissions and, to a smaller extent, on reduction of the total resources consumption and the well-being level increase for the considered time interval for developed countries. It was confirmed for developing countries that there was a major positive effect of the NP share on the level of income and, to a smaller extent, on the level of CO_2 emissions and the expected education level. For most of the countries under consideration, the effect of the change in the NP share on the SDI components is observed after three to four years.

The dependencies identified using the developed models made it possible to estimate the effect of the NP share on the HDI and SDI components in conditions of different scenarios for the long-term evolution of global power. The composition of the analyzed scenarios was determined based on citation indicators of the global energy balance structure forecasts from the world's leading analytical organizations (Fig. 1) (Podchufarov et al. 2022). There is a substantial variation in the forecast indicators observed in the composition of the list of scenarios formed, this being explained by the difference in the assumptions made by the authors, based both on trends for an advanced increase in the share of renewable energy sources and on the need for the rapid evolution of nuclear facilities.

For the analyzed scenarios, weighted average prices for primary energy sources until 2050 were forecast, taking into account the potential for a transboundary carbon regulation (TCR) mechanism to be introduced (Fig. 2 shows the authors' calculations based on the scenarios from the IES, the CNPC (China), the EIA (USA), the IPCC, the IEA, the IEC, and Bloomberg NEF, and the global energy price index).

As part of estimating the potential for the effect of the NP evolution on the integrated SDG indicators until 2050, three base scenarios were selected that characterized the change in the share of NP in the global energy consumption structure: a scenario with a major decrease in the share of NP (the share of NP to decrease to 2%), a scenario with a slow growth in the share of NP (a planned growth at a level of 9%), and a scenario with a highly dynamic evolution of NP (the share of NP to increase to 66%). The selected scenarios correlate with the Stagnation Scenario from the Institute for Energy Strategy, the IEA's Sustainability Scenario, and Bloomberg NEF's Red Scenario. Based on the produced VAR models, the HDI and SDI components were forecast for each scenario. For countries other than on the analyzed list, the change in the index components was assumed to be equal to the historical growth rates. To calculate the world SDI index in accordance with the methodology described in Hickel 2020; Sustainable Development Index 2021, the calculated SDI indices by countries were taken into account in proportion to the share in the number of the world's population.

