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Research Article

Comparative analysis of the investment attractiveness of nuclear power plant concepts based on small and medium sized reactor modules and a large nuclear reactor*

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Abstract

It seems to be of current interest to consider and analyse possible electrical and non-electrical applications of small and medium sized reactors for both the nearest and more distant future. The paper presents the results of a comparative analysis of the economic attractiveness of nuclear power plant (NPP) designs based on small and medium-sized reactor modules and a large-sized reactor in order to identify conditions for increasing the investment attractiveness of NPP modular design concept. The analysis is based on the evaluation of such economic performance metrics as net present value, present value, internal rate of return, discounted payback period, and levelized cost. It was shown that, in terms of the present value and levelized costs, the NPP modular design concept is less economically attractive in comparison with the NPP design based on a large-sized reactor. In terms of the net present value, internal rate of return and payback period, the NPP modular design concept can be considered economically attractive if only the predicted learning effect is observed when the modules are constructed and the scale factor is not less than 0.5. In this case, it will be economically feasible to construct an NPP based on a small number of medium sized reactor modules. If the scale factor is not less than 0.6, one may talk about the economic attractiveness of NPP designs based on reactor modules of lower power. The impact of various debt financing schemes was analysed and it was demonstrated that, in relative terms, changes in the economic performance indicators are comparable in the implementation of the NPP modular design and a large sized reactor.

Keywords

Small and medium sized reactors, modular NPP, economic efficiency indicators, economic risk

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Introduction

At present, there is the renewed interest in developing small and medium sized reactors (SMR) and considering their possible applications in many regions of the world*. These reactors are of interest for both electrical and non-electrical applications in the short term (seawater desalinization, central heating) and in the longer term (hydrogen production, conversion of fossil fuels). About 20 projects of promising SMRs are currently at various development stages. Much attention is paid to SMRs in Argentina, China, India, the Russian Federation, South Korea, and the United States (IAEA-TECDOC-1485, IAEA-TECDOC-1536, IAEA-TECDOC-881, ARIS 2011).

The advantages of this concept are well known: relatively small absolute project implementation costs and, consequently, lower financial risk; the modular structure gives a possibility to gradually expand capacities and create an NPP with a flexible power configuration; units with small and medium sized reactors can be located closer to customers; small sized reactors can be operated without on-site refueling, thus eliminating the need for SNF and HLW handling (Kessides and Kuznetsov 2012, NEA/OECD 2011, Approaches for Assessing 2013), however, the issue of SNF management responsibility transfer is rather complicated and there is no full consensus on it so far.

Reviews of the concepts and current situations in the field of SMRs are regularly presented in publications issued by the IAEA and reports prepared under the auspices of the OECD NEA (IAEA-TECDOC-1485, IAEA-TECDOC-1536, IAEA-TECDOC-881, ARIS 2011, NEA/OECD 2011, Approaches for Assessing 2013). In these publications, along with considerations of technical aspects and analyses of possible niches for the use of small sized reactors, great attention is paid to the competitiveness and economic performance of this type of reactors (NEA/OECD 2011, Approaches for Assessing 2013, Kuznetsov and Barkatullah 2009), which, according to all accounts of experts, remain a weak point. In this context, much attention is paid to the analysis and evaluation of factors affecting the competitiveness and economic performance of the SMRs.

The liberalisation of energy markets has given high decision-making autonomy to business entities, which in the new conditions, first of all, seek to maximise their profits. In this context, the cash flow theory has come into use as the main tool for choosing efficient investment projects, where the criteria of net present value, present value, internal rate of return, payback period, and some others are used as the primary criteria of decision-making (INPRO Methodology 2014, Nuclear Energy Series No. NG-T-4.2 2008, NEA/OECD 2009, Belli et al. 1998).

* According to the classification adopted by the IAEA, small reactors are reactors with an equivalent electric power of less than 300 MW(e) and medium sized reactors are reactors with an equivalent electric power of between 300 and 700 MW(e).

