

Criteria of return on investment in nuclear energy

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Abstract

Analytical relationships between the investment performance criteria (net present value (*NPV*), levelized cost of electricity (*LCOE*), internal rate of return (*IRR*), discounted payback period (*T_{PB}*), and discounted costs (*Z*)) and basic engineering-economic parameters of nuclear reactors (capital costs *K*, annual operating costs *Y*, annual revenue *R*, NPP construction *T_C* and operation *T_E* periods), characterizing the NPP profitability and competitiveness at the microeconomic level, are defined for the first time. The power function of discounted cash flows was used in calculations.

It is shown that the joint analysis of the entire set of investment efficiency criteria (not only *LCOE* as it is often done) can help avoid contradictions in assessing the NPP project profitability and formulate optimal requirements on the reactor engineering and economic parameters. The obtained analytical expressions provide solutions not only of the traditional «direct problem» (assessing efficiency criteria according to the forecasted capital and operating costs and profit stream) but, which is of equal importance, the solution of the «inverse problem»: assessing restrictions on capital and operating costs, i.e. identifying «investment corridors», based on the desired values of efficiency criteria.

The investment risk assessment results obtained by Monte-Carlo method are presented in order to account for the inherent uncertainties in the forecasts of long-term cash flow during the NPP construction and operation required for assessing the efficiency of investments. The calculation results of probability distributions of the investment efficiency (profitability) criteria are presented for the specified ranges of uncertainties the forecasted cash flow. It is shown that the risk of project unprofitability can be quite high. In order to reduce investment risks, it is necessary to justify the changes in basic reactor parameters (decrease in *K*, *Y*, *T_C* and increase in *R* and *T_E*) and uncertainty ranges in the initial data.

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Keywords: Investment efficiency criteria; Nuclear energy; Nuclear power reactor; Capital and operating costs; Revenues; Discount rate; NPP competitiveness; Monte-Carlo method.

Introduction

The conditions of stiff competition between the companies offering Generation III and Generation III+ nuclear power reactors are currently being shaped on the global oligopolistic NPP construction market [1–3]. A number of criteria (indicators) are used for assessing competitiveness of different reactor design projects which can be subdivided into the following levels: microlevel, mesolevel and macrolevel [4,5]. However,

the primary “nucleus” of the system of indicators of competitiveness of the NPP construction project is the set of technical and financial parameters of the nuclear power reactor which ensures investment attractiveness of the project, i.e. its guaranteed return on investment or profitability (microlevel).

After publication in 2000 of IAEA guidelines [6] on the economic assessment of tender offers as pertains the NPP construction on the basis of “discounted cost of electricity” during the whole lifecycle of electric power generation facility *LCOE* (levelized cost of electricity) the *LCOE* value representing the minimum cost of produced and delivered electricity becomes both in Russian and in foreign literature the main criterion of competitiveness of construction of power plants of different types [7–12]. However, the so-called “net present value” *NPV* [1,13–18] serves as the principal crite-

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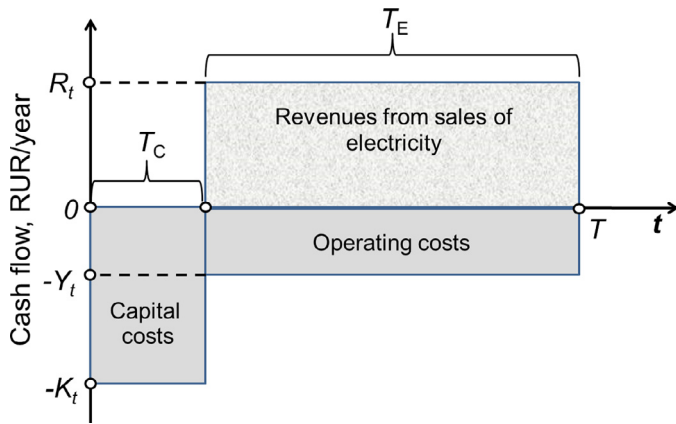


Fig. 1. Base layout of expected annual cash flows within the investment project (power plant construction and operation) throughout the whole life-cycle duration T .

tion of profitability of investment project. In this case, other auxiliary criteria such as the levelized cost of electricity $LCOE$, internal rate of return (IRR) and discounted payback period (T_{PB}) follow from the mathematical definition of the net present value. Emphasis laid in a number of publications solely on the levelized cost of electricity, which is, of course, a very convenient parameter for comparison of different power generation facilities, may result in the controversy with the criterion of profitability of the project NPV . In a number of studies, for instance, in [11,12,19,20], NPV , $LCOE$ and IRR criteria are discussed in the economic analysis of NPP projects, but, however, their mutual interference has not yet been investigated.