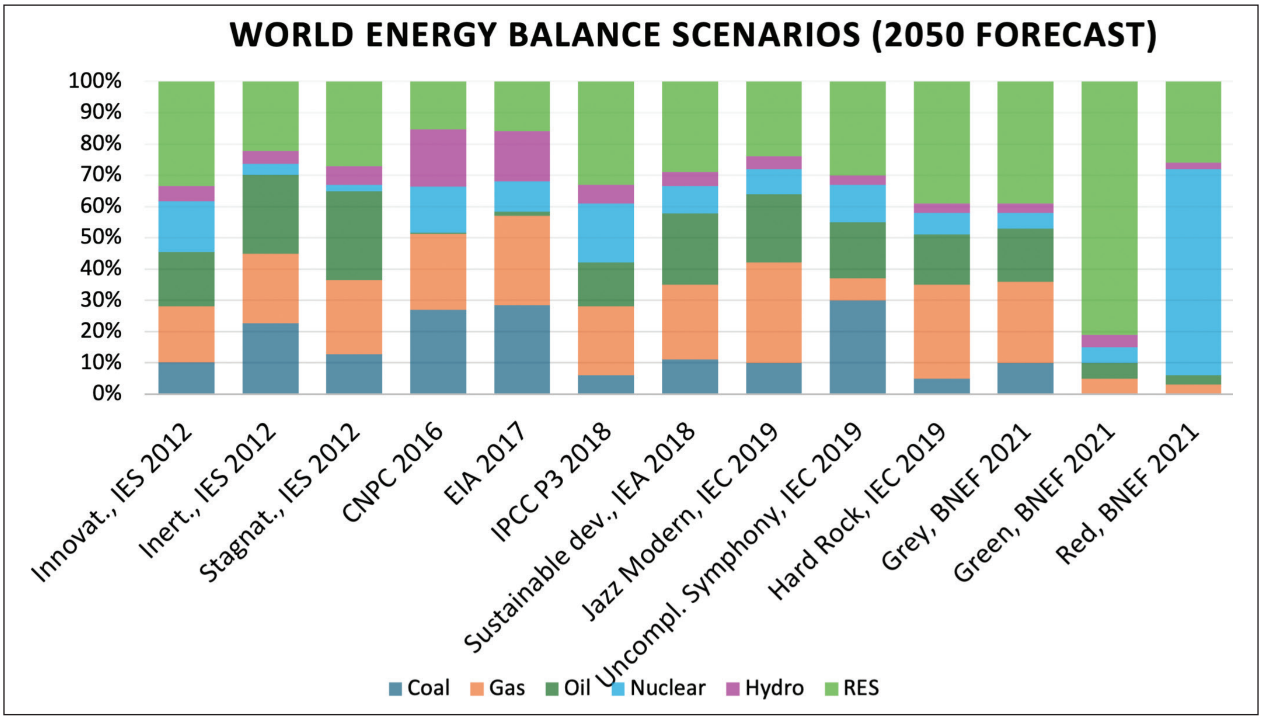

Figure 1. Comparative overview of the world energy balance scenarios (2050 forecast, scenarios from IES, CNPC (China), EIA (USA), IPCC, IEA, IEC, Bloomberg NEF).

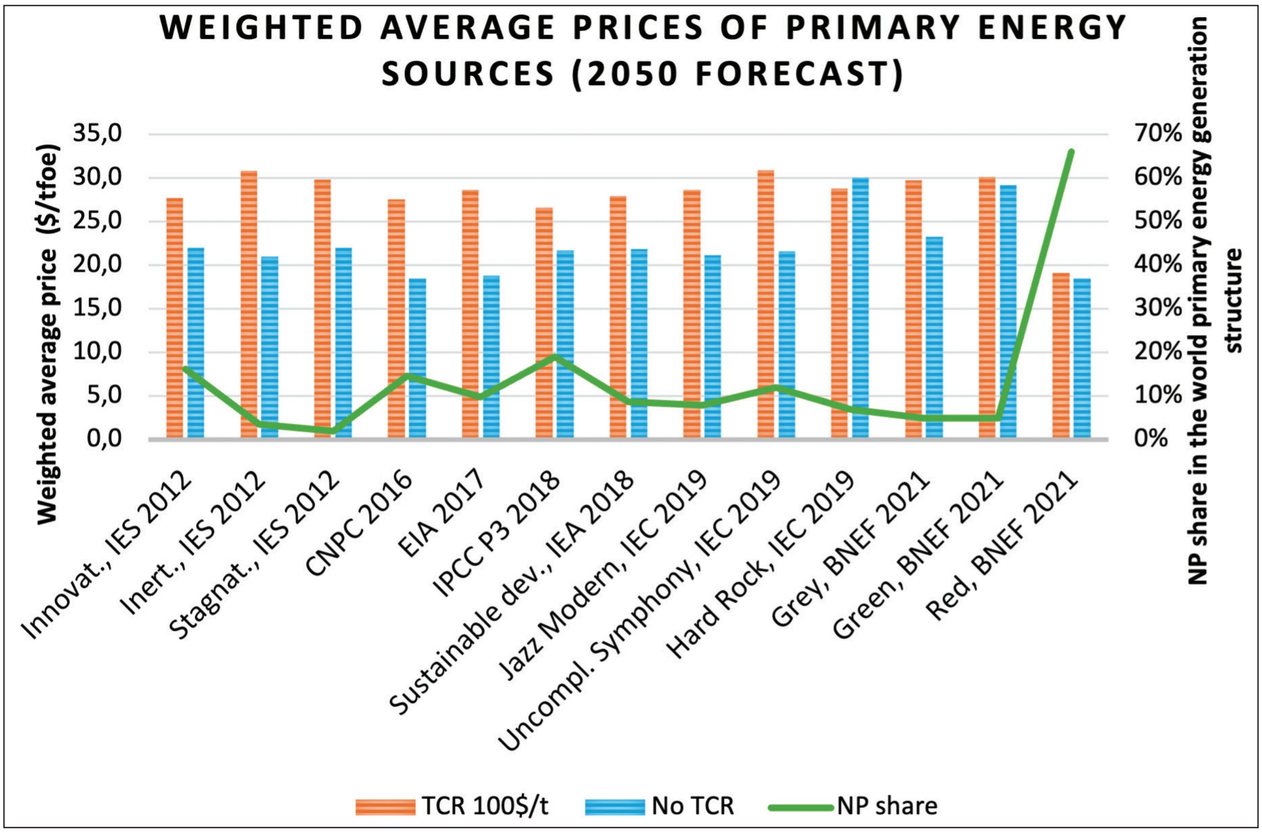

Figure 2. Comparative overview of weighted average prices for primary energy sources (2050 forecast).

