Research Article

Systemic competitiveness of nuclear energy sources*

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Abstract

Possibilities are analyzed for improving the commercial attractiveness of nuclear electricity generation in market conditions. A model is presented in which a financially integrated electricity generating system comprising several units of one technological type, rather than a single unit, is subject to an economic analysis. Issues have been considered involved in the calculation of the electricity cost in such systems and their construction. It has been shown that the calculated unit cost of the electricity generated in a financially integrated nuclear energy system with the number of units being more than one, provided it is financed by shareholders and creditors, can be lower as compared with the cost of the electricity generated by power units, not integrated economically, of the same capacity under the same investment conditions.

The effect is achieved thanks to the short-term crediting component in the electricity cost the funds on which can be returned, at a time, for a smaller number of units (even for only one), as electricity is produced by all units in the system. The results of the calculations for nuclear energy sources and combined-cycle plants using the developed model make it possible to conclude that the switch from economic models of individual nuclear units to models of integrated energy systems can bring the calculated economic performance of nuclear power closer to (or better) the performance of fossil-fuel energy sources. If achieved, this may increase the commercial attractiveness of nuclear power and contribute to a growth in the public and private investments in nuclear power business.

Introduction

Competitiveness of nuclear power plants is one of the key requirements for the sustainable nuclear electricity generation. However, the existing electricity generation calculation methods show that high unit capital costs and lengthy NPP construction times in conditions of high interest rates on capital may lead to the loss of the economic competitiveness by nuclear power technologies.

Models based on comparing the cost of energy generation by single power plants are used to estimate the competitiveness of energy sources (Belyaev 2009, The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012, INPRO Manual 2014, Technical Reports Series No. 396 2000, Projected costs 2015). Meanwhile, the energy generation cost may depend on how individual structural units are organized

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into a system, and the nature of this dependence may differ for particular technologies.

This paper presents a model, in which a financially integrated system comprising several units of one technological type, rather than a single unit, is subject to an economic analysis. Issues involved in the calculation of the electricity cost in such systems and their construction have been considered. The study focuses on analyzing the possibilities for improving the commercial attractiveness of nuclear electricity generation in a tough market environment and for recruiting private investors for the nuclear energy sector. It has been shown that the calculation results obtained using the proposed model may differ markedly from the results of a calculation based on other models.

Methods and models

Levelized cost of a unit of product (Belyaev 2009, The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012, INPRO Manual 2014, Technical Reports Series No. 396 2000, Projected costs 2015, Recommended practices 2008, Kovalev 1995, Shevelev and Klimenko 1996, Karkhov 1998, Karkhov 1999, Karkhov 2014, Kazachkovskiy 2000, Kharitonov and Kosterin 2017, Rachkov et al. 2008, The Economics of Nuclear Fuel Cycle 1994, IAEA Nuclear Energy Series NP-T-1.14 2013) is used to compare the economic competitiveness of electricity generation by power plants (Belyaev 2009, The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012, INPRO Manual 2014, Technical Reports Series No. 396 2000, Projected costs 2015, Recommended practices 2008, Kovalev 1995, Shevelev and Klimenko 1996, Karkhov 1998, Karkhov 1999, Karkhov 2014, Kazachkovskiy 2000, Kharitonov and Kosterin 2017, Rachkov et al. 2008, The Economics of Nuclear Fuel Cycle 1994, IAEA Nuclear Energy Series NP-T-1.14 2013). The product (electricity) cost r is determined as the ratio of levelized cost to levelized output. The levelized cost is composed of the cost components going toward the recovery of the investments in the power unit construction and the operating costs including the fuel cost. The paper focuses on the first of the above components. The electricity cost component r going toward the capital recovery is calculated based on the exponential presentation form justified and used in (Kovalev 1995, Shevelev and Klimenko 1996, Karkhov 1998, Karkhov 1999, Karkhov 2014, Kazachkovskiy 2000):

$$r = k \times i / [q \times (1 - \exp\{-iT\})], \qquad (1)$$

where k is the sum the funds invested in the power unit construction and the interest on the investments by the start of the commercial unit operation; i is the discount rate; q is the annual electricity generation by the power

unit; and T is the period for the return of the funds invested in the power unit construction.

