Estimating the Levelized Cost of Electricity of the First Nuclear Power Plant in Bangladesh

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Abstract. In this work, an economic study of Rooppur Nuclear Power Plant is conducted. It is the first nuclear power plant being constructed in Bangladesh. Correlation from available literature is used to predict the net power output of VVER-1200 type nuclear power plant in the weather condition of Bangladesh. This predicted value is used to estimate the Levelized Cost of Electricity (LCOE) of the plant. Results reveal that the estimated LCOE for the plant is 91.19 $/MWh for 50 years operating life, lower than most of its conventional and renewable competitors. However, LCOE of the nuclear power plant becomes higher than that of coal-based power plants in the country if the plant lifetime is 20 years. This is, however, very unlikely since the average lifetime of a nuclear power plant is much longer. Therefore, Rooppur nuclear power plant is found to be a feasible option from geo-economic point of view.

Keywords: Rooppur nuclear power plant · Levelized cost of electricity · Economic feasibility

1 Introduction

Nuclear power plants (NPPs) are thought to be among the most realistic solutions to greenhouse effect due to their low carbon footprints [1]. Yet, the sector experienced a stagnation period in late twentieth and early twenty first century owing to accidents like Chernobyl disaster and Fukushima disaster, which have shaped a negative public opinion towards nuclear power [2, 3]. Still, the enhanced safety features of Gen III+ reactors have succeeded in convincing a portion of the world population that nuclear power can also be safe if design-in-depth is ensured [4]. Many countries are now going for nuclear to meet their ever-growing need of energy. Bangladesh, a middle-income

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country, is in the same path to sustain its economic growth which is directly related to energy consumption, and thus, to energy production [5].

Rooppur NPP is the first nuclear power plant being constructed in Bangladesh. Russian VVER-1200 technology is to be adopted in this NPP. There are two units of this NPP and the total rated capacity of this power plant is 2400 MW_e [6]. The first unit of this power plant is expected to be operational by 2023 [6]. The estimated cost of the plant is approximately 12.65 billion USD, 90% of which is to be financed by the Russian government on a 1.75% interest rate capped at 4% for 28 years with 10 years grace period [7]. The government of India is also expected to finance multiple projects at an interest rate of 1% for 20 years with 5 years grace period [8], Rooppur NPP being one of those projects. Nevertheless, the investment required for this power plant is much higher than most other NPPs being built across the world [7], although the low-interest rate on debt is quite favorable for the project. Therefore, an economic feasibility study of the nuclear power plant is very crucial.

There are many approaches to studying the economic feasibility of a power plant. However, one of the most common parameters used to describe the feasibility of a power plant is the Levelized Cost of Electricity (LCOE), also called the Levelized Cost of Energy or Levelized Unit Electricity Cost (LUEC). It is a useful parameter for comparing different power generation options such as conventional, nuclear, renewable, etc., and predicts the possible cost of electricity per unit consumed [9]. There have been numerous studies focusing on LCOE to understand the prospect of various power generation technologies in the socio-economic scenario of Bangladesh [10–12]. However, these studies didn't consider the effect of weather of Bangladesh on the performance of the power plants, which is actually a very important factor [13]. Thus, an economic feasibility study of the first NPP in Bangladesh considering the effects of both weather and existing socio-economic parameters of the country is yet to be done.

In this work, the economic feasibility of Rooppur NPP is studied. At first, the important performance parameters of the NPP such as efficiency, output power etc. are calculated the weather condition of Bangladesh using the correlations proposed by Khan and Islam [13]. The optimum performance parameters obtained from the analyses are used to calculate the LCOE of Rooppur NPP for various plant operational lifetimes. Finally, a comparative study is conducted among Rooppur NPP and other conventional and renewable power plants in context to the socio-economic scenario of Bangladesh to determine the feasibility of the Rooppur project.

2 Methodology

2.1 Predicted Energy Generation from Rooppur NPP

VVER-1200 is a Gen III+ Pressurized Water Reactor (PWR) developed by ROSATOM, Russia with increased safety features such as passive safety systems, inherent safety systems, double containment, core catcher, etc. [14]. PWR are the most common reactor type used worldwide [15]. The enhanced safety features of VVER-1200 are the key reasons behind choosing this reactor technology by the Government of Bangladesh for the Rooppur NPP. However, these enhancements came with an increased cost of installation and commissioning. While the investment cost for starting up a single reactor unit of an NPP with output capacity in the range 700–1200 MWe was around 2–3.5 billion USD in the past for many countries [7], Rooppur NPP is expected to cost around 12.65 billion USD for two reactor units of 2400 MWe cumulative power output [7]. That's why it is very important to study the feasibility of the first NPP in Bangladesh.