The obtained indicators of the NP share in the global energy balance and the global SDI index, depending on the power evolution scenarios, were calculated by the authors based on the Sustainable Development Index Time Series and the IEA and are disclosed in Fig. 3.

The scenario with a major decrease in the share of NP as described in the IES report aims to minimize the share of NP in the world energy balance by 2050, and suggests that the existing groundworks are dismantled, and the development of industrial peaceful atom technologies is abandoned.

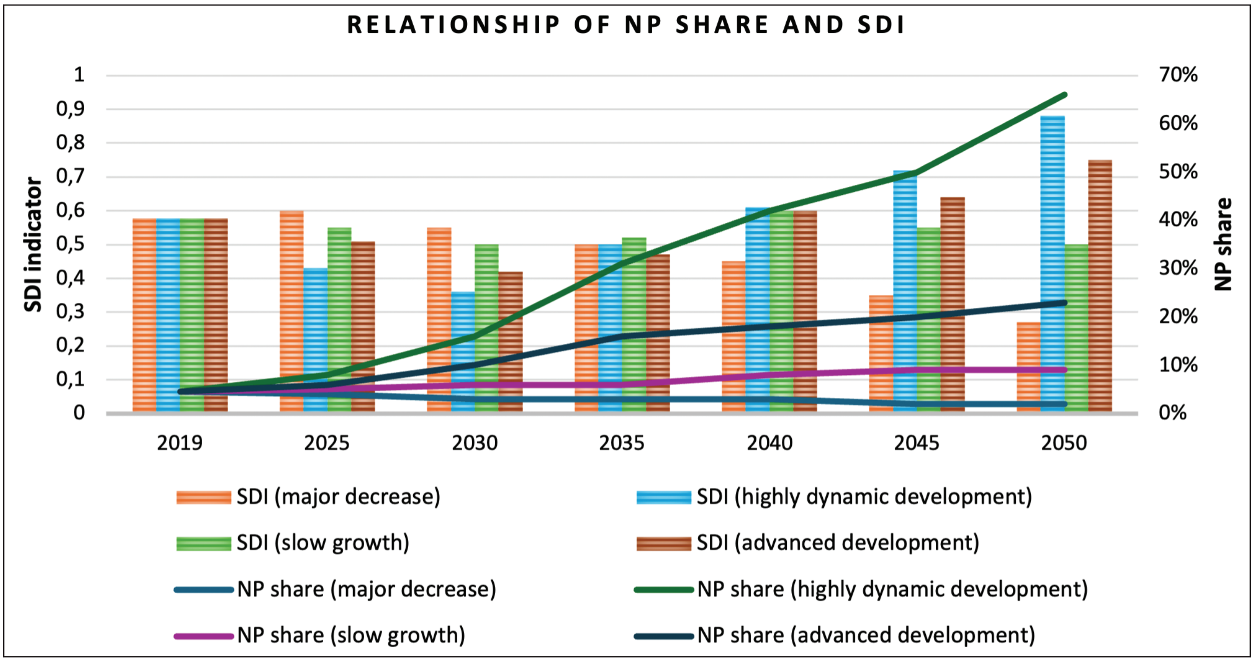

Figure 3. Sustainable Development Index (SDI) as a function of the nuclear power share in the world energy balance.

As part of this scenario, until 2040, the world SDI index will not change greatly, but given the depletion of natural resources and smaller use of these by 2050, it shows a decrease, which is associated with the growth in the cost of primary energy resources leading to a decrease in the population's income level. The predominance of nonrenewable energy sources in the energy balance and the consequences of fossil fuel burning increase the environmental and CO_2 emission impacts from extraction of resources. A further negative effect on the population's well-being can be caused by job cuts as the result of a decline in production due to an energy cost increase which, in turn, is expected to slow down the development of related branches of the high-tech sector. As part of the scenario in question, some of the developed countries have a potential for improving their economic positions, but changes are possible exclusively due to a major decrease in the population's living conditions in developing countries and a growth in the share of the planet's population living below the poverty line. The forecast SDI indicator by 2050 for the given scenario is estimated at 0.25 to 0.3.