Many papers on economics, including economics of nuclear power, connect the discount rate with the "value of money", the so called *weighted average cost of capital* (WACC), for all sources of funding (The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012, Solodov 2013, Blank 2010). If the power unit construction is financed based on the owner (shareholder) funds and liabilities on external capital market loans, the discount rate for a "generalized" investor is determined as

$$i = \varepsilon_D \times i_D + \varepsilon_E \times i_E,$$

where ε_D, ε_E are the shares of the shareholder liabilities and funds respectively ($\varepsilon_D + \varepsilon_E = 1$); and i_D, i_E are the interest on the loan capital (interest on the credit) and the stock capital (rate of return on shares).

If the operating costs u do not depend on time, then the calculated electricity unit cost c will be

$$c = r + u. \qquad (2)$$

As in (The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012), a nuclear power project is considered efficient if it provides for the payback of the investments with regard for the discounted incomes and costs on the rates defined by the shareholders and creditors, and simultaneously supplies competitive electricity to the free (open) market.

Instead of a single power unit, the approach proposed in this paper considers a *financially integrated electricity generating system* comprising a number of power units owned by one company with integrated financial management. We shall call the results of the electricity cost calculation using this model the *systemic cost* of electricity. The competitiveness of alternative energy sources will be determined by comparing the systemic cost of the electricity they generate and the cost of the electricity produced by individual power units. The peculiarities of various tools used by investors for the power plant construction funding have been taken into account. Expression (1) for the calculation of the electricity cost component R for the replacement of capital in the event of a financially integrated system with different investment schemes takes the form

$$R = \sum_{f=1}^{F} R_f = \sum_{f=1}^{F} \frac{K_f \cdot i_f}{Q \cdot (1 - e^{-i_f T_f})}. \qquad (3)$$

The capital letters in expression (3) denote the same quantities as the respective lower-case letters in (1) but for the system rather than for a single unit. The index f denotes the investors with a particular scheme for the construction funding and for the return of the invested funds. Expression (3) shows that the formula to calcula-

te the electricity cost component R for the replacement of capital for a financially integrated system, taking into account the specific features of particular investors, has a more complex form, than formula (1), for the levelized cost calculation. For simplicity, the paper considers only two types of investors: $f = 1$ are shareholders, and $f = 2$ are external creditors (banks, funds, etc.).

It is highly important to consider the power unit construction funding by two or more investors with different loaning and payback conditions as the distribution of the investment flows for each of them may differ markedly, this affecting the cost calculation results (The Future of Nuclear Power 2003). Owners are interested in being received dividends for a long time, up to the entire power plant commercial operation period $T_1 = T_L$. The standard time T_2 for the debt repayment (the liability period) to creditors (banks) is much shorter (5 to 15 years). Besides, the investment in an enterprise is attractive to private shareholders only provided the interest on the capital invested in the enterprise is higher than the average deposit interest paid to the bank clients.

Since the operating costs and the cost of the fuel in the system, as well as the annual electricity generation by the system, are proportional to the number of the units N, the operation cost components for the system will be the same as for a single power unit. Then the unit electricity cost for the system will be written as

$$c = R + u. \qquad (4)$$

The recovery profile for the NPP shareholder and creditor investments in the construction of one unit, after it starts to operate, for the case of the two funding sources mentioned above is a stepped function (Fig. 1). First, the debt is repaid to the loan capital owners with an interest on the capital invested, and when the loan is repaid then only dividends are paid to the shareholders. The levelized cost of electricity (the dashed line) is determined such that to provide for the "levelized" return of the funds to both.

The time-dependent profiles for the return of investments to the NPP shareholders and creditors as applied to the thermal and nuclear power plant (TPP and NPP) units differ greatly. The investment return component is small, as compared with the operating and fuel costs, in technologies based on combustion of fossil fuel. So the difference in the amounts of the funds returned in the periods of the capital repayment to the shareholders and creditors is small against the background of the operating costs. In this case the estimated constant value of the levelized electricity cost differs insignificantly from the time-variable real stepped function and may be considered as a fairly acceptable estimate.