Novovoronezh NPP-2 in Russia is the reference plant for Rooppur NPP. This power plant is also based on the VVER-1200 nuclear reactor [16]. Although they are identical in design, the weather conditions of the surroundings of the two plants are completely different. Novovoronezh NPP-2 can operate with 4–5 kPa condenser pressure as it is located in a cold weathered country. On the other hand, the condenser pressure is expected to be at least 7 kPa for Rooppur NPP since it is located in a tropical region country [13].

Khan and Islam [13] proposed a simplified Rankin cycle model for analyzing the secondary coolant loop of a VVER-1200-based NPP. The authors also developed correlations for multiple plant performance parameters such as plant efficiency, power output, condenser thermal load, etc. The developed correlation for power output is [13],

$$W = 991.59 + \frac{2203.97(2524.03 - h_{cond,in})}{2524.03 - h_{cond,out} - \vartheta(50 - P)} \tag{1}$$

Here, $h_{cond,in}$ and $h_{cond,out}$ are the specific enthalpies of condenser inlet steam and water entering low-pressure pump respectively. Also, υ and P are specific volume of liquid water and condenser pressure respectively.

Using the correlation, it is estimated that the net power output of Rooppur NPP should be around 1152 MW_e, which is much below its rated output of 1198 MW_e. This limitation is also acknowledged by the manufacturer. Thus, Rooppur NPP will have decreased power production and subsequent increase in its investment cost per unit energy produced due to the weather condition of Bangladesh.

2.2 Levelized Cost of Electricity for Rooppur NPP

Although NPPs and renewable power plants have much lower thermal efficiency than other thermal power plants like Combined Cycle Power Plants (CCPP), Coal-based power plants, etc. [13], they are preferred on many occasions depending on their economic feasibility. One way to compare the economic competitiveness of different power generation options is to compare their Levelized Cost of Electricity (LCOE). It denotes the ratio of the sum of all the levelized costs of a power plant over its lifetime to the sum of the levelized energy production during the same period [9]. LCOE for a NPP may be calculated using Eq. (2),

$$LCOE = \frac{\sum_{t=1}^{TL} \frac{(I_t + OM_t + FC_t + DC_t)}{(1+r_{AI})^t}}{\sum_{t=1}^{TL} \frac{E_t}{(1+r_{AI})^t}} \tag{2}$$

Here, I_t, OM_t, FC_t, DC_t and E_t, denote investment expenditures (in USD), operation and maintenance costs (in USD), fuel costs (in USD), average annual decommissioning cost (in USD) and electricity generated (in MWh) at year t respectively. r_{AI} denotes the annual discount rate of money due to inflation. Also, TL is the total life of the plant from the beginning of installation to the end of decommissioning. Ignoring the cooling down time of a NPP after shutdown, *TL* is given by,

$$TL = IT + OLT + DT \tag{3}$$

Here, *IT* is installation time, *OLT* is operational lifetime and *DT* is decommissioning time. In this work, the LCOE of Rooppur NPP has been calculated for different *OLT*s within the range of 10–50 years to predict the minimum required years of operation for being economically competitive to other power options.

The investment expenditure may account for multiple areas of expenses such as installation and commissioning costs, interest on loan, annual allowance for investment return, decommissioning costs, income taxes, etc. One or more of these expenses may be omitted depending on the type and location of the power plant. Thus, there is no universal equation of investment expenditure. The investment expenditure considered in this work at a specific year *t* is given by,

$$I_t = IC_t + YIOL_t + ROCEA_t + ITX_t; t = 1, \ldots TL \tag{4}$$

Here, IC_t is the average annual installation and commissioning cost (in USD), $YIOL_t$ is the annual payable interest amount on loan (in USD), $ROCEA_t$ is the annual return on common equity allowance, and ITX_t is income tax (in USD) at year *t*. Average annual installation and commissioning cost may be obtained from Eq. (5),

$$IC_t = \frac{TNI}{IT}; t = 1, \ldots IT \tag{5}$$

Here, *TNI* is the total net investment. For Rooppur NPP, the loan amount from Russia is approximately 11.38 billion USD on a 1.75% annual interest rate and 28 years duration [7]. Equation (5) considers the worst-case scenario where the plant takes the total allocated time limit to repay the debt. The usual repay time is 7–8 years [12]. In this study, this longer than usual loan repay time has been considered, keeping in mind the socio-economic instability of the country.