Assessment of SMR economic performance and competitiveness

Factors Determining the Economic Performance and Competitiveness of SMRs

It is well known that the main reason for the SMR economy remaining a weak point is the so called ‘effect of economies of scale’ (scale effect) which implies that a decrease in a unit power, without making any fundamental changes, results in an increase in capital costs (NEA/OECD 2011, Approaches for Assessing 2013).

At the same time, there are factors mitigating an adverse impact of the scale effect. First of all, it is possible to simplify the reactor construction. Thus, according to the assessments in a number of studies, it has been shown that the primary circuit integral layout leads to cost saving by a factor of 0.85. If several small sized reactors are installed at the site, it will be possible to organise some common systems for them, thus reducing licensing costs. The so called ‘learning effect’ is also well known: the construction and operation of each next unit will be cheaper than the previous one. According to the estimates, it can be expected that the construction costs will be reduced by 25–30% for the fifth or sixth reactor as compared to the first one. An additional gain is associated with shorter construction periods for SMRs and cost-cutting for a floating NPP (NEA/OECD 2011, Approaches for Assessing 2013).

For a modular NPP, it is possible to reduce investment risks if capacity commissioning is performed on a ‘module by module’ basis without waiting for the plant to achieve its planned total power output. At the same time, the required investments will be distributed in time and may have a more attractive profile while a large unit of equal power would require investments immediately. Gradual capacity expansion reduces both the initial investment and the amount of capital at risk (NEA/OECD 2011, Approaches for Assessing 2013).

For a correct assessment of the competitiveness and economic performance of SMRs, it is required to consider the totality of factors influencing positively (multi-modularity, factory-made modules, etc.) and negatively (the scale effect) their economic competitiveness. For an analysis of the concepts, it is required to collect data on capital expenditures for their construction, fuel, operating costs, etc.

Metrics for Assessment of the Economic Performance and Competitiveness of SMRs

An evaluation of the economic performance and competitiveness of the SMR deployment can be carried out using the economic performance indicators characterizing the attractiveness of investments and the profitability of relevant projects (INPRO Methodology 2014, Belli et al. 1998, Requirements and criteria for nuclear technologies, Integrated Model for Competitiveness Analysis, Technical Reports 2000, Expansion Planning 1984, Cost estimating guidelines 2007), namely, Net Present Value (NPV), Present Value (PV), Internal Rate of Return (IRR), Discounted Payback Period (DPP), and Levelized Cost (LC) (see Table 1).

Table 1. Economic Performance Indicators.

Indicator	Calculation Formula
Net Present Value (NPV)	$NPV = \sum_{t=T_1}^{T_2} \frac{D_t}{(1+d)^t} - \sum_{t=0}^{T_2} \frac{R_t}{(1+d)^t}$
Present Value (PV)	$PV = \sum_{t=0}^{T_2} \frac{R_t}{(1+d)^t}$
Internal Rate of Return (IRR)	The interest rate at which the NPV is equal to 0.
Discounted Payback Period (DPP)	The period of time required for the revenue generated by the investment, taking into account the discount, to cover the investment cost.
Levelized Cost (LC)	$LC = \sum_{t=0}^{T_2} \frac{R_t}{(1+d)^t} \Big/ \sum_{t=T_1}^{T_2} \frac{W_t}{(1+d)^t}$

where D_t is the operating income at the time t; R_t is the operating costs at the time t; W_t is the current power generation; d is the rate of discount; T_1 is the construction period (years); T_2 is the project lifetime (years); t is the discrete time.

Depending on the task at hand, it is necessary to use one or another set of performance criteria. For example, in the case of orientation mainly to investors, the main indicator is the net present value which depends on an indefinite electricity tariff. In the case of owner orientation (when the construction of NPPs is mainly paid by the State), the main indicators for assessing the cost-effectiveness of NPP designs usually are total discounted costs. Generally, it is necessary to take into account the entire spectrum of performance indicators that reflect different aspects of the project.

While performing evaluation of economic performance and competitiveness of SMR deployment, it is necessary to consider not only the main factors influencing the economic indicators of SMRs but also a possibility of involving debt financing. The initial data are external conditions (price per unit of electricity sold, nuclear fuel cost, plant factor, discount rate, income tax rate), financing scheme (share in total capital investment, credit payment period, credit interest), unit performance parameters (installed capacity, construction time and unit cost, fixed cost, operation and maintenance costs, fuel burn-up, plant efficiency, annualized share of capital investment). The basic set of initial data used in the present study, which corresponds to some hypothetical (country neutral) situation is shown in Table 2.