For nuclear units, the relative contribution of the investment cost repayment component to the unit cost of electricity is determining, so the difference in the amount of the funds returned in the periods of the capital repayment to the shareholders and the creditors and only to the
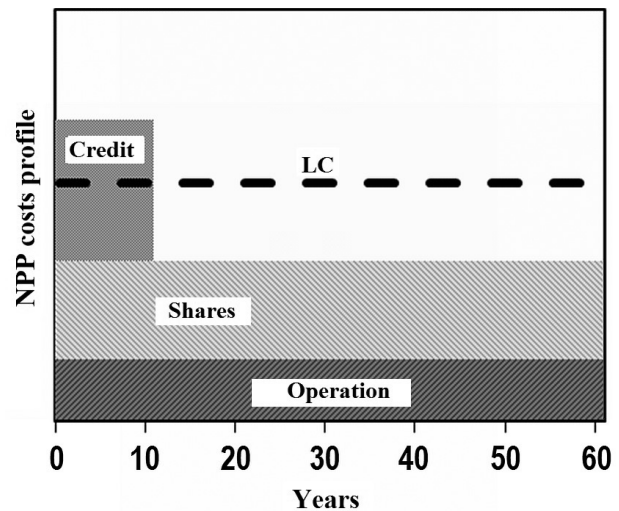

Figure 1. Time-dependent profile for the return of investments to the NPP shareholders and creditors (LC – levelized cost of electricity)

shareholders is very great. The required amount of the funds to be returned in the period of the capital repayment to the shareholders and the creditors is much larger for nuclear power units than for units of the thermal power plants which means that the component of the investments return in the cost of electricity will also be much larger. In the financially integrated system this component can be partly reduced.

Model of a financially integrated system

We shall assume that the introduced financially integrated energy generating system has reached a certain "asymptotic" state with the fixed capacity and it operates in a steady-state mode. The reactor unit decommissioned after its service life is over is replaced by a new unit on a timely basis. Thus the system is kept in a state with the constant number N of power units of one and the same type. The investment process connected with keeping the system in a steady power state is as follows (Fig. 2).

The shareholders receive payments throughout the commercial operation period of each power unit. The construction of the unit "$n + 1$", according to the adopted unit commissioning and decommissioning scheme, is credited such that the unit "$n + 1$" is commissioned by the time the debt for crediting the construction of the unit "n" has been repaid in full.

As it follows from Fig. 2, the profile for the return of the invested funds in the financially integrated system introduced above differs in principle from the funds return profile for a single unit (see Fig. 1). The cost of the electricity generation in such a system is constant. The sum of the funds returned to the shareholders, as well as the amount of the generated electricity, is proportional to the number of the power units N, so the component of the
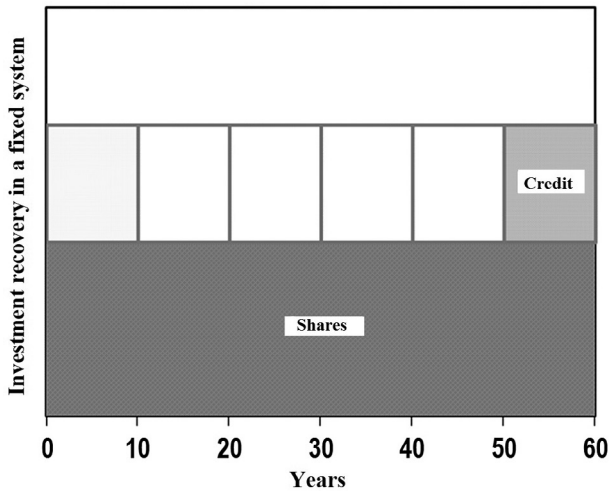
Figure 2. Investment return scheme in a fixed financially integrated system

funds return to the shareholders in the electricity cost r_1 is the same as for one unit:

$$R_1 = \frac{k_1 \cdot N \cdot i_1}{q \cdot N \cdot (1 - e^{-i_1 T_1})} = r_1, \quad (5)$$

where k_1 is the sum of the shareholder investments in the power unit construction; i_1 is the rate for the shareholder dividends; q is the annual generation of electricity by one unit; and T_1 is the time for the return of the shareholder investments in the power unit construction.