Therefore, the purpose of the present study is the determination of the analytical interrelation between technical and financial parameters of nuclear reactors and the criteria of efficiency of investments in NPP construction characterizing competitiveness (payback) of NPP on microeconomic level. Results of assessment of investment risks for NPP construction project using Monte-Carlo method are presented in connection with uncertainties inherent in the long-term forecasting of cash flows during construction and operation of NPPs required for assessing efficiency of investments.

Net present value

Net present value NPV (in rubles) is the “net discounted profit” [1,6,8,13–16] accrued (summed up) during the whole life-cycle T (years). Taking into account that annual monetary expenditures (runoffs) $C_t = K_t + Y_t$ (RUR/year) are divided for the sake of convenience of analysis into the following two components – capital costs K_t and operating costs Y_t (for example, as in Fig. 1), general expression for NPV is split into two parts with different limits of summation as follows:

$$NPV = \sum_{t=1}^T \frac{R_t - C_t}{(1+p)^t} = - \sum_{t=1}^{T_C} \frac{K_t}{(1+p)^t} + \sum_{t=T_C+1}^T \frac{R_t - Y_t}{(1+p)^t}. \quad (1)$$

Here, $R_t - C_t$ is the net profit during year t defined as the difference between the expected annual revenue flow R_t and

the expected costs flow C_t . Each annual difference ($R_t - C_t$) is reduced to the starting moment by multiplication by the reduction factor (present value index) $(1+p)^{-t}$. The value p (1/year) is the discount rate (norm). This value characterizes the annual profitability of the project similarly to the profitability (interest rate) of a bank account (deposit) and must exceed the cost of capital attracted as investments. There exist numerous guidelines on the selection of discount rates taking into account inflation, investment risks and other factors influencing the profitability of the project [6,8,11,12,17,18]. Similar discount rates equal to 3, 5 (or 7) and 10%/year are often used abroad for preliminary comparative assessments of different power generation projects [9,19,18]. It is clear from formula (1) that capital costs are taken into account only during the period of construction of the object covering the time period with duration equal to T_C , i.e. the period from $t=0$ to $t=T_C$ (see Fig. 1), while operating costs Y_t , as well as revenues R_t are accounted only during the process of operation with duration equal to T_E , i.e. from the time moment $t=T_C$ to $t=T \equiv T_C + T_E$. The moment to which reduction is made in formula (1) is the first year of the project. The first year of operation of the object is taken in a number of publications as the year to which the reduction is made. Result of NPV calculation is not dependent on the choice of the year to which the reduction is made.

Investments with the highest positive net present value (non-negative, i.e. with accrued profit) are preferable. In other words, investment costs for the construction of NPP must be covered and repaid from the revenues coming from generated and sold electricity. Consequently, the sign of NPV criterion means that the project is profitable ($NPV > 0$) or loss-making ($NPV < 0$) by the end of its lifecycle. When $NPV = 0$ the cost of the project is paid back only by the moment of completion of its lifecycle which may exceed 100 years for NPP.

Let us note that the purpose of NPV is solely for determining the conditions of project’s profitability. Distribution of profit generated in the process of implementation of investment project is a completely different task not addressed in the present study (see Refs. [14,15,21,22]).

Let us examine first the ideal (best) scenario of the project in the approximation “fast construction when $T_C \rightarrow 0$ and extended period of operation when $T \approx T_E \rightarrow \infty$ ”, which provides clear and straightforward relations for the criteria. Let us assume for the sake of simplicity that annual revenues and operating costs are constant and are equal, respectively, to $R_t = R$ and $Y_t = Y$ (base option). Then, the first sum on the right side of (1) is the total capital costs ($-K$), while the second sum represents the infinite converging geometric progression with progression ratio equal to $q = (1+p)^{-1}$ and the sum of the progression equal to $(R-Y)/p$. As the result, for the given technical and financial parameters of power reactor (K, Y, R) we obtain the highest value for NPV :