Table 2. Initial data.

External Conditions	
Price per unit of electricity sold (cent/kWh)	10.5
Nuclear fuel cost (dollar per kg of U)	1800
Plant factor	0.8
Discount rate (%)	5
Income tax rate	24
Unit performance parameters	
Installed electric power (MW)	1200
Construction period (years)	6
Unit construction cost ($/kW)	4500
Fixed service, maintenance and repair costs ($MM/yr)	90.00
Fuel burn-up (MWth d/kg U)	43.00
Plant efficiency (%/100)	0.334
Annualized constant capital investment (%)	16.7
Financing scheme	
Share in total capital investment (%)	0–100
Credit payment period (years)	15–20
Credit interest (%)	7–10

Results and discussion

Comparison of economic performance metrics for NPP concepts based on SMR modules and a large nuclear reactor

The effect of economies of scale implying that an increase in unit power leads to a reduction in installed cost per kW works in the case when one reactor design similar to itself increases or decreases in power. The following correlation between capital costs and power unit is established according to the formula (NEA/OECD 2011, Approaches for Assessing 2013):

$$OCC(P_1)=OCC(P_0)\cdot\left(\frac{P_1}{P_0}\right)^n \quad (1)$$

where OCC are the Overnight Construction Costs, the scale factor n is in the range from 0.4 to 0.7, P is the reactor unit capacity. Different reactor technologies are characterized by their own scale factor. It should be noted that an increase in its value entails reducing the cost sensitivity to the power unit. In particular, if the scale factor value is equal to 1, there will be no economies of scale and the capital costs will no longer depend on the power unit.

Figure 1 shows a typical graph of the cumulative net present value for the investment project life cycle. The following deployment scenarios have been considered: one 1200 MW unit, two 600 MW units, and four 300 MW units. The last two are constructed on a module by module

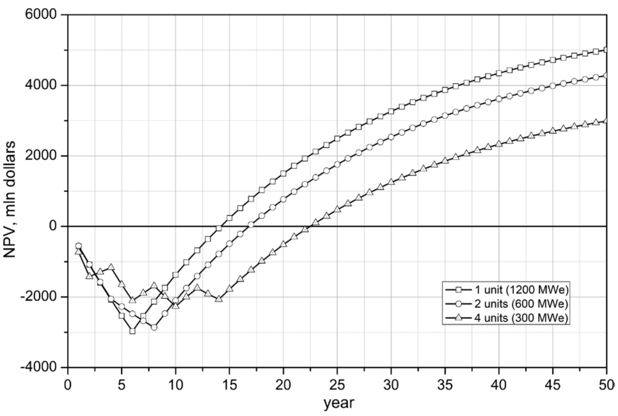

Figure 1. Change in NPV with time.

basis. The evaluations are made on the assumption that n = 0.6, excluding the learning effect.

Figure 1 shows two sections: the flow of accumulated capital investment in the construction of the units for a given period and the cumulative net present value at the unit operational site from the commencement of operation up to the end of its life cycle. The cumulative net present value at the end of the considered period will amount 5010, 4278, and 2991 million dollars.

Figure 1 makes is possible to determine the discounted payback period (DPP) as the point of intersection of the accumulated flow with the horizontal axis, where the NPV is equal to 0. As can be seen from the figure, the payback periods of the investment projects are 15, 17, and 21 years, respectively. As far as the investor begins to receive the income from the project only when the time is longer than the payback period, it is clear that the payback period should be considerably shorter than the life cycle duration.

The internal rate of return (IRR) of the project, i.e. the interest rate at which the NPV is equal to 0, for the considered scenarios is 11.7, 10.5, and 9.2%, respectively. It is believed that the higher the IRR and the greater the difference between its value and the predetermined discount rate, the more profitable the project is.

