Fuel and O&M Costs Estimation of High Temperature Gas-cooled Reactors and Its Possibility to be Implemented in Indonesia

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Abstract. This research discussed an estimation of High Temperature Gas-cooled Reactor (HTGR) O&M and fuel cost and the potency of HTGR implementation in Indonesia. The cost estimation was done by using scaling method. The O&M and fuel cost compared with the O&M and fuel cost from others power plants. By using the comparison, it could be known that HTGR potentially could be used or not. This research’s purposes were to obtain an estimation of HTGR O&M and fuel costs for various capacities and to know the possibility of HTGR implementation in Indonesia. The results showed the O&M costs were 59.78 million USD for 600 MWth, 56.63 million USD for 350 MWth, 52.04 million USD for 50 MWth, and 51.10 million USD for 10 MWth. The fuel costs were 57.28 million USD for 600 MWth, 33.41 million USD for 350 MWth, 9.55 million USD for 100 MWth, 4.77 million USD for 50 MWth, 2.86 million USD for 30 MWth, and 0.95 million USD for 10 MWth. Based on the comparison with fossil power plants in Indonesia, due to the fuel and O&M cost of HTGR were less than or nearly same with the fuel and O&M cost of fossil power plants, it could be concluded that HTGR 600 until 30 MWth had high possibility to be implemented in Indonesia.

Keywords: High Temperature Gas-cooled Reactor, Scaling law, O&M cost, Fuel cost

1. Introduction

High temperature gas-cooled reactor (HTGR) can be used for cogeneration processes (electricity and heat)[1,2]. With these cogeneration capabilities, HTGR potentially can be used as a power plant and steam producer for industrial applications in Indonesia’s industrial estates[3–16]. Based on the National Energy Policy (NEP), a factor that should be considered to use nuclear energy in Indonesia is an economic factor[17].

The economic factor can be represented by using fuel and O&M cost of HTGR. If the cost is less than or nearly same with others power plants, especially fossil power plants, we can say that HTGR has high possibility to be implemented in Indonesia. We still say “has high possibility to be implemented” because to know exactly HTGR is economic or not, it needs economic analysis. To conduct the economic analysis, we required others cost that beyond this research purposes.
The fuel and O&M costs can be determined based on operation experience of HTGR. However, the current status of HTGR technology is still in an experimental stage, so the costs cannot be known exactly [18]–[25]. Because of that, we need an estimation of fuel and O&M costs of HTGR.

Idaho National Laboratory (INL) has estimated the HTGR costs based on their experience [26]. The estimation is included in the AACE International Class 4 that can be used for economic analysis at a feasibility study stage [25, 26]. INL only makes an estimation for HTGR 600 MWth and HTGR 350 MWth. Whereas, the demand for power supply in industrial estates has ranged from 1 MWe to 1000 MWe [28]. Therefore, it is necessary to estimate the HTGR costs for varying capacities.

Research [28–30] have used statistical models to perform costs estimation. The statistical models require considerable historical data. Therefore, the statistical models are difficult to be used in this research.

Research [31, 32] stated that estimation of a real model can be done by using scaling factor. Research [33, 34] used the scaling law to estimate production cost based on experimental stage cost. Research [35, 36] made an estimation of a pressurized water reactor (PWR) investment cost by using scaling law. Based on research [33–37], scaling law can be used to make a cost estimation based on cost at a certain capacity.

This research used scaling law to estimate the HTGR costs. The HTGR costs that estimated in this research are fuel and O&M costs. HTGR Next Generation Nuclear Plant (NGNP) costs are used as a reference costs [26].

By using the estimated fuel and O&M cost, we can analyze the possibility of HTGR implementation in Indonesia. The analysis is done by comparing the fuel and O&M cost of HTGR to the fuel and O&M cost of fossil power plants. The consideration of why we use fossil power plants as a comparison is many industry use fossil power plant to supply heat and electricity demands.

The research’s purpose is to obtain an estimation of HTGR annual O&M cost and annual fuel cost for various capacity values and to know the possibility of HTGR implementation in Indonesia. The difference of this research to the previous research are we estimated fuel and O&M costs of HTGR for various capacities and analyze the possibility of HTGR implementation in Indonesia.

It is expected that by using this research results, we can know the estimated fuel and O&M costs of HTGR and the possibility of HTGR implementation in Indonesia. In other hands, this research results can be used by Indonesia government to start thinking about HTGR implementation in Indonesia.