The situation is different for the electricity cost component connected with the return of the credited funds. In each credit repayment time interval T_D, payments to the creditors are made only for the final of the system's power units built (Fig. 2), while the electricity generation is proportional to the number of the units N. Therefore, the component of the money return to the creditors in the electricity cost r_2 is N times as small as for one unit:

$$R_2 = \frac{k_2 \cdot i_2}{q \cdot N \cdot (1 - e^{-i_2 T_2})} = \frac{r_2}{N}, \quad (6)$$

where k_2, i_2, T_2 are the parameters meeting the crediting conditions; and $k = k_1 + k_2$ is the total sum of the shareholder and creditor investments in the construction.

Substituting (5), (6) in (3), (4), we shall get the expression that determines the systemic electricity unit cost c in a fixed model of a financially integrated electricity generating system:

$$c = R_1 + R_2 + u = r_1 + \frac{r_2}{N} + u = \frac{k_1 \cdot i_1}{q \cdot (1 - e^{-i_1 \cdot T_1})} + \frac{k_2 \cdot i_2}{N \cdot q \cdot (1 - e^{-i_2 \cdot T_2})} + u. \quad (7).$$

To obtain the minimum systemic electricity unit cost c, with $N = 1$, one needs to optimize the shares of the funds invested in the power unit construction by the shareholders and by the creditors (k_1 and k_2 respectively) depending on the ratio of the return interest rate for the shareholders and the credit interest rate. With a higher rate of return (of the dividends) for the shareholders (15%), as compared with the credit interest rate (8%), the best ratio is 50% by 50% (The Future of Nuclear Power 2003).

If the number of the reactors N in the system is large and the shareholder contribution to the project prevails ($k_1 \gg k$), then we arrive at the standard procedure for the calculation of the levelized electricity cost for one unit with one investing shareholder.

However, as it follows from (7), with the project funded jointly by shareholders and creditors, and with a sufficiently large number of units, the calculated unit cost of generated electricity may turn out to be smaller for a financially integrated system, as compared with the cost of the electricity generated by a system of units, not integrated economically. This is due to a reduction in the second component in formula (7) that determines the contribution of short-term crediting to the electricity cost. This may lead to a decrease in the unit cost of electricity.

Numerical examples

The peculiarities involved in the calculation models of the electricity generation cost and the differences in the results obtained using these models are discussed in the context of light-water reactors (LWR) and combined-cycle plants (CCP).

The initial performance parameters of plants and the financial conditions of their construction are presented in Tables 1 and 2. The discount rate for the calculation using formula (1) was determined as the average value of the interest rate on the capital provided by the investors (the value of money). The financial figures are taken from sources in which the competitiveness of nuclear power is considered in a tough market environment with a high value of money.

In calculating the electricity generation cost, the plant lifetime costs are discounted separately with interest rates on the credit and the rate of return on shares. The rate of return for the owners (shareholders) of the enterprises using nuclear energy sources is higher than for the technology based on combustion of natural gas. This agrees with the data in (The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007) and is explained by high investment risks involved in implementation of nuclear projects. The LWR and CCP electricity cost is compared in a market environment without regard for the economic and social policy of the state which in many countries affects considerably the situation in the real energy sector, including the investment rates and conditions.

Fig. 3 shows electricity cost calculation results for the systems consisting of different number of LWR and CCP units (N) obtained using the initial data (see Tables 1 and 2) and the models considered in this paper. The credit repayment period is assumed to be equal to 10 years.

As it follows from Fig. 3a, the electricity cost for the CCP system has a low sensitivity to the number of units

Table 1. Performance of nuclear and conventional plants (The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Alan et al. 2012, INPRO Manual 2014, Technical Reports Series No. 396 2000, IAEA Nuclear Energy Series NP-T-1.14 2013)

		LWR	CCP
Installed power, MWel		1000	500
Thermal efficiency, %		31	45
Installed capacity utilization factor, %		80	80
Service life, years		60	60
Construction period, years		5	2
Unit capital costs, $/kW(el)	Low estimate	2000	700
	High estimate	4000	900
Investments per unit, $/kW(el)	Low estimate	2500	770
	High estimate	5100	990
Fuel cost, $/MW·h		5,5	40,0
Operating costs, $/MW·h		7,0	10,0
Number of units in system		6	6
Construction time and unit replacement frequency, years		10	10