If the investor is the owner, for example, the State, the main economic performance indicators are usually the present value (PV), which for the considered investment projects are 4827, 5475, and 5634 million dollars, respectively. In this case the indicator of levelized costs (LC) will be 4.14, 4.68, and 5,28 cents per kWh, respectively.

As is seen from the estimations under the presented assumptions, the construction of one 1200 MW unit is more economically attractive. However, the implementation of the modular NPP concept based on small modular reactors includes provisions that increase their competitiveness due to the factors that determine the specifics of SMRs (in addition to traditional advantages of the modular concept such as high quality of manufacture and assembly of the main equipment at the factory, short production time, the possibility of transporting reactor units by rail, etc). In this regard, it seems appropriate to perform evaluations aimed at identifying areas where the implementation of the modular concept may be beneficial. To solve this problem, the following options have been considered: the possibility of building up to 20 units, the scale factor n is in the range from 0.4 to 0.7, assessments are made both including and excluding the learning effect (in accordance with (NEA/OECD 2011)).

Figure 2 shows the dependence of the net present value on the reactor module capacity and various assumptions regarding the scale factor including and excluding the learning effect. It is obvious that an increase in the scale factor, and with an allowance for the learning effect, the net present value will grow as the capital costs are reduced. It should be noted that the learning effect is equivalent to an increase in the scale factor by 0.1. The values of the net present value less than 0 indicate that the relevant investment project is not economically attractive.

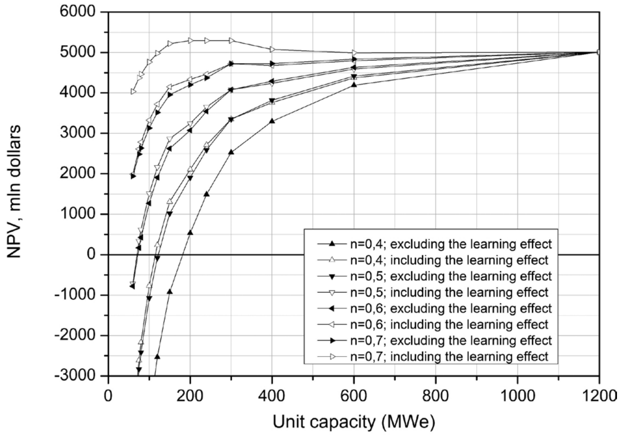

Figure 2. Net Present Value.

Figure 3 shows the dependence of the present value on the reactor module power. In contrast to the net present value, the discounted costs for all values of the scale factor are reduced with an increase in the unit power.

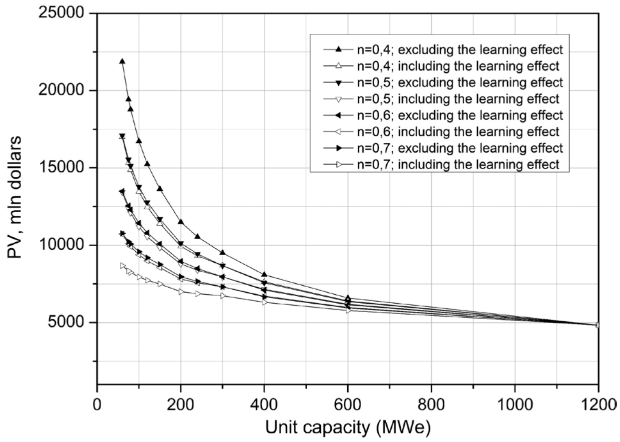

Figure 3. Present Value.

The discounted payback period and internal rate of return are important additional metrics of the investment project characterizing its economic performance and stability. Figures 4, 5 provide these metrics depending on the

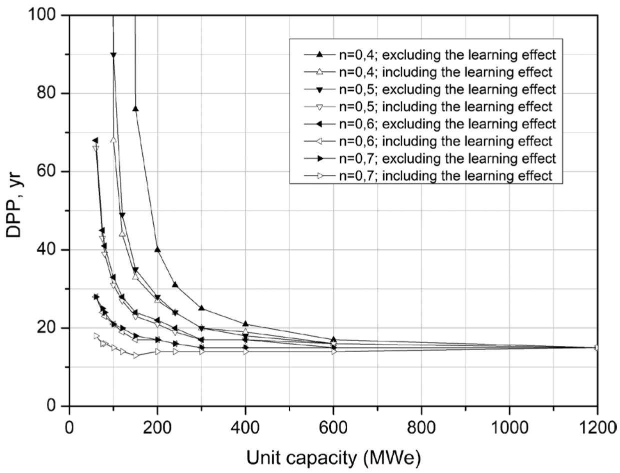

Figure 4. Discounted Payback Period.