The annual decommissioning cost may be obtained from Eq. (6),

$$DC_t = \frac{TDC}{DT}; \quad t = (TL - DT + 1), \ldots TL \tag{6}$$

Here, *TDC* is the total decommissioning cost. To simplify calculations, it has been assumed that annual decommissioning cost is constant. Finally, the income tax rate is assumed 25% [19]. The annual operation and maintenance (O&M) cost of an NPP may be calculated using Eq. (7),

$$OM_t = OM_0(1 + r_{OM})^t; \quad t = (IT + 1), \ldots (TL - DT) \tag{7}$$

Here, OM_0 is the operation and maintenance cost at the beginning year of operation and r_{OM} is the operation and maintenance discount rate. OM_0 may be calculated using Eq. (8),

$$OM_0 = COM \times NU \times 1200 \times 365 \times 24 \times PUF \tag{8}$$

Here *COM*, *NU*, and *PUF* are the O&M cost per MWh, number of plant units (02 for Rooppur NPP), and plant utilization factor respectively. Similarly, the annual fuel cost may be calculated using Eq. (9),

$$FC_t = FC_0(1 + r_F)^t; \quad t = (IT + 1), \ldots (TL - DT) \tag{9}$$

Here FC_0 is the fuel cost at the beginning year of operation and r_F is the fuel discount rate. FC_0 may be calculated from Eq. (10),

$$FC_0 = CNF \times NU \times 1200 \times 365 \times 24 \times PUF \tag{10}$$

Here *CNF* is the cost of nuclear fuel. In most cases, a country has to keep an allowance in the LCOE for radioactive waste disposal. This allowance is called a waste fee. Including the waste fee, the corrected LCOE for the NPP becomes,

$$LCOE_{IWF} = LCOE_{EWF} + WF \tag{11}$$

Here, $LCOE_{IWF}$ and $LCOE_{EWF}$ denote LCOE including and excluding waste fees respectively. *WF* denotes the waste fee, taken as 1.0 $/MWh, following the regulations of the US government [18]. All the economic constants and assumptions considered in this study are summarized in Table 1.

Table 1. Economic constants and assumptions [17–19]

Economic parameter	Value
Installation and commissioning time, *IT* (years)	8
Plant operational lifetime, *OLT* (years)	10–50
Decommissioning time, *DT* (years)	5
Debt terms, *LT* (years)	28
Annual discount rate of money, r_{AI} (%)	5.0
Fuel discount rate, r_F (%)	−5.0
O&M discount rate, r_{OM} (%)	5.0
Income tax rate, r_{TX} (%)	25.0
Debt fraction, r_D (%)	90.0
Return on common equity allowance, r_{CE} (%)	12.5
Cost of fuel, *CNF* ($/MWh)	4.1
Cost of O&M, C*OM* ($/MWh)	10.0
Total net investment, *TNI* (billion $)	12.65
Total decommissioning cost, *TDC* (million $)	700
Radioactive waste fee, *WF* ($/MWh)	1.0

3 Results and Discussion

Figure 1 shows the LCOEs of Rooppur NPP for different plant operating lifetimes. The Figure also presents LCOEs for a hypothetical VVER-1200 NPP that has the same economic parameters as Rooppur NPP but is located in a cold-weather country. This was done to compare these two NPPs and identify the economic disadvantage that Rooppur NPP may face due to the weather condition of Bangladesh. From Fig. 1, it may be observed that the LCOEs of Rooppur NPP were higher than those of the hypothetical NPP, as one would expect due to the lower power output. The difference between the LCOEs decreased with the increase in the operating lifetime of the plant. The minimum difference was observed to be 2.52 $/MWh and the maximum difference was observed to be 7.02 $/MWh. Thus, it may be opined that the economic disadvantage of Rooppur NPP may be minimized by increasing plant operating lifetime. It is noteworthy that after 30 years of operational lifetime, the LCOE became less responsive to further increase in plant operational lifetime.

The LCOE of Rooppur NPP was estimated to be within the range of 91.19–179.25 $/MWh. The predicted values were somewhat lower than the predicted range of LCOE for an NPP in the USA, typically within 118.0–192.0 $/MWh [20]. This may be due to the comparatively lower interest rate on debt for Rooppur NPP (only 1.75% compared to 4–5% in the USA [18]) and a lower income tax rate in Bangladesh (25% compared to around 38% in many developed countries [18]). Further subsidy on this sector may make the power plant even more feasible from an economic point of view. The global average value in 2015 was found to be 95.9 $/MWh in the available literature [12], very close to but slightly higher than the predicted value of 91.19 $/MWh for 50 years plant operational lifetime. The results of a study conducted by Sieed et al. [21] found the LCOE for Rooppur NPP aound 94.8 $/MWh for a plant lifetime of 60 years using INPRO method, again very similar to the findings of this study.