Table 2. Financial conditions (The Future of Nuclear Power 2003, The Economic Future of Nuclear Power 2004, GIE/EMWG /2007/ 004. Revision 4.2 2007, Projected costs 2015)

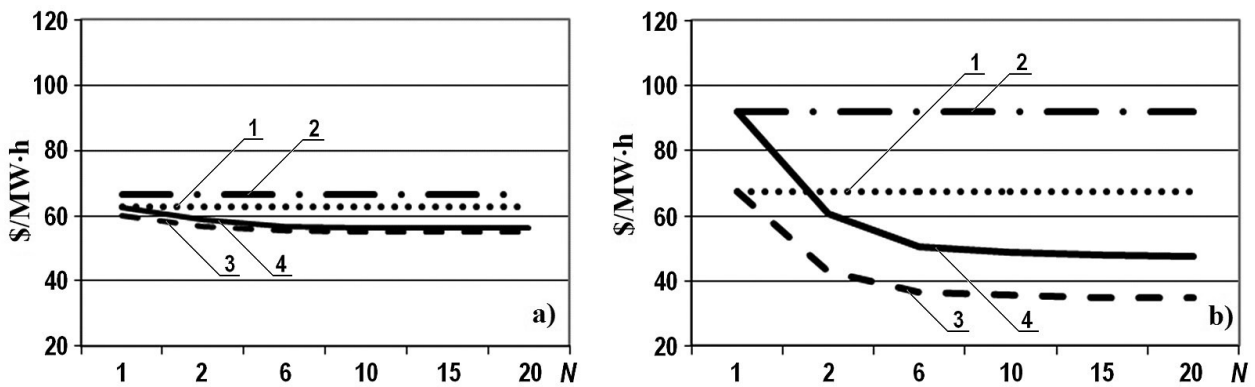|		Model	
	Unit type	Formula (1) with mean discount rate i	Systemic cost formula (7)
Rate of return on shares, %	VVER		15
	CCP		12
Credit interest, %			8
Mean discount rate, %	VVER	11.5	
	CCP	10	
Share of stock capital, %		50	20
Equity to debt ratio, %		50	80
Shareholder dividend payment period, years		60	60
Debt repayment period, years		60	10

Figure 3. Electricity cost for individual units and for a system (IU – investments per unit): a) – CCP: 1 – unit (IU 770 $/kWel); 2 – unit (IU 990 $/kWel); 3 – system (IU 770 $/kWel); 4 – system (IU 990 $/kWel); b) – LWR: 1 – unit (IU 2500 $/kWel); 2 – unit (IU 5100 $/kWel); 3 – system (IU 2500 $/kWel); 4 – system (IU 5100 $/kWel)

in the system and to variations in the unit capital costs in the probable range of their changes. The model of a financially integrated system with the number of units being more than one gives a lower systemic cost of electricity as compared with the levelized cost (LC) calculated for one unit, but the effect is not great. The situation is different when the electricity cost is analyzed for a nuclear energy source (Fig. 3b).

In this case, the electricity cost falls into a broad range of values depending on the models used and the amount of the unit capital costs. The levelized cost calculation results for one unit based on formula (1) with the mean discount rate i show that nuclear power remains competitive against CCPs with the LWR investments per unit being not more than 2500 $/kWel. With the investments per unit amounting to ~5000 $/kWel, the VVER electricity cost is however much higher than for CCPs, and NPPs cease to be competitive.

The transition to a financially integrated system makes it possible to increase greatly the competitiveness threshold of nuclear power. It can be seen from the comparison of diagrams in Figs. 3a and 3b. that, The unit capital costs for the LWR unit construction being ~5000 $/kWel, the cost of electricity generation, where the number of units is more than two, decreases to the competitive level in an option with the share of external loans being at a level of 80%.

The above numerical example confirms that the competitiveness estimate at a systemic level may differ greatly from the estimate at a level of individual units. Primarily, this conclusion applies to capital-intensive technologies.

