Nuclear Power Plants in the U.S. and China: Procedure for Determining and Comparing Operating and Construction Costs

Volodymyr (Vladimir) Mamalyga, Ph.D.,
Stephen A. Roosa, Ph.D., Yu Qiang, Jiyong Yan
and *Olha Varava*

ABSTRACT

The objective of this study is to create a procedure for determining and calculating the operating and construction costs (OCC) for nuclear power plants and to identify the factors that affect them. Our study revealed patterns of growth and decline in OCC for nuclear power plants (NPPs) when considering the duration of the plant's operation and the cost of money invested in its implementation.

Our results were derived from estimates obtained using an equation that accounts for the electricity generated by a NPP, capital costs per MWh, operating costs per MWh, time that the plant operates according to standards, electricity tariffs, plant capacities, and the cost of money. The results indicate that the calculation of OCC for NPPs should consider not only the technical characteristics of the plant, but also the level of tariffs, the location of the plant, and the conditions of its connection to the grid. Another important indicator is the value of money; as it declines, the OCC for the NPP tends to increase.

This comparative study uses information on nuclear power plants in the United States and the People's Republic of China. The results of this study are recommended to be used in the development of feasibility studies for the construction of NPPs around the world. For a satisfactory indicator, the calculation of the OCC for a NPP must include the regularity tariff parameters, technical data, and the cost of money for the specific plant. This article is useful to energy auditors, industrial managers, heads of government regulatory agencies, and university students interested in the costs of nuclear power plants.

INTRODUCTION

Developing nuclear power plants is an important way for electricity suppliers to meet the demand for clean energy. Compared to other alternatives, nuclear power has advantages over contenders to replace traditional coal and oil sources. For example, nuclear energy technologies offer reliable and resilient energy supplies. Nuclear energy is not dependent on weather conditions, as is the case of using some types of renewable energy resources. Unlike wind or solar energy, nuclear power can produce much larger amounts of energy in a limited land area due to its high energy efficiency and power density. Relying on a relatively ubiquitous mineral for a fuel source, the technology provides electrical generation at higher capacities than fossil fuel-fired processes.

Ways to assess the economic performance of nuclear plants are important due to the extent of nuclear development. Today's nuclear power plants function as utility-scale generation facilities. They have fission reactors and use enriched uranium-235 as the fuel source. This technology offers seemingly infinite supplies of energy and perhaps more importantly, provides base-load electrical power generation at high operating capacities [1]. With a world-wide fleet of over 800 operating reactors, nuclear energy accounts for almost 10% of the world's electrical energy production.

Nuclear reactors that generate electricity in the U.S. fall into two main categories: boiling water reactors (BWRs) and pressurized water reactors (PWRs) [2]. Both systems use Rankine cycle processes to boil water to make steam (BWRs within the reactor and PWRs outside the reactor) [2]. The steam must be cooled after it is directed through a turbine to produce electricity which necessitates their signature cooling towers.

As nuclear technologies advance, the economics of nuclear power must be considered. Cost calculation procedures allow comparative assessments with other energy sources which indicate the economic efficiency of the final product. An important aspect is the formation of the final price of electricity for consumers. In the different regions of the world electricity costs are highly variable.

There are various methods for calculating the operating and construction costs for NPPs, but many do not include all the relevant factors: electricity tariffs, plant operating time during the year, and monetary values for different countries. Our research was devoted to the development of a simplified procedure for determining the OCC for NPPs that accounts for these relevant factors.

LITERATURE REVIEW AND PROBLEM STATEMENT

The World Nuclear Association has indicated the performance of nuclear power plants, and provided detailed descriptions of the economic aspects that affect the price of electricity using nuclear power technologies [3]. Production costs for 2025 often use discount rates of 3% and 10%. If the discount rates increase to the upper limit of 10%, nuclear energy technologies become more expensive to use than coal in the countries of Japan, China, and India, and more expensive than natural gas in the U.S. and Japan. Consistent methodologies that account for changes in indicators such as the discount rate or the cost of money have yet not been established.