An exceptional contradiction is observed between the predicted values of LCOEs in this study and the ones in a study conducted by Islam and Bhuiyan [12]. The later one predicted the LUEC for Rooppur NPP in the range 43.8–82.5 $/MWh for 60 years plant lifetime using FINPLAN model. Although the upper limit of LUEC obtained in the study is realistically close to the world average, the lower limit of 43.8 $/MWh is too low, even for the leaders of nuclear power sector like USA, RUSSIA, France, etc. Bangladesh is a newcomer country and lacks necessary technology as well as technical knowledge in this field. The fuel and O&M costs assumed in the study of Islam and Bhuiyan [13] for obtaining this lower limit of LUEC are, therefore, very difficult to achieve considering the absence of local source of nuclear fuel and the technological dependence of the country. In contrast, this work presents a somewhat conservative range for the LCOE of Rooppur NPP [22, 23].

A comparative study among different power options for Bangladesh is presented in Fig. 2. From Fig. 2, it may be observed that for 50 years operating lifetime, Rooppur NPP is predicted to have lower LCOE (91.19 $/MWh) than almost all of its conventional and renewable competitors, except for solar PV (91.00 $/MWh), hydroelectric (14.00 $/MWh), and gas-fired (28.00 $/MWh) power plants. However, both solar PV and hydroelectric power plants require a huge land area (31.35 and 237.55 acres/MW respectively), as shown in Table 2, which is not feasible for a densely populated country like Bangladesh; although this is not the case for gas-fired power plant (0.34 acres/MW). A typical NPP requires 0.93 acres of land per MW capacity. Thus, gas-fired is the only power option that is better than Rooppur NPP from a geo-economic point of view, which is why it is the most common type observed in Bangladesh till date. The only reason behind choosing an NPP over a gas-fired plant in Bangladesh for future projects is the rapid depletion of natural gas from the gas-fields in the country. Bangladesh doesn't have enough gas reserved in its gas-fields to support its growing energy demand in the future.

Another reason behind preferring nuclear power over gas and coal, another close competitor, is that both gas and coal power plants emit significantly higher greenhouse gas (GHG) (499 and 888 t-CO2/GWh respectively) compared to an NPP (29 t-CO2/GWh). Even solar PVs have higher GHG emissions than a typical NPP, as seen in Table 10. Only hydro has less GHG emission than NPP, but their land requirements make them unrealistic in the context of Bangladesh. Therefore, it may be stated that Rooppur NPP is geo-economically feasible for Bangladesh and, perhaps, one of the best power generation options for fighting climate change besides keeping the economy of the country stable.

Finally, it may be observed from Fig. 2 that the LCOE of Rooppur NPP is slightly higher than that of a coal-fired power plant in Bangladesh if the operating lifetime is 20 years. This difference may be neglected considering the huge difference in the GHG emissions for the two plants. However, a further decrease in the operational lifetime of Rooppur NPP will increase the LCOE significantly, taking the NPP almost out of the competition against coal-fired power plants. Thus, it is suggested that Rooppur NPP has to operate for 20 years or higher to be economically feasible for Bangladesh.

Table 2. Comparison of GHG-emission and land requirement of different power generation options for Bangladesh.

Type of power source	GHG emission (t CO_2/GWh)	Typical land requirement (acres/MW)
Proposed		
Rooppur NPP	**29** [1]	**Plant: 0.90** [23] **Storage: 0.03** [23]
Solar PV	85 [1]	Total: 31.35 [23]
Rooftop solar PV	85 [1]	–
CSP	–	Total: 45.25 [23]
Wind	26 [1]	Total: 60.00 [23]

(*continued*)

Table 2. (*continued*)

Type of power source	GHG emission (t CO_2/GWh)	Typical land requirement (acres/MW)
Existing (report of 2016)		
Hydro	26 [1]	Excluding Catchment Area: 237.55 [23]
Gas	499 [1]	Plant: 0.34 [23]
Coal	888 [1]	Plant: 0.70 [23] Mine and Storage: 0.72 [23]
HFO	733 [1]	–
Diesel	733 [1]	–