The scenario with a slow NP growth presented in the IEA's World Energy Outlook 2018 takes into account in part the current trends in the world power, considers the NP technologies as part of the "green" agenda's transitional status, and expects the share of NP to double gradually against the present-day value. In this scenario, the SDI index grows at a small rate, but decreases by 2050 since an increase in the energy consumption and depletion of natural resources will cause a growth in energy carrier prices, and the forecast share of NP is not enough to keep prices down. As a consequence, a further increase can be predicted in the gap between the population's living standards in developed and developing countries. The SDI indicator is expected to be 0.45 to 0.5 by 2050.

The scenario with a highly dynamic development of NP presented by Bloomberg NEF in 2022 provides for an increase in the current share of NP by more than a factor of 16. It takes into account a major amount of financial investment at the initial stages of the nuclear generation capacity growth. The potential result is redistribution of funds, underfunding of particular industries and, as a result, a decrease in the SDI within the initial decades. The SDI positive dynamics indicators will have additional inertia characterized by a time lag of four to five years to be required to increase the capacity of NP-related high-tech industries. The calculated SDI indicator for this scenario by 2050 is equal to a value between 0.85 and 0.90 but the scenario is not feasible due to the existing resource constraints.

An analysis was undertaken which made it possible to justify the preferred scenario for achieving the integrated SDG indicators referred to as the NP Advanced Development Scenario. The proposed option takes into account the indicators for the scenario with a highly dynamic NP development and the existing resource constraints (Fischer 1993), and is characterized by the following shares of energy sources in the world energy balance by 2050: NP (20 to 25%), RES (up to 30%), hydropower (5 to 10%), coal (5 to 10%), natural gas (20 to 25%), oil (10 to 15%). The NP Advanced Development Scenario has an intermediate position between the highly dynamic development and slow growth scenarios. It provides for an increase in the share of nuclear generation by nearly five times against the current indicators, while is two and a half times behind the highly dynamic evolution scenario. The applied nature of the estimates obtained for the increase in the share of NP in the energy balance is confirmed by strategic energy development programs in most of the countries under consideration as part of the study, including Russia, India, China, Brazil, the USA, Canada, France, and Great Britain. The results of the world SDI index forecast for the NP Advanced Development Scenario show the SDI index dynamics to be similar to the highly dynamic NP development scenario. By 2050, the index value increases while having shown previously a minor drop caused by the high cost of investment projects in nuclear industry. Beginning in the second half of the 2030s, with a lag of four to five years taken into account, the SDI starts to grow and will reach a global average figure of 0.7 to 0.75 by 2050, the current value being 0.57. The expected changes in the framework of this scenario are associated with a smaller gap in the living standards between developing and developed countries, a major improvement in the living conditions for the global majority of the planet's population, and a decrease in the poverty rates.

Conclusions

This study presents an analysis of the prerequisites for the sustainable development concept and approaches to estimating the SDG indicators based on integral indices, and an analysis of the relationships between NP and the SDG indicators. Peculiarities have been identified in the development of recognized regularities that define the effects of the energy resources cost on the population's income level for different categories of countries (developed and developing), including countries with domestic energy resources and energy-dependent countries. Using the developed models, dependencies have been justified which links the share of nuclear generation in the global energy balance and the HDI and SDI indices used in the study as integral indicators of the SDG achievement.

The obtained results were used to estimate the effect of the NP share on the HDI and SDI components as applied to scenarios for the long-term development of the global energy industry. An interpretation of the findings is presented. In conditions of the existing resource constraints and the objectives defined for achieving the integral SDG indicators, the NP Advanced Development Scenario has been justified as the preferred one as compared with the alternative options considered. The proposed scenario provides for an increase in the NP share in the global energy balance to between 20 and 25% by 2050. The world SDI index for the presented scenario is forecast to be in a range of 0.7 to 0.75, the current value being 0.55. Major changes are expected in the field of substantial improvements in the living conditions for the global majority of the world's population, a decrease in the gap between developing and developed countries, and the poverty rate reduction.

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