$$NPV \leq -K + (R - Y)/p. \quad (2)$$

In the general case for specific duration of NPP construction T_C (year) and operation T_E (years), we obtain from (1) instead of (2) the following expression which is convenient

for subsequent analysis:

$$NPV = -K \cdot f_K + (R - Y) \cdot f_Y / p \leq -K + (R - Y) / p. \quad (3)$$

Here dimensionless coefficients $f_K \leq 1$ and $f_Y \leq 1$ are determined taking into consideration the duration of NPP construction and operation by the following formulas:

$$f_K = \frac{1}{K} \sum_{t=1}^{T_C} \frac{K_t}{(1+p)^t}; \quad f_Y = \frac{p}{R-Y} \sum_{t=1}^T \frac{R_t - Y_t}{(1+p)^t}, \quad (4)$$

where R and Y are the revenues and operating costs during the first year of reactor operation. In a particular case when annual costs and revenues are constant (as in Fig. 1) the sums in (4) represent sums of geometric progressions, so that coefficients take on the form of explicit analytical functions of durations of NPP construction (T_C) and operation (T_E) and of cash flow discount rate (p):

$$f_K = \frac{1 - (1+p)^{-T_C}}{pT_C}; \quad f_Y = \frac{1 - (1+p)^{-T_E}}{(1+p)^{T_C}} \quad (5)$$

Here, the condition $f_K > f_Y$ is always satisfied and, therefore, inequality in (3) is also satisfied. In ideal case of ($T_C \rightarrow 0, T_E \rightarrow \infty$) we obtain $f_K = f_Y = 1$ independently of the discount rate. For instance, if $T_C = 6$ years, $T_E = 60$ years and $p = 10\%$ /year we obtain $f_K = 0.726$ and $f_Y = 0.563$. With decreasing discount rate, the factor f_K monotonously increases tending to unity and coefficient f_Y passes through the maximum and tends to zero for $p \rightarrow 0$ (as $\approx pT_E$).

Numerical example. Let reactor with 1000MW power can produce 7 billion kW/hours of electricity during one year with installed capacity duty factor ICDF=0.8. Selling electricity at 50 \$(/MWhour) the NPP will collect annually revenues $R = 350$ million \$/year. For operating costs equal to $Y = 150$ million \$/year and discount rate equal to $p = 10\%$ /year the project of NPP with such reactor will be profitable for capital costs less than $K < 2$ billion \$ in ideal case. If construction of the reactor lasts $T_C = 6$ years and the reactor is in operation during $T_E = 60$ years than, according to (3) and (5) the project will be profitable at $K < 1.4$ billion \$, ($f_K = 0.726$ and $f_Y = 0.563$) for $p = 10\%$ /year. If the reactor costs 5 billion \$ then profitability is reached when only very low-profit loans are accessible ($p < 3\%$ /year, $f_K = 0.903$ and $f_Y = 0.695$). As it is clear, extension of duration of NPP construction significantly aggravates the overall efficiency of investments (even disregarding potential penalties, interest payable, etc.).

Thus, the main criterion of efficiency of investments NPV determined by expressions (1–3) must be positive (greater than zero) for the purpose of ensuring profitability of the investment project. To what extent it must be greater than zero? Auxiliary and more convenient criteria of efficiency following from the definition of NPV , namely, the discounted payback period T_{PB} , levelized cost of electricity $LCOE$ and internal rate of return IRR , allow finding the answer to this question. Let us examine interrelations between these criteria and NPV , discount rate and technical and financial parameters of reactors (K, Y, R, T_C, T_E).

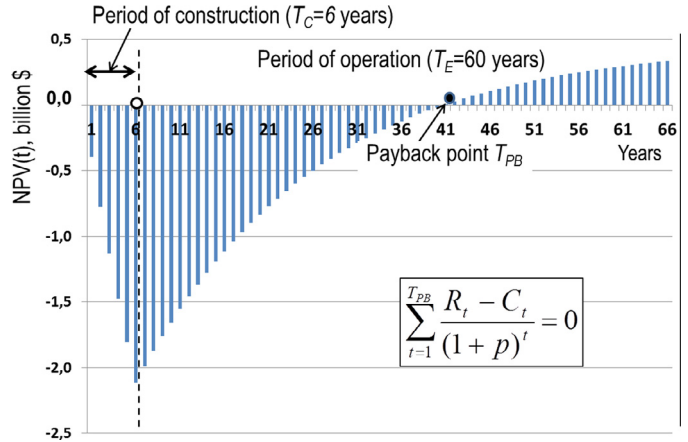


Fig. 2. Example of dependence of net present value NPV of investment project on the duration of lifecycle T (years).