2. Research Method

Figure 1 shows how this research is conducted. From the literature review, we got data about HTGR’s O&M and fuel costs reference data and the method that can be used to make the estimation. The O&M and fuel cost references took from Dominion and Idaho National Laboratory (INL) studies [25, 38]. There were three types of the cost data: NGPP (experimental stage), FoAK (First of A Kind), and NoAK (Nth of A Kind). By considering the development stage of HTGR, we used the NGPP data. The O&M and fuel costs estimation is done by using a scaling law method.

![Figure 1. Research’s Flowchart](image-url)
2.1. O&M Costs of HTGR

O&M Costs of HTGR consist of various components. The components of O&M cost of HTGR that used in this research are based on studies conducted by Dominion and INL [25, 38]. Based on these studies, O&M costs consist of payroll, NRC fees, INPO fees, NEI fees, insurances and taxes, material supplies and services, outage costs, administration and general cost overhead. Table 1 shows the annual O&M costs of HTGR estimated by INL.

| Item                  | HTGR 600 MWth | HTGR 350 MWth |
|-----------------------|---------------|---------------|
| Payroll               | 39.16         | 39.16         |
| NRC Fees              | 4.78          | 4.78          |
| INPO Fees             | 0.71          | 0.71          |
| NEI Fees              | 0.06          | 0.03          |
| Insurance and taxes   | 3             | 3             |
| Material supplies and services | 5       | 3             |
| Outage costs          | 4.07          | 2.95          |
| Administration & general cost overhead | 3        | 3             |
| Total Annual O&M costs| 59.78         | 56.63         |

2.2. Fuel Costs of HTGR

This research used INL and Dominion data for fuel costs data [25, 38]. Fuel costs consist of uranium ore cost, uranium conversion cost, uranium enrichment cost, tails disposal cost, fuel fabrication cost, spent fuel storage cost, and spent fuel disposition cost. Table 2 shows the annual fuel costs of HTGR 600 MWth.

| Item                        | HTGR 600 MWth |
|-----------------------------|---------------|
| Uranium ore cost            | 5.37          |
| Uranium conversion          | 0.46          |
| Uranium enrichment          | 6.04          |
| Tails disposal              | 0.44          |
| Fuel Fabrication            | 39.68         |
| Spent fuel storage          | 0.34          |
| Spent fuel disposition      | 4.97          |
| **Total Annual Fuel Costs** | **57.30**     |

By using the same items as Table 2, INL has estimated the annual fuel costs for HTGR 350 MWth. The annual fuel cost is 33.41 million USD [26].

2.3. Scaling Law and Scaling Factor

The scaling law is used to estimate costs based on existing costs [33–37]. Association for the Advancement of Cost Engineering (AACE) has classified the scaling law estimation into AACE international class 4. Class 4 estimation had error -30% to +50% and can be used for feasibility study [25, 26].
The estimation cost by using scaling law was done by using equation 1. Equation 1 showed that the value of the estimated cost depends on the value of n. n is the scaling factor.

\[ \text{NewCost} = \text{KnownCost} \times \left( \frac{\text{New Capacity}}{\text{Known Capacity}} \right)^n \]  

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The scaling factor was unknown and need to be calculated. The scaling factor calculated by using data obtained from INL. Equation 2 is used to calculate the scaling factor.

\[ \left( \frac{350}{600} \right)^n = \frac{\text{Costin 350 MWth}}{\text{Costin 600 MWth}} \]  

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2.4. Error Calculation
The error calculation was done by comparing this research’s results with previous research. The previous research had estimated the HTGR’s O&M and fuel costs. The previous research had estimated the O&M cost based on supplier’s point of view and its extrapolation for other capacities [26]. Table 3 shows the O&M cost based on supplier’s point of view. While the fuel cost is estimated linear with the capacity. Table 4 shows the fuel cost based on the previous research.

Table 3. HTGR’s O&M Cost based on supplier’s point of view (million USD) [26]

| Item                      | Capacity       |
|---------------------------|----------------|
|                           | 600  | 350  | 100  | 50   | 30   | 10   |
| Payroll                   | 16.92 | 16.92 | 16.92 | 16.92 | 16.92 | 16.92 |
| NRC Fees                  | 4.78  | 4.78  | 4.78  | 4.78  | 4.78  | 4.78  |
| INPO Fees                 | 0.71  | 0.71  | 0.71  | 0.71  | 0.71  | 0.71  |
| NEI Fees                  | 0.06  | 0.03  | 0.0062 | 0.0026 | 0.0014 | 0.0004 |
| Insurance and taxes       | 3     | 3     | 3     | 3     | 3     | 3     |
| Material supplies and services | 5   | 3     | 0.91  | 0.47  | 0.29  | 0.10  |
| Outage costs              | 4.07  | 2.95  | 1.39  | 0.92  | 0.68  | 0.35  |
| Administration & general cost overhead | 3 | 3 | 3 | 3 | 3 | 3 |