Woite presented various cost models for nuclear power plants and provided estimates of total investment costs, focusing mainly on the costs of reactors and infrastructure [4]. However, there is no attempt to account for income from the sale of the electricity produced; the focus is on the capital costs of construction and operation over time. It is necessary to account for the cost of money for the sale, electricity tariffs, and the duration of a nuclear plant's operation over its lifecycle (typically 40-60 years), so as not to limit the economic comprehensiveness of the analysis.

The approaches to conducting technical and economic calculations presented by Pratt and Banerjee are interesting and valuable [5,6]. However, they fall short when used to guide the operating and construction costs for NPPs because they do not fully account for the impacts of the duration of plant operation and the cost of money invested for its development.

Information about nuclear reactors in various countries of the world has been provided by Alam et al. [7]. They emphasize the importance of nuclear power in developing countries and the need to advance regional human resources. Given this perspective it is notable that there are only seven nuclear reactors in operation in the southern hemisphere.

Detailed descriptions of economic factors and indicators, such as construction costs and duration, cost of capital, operating costs, maintenance costs, fuel costs, estimated plant lifecycle, waste disposal costs and reserves, insurance, and liabilities are presented by Lucet [8]. However, these assessments fail to account for the lifetime of alternative equipment options. It is also rare that decommissioning costs are adequately considered in the buildup of lifecycle costs for NPPs and such costs can be substantial and widely variable [1,9].

Utility-scale nuclear reactors that supply power to electric grids have limitations which create challenges for assessments of operating costs. Design, permitting, development, and prove-out may require a decade or more and construction delays increase costs [10]. Other viable concerns include refined uranium's price volatility, how the converted uranium is sourced (about 40% of the refined global supply comes from the Russian Federation), the ultimate disposition and storage of spent fuel rods, and public concerns about safety and the potential of meltdowns [10]. Another more common concern is that traditional nuclear plants withdraw and consume vast volumes of water, more than coal-fired plants of similar capacities [10]. If a plentiful water supply is unavailable, a nuclear power station may be forced to shut down. This is the primary reason why nuclear plants are located near large natural bodies of fresh water.

The approaches to conducting feasibility studies for various facilities are described in recent literature [3,12-14]. Many have been used in the past to perform technical and economic calculations for NPPs. There are other methodologies available for developing feasibility studies for the use of equipment which account for plant lifecycle, cost of money, capital costs, and value of tariffs [11]. However, they often do to account for the separation of costs into operating and capital costs (construction costs) for each specific locale. Some past analysis approaches have considered examples in specific countries, but do not consider comparing those costs to different countries [12]. For others, the cost of money may be accounted for but the tariffs for different countries are overlooked.

For NPPs, there are few recent U.S. examples of newly constructed plants and the costs are variable or unavailable. The number of nuclear reactors that are being retired in the U.S. is greater than new ones that are being constructed [14]. Not so for most other clean energy technologies. Comparisons of solar power plant performance indicators for different U.S. states are not uncommon [13]. However, the effects of comparative equipment operating times are often not considered in analysis of the performance and costs.

These sources provide grounds for conducting a study to improve the calculation procedures related to the costs of operating and constructing NPPs either for ownership purposes or commercial exploitation. There is a need to clarify and refine the calculation procedures to include indicators and factors that were not previously considered, such as the revenues from the sale of electricity. Important tasks include determining the variable parameters that can be changed and addressing the question of the economic profitability of electricity generation at nuclear power plants.

STUDY OBJECTIVES AND RESEARCH METHODOLOGY

The goal of our study was to develop a methodology to better determine the cost of operating nuclear power plants. This enables us to substantiate the factors that influence the variable cost of electricity tariffs. It also provides opportunities to compare the difference in values for power plants in different countries, particularly the U.S. and China. To achieve the research goal, the following objectives required resolution:

- analyze the dynamics changes of OCC on NPPs depending on changes in the lifecycle of nuclear power plants;
- analyze the dynamics of OCC on NPPs accounting for changes in electricity tariffs in the region of their operation;
- compare the results obtained for sample NPPs (one in the U.S. and one in China);
- determine how changes in the indicators (cost of money, duration of plant operation during the year, electricity tariffs, etc.) affect the level of OCC on NPPs.