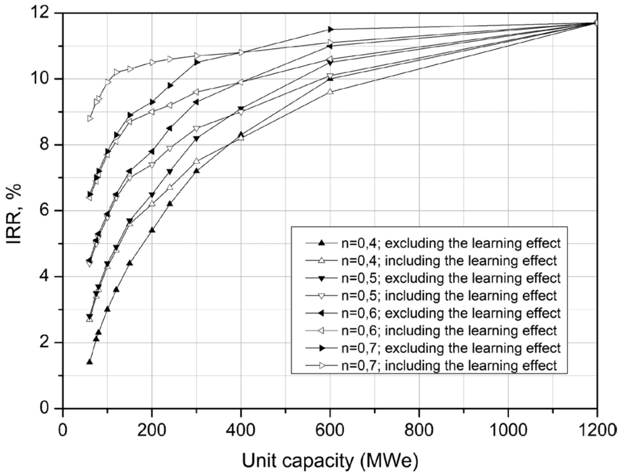

Figure 5. Internal Rate of Return.

module power. It is arguable that even at low scale factor values the construction of a modular NPP with a small number of modules (2–3), according to the economic effect determined by these parameters, may be comparable with the construction of a large nuclear reactor. Due to the scale factor increase and the learning effect taken into account, a further decrease in the unit power becomes economically attractive.

Figure 6 shows the dependence of the levelised cost on the reactor module power. For 1200 MW reactor, an increase in the unit power leads to a reduction in the levelised costs which reach their lowest value of 4.5 cent per kWh. For modules of lower power, the indicator value may be increased up to 15 cents per kWh. As can be seen in Figs 3, 6, the indicators of total and levelised costs do not demonstrate the economic attractiveness of the modular concept within the whole area of possible power for reactor modules: as the reactor module power increases, these values decrease monotonically.

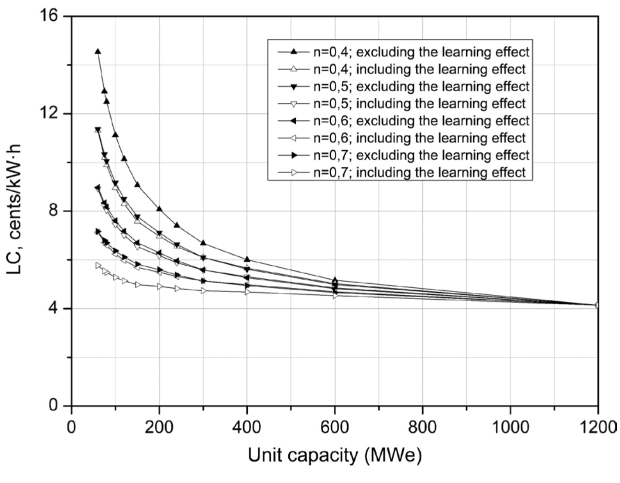

Figure 6. Levelized Costs.

One of the arguments in favor of the SMR is that the deployment of a nuclear energy system based on them can reduce the risks associated with the loss of capital investment (NEA/OECD 2011, Approaches for Assessing 2013, Andrianov et al. 2017). As a measure of the risk of capital investment loss, the concept of Value at Risk (VaR) (Andrianov et al. 2017) can be used. VaR is a measure of loss which will not exceed the expected loss with a specified probability equal to the α confidence level. Therefore, in 1–α cases the amount of loss will be greater than VaR. Thus, it is possible to assert with probability α, that the losses do not exceed the VaR of dollars (Andrianov et al. 2017).