Table 4. HTGR’s Fuel Cost based on previous research (million USD) [26]

| Capacity (MWth) | 600     | 350     | 100     | 50      | 30      | 10      |
|-----------------|---------|---------|---------|---------|---------|---------|
| Annual Fuel Cost (million USD) | 57.28 | 33.41 | 9.55 | 4.77 | 2.86 | 0.95 |

With data from Table 3 and Table 4 as a comparison, we calculated the error of our estimation by using equation (3).

\[ \text{Error} = \left[ \frac{\text{Our estimation} - \text{Previous estimation}}{\text{Our estimation}} \right] \times 100\% \]  

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2.5. Fuel and O&M Cost of Fossil Power Plants in Indonesia
Fuel and O&M cost of fossil power plants used as a comparison to know that HTGR had a chance to be developed in Indonesia or not. If the fuel and O&M cost of HTGR were less than or nearly same with the fuel and O&M cost of fossil power plants, we said that HTGR had high possibility to be developed in Indonesia. If the fuel and O&M cost of HTGR were higher than fossil power plants, we said that HTGR had low possibility to be developed in Indonesia. Figure 2, Figure 3, Figure 4, and Figure 5 showed the fuel and O&M cost of Indonesia’s fossil power plants[40]–[47].

![Figure 2. Coal power plant’s cost](image1)
![Figure 3. Diesel power plant’s cost](image2)
![Figure 4. Gas Turbine power plant’s cost](image3)
![Figure 5. Combine Cycle power plant’s cost](image4)

3. Results and Analysis
By using the data in Table 1 and equation 2, it can be obtained the scaling factor values for each O&M cost components. Table 5 shows the scaling factor values for each component of HTGR O&M costs. Some of the components have zero scaling factor. It means the changing of the capacity does not affect the cost. Payroll associated with salary staff. The staff salary is influenced by the number of staff and the salary standard. Based on the study conducted by Dominion, the number of staff and the salary standard does not depend on HTGR capacity, so the payroll will be same for HTGR capacity included in the research.

In addition to payroll, there are some O&M cost components that are not influenced by HTGR capacity, i.e. Nuclear Regulatory Commission (NRC) fees, Institute of Nuclear Power Operation (INPO)
fees, insurance and taxes, dan administration & general cost overhead. These cost components are more influenced by technology types.

Table 5. Scaling factor of HTGR O&M Cost Component

| Item                  | 600 MWth | 350 MWth | Scaling Factor |
|-----------------------|----------|----------|----------------|
| Payroll               | 39.16    | 39.16    | 0              |
| NRC Fees              | 4.78     | 4.78     | 0              |
| INPO Fees             | 0.71     | 0.71     | 0              |
| NEI Fees              | 0.06     | 0.03     | 1.25           |
| Insurance and taxes   | 3        | 3        | 0              |
| Material supplies and services | 5      | 3        | 0.95           |
| Outage costs          | 4.07     | 2.95     | 0.6            |
| Administration & general cost overhead | 3 | 3 | 0 |

The changing of HTGR capacity will affect some components in O&M cost, i.e. Nuclear Energy Institute (NEI) fees, material supplies and services cost, and outage costs. This is indicated by the scaling factor values. Greater scaling factor will make the effect of capacity changes on the cost changes greater.

The scaling factor calculation for fuel cost uses equation 2 and annual fuel cost data of HTGR 600 and 350 MWth. Table 6 shows the scaling factor value of HTGR fuel cost. The scaling factor is equal to one, it means that the cost will change linearly with the capacity changes. This is appropriate with the result of the Dominion studies. According to the Dominion studies, fuel cost will be affected by the capacity changes in a linear pattern.

Table 6. Scaling factor of HTGR Fuel Cost Component

| Item             | 600 MWth | 50 MWth | Scaling Factor |
|------------------|----------|---------|----------------|
| Annual Fuel Cost | 57.28    | 33.41   | 1              |

By using the scaling factor values in Table 5, it can be estimated the O&M costs for some capacities. Table 7 shows the estimated O&M costs. The O&M costs will change according to the scaling factor value. The changes can be seen in Figure 6.