Research Methodology

To achieve the objectives of our study, an approach was developed to determine the costs of operating and building a nuclear power plant, accounting for revenues received from the sale of electricity and the value of money. A mathematical equation was developed capable of incorporating the range of economic factors required to fully access the various operating costs. Incorporating and assessing the following factors served as the foundation of our research methodology: costs for construction, capital, operations, maintenance, plant capacity, lifecycle, electricity tariff, and the cost or time value of money. The analysis used publicly available data for selected nuclear power plants in China and the U.S.

Equation 1 was developed with these factors in mind. The per MWh costs of operating and building a nuclear power plant, including revenues from electricity sales and the value of money are incorporated into Equation 1. If the results yield a positive value for the factor e, then the operation of the nuclear power station is profitable. If the calculation result is a negative value for the factor e, then the project is considered unprofitable, i.e. economically impractical, because the costs of its operation will exceed the anticipated income.

$$e = \frac{-C_c}{(1+i)^k} + \frac{-O_c + E_c}{(1+i)^k} + \ldots + \frac{-O_c + E_c}{(1+i)^k}, \qquad (1)$$

In Equation 1, C_c is the capital costs per MWh, which includes the cost of building a nuclear power plant and values the cost of land, construction, equipment and project financing. Operating costs per MWh, O_c, include the fixed costs of operating and maintaining a nuclear power plant, such as employee labor, maintenance, insurance, etc. The cost or time valuation of money, i, varies from 3% to 15%; k counts the age of the NPP in years.

Equation 2 is used to estimate the electricity generated, E_c, by a NPP as measured in watt-hours (Wh) or kilowatt-hours (kWh). H_{work} is the length of time the plant operates according to regulated standards as measured in hours per year. Other variables include the electricity tariff, T, and plant capacity, P_s.

$$E_c = H_{work} \bullet T \bullet P_s \qquad (2)$$

The data for the calculations were obtained for the Davis-Besse Nuclear Power Plant, located in the U.S. northeast of Oak Harbor, Ohio, and the Tianwan Nuclear Power Plant (also called the Jiangsu Nuclear Power Station or Lianyungang NPP), located on the coast of the Yellow Sea, approximately 30 km east of downtown Lianyungang, Jiangsu Province in China (see Table 1) [15-22]. In addition to the OCC, changes in electricity prices are accounted for in the calculations. It is also important to consider the technical characteristics of the plant, operating costs, etc.

Designated terms	*U.S.*	*China*
C_c	$2.84 billion	$3.2 billion
O_c	$5.55 million	$4.9 million
E_c	773,989,440 MWh	3,765,994,560 MWh
k	45 years	16 years

Table 1. NPP indicators used for calculation.

This methodology makes it possible to analyze the operation of NPPs in different countries, with various plant capacities and lifecycles and allows indirect accounting for labor costs and regulatory policies through the level of tariffs. Unlike the U.S. or China, a comparison using plants in France was determined inappropriate as France is highly dependent on nuclear power—about 70% of its electricity is from nuclear power plants.

RESULTS OF THE STUDY

The results of our study are obtained by using specific factors to demonstrate their influence on selected NPP performance indicators for plant operating and construction costs. These selected factors are the relationships between $/kWh and annual operating hours and between $/kWh and the cost of money.

Figures 1 and 2 indicate the relationships between $/kWh and the cost of money, *i*, as a function of the plant's annual hours of operation. For the different estimates of annual operating hours, comparisons are graphically presented for the following cases:

- For the U.S: 1) at an average estimate of operating hours; 2) at a lower operating hour estimate of 5,000 hours; and 3) at a higher operating hour estimate of 7,000 hours (see Figure 1).
- For China: 1) at an average estimate of operating hours; 2) at a lower operating hour estimate of 6,000 hours; and 3) at a higher operating hour estimate of 8,000 hours (see Figure 2).