Construction of a financially integrated system

A financially integrated system is an entity that differs to a great extent, in economic terms, from individual units, and its construction seeks to search for the best funding schemes with regard for the peculiarities of the new entity in question so that to have a positive systemic effect in the shortest time possible.

The calculation results presented below are for the scenario of a financially integrated system built using the initial data given in Tables 1 and 2 for the case with a high value of the investments per unit (5100 $/kWel) for nuclear power units. One of the system construction conditions was the requirement that the calculated cost of the system-generated electricity was not higher than the levelized cost (LC) determined for an individual unit with the same value of money. The cost of the electricity generated by an individual unit was calculated using a model similar to that presented in (The Future of Nuclear Power 2003). The calculations were performed using Excel spreadsheets.

As shown by the calculation results for the financially integrated system construction options, the key role in reducing the period for a low systemic electricity cost to be achieved is played by the financial conditions during the construction of the first unit in the system. Therefore, it was assumed in the scenario, the results of the electricity cost calculation for which are presented below, that a public or a large private energy company, when solving its strategic tasks, can grant certain benefits for the investment in the construction of the pilot unit in a financially integrated nuclear energy system.

The ratio of the authorized and debt capitals for the first unit was 50% by 50%, and it was assumed for keeping the electricity cost competitive for the initial ten years of the unit operation, as it is with (The Future of Nuclear Power 2003), that its shareholders were awarded 11.5% on the capital instead of the nominal 15%. In the subsequent years, the dividends were increased to above 15% in order to compensate for the shareholder financial loss in the initial decade. Thereby the nominal rate for shareholders of the first unit during the operating time was 15%. It was assumed for the construction of the further units that the debt capital would grow gradually to 60% for the second unit, to 70% for the third unit, and to 80% for the fourth unit and further. And it was assumed for the further units
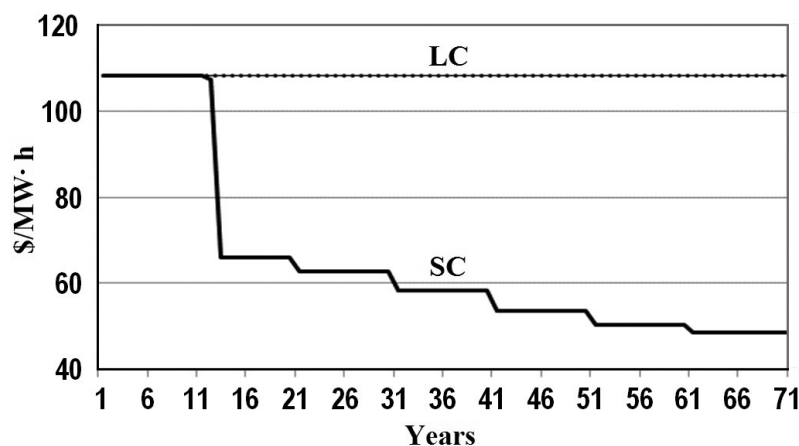

Figure 4. Calculated electricity cost: LC – levelized cost for one unit; SC – systemic cost

that the dividends were paid to the shareholders of the units in question right from the start and in full (15%).

The results of the calculation show (Fig. 4) that the cost of the generated electricity was successfully reduced to 40% of the electricity cost for one unit, the rate of return on shares and the credit interest rates being equal, as soon as at the operation stage of a financially integrated system comprising two units.

With a larger number of units in the system, the systemic cost of electricity decreases further, as compared with the cost of the electricity generated by a single unit. As can be seen from Figs. 1 and 4, the operation of a nuclear energy system comprising two or more units leads to the cost of the electricity generation (about 60 \$/MWh) comparable with the cost of the CCP-produced electricity.

Conclusion

The cost of the electricity generated by a financially integrated nuclear energy system may be lower than the cost of the electricity generated by individual units of the same type as in the system. The transition from the economy of individual units to the economy of integrated energy generating systems is expected to improve the commercial attractiveness of nuclear power, to bring its economic performance closer to the best performance indicators of fossil-fuel energy sources, and to contribute to expanding the public and private investments in nuclear power business.

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