Figure 7 shows the amount of losses which at the 99% confidence level is not exceeded as a function of a single module power and the probability of the module construction failure which is equal to 0.01%, respectively. The estimates were made on the condition that the construction is performed on a 'module by module' basis. As one can see, the VaR index tends to decrease with a decrease in the power of one module, which is due to a decrease in the overall level of losses if the construction of a part of modules fails.

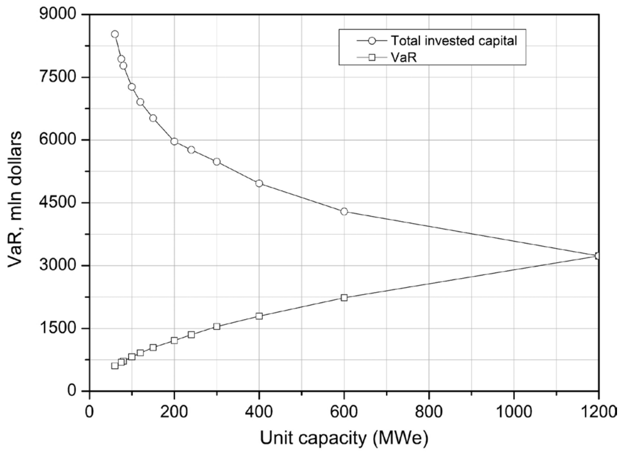

Figure 7. VaR.

The general conclusion that can be drawn from these evaluations, is as follows. In terms of the costs (present value and levelized cost), the economic attractiveness of the modular concept is missing. In terms of the net present value, internal rate of return and discounted payback period, it is possible to talk about the modular NPP feasibility in case the predicted learning effect is observed during the construction of the modules and the scale factor is not less than 0.5. In this case, it seems economically reasonable to construct an NPP from a small number of medium sized modules. If the scale factor is not less than 0.6, one can talk about the feasibility of constructing units of lower power.

Specifying Compromise Strategies for the SMR Deployment

Choosing the optimal SMR deployment strategy is a multi-criteria problem: it is reasonable to use the NPV and VaR indicators as the main criteria. These indicators are conflicting in nature: an improvement of one entails a deterioration of another. Therefore, it is necessary to look for compromise SMR deployment options: which would maximise the net present value on the one hand and minimise the value at risk on the other hand. The parameters that require definition are the power and start-up time of a reactor module. Selection of non-dominated deployment strategies makes it possible to define compromise deployment options of the system.

The values of NPV and VaR indicators for various SMR deployment scenarios are presented in Fig. 8. Taking into account the variety of possible options for the strategy implementation in order to reduce their number and select the most appropriate one, it is necessary to make a preliminary selection of trade-off (non-dominated) options for which an improvement in the value of one indicator will entail deterioration in the value of another. The "northwestern" border of the point cloud in Fig.8 is a criteria substitution curve characterizing the measure of loss in the value of one indicator due to the acquisition in the value of another, and the corresponding scenarios lying on this curve are compromise ones. The two extreme options are as follows. The greatest risk is presented (but the highest net present value can be obtained) in the construction of a large nuclear reactor (3231 and 5010 million dollars, respectively point #1). On the contrary, the deployment of a series of small sized reactors (60 MW, in a scenario of sequential start-up of two modules) reduces the net present value up to 2010 million dollars (2.5 times), while decreasing the risks of investment loss, characterized by a VaR indicator to the level of 600 million dollars (5.4 times) in comparison with the construction of a large nuclear reactor (point #2). Other possible trade-off scenarios are concluded between these two extreme options.

The final choice of the most appropriate option from a set of trade-off ones should be made based on an analysis of the NPV and VaR indicators substitution curve, taking into account an additional alternative analysis using other performance indicators and experts' judgments as well as the entire set of graphic and attribute data with due regard for the sensitivity analysis results. Such an analysis will make it possible not only to select a scenario (capacity and commissioning periods for reactor modules) which will provide an acceptable value of one indicator for a given constraint on the other, but also to formulate recommendations on how to increase the overall economic performance keeping associated risks at the acceptable level.