Discounted payback period

The criterion in question is determined by the sequential calculation of $NPV(t)$ as the function of time (duration of lifecycle T). As it is shown in Fig. 2, by the moment of completion of NPP construction ($T = T_C$) the value of NPV reaches the largest negative value because of the incurred capital costs. After that with increasing time $T > T_C$ negative value of NPV decreases due to the termination of capital investments and start of accrual of revenues from sales of the production, and by the time moment T_{PB} the curve $NPV(T)$ passes through zero. This is the moment (point) of breakeven and started payback of the project. Further increase of duration of lifecycle of the project (operation of the power plant) results in the increase of positive value of NPV reaching the largest value by the moment of completion of NPP operation. *Investment project with the shortest payback period (period when return on investments begins) is the best.* In the general case, it is sufficient for numerical calculation of T_{PB} to replace in the second term in the sum in expressions (1) or (4) the upper summation limit T with T_{PB} and set NPV to be equal to zero.

In particular case when annual costs and revenue are constant (see Fig. 1), we obtain, using relations (3) and (4), explicit interrelation between the payback period of the project $\Theta = T_{PB} - T_C$ and technical and financial parameters of the reactor and with NPV in the following form:

$$\Theta = \frac{-\ln\left(1 - K \frac{(1+p)^{T_C} - 1}{(R-Y)T_C}\right)}{\ln(1+p)}; \quad \frac{NPV}{K \cdot f_K} = \frac{1 - (1+p)^{-T_E}}{1 - (1+p)^{-\Theta}} - 1 \quad (6)$$

Setting the target value of the payback period (calculated from the beginning of reactor operation) $\Theta = T_{PB} - T_C$ we can obtain from (6) the value of $NPV > 0$ required for achieving this purpose. Ratio $NPV/(Kf_K)$ is called the discounted profit investment ratio of the project. In accordance with relation (6) for $NPV = 0$ the project starts to pay back at the moment of completion of its lifecycle $\Theta = T_E$. With reduction of the desired payback period duration ($\Theta < T_E$) the required

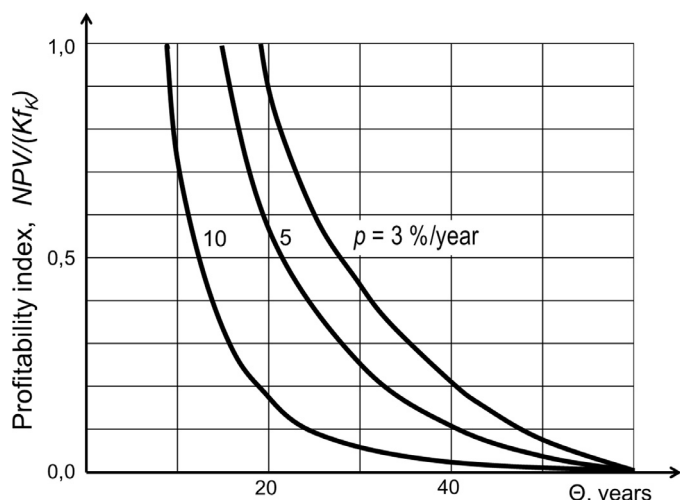


Fig. 3. Dependence of the profit investment ratio of the project $NPV/(Kf_K)$ on the duration of payback period Θ (from the beginning of operation, years) and the discount rate p for the duration of NPP operation $T_E = 60$ years. Calculation was performed using (6).

value of NPV increases (Fig. 3). For instance, in order for the payback period to stay within $\Theta = 15$ years from the beginning of operation (duration of which $T_E = 60$ years and the period of reactor construction is equal to $T_C = 6$ years) the value of NPV must be larger than $0.43K$ (taking into account $f_K \approx 0.726$) at $p = 10\%/year$, and for $p = 3\%/year$ the required NPV increases by 3.4 times to reach $NPV > 1.46K$ (taking into account $f_K \approx 0.903$).

For high capital costs, such big values of NPV cannot be achieved because of the restrictions on the revenues from sales of electricity. This is the “price” to be paid for the desired reduction of the payback period of the project.

