Cost-Benefit Analysis of G.A. Siwabessy Reactor Revitalization for I-131 Production

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A B S T R A C T

One of the IAEA expert team's recommendations in the peer review of three Indonesian research reactors in 2022 was to increase their utilization, especially for the production of radioisotopes and radiopharmaceuticals, through a revitalization program and operating permits extension, such as for the G. A. Siwabessy Multipurpose reactor (RSG-GAS). One of the radioisotopes widely used in the health sector is I-131. The existing I-131 domestic demand is recorded at 2,869.35 Ci per year and is projected to increase along with cancer prevalence. Imports fully meet the current demand at quite high prices. Therefore, the RSG-GAS and its supporting facilities revitalization project and post-revitalization have strategic value for the national pharmaceutical industry independence, which could be started with the I-131 production. The revitalization requires large funds, so the benefits are expected to be greater than the investment. This study aims to conduct a cost-benefit analysis of the revitalization project plan. Two scenarios were formulated, such as the I-131 production scenario ('*with the project*') and the counterfactual scenario (*'without the project'*). The '*with the project*' scenario was carried out for reactors with varied operating power (5 MW, 15 MW, and 30 MW). The results show that with the current rate for Non-Tax State Revenue (PNBP) tariff, the *'without the project'* scenario is unfeasible, indicated by a negative net present value (NPV) of IDR -114,32 billion. The '*with the project*' scenario is also unfeasible at all reactor capacities, indicated by negative NPV (IDR -418.17 billion at 5 MW; IDR -540.72 billion at 15 MW, and IDR -722.51 billion at 30 MW). Negative incremental NPV values relative to their counterfactual scenario also emphasize the unfeasibility of this scenario (at IDR -303.85 billion at 5 MW; IDR -426.40 billion at 15 MW, and IDR -608.19 billion at 30 MW). Sensitivity analysis of I-131 PNBP tariff for '*with the project*' scenario under 15 MW RSG-GAS power shows that the project will be feasible at a minimum PNBP tariff of IDR 21,000 per mCi.

1. INTRODUCTION

As one of the research tools in the field of nuclear energy, research reactors have greatly contributed to national development, including application in the fields of food and the environment, providing irradiation services, developing Human Resources (HR), and supporting health care initiatives, particularly for cancer diagnosis and therapy [1].

Indonesia has three research reactors; one of them is the G. A. Siwabessy Multipurpose Reactor (RSG-GAS) in Serpong. The main challenges faced by these research reactors, including RSG-GAS, are currently related to aging components and outdated technology. As a result, their utilization is currently far below the ideal conditions planned at the beginning of their construction. One of the recommendations of the International Atomic Energy Agency (IAEA) expert team during the peer review of the three research reactors on October 10-19, 2022, was to increase the utilization of research reactors, especially to produce Radioisotopes and Radiopharmaceuticals (RIRF), considering that their market share is still very large, especially in Asia and Europe. This effort can be taken through revitalizing research reactors and extending their operating permits. Revitalization is an effort to enhance the utilization of research reactors following the decline in performance of various components caused by the aging process. With revitalization, it is expected that the operational performance of the reactor will be more reliable and efficient, and ensured to be safe and secure so that its operational lifetime can be extended [1].

Regarding the RIRF market potential in Indonesia, currently, cancer remains a major challenge and is the second largest cause of death after cardiovascular disease [2]. The characteristic of cancer is the growth of abnormal cells that can occupy several organs in the human body [3]. Referring to the 2018 Basic Health Research data, there was an increase in the prevalence of cancer sufferers from 2013 to 2018, namely from 1.4 per 1,000 population in 2013 to 1.8 per 1,000 population in 2018, or an increase from 354,620 people in 2013 to 471,060 people in 2018 [4]. Meanwhile, data from the Global Burden of Cancer Study (GLOBOCAN) recorded that in 2020, there were 396,914 new cancer cases and a total of 234,511 deaths in Indonesia. The prevalence rate for the last 5 years until 2020 was recorded at 946,088 cases [5]. Both data show the increasing potential of the RIRF market in Indonesia.