The Impact of Debt Financing on the Economic Performance Indicators

Let us compare the effect of debt financing on the values of economic effectiveness indicators for the NPP based on SMRs and a large nuclear reactor for the following scenarios: one 1200 MW unit, two 600 MW units, and four 300 MW units. The last two are constructed on a module by module basis. The evaluations are made on the assumption that n = 0.6, excluding the learning effect.

The following are three financing schemes of the investment project: (1) at its own expense without involving outside investors (zero share of external credit); (2) credit financing scheme (share in the total investment is 100%); (3) debt financing (share of the total investment is 10–90%). The credit payment period is 15–20 years. The interest rate is 7–10%. The values of performance indicators for financing the construction at its own expense without involving outside investors, corresponding to the zero share of external credit, are listed above.

As can be seen in Fig. 9, involving debt financing deteriorates the economic performance. Thus, in the case of a credit financing scheme (share in the total investment is 100%), the net present value is reduced by 15%, the discounted costs is increased by 28%, the internal rate of return and payback period are increased by 18 and 12%, respectively.

A comparison of different credit schemes from the standpoint of changes in the economic performance during the implementation of the modular NPP and the NPP based on a large nuclear reactor shows that the scaling effects are comparable in these cases. This does not make SMR more sensitive to a share of debt capital in the total capital investments, nor does it substantially deteriorate their adaptation to financing with the involvement of external credits as compared to large nuclear reactors.

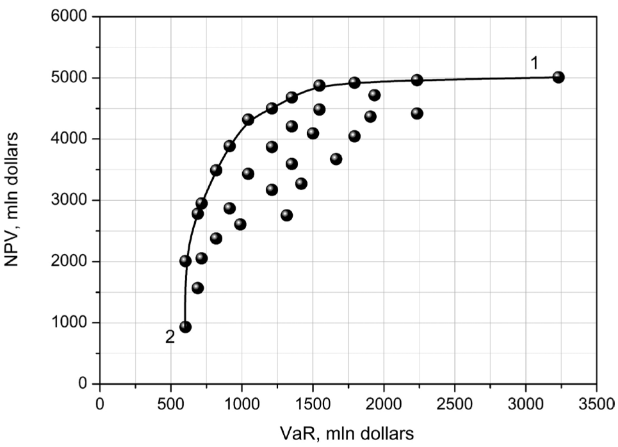

Figure 8. NPV and VaR values for various SMR deployment scenarios.

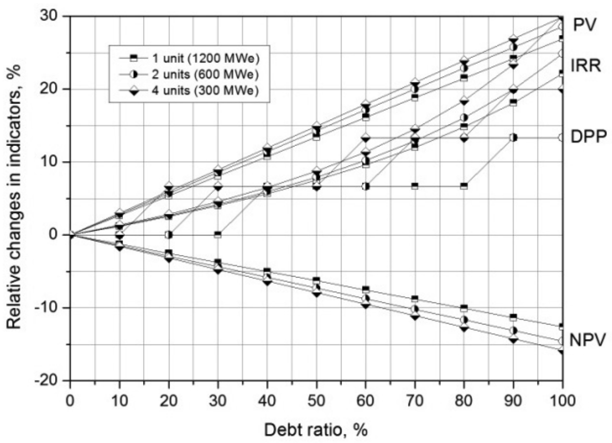

Figure 9. Relative changes in performance indicators, depending on the share of debt capital in the total investments.

Conclusion

The comparative analysis of the investment attractiveness of the NPP designs based on SMR modules and a large nuclear reactor has shown that, in terms of the total discounted and levelised costs, the NPP modular design concept has no economic attractiveness in comparison with a large nuclear reactor. In terms of the net present value, internal rate of return and payback period, the NPP modular design concept can be considered economically attractive if only the predicted learning effect is observed when the modules are constructed and the scale factor is not less than 0.5. In this case, it will be economically feasible to construct an NPP based on a small number of medium sized modules. If the scale factor is not less than 0.6, then we can talk about the feasibility of NPP designs based on reactor modules of lower power. The analysis of the impact of various debt financing schemes has demonstrated that, in relative terms, changes in the economic performance indicators are comparable in the implementation of the NPP modular design and a large sized reactor.

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