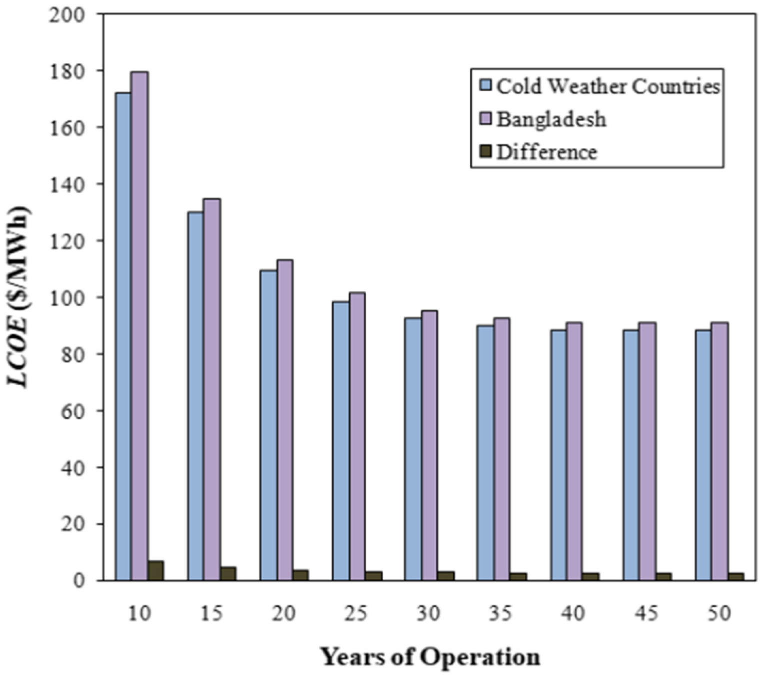

Fig. 1. Comparison of LCOEs for different NPP operational lifetimes

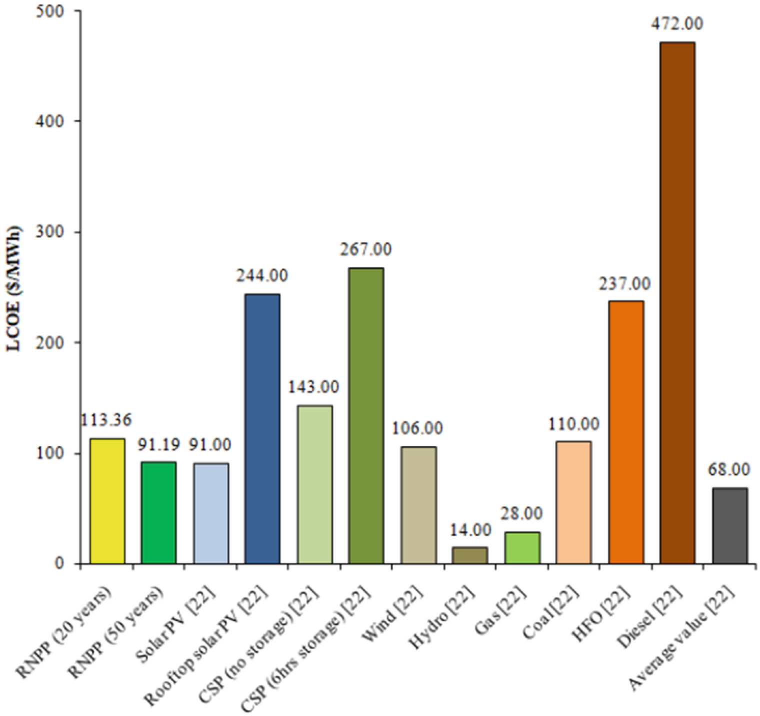

Fig. 2. Comparison of LCOE of different power generation options for Bangladesh

4 Conclusion

This work attempts to estimate the LCOE of Rooppur Nuclear Power Plant. While doing so, the effect of weather condition of Bangladesh on the net power output of the plant is considered. The correlations proposed by Khan and Islam are utilized to predict the reduction in net power output. After that, LCOE is calculated for different plant operational lifetimes.

Results reveal that the LCOE of Rooppur NPP is within the range of 91.19–179.25 $/MWh. This value is comparable to the LCOEs of other NPPs in different countries. Results also suggest that Rooppur NPP is expected to have lower LCOE than most of its conventional and renewable competitors if the plant operational life is 50 years, except for solar PV, gas-fired power plants, and hydroelectric power plants. However, considering GHG emission and land requirement, Rooppur NPP is found as the most feasible and promising power generation option for Bangladesh. Another important finding is that Rooppur NPP should operate for 20 years or longer to remain economically competitive with the coal-fired power plants.

This study is based on a specific nuclear reactor technology, which is VVER-1200. Further studies may be conducted to evaluate the effect of weather on the performance of NPPs with other reactor designs. A comparative study with different reactor technologies may also be carried out to find the best performing technology in the weather condition of Bangladesh, both from a thermodynamic and economic standpoint.

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