Table 7. Estimated HTGR O&M Costs (million USD)

| Item                  | Capacity |
|-----------------------|----------|
|                       | 600      | 350   | 100  | 50  | 30  | 10  |
| Payroll               | 39.16    | 39.16 | 39.16| 39.16| 39.16| 39.16|
| NRC Fees              | 4.78     | 4.78  | 4.78 | 4.78 | 4.78 | 4.78 |
| INPO Fees             | 0.71     | 0.71  | 0.71 | 0.71 | 0.71 | 0.71 |
| NEI Fees              | 0.06     | 0.03  | 0.0062| 0.0026| 0.0014| 0.0004|
| Insurance and taxes   | 3        | 3     | 3    | 3   | 3   | 3   |
| Material supplies and services | 5 | 3 | 0.91 | 0.47 | 0.29 | 0.10 |
| Outage costs          | 4.07     | 2.95  | 1.39 | 0.92 | 0.68 | 0.35 |
| Administration & general cost overhead | 3 | 3 | 3 | 3 | 3 | 3 |
| **Total Annual O&M costs** | **59.78** | **56.63** | **52.96** | **52.04** | **51.62** | **51.10** |

Figure 6 shows that each component of the O&M cost has different cost change characteristics. Annual O&M cost is the sum of the cost components of O&M cost, so it will have different scaling
factor characteristics and values. The annual O&M cost has a scaling factor = 0.12. While the change characteristic is shown in Figure 7.

**Figure 6.** Estimation of the components of HTGR O&M Cost
By using the scaling factor value in Table 6, it can be estimated the HTGR fuel cost for various capacity values. Table 8 shows the estimated annual HTGR’s fuel cost. While the characteristic of capacity change to fuel cost is shown in Figure 8. Figure 8 shows that the capacity change is linear to the fuel cost changes.

**Table 8. Estimation of Annual HTGR Fuel Costs**

| Capacity (MWth) | 600 | 350 | 100 | 50 | 30 | 10 |
|----------------|-----|-----|-----|----|----|----|
| Annual Fuel Cost (million USD) | 57.28 | 33.41 | 9.55 | 4.77 | 2.86 | 0.95 |

The error is calculated by using equation (3). The estimation errors are shown in Figure 9. Both of the O&M and fuel cost are located in acceptable error area (between upper and lower limit). Based on the errors, we can say that our estimation is valid and included in AACE international class 4.

After we obtain the estimated O&M and fuel cost, analysis of HTGR implementation possibility has been done by using comparative analysis. Figure 10 shows the comparison of fossil power plants cost in Indonesia to the HTGR cost. The fuel cost of fossil power plants has bigger value than the O&M cost and fluctuate depending on the global price of fossil fuel. While the fuel cost of HTGR is relatively stable because the global price of uranium is more stable than fossil fuel. The HTGR O&M cost gives bigger value than the HTGR's fuel cost because of the complexity and the safety aspect of HTGR. Less capacity makes the O&M cost higher because the O&M cost does not change linearly with the capacity change. There are some O&M cost components that are not influenced by HTGR capacity, i.e. Nuclear Regulatory Commission (NRC) fees, Institute of Nuclear Power Operation (INPO) fees, insurance and...
taxes, dan administration & general cost overhead. These cost components are more influenced by technology types.

![Figure 9. Estimation Errors](image1)

![Figure 10. Power plants cost comparison](image2)

HTGR 600 MWth until 30 MWth have high possibility to be developed in Indonesia because the O&M and fuel cost can compete with fossil power plants. Based on the O&M and fuel cost, HTGR 600 MWth and 350 MWth can compete with coal power plant, HTGR 100 MWth can compete with the combined cycle power plant, and HTGR 50 MWth and 30 MWth can compete with diesel and gas turbine power plants. While the cost of HTGR 10 MWth is too expensive for normal usage. But the HTGR10 MWth cost is nearly same with the gas turbine power plant in 2017, so HTGR 10 MWth can be used for specific purposes such as isolated area, military area, or research area.
4. Conclusion

Based on the estimation results by using scaling method, it can be obtained the annual O&M and annual fuel costs of HTGR for various capacities. HTGR 600 MWth has annual O&M cost 59.78 million USD and annual fuel cost 57.28 million USD. HTGR 350 MWth has annual O&M cost 56.63 million USD and annual fuel cost 33.41 million USD. HTGR 100 MWth has annual O&M cost 52.96 million USD and annual fuel cost 9.55 million USD. HTGR 50 MWth has annual O&M cost 52.04 million USD and annual fuel cost 4.77 million USD. HTGR 30 MWth has annual O&M cost 51.62 million USD and annual fuel cost 2.86 million USD. HTGR 10 MWth has annual O&M cost 51.10 million USD and annual fuel cost 0.95 million USD. Based on the comparison, we knew that HTGR 600 until 30 MWth had high possibility to be implemented in Indonesia because the total of O&M and fuel cost still competitive with fossil power plants.

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