Internal rate of return IRR

As it follows from expressions (1)–(3) the value of NPV significantly reduces with increase of discount rate. *Maximum possible discount rate for which $NPV = 0$ at the end of lifecycle is called the internal rate of return IRR* , i.e. for $p = IRR$ we obtain $NPV = 0$ and $T_{PB} = T_C + T_E$. It is important to underline that in order to achieve breakeven of the project the discount rate can vary within the limits from zero to IRR . IRR is also important for assessment of upper level of interest rate for the borrowed funds (credit). Correspondingly, the higher is the IRR value the more possibilities exist to find the required amount of investment funds on the market. *The higher is the value of IRR and the difference $(IRR - p)$ the more positive the value of NPV appears to be and the more stable is the project* (lesser risks).

In the general case, the value of IRR can be determined by iteration numerical calculation. In particular case, when annual costs and revenues are constant (see Fig. 1), there exists analytical relation between the internal rate of return and technical and financial parameters of the reactor which is found by us using relations (3) and (5) by replacing p with

IRR in the last formula:

$$IRR \cdot f_K(IRR)/f_Y(IRR) = (R - Y)/K. \quad (7)$$

In ideal case of “fast construction and extended operation” when $f_K/f_Y \approx 1$ we obtain from (7) or directly from (2):

$$IRR \leq (R - Y)/K; \quad NPV/K = IRR/p - 1. \quad (8)$$

As it is clear, internal rate of return IRR linearly increases with increasing difference $(R - Y)$ between the revenues and operating costs (i.e. with increasing annual profit) and hyperbolically decreases with increasing capital costs K . For instance, for NPP at $K = 2.5$ billion \$, $Y = 150$ million \$/year and $R = 400$ million \$/year we obtain $IRR \leq 0.1/year$ (10%/year). If NPP power unit costs $K = 5$ billion \$, then, with all remaining conditions being equal, $IRR \leq 5\%/years$, which requires more cheap credits not attainable in many banks.

Explicit analytical dependence of NPV on IRR and durations of NPP construction T_C and operation T_E can be obtained in the case when annual costs and revenues are constant (see Fig. 1) using expressions (3) and (5). As the result, we have:

$$\frac{NPV}{K \cdot f_K} = \frac{(1 + IRR)^{T_C} - 1}{1 - (1 + IRR)^{-T_E}} \cdot \frac{1 - (1 + p)^{-T_E}}{(1 + p)^{T_C} - 1} - 1. \quad (9)$$

For the preset value of IRR determined by the ratio $(R - Y)/K$, higher NPV values are required in the general case as compared with the ideal case.

Discounted cost of electricity

Annual revenues R from sales of electricity entered into the expression for NPV can be represented in the form of the product of annual output of the electric power plant E (kW hour/year) by the per unit price P of sold (delivered) production (RUR/(kW hour)): $R = E \cdot P$. Evidently, the less is the selling price, the less are the revenues and the NPV value. Minimal possible price of the product at which $NPV = 0$ and the project reaches breakeven by the end of its lifecycle is called the per unit present value of the product or present cost of production (in our case $\min P \equiv LCOE$). *The project for which the present (discounted) cost of electricity is minimal below the market price is preferable*. In accordance with (3) we have:

$$LCOE = (p_{EF}K + Y)/E \geq (pK + Y)/E; \quad NPV = Z \cdot (P/LCOE - 1). \quad (10)$$

Here $p_{EF} = p \cdot f_K/f_Y \geq p$ is the effective “rate of depreciated capital costs”; $Z = Kf_K + (Y/p)f_Y$ are the discounted costs during the whole lifecycle period; dimensionless coefficients f_K and f_Y are determined by expressions (4) or (5). Let us note that reduced costs Z are widely applied for comparison of projects with similar type of products, for instance, for comparison of different electric power plants. *The project with minimal reduced costs, which ensures the largest NPV value and the lowest value of reduced cost of electricity with all remaining conditions being equal, is considered to be preferable*.