The irradiation facility on the RSG-GAS core can produce several radioisotopes by fission or activation methods. Radioisotopes are isotopes of radioactive substances that can emit radiation [6]. Radioisotopes tend to play important roles in many fields, and are widely applied in various fields, such as industry, healthcare, agriculture, aerospace, etc [7]. One of the radioisotopes that is widely used for medical purposes is Iodine-131 (I-131). This radioisotope can be processed into oral I-131 and I-131 MIBG (meta - meta-iodobenzylguanidine). Oral I-131 is widely used for the detection and therapy of thyroid cancer, while I-131 MIBG is widely used in the diagnosis and therapy of neuroendocrine cancers, including neuroblastoma [8],[9],[10].

The incidence of thyroid cancer diagnosis has increased 169% over the last 3 decades [11]. In 2020, there were 13,114 new cases of thyroid cancer in Indonesia, and it was ranked 12th based on the number of cases of all types of cancer; the death rate was 2,224 cases, and the prevalence rate for the last 5 years until 2020 was 38,650 cases [5]. Meanwhile, Neuroblastoma is the most common extracranial solid tumor in children and the most commonly diagnosed tumor in infancy [12]. Neuroblastoma is a solid embryonal tumor of the sympathetic central nervous system from the primitive neural crest [13]. I-131 MIBG is highly effective in the treatment of neuroblastoma, particularly when given to patients at diagnosis and in combination with chemotherapy, and should be included in all induction regimens to improve early response rates and, consequently, long-term survival [14].

According to data from the Nuclear Energy Regulatory Agency (BAPETEN), as of February 19, 2022, there were 10 nuclear medicine therapy facilities with I-131 in Indonesia with a total service capacity of 106,166.3 GBq or equivalent to 2,869.35 Curies (Ci) per year. In addition, there are new facilities under construction for nuclear medicine therapy in 6 hospitals with a total proposed capacity of 8,516.96 GBq, or equivalent to 230.19 Ci per year [2]. Thus, if the new facilities are operational, the total demand for I-131 radioisotope will be 3,099.54 Ci per year. The fulfillment of the I-131 demand has been dominated by imports by 5 importing companies and transfers. PT Kimia Farma (PT. KF) was previously a distributor of RIRF produced by RSG-GAS. According to an expert from the Indonesian Nuclear Medicine Association (PKNI),

the use of I-131 MIBG from PT. KF can reduce the therapy tariff at Dharmais Hospital. Since production stopped in 2021, 100% of RIRF products have been imported at quite expensive prices. Therefore, the RSG-GAS and its supporting facilities revitalization project for RIRF production are considered quite strategic to achieve independence for the national pharmaceutical industry.

Initial calculations conducted by an expert team from the Directorate of Nuclear Facility Management (DPFK - BRIN) showed that the RSG - GAS and its supporting facilities revitalization project would cost around IDR 320 billion. The supporting facilities include the facilities used for post-irradiation treatment in the context of RIRF production. Given the considerable investment funds, it is expected that the benefit value obtained from the project will be able to exceed the investment value so that investment in the project can be justified. A systematic process used for calculating and comparing the costs and benefits of any project or policy is called Cost Benefit Analysis (CBA) [15]. Therefore, it is necessary to conduct a cost-benefit analysis of the implementation of RSG-GAS and its supporting facilities revitalization project.

Several studies have used CBA as a tool to assess the feasibility of a project to be implemented. Y. Wu *et al.* (2023) conducted a CBA of the switching program from conventional fuels to ammonia or hydrogen at the Port of Guangzhou and found that ammonia and hydrogen fuels still do not have a cost advantage compared to conventional fuels [16]. A. R. M. T. Islam *et al.* (2024) conducted a CBA of the FEWS (Flood Early Warning Systems) project in preventing flood damage in Bangladesh, and the results showed that FEWS generated a large Return on Investment (ROI) in various scenarios [17]. H. Ding. et al.'s research (2023) analyzed the CBA of a unified regulatory guidance for emergency preparedness (EP) project for all SMR designs in China and concluded that the program was beneficial in terms of cost savings in most cases [18]. J. Eom *et al.* (2024) study demonstrated the use of CBA to evaluate the economic feasibility of implementing the Human adenovirus (HAdV) vaccine for the Korean military, and the results showed that the project was economically beneficial, with a cost-benefit ratio over a decade reached 2.72 [19]. B. Jain *et al.* (2024) conducted a CBA of the use of IONM in patients undergoing cardiac surgery, and the results showed that the application of IONM could save lifetime costs [20].