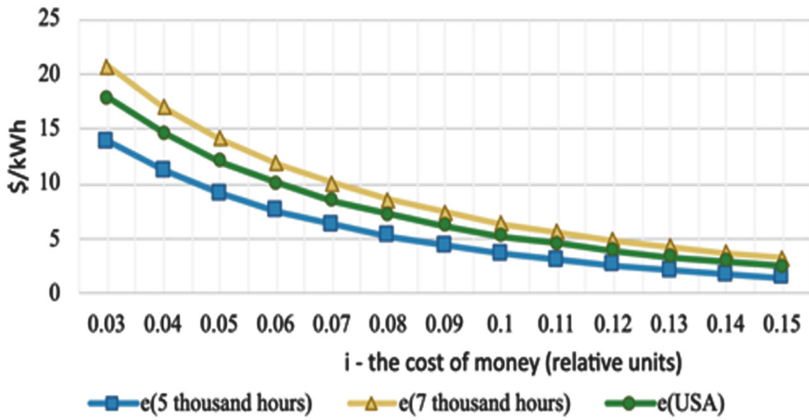

Figure 1. Dependency of OCC on NPPs in the U.S. for 5,000 and 7,000 hours of operation annually.

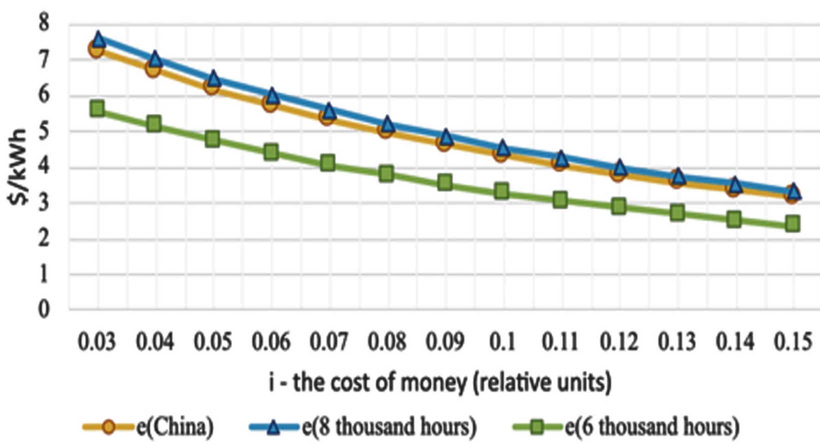

Figure 2. Dependency of OCC on NPPs in China for 6,000 and 8,000 hours of operation annually.

Extending the operating hours of the nuclear station increases the cost per kWh in both the U.S. and China. In all cases, the plotted cost per kWh is higher regardless of the cost of money. Figures 1 and 2 show that as the cost of money increases, the OCC decreases; i.e. revenues from the sale of electricity for nuclear power plants in the U.S. and China decline.

The results of tariff calculations for nuclear power stations in the U.S. and China are shown in Figures 3 and 4. For the different tariff levels, comparisons of tariffs are graphically presented for the following cases:

- For the U.S: 1) at an average rate 14¢/kWh; 2) at a lower rate of 10¢/kWh; and 3) at a higher rate of 20¢/kWh (see Figure 3).
- For China: 1) at an average rate 81¢/kWh; 2) at a lower rate of 70¢/kWh; and 3) at a higher rate of 90¢/kWh (see Figure 4).

Tariffs for electricity are substantially higher in China than in the U.S. Figures 3 and 4 indicate that the lower the electricity tariff, the lower the OCC or income from the operation of nuclear power plants in the U.S. and China.

Comparing Costs for Nuclear Power Plants in the U.S. and China

To visualize the comparative operating and construction costs for nuclear power stations in the U.S. and China, their data can be overlayed on the same graph. The results are indicated in Figure 5 which show the various values of operating and construction costs. The income from the implementation of nuclear power plant projects in the U.S. is higher than in China for lower values of i, the relative cost of money.

Changes in the Indicators

The impacts of changes in indicators (cost of money, duration of plant operation during the year, electricity tariffs) on the level of operating and construction costs for NPPs can be estimated. The results of the estimates for calculating the operating and construction costs for nuclear stations in the U.S. and China are consistent and intuitive. They indicate how changes in the indicators (cost of money, duration of plant operation during the year, electricity tariff) affect the level of OCC on NPP.