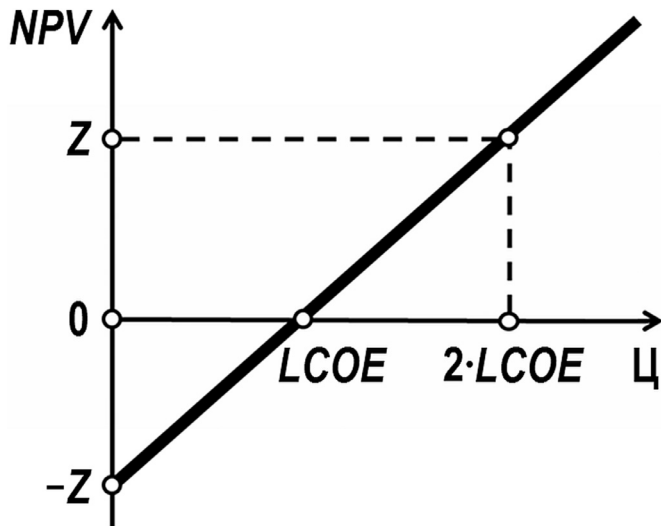


Fig. 4. Dependence of net present value NPV of the investment project (RUR) on the price of sold electricity P (RUR/(kWhour)). $LCOE$ is the leveled cost of electricity (10).

It follows from the last expression in (10) that the value of NPV is determined by the following two parameters: total reduced costs Z and excess of the selling price P over $LCOE$ (i.e. the “margin”) (Fig. 4). $LCOE$ value must be less than the electricity tariff P , acting in the region in question. In the opposite case, the project of NPP (or thermal power plant, or solar electric power plant, etc.) is loss-making. It follows from the definition of $LCOE$ that projects with high capital costs typical for NPPs can be successful (have the lowest $LCOE$) at low discount rates (small pK), i.e. in the case when cheap credits are accessible.

For instance, let $E=7$ billion kWhour/year, $Y=0.15$ billion \$/year and $K=3$ billion \$. If the reactor is under construction during $T_C=6$ years and is in operation during $T_E=60$ years, then for $p=5\%$ /year coefficients $f_K=0.846$ and $f_Y=0.706$, which gives as the result $p_{EF} \approx 6\%$ /year, $Z \approx 4.65$ billion \$ and $LCOE \approx 47$ \$(/MW hour) (by approximately 9% more expensive than in the ideal case). For selling price of electricity $P=55$ \$(/MW hour) the value of IRR will amount to only about 6.5%/hour the payback period $\Theta \approx 26$ years and $NPV \approx 0.78$ billion \$. In the example under discussion the internal rate of return only slightly exceeds the discount rate which makes the project fairly risky.

Risks of the investment project

Accuracy of estimation of criteria of efficiency of investments depends on the accuracy of forecasting the cash flows K_t , Y_t and R_t during all phases of lifecycle of the power plant. By setting a certain range of possible values of technical and financial parameters of the reactor and conditions of its operation (Table 1) it is possible using Monte-Carlo method to estimate the dispersion of criteria of efficiency of investments in NPP relative to the base values (Fig. 5, Table 2), i.e. to

Table 1

Initial data for analysis of risks of investment project of the NPP with one power unit.

Item no.	Parameter	Base value	Lower boundary	Upper boundary
1	Installed power of the reactor (electric), MW		1170	
2	Duty factor	0.88	0.60	0.93
3	Annual production of electricity E , billion kWhour/year	9	6.1	9.5
4	Capital costs K , billion \$	5	3	7
5	Operating costs Y , million \$/year	150	100	200
6	Duration of construction of the power unit T_C , years	6	4	10
7	Duration of operation of the power unit T_E , years	60	30	75
8	Discount rate p , %/year	7	3	15
9	Selling price of electricity P , \$(/MW hour)	72	45	85
10	Annual revenue $R=EP$, million \$/Year	650	277	810

estimate risks of the project. Hypothetical project of NPP with one power unit and parameters presented in Table 1 was examined as an example. Probabilistic distribution of the value of each of the initial eight parameters was accepted in the form of widely spread PERT β -distribution described, for instance, in [1]. The range of variation of each of the eight parameters was set arbitrarily as an example but, however, from the range of realistic values.

More than 1 million numerical experiments (project scenarios) were performed by Monte-Carlo method and probabilistic distributions of criteria were obtained with areas under curves of distributions of NPV and $LCOE$ equal to unity. As it follows from Fig. 5, dispersions of efficiency criteria relative to base values and, therefore, risks of the project under examination are high enough. Thus, area under the curve of NPV distribution in the zone of negative values (towards left from $NPV=0$) exceeds the area under the curve within the zone of positive values, i.e. the probability of the project to make losses exceeds the probability of its profitability. The most probable value of NPV lies within the zone of negative values (Fig. 5a). Probability of excess over the base value of cost of electricity is also high (Fig. 5b). The most probable value of the internal rate of return is less than 8%/year.