This study aims to conduct a CBA of RSG-GAS and its supporting facilities revitalization project scenario dedicated to the production of the I-131 radioisotope (called the 'with the project' scenario). Based on its scope, CBA can be categorized into financial CBA, where the costs and benefits calculated are costs and benefits that have monetary value, and economic CBA, where cost and benefit variables that do not have monetary value are also considered. This study focuses on financial CBA. The results of this study are expected to provide an overview of the feasibility of the project in terms of its cost and benefit aspects so that it can be input for stakeholders. The novelty of this study is shown in Figure 1.
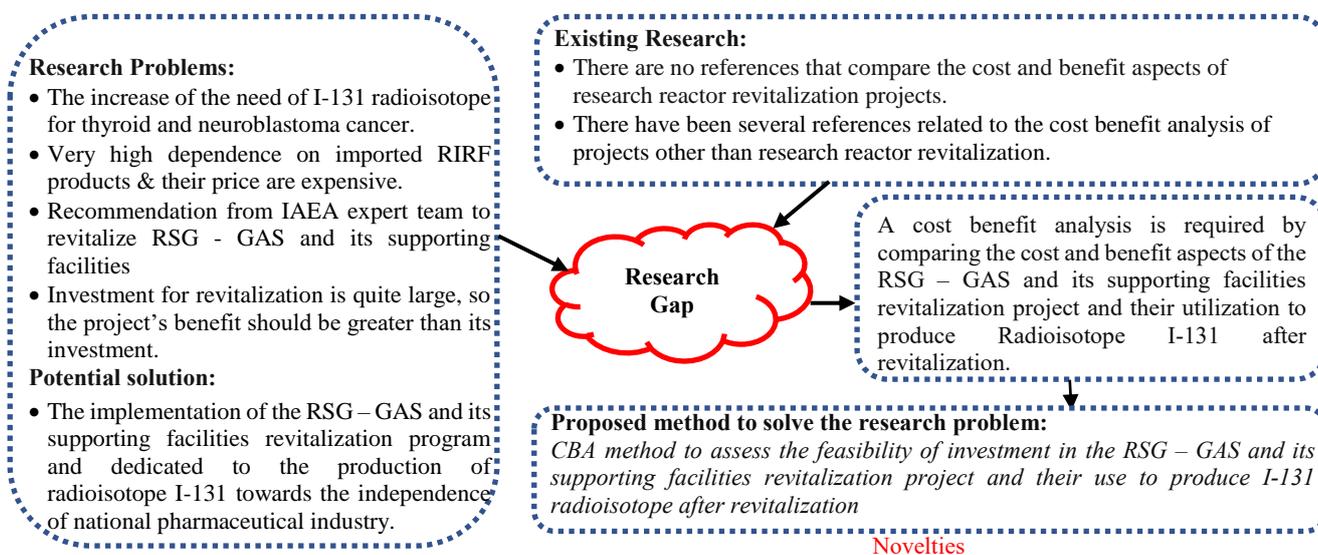
Research Problems:
- The increase of the need of I-131 radioisotope for thyroid and neuroblastoma cancer.
- Very high dependence on imported RIRF products & their price are expensive.
- Recommendation from IAEA expert team to revitalize RSG - GAS and its supporting facilities
- Investment for revitalization is quite large, so the project's benefit should be greater than its investment.

Potential solution:
- The implementation of the RSG – GAS and its supporting facilities revitalization program and dedicated to the production of radioisotope I-131 towards the independence of national pharmaceutical industry.

Existing Research:
- There are no references that compare the cost and benefit aspects of research reactor revitalization projects.
- There have been several references related to the cost benefit analysis of projects other than research reactor revitalization.

Research Gap

A cost benefit analysis is required by comparing the cost and benefit aspects of the RSG – GAS and its supporting facilities revitalization project and their utilization to produce Radioisotope I-131 after revitalization.