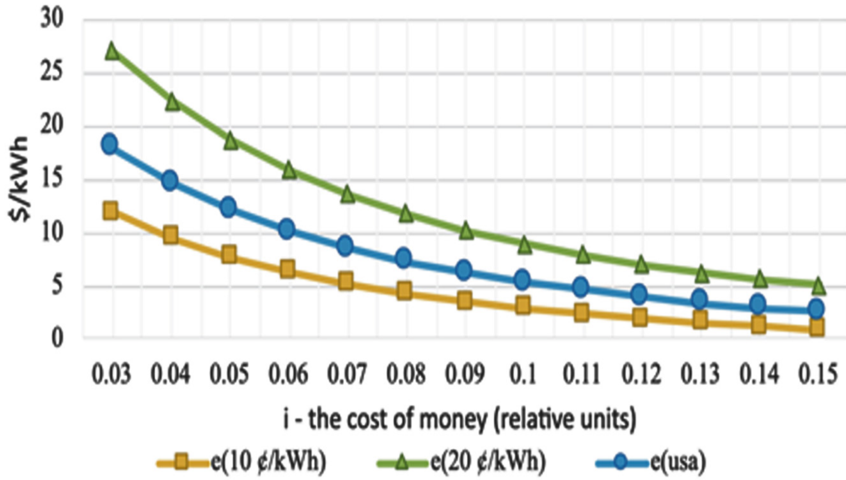

Figure 3. Dependence of nuclear power plants on OCC in the U.S. for tariffs of $0.10/kWh and $0.20/kWh.

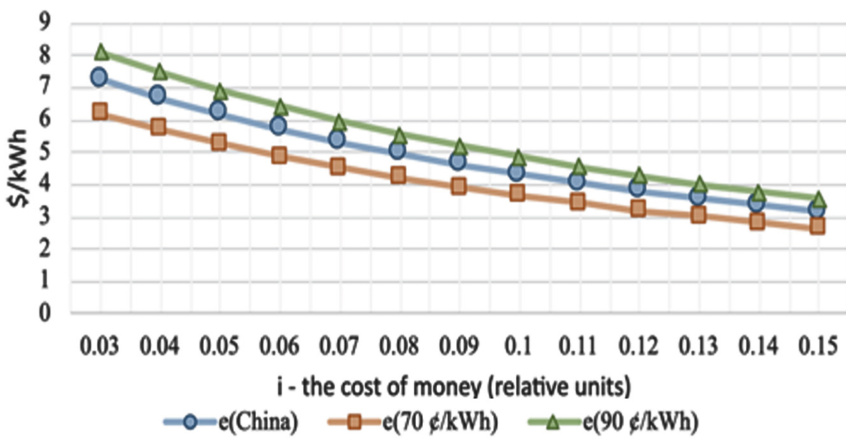

Figure 4. Dependence of nuclear power plants on OCC in China for tariffs of $0.70/kWh and $0.90/kWh.

The analysis demonstrates that for China's nuclear power plants, the operating and construction costs do not fall as sharply when the cost of money increases. This contrasts with the U.S. experience, as can be observed in the relationships of U.S. electricity tariffs to the cost of money. For China's NPPs operating and construction costs decline using a 3%-15% cost of money. The analysis shows that as the value of money rises, the OCC for the NPPs decline in both cases.

DISCUSSION

The results focus on determining and comparing the operating and construction costs of NPPs. Here we analyze the level of costs for the operation and construction of the NPPs in the U.S. and China, accounting for the proceeds from the sale of electricity and the cost of money for different operating hours during the year—specifically 5,000 and 7,000 hours for nuclear power stations in the U.S. and 6,000 and 8,000 hours for those in China.

Analysis for the U.S.

The analysis shows that for the U.S. (see Figure 1), at a cost of money i = 3%, the OCC on NPP is equal to:

- $20.70/kWh when the plant operates for 7,000 hours per year.
- $17.89/kWh when the plant operates for 6,184 hours per year.
- $13.83/kWh when the plant operates for 5,000 hours per year.

The fewer the annual operating hours, the lower the cost per kWh produced. Increases in the cost of money reduce the differences between OCC on NPP: $1.44/kWh at 5,000 hours/year, $2.54/kWh at 6,000 hours/year, and $3.30/kWh at 7,000 hours/year.