What is the way for reducing risks of the project? The obtained analytical expressions for the efficiency criteria allow implementing analysis of sensitivity of the criteria to the initial (design) technical and financial parameters of the reactor. Following this, by searching possibilities for entering corrections (changes) in the initial data of the investment project and reducing the uncertainties of its base technical and financial parameters, it is possible to achieve enhancing the efficiency of investments and reducing economic risks associated with the project.

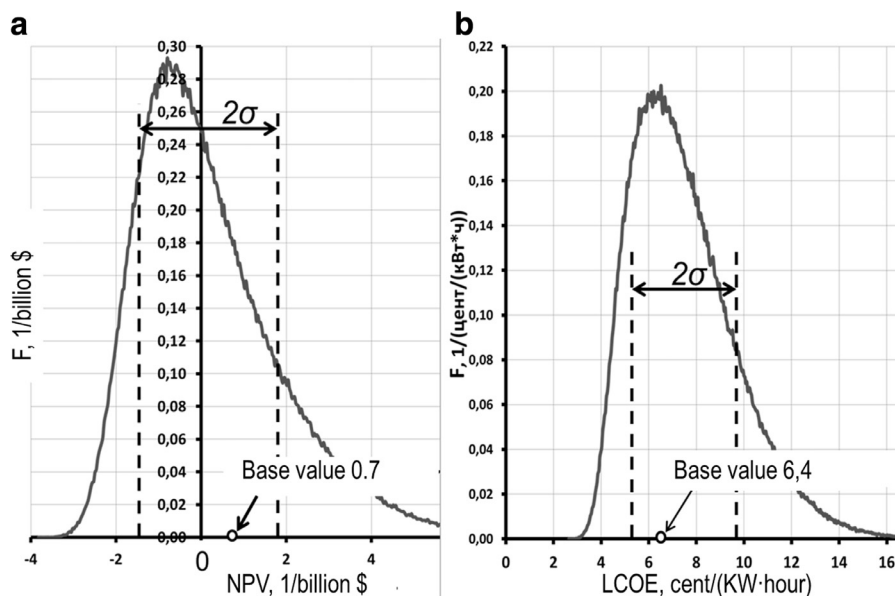


Fig. 5. Probabilistic distributions of the net present value (NPV , billion \$) and levelized cost of electricity ($LCOE$, cent/(KW hour)) for the investment project of NPP with one power unit with parameters from Table 1. Calculation was performed using formulas (3), (5) and (10) by Monte-Carlo method. Letter σ stands for the standard deviation. Base value of the criterion is taken from Table 2.

Table 2

Calculation of criteria of efficiency of investments in the NPP with one power unit (for base values from Table 1 and discount rate $p=7\%$ /year).

Efficiency criterion	In the approximation of $T_C=0, T_E=\infty$	For $T_C=6$ years, $T_E=60$ years
Discounted costs Z , billion \$	7.1	5.37
Net present value NPV , billion \$	2.1	0.704
Levelized cost of electricity $LCOE$, \$(/MW hour)	55	64
Fraction of capital costs in $LCOE$, %	70	74
Internal rate of return IRR , %/year	10	8.1
Payback period T_{PB} , years	17	33
Payback period after the beginning of operation Θ , years	17	27

Conclusion

Analytical relationships between the investment performance criteria (NPV , $LCOE$, IRR , T_{PB} , Z) and basic engineering and economic parameters of nuclear reactors (K , Y , R , T_C , T_E), characterizing the NPP competitiveness at the microeconomic level, are defined for the first time. The power discount function of cash flows was used in the calculations. Joint analysis of the whole complex of efficiency criteria (and not only $LCOE$) and their dispersion (for instance, using Monte-Carlo method) allows escaping controversies in the assessment of profitability of the NPP project and formulating optimal requirements on the technical and financial parameters of reactors for enhancing their competitiveness including the reduction of economic risks.

The obtained analytical expressions allow solving not only the traditional “direct problem” (assessing the performance criteria according to the forecasted capital and operating costs and profit stream) but, which is of equal importance, solving the “inverse problem” of assessing the restrictions on capital and operating costs, i.e. identifying “investment corridors”.

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