The differences in levels of operation and construction costs between the operation of a plant with a minimum the cost of money (i = 3% per year) when increasing and decreasing the plant's operating time are $2.82/kWh and $4.06/kWh, respectively. When i equals the maximum value of 15%, the differences are $0.76/kWh and $1.1/kWh. The analysis for the U.S. (shown in Figure 3) yields the following results for the various costs for money:

- For the low value i = 3% per year, the OCC for the NPP is equal to $17.89/kWh at the current electricity tariff of 14¢/kWh, and $26.99/kWh at an increased tariff of 6¢/kWh (i.e., 20¢/kWh) which is more than one and a half times higher than the current tariff. Using a reduced tariff of 4¢/kWh (i.e., 10¢/kWh, OCC on NPP is $11.83/kWh) the cost is much lower than the current tariff.
- For the average value i = 9% per year, with the increased tariff of

20¢/kWh, the current tariff of 14¢/kWh and the reduced tariff of 10¢/kWh, the OCC for the NPP are $10.21/kWh, $6.17/kWh and $3.48/kWh respectively.

- For the maximum value *i* = 15% per year, the OCC for the NPP are $5.01/kWh, $2.54/kWh, and $0.89/kWh.

As the cost of money increases from 3% to 15%, the difference between the values becomes less noticeable.

Analysis for China

For China (see Figure 2), the analysis yields much different results. The level of OCC on NPP is lower than for the U.S. The analysis shows that when the Tianwan plant operates for 7,647 hours annually compared to an operation time of 8,000 hours per year, the OCC does not differ significantly. The analysis for China (shown in Figure 2) yields the following results for the various costs for money:

- For the low value *i* = 3% per year, the respective NPP levels are $7.24/kWh and $7.06/kWh.
- For the average value, *i* = 9%, the NPP levels are $4.61/kWh and $4.85/kWh.
- For the maximum value, *i* = 15%, the NPP levels are $3.15/kWh and $3.32/kWh.

In the case of 5,000 plant operating hours/year, the difference in the level of OCC on NPP decreases with increases in the cost of money:

- If *i* = 3%, $7.24/kWh and $5.56/kWh.
- If *i* = 9%, $4.61/kWh and $3.5/kWh.
- If *i* = 15%, $3.15/kWh and $2.36/kWh.

The analysis for China shows that the difference between the indicators at the cost of money *i* = 3% is the most significant. At the lowest tariff of 11¢/kWh, namely 70¢/kWh, the OCC on NPP equals $6.18/kWh, at an increase of 9¢/kWh, the NPP reaches $8.1/kWh, and at the current tariff, the OCC on NPP equals $7.41/kWh. The analysis demonstrates that as the cost of money increases, the difference of OCC on NPP decreases. At the maximum cost of money, i = 15%, the value of OCC on NPP relative to different tariffs in China is: $3.56/kWh, the least costly tariff; $3.15/kWh, the current NPP tariff; and $2.65/kWh, the most expensive tariff.

Comments

The tariff structures for electricity in China are typically more costly on a per kWh basis than those in the U.S. (see Figure 4). The tariff of 81¢/kWh is 5.5 times more than that of the U.S. tariff of 14¢/kWh. The analysis clearly demonstrates that for China's NPP, the operating and construction costs do not fall sharply when the cost of money changes, as can be observed compared to the OCC for the U.S. NPP. This is understandable because for U.S. NPPs, the data used was from the Davis-Besse NPP which has been operating for 45 years; for China, data was taken from the Tianwan NPP which has been operating for 16 years. China's electricity tariff is more expensive (by 66¢/kWh) than that in the U.S. China's NPP OCC relative the cost of money at the example rates of 3%, 9%, and 15% is $7.24/kWh, $4.61/kWh and $3.15/kWh, respectively. With the same percentage values of the cost of money, the U.S. NPP OCC is: $17.89/kWh, $6.71/kWh and $2.65/kWh, respectively. The analysis shows that as the cost of money rises, OCC on NPP falls in both the U.S. and China.

CONCLUSIONS

All electrical power plants, regardless of type or energy resource used, have a finite lifecycle. Nuclear power plants became an option for the generation of electricity beginning in the mid-1950s. Their lifecycle is typically 40 to 60 years. Seen as a high-capacity and reliable means of generating power, the growth of the nuclear power industry seems unstoppable [9]. Compared to fossil fuel-fired plants, the use nuclear power is viewed as a solution to reducing the greenhouse gas emissions of utility-scale electric generation. In January 2025 there were 812 nuclear reactors in operation worldwide with 94 in the U.S. and 59 in China [23]. Using examples from these countries for our analysis is appropriate.

The goal of our study was to develop a methodology to better determine the cost of operating nuclear power plants. To this end, we compared the levels of OCC for example NPPs in the U.S. and China in terms of various indicators (i.e., electricity tariffs, plant operation time during the year). To achieve the objectives of our study, an equation was developed which incorporated the costs of operating and building a nuclear power plant, accounting for the revenues received from the sale of electricity and the cost of money. The OCC for the NPPs was compared for different costs of money in the U.S. and China. The comparisons were made for cases in which the possible options provide the optimal levels of OCC. It was shown that the calculations should account for the level of electricity tariffs, including the cost of money that can be raised for the project, the amount of capital investment, the duration of the plant's operation during the year, the plant's capacity, the costs of operation and maintenance of the nuclear power plant.

Our analysis proved that it is more expedient to implement projects when the cost of money is less than 15% in the case of operations for 5,000 hours annually in the U.S. and 6,000 hours annually in China. If the plants operate up to 7,000 hours annually in the U.S. and 8,000 hours annually in China, they are more profitable only at higher tariffs (42% higher for the U.S. and 11% higher for China compared to current levels).

The construction and operating costs of nuclear power stations vary widely from country to county. The ability to use a common methodology to assess the operations and construction costs of nuclear power plants is a considerable achievement. This analysis methodology can be used in the development of feasibility studies for the construction and operation of a nuclear power plants.

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AUTHOR BIOGRAPHIES

Volodymyr (Vladimir) Mamalyga, Ph.D., is a professor at the National Technical University, Kyiv Polytechnic Institute named after Igor Sikorsky, Ukraine. He is the author of more than 40 national standards in the field of energy and energy conservation. He has conducted more than 40 energy audits for large enterprises. Volodymyr (Vladimir) Mamalyga specializes in the design and adjustment of electric drives: multi-motor electric drive system, including for belt conveyors, energy saving in electric drive systems (algorithm and methodology for selection and calculation). He is also owner and director of Electrical Mechanics, located in Ukraine and Chief Engineer of the Machinery Manufacturing Company WNJ, located in China. Dr. Mamalyga has conducted exclusive energy training programs for more than 5,500 participants from seven countries. E-mail: v.mamalyga@gmail.com.

Stephen A. Roosa, Ph.D., MBA, CEM, BEP, CSDP, REP, CBCE, CMVP, LEED AP, is an energy engineering professional focused on developing solutions that bridge the gaps between energy and sustainability. He is the AEE's Director of Sustainable and Local Programs. Dr. Roosa has taught courses at three major U.S. universities. During his career, he has also taught over 150 seminars and workshops on the topics of energy management, sustainable development, renewable energy and microgrids in 12 countries. He is a past AEE president, an AEE Fellow, and a member of the Energy Manager's Hall of Fame.

He has written and edited six books and over 200 published journal articles related to energy conservation, energy engineering, energy management, renewable energy, electrical energy generation, carbon reduction, sustainable development and microgrids. E-mail: roosa.stephen@yahoo.com.

Olha Varava received her bachelor's degree from the National Technical University of Ukraine, Igor Sikorsky Kyiv Polytechnic Institute. She studied at the educational program of digital technologies in energy, specializing in computer science. E-mail: varavaola@gmail.com.

Jiyong Yan is chairman of Zhejiang Nuocai Technology Co., Ltd., responsible for overall company strategic planning, positioning, and management. Achievements include ranking 13th in Zhejiang Province's top 100 headhunting companies, being among the top ten in the introduction of overseas talents (projects) in Zhejiang Province, and securing the first position in the top five headhunting companies in Shaoxing City. The company has six subsidiaries within Zhejiang Province and more than 10 overseas talent acquisitionsites. Jiyong has over 15 years of experience in high-end talent recruitment and industry project settlement. Email: yx@1000top.cn.

Qiang Yu is an engineer with Zhejiang Omnipotent Spring Machine Co., Ltd. and has written national, industry, and group standards for machinery and motors. He has participated in many reviews in machinery related industries. Qiang Yu specializes in machinery manufacturing design and adjustment, including multi-axis linkage technology, and clamping technology. Email: 125664409@qq.com.