Proposed method to solve the research problem:
CBA method to assess the feasibility of investment in the RSG – GAS and its supporting facilities revitalization project and their use to produce I-131 radioisotope after revitalization

Novelties

Figure 1. The conceptual framework of this research and the novelty offered

CBA, which is conducted by comparing the 'with the project' scenario to its counterfactual scenario ('without the project' scenario), is needed to fill the research gap. The 'with project' scenario means that RSG - GAS and its supporting facilities are revitalized and then, post-revitalization, dedicated to the production of the I-131 radioisotope. The 'without the project' scenario means that no revitalization project has been carried out on RSG-GAS and its supporting facilities. The novelty offered in this study is the assessment of investment feasibility in the RSG-GAS and its supporting facilities revitalization project, and their utilization to produce I-131 radioisotope after revitalization using the CBA method, so that stakeholders are expected to be able to formulate better policies.

The next part of this study is constructed as follows: Section 2 briefly describes RSG-GAS, the I-131 production method, and Cost-Benefit Analysis. Section 3 describes the research method used in this research. Section 4 discusses the research results, and Section 5 concludes this research.

2. THEORY

2.1. G.A. Siwabessy Multipurpose Reactor (RSG-GAS)

RSG-GAS is an open-pool, water-cooled, water-moderated reactor with a power capacity of 30 MW, which reached its first criticality in July 1987 [21]. The RSG-GAS core uses plate-type U_3O_8 - Al fuel, which is then converted to U_3Si_2 - Al fuel with the same uranium density of 2.96 g/cc and enriched at 19.75%. For better neutron conservation, beryllium is used as the reflector. The Typical Working Core (TWC) configuration of RSG-GAS consists of 40 fuel elements (FE), 8 control rod elements (CE), and 30 beryllium reflector elements, as stated in Figure 2 [22]. The TWC core is achieved through 5 transition cores with different fuel loading amounts. The average thermal neutron flux is 2.0×10^{14} n/cm²s, and the maximum neutron flux is at the Center Irradiation Position (CIP), up to 5.38×10^{14} n/cm²s. RSG-GAS is equipped with several test facilities, including a CIP, four small Irradiation Positions (IPs) in the reactor core, beam tubes for radioisotope production and basic science experiments, and facilities for power reactor fuel development, such as power ramp tests and fuel irradiation facilities.[21]. Research reactors typically have significantly lower operational capacities and smaller radioactive inventories compared to nuclear power plants [23].
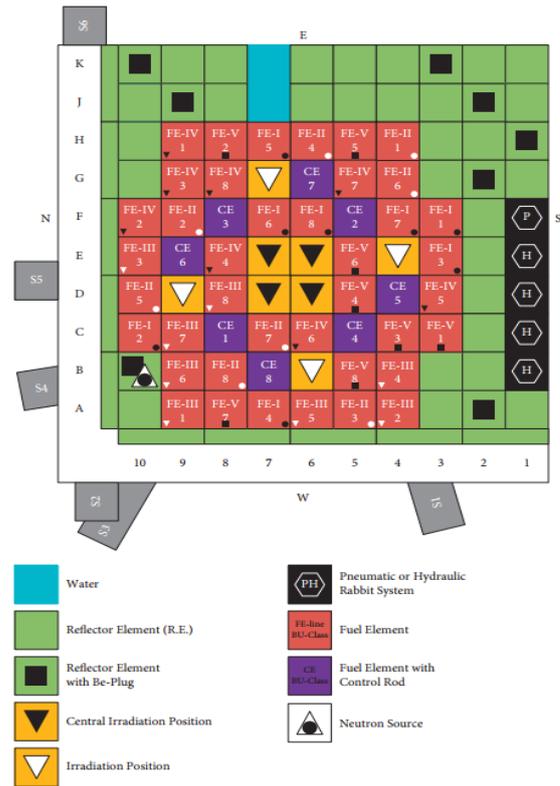

Figure 2. RSG-GAS reactor core[22]

2.2. I-131 Radioisotope

I-131 is an important radioisotope of iodine discovered by Glenn Seaborg and John Livingood in 1938, which has a half-life of 8.02 days and releases a total 970.8 keV decay energy by transforming into the stable nuclide Xe-131 [24]. The production of I-131 is carried out by neutron irradiation of natural Tellurium targets in a nuclear reactor, followed by separation to extract I-131. In general, the neutron activation-based production method of I-131 can be expressed by the following reaction equation:

$$^{130}_{52}Te + 1_n \longrightarrow ^{131}_{52}Te$$

$$^{131}_{52}Te \longrightarrow ^{131}_{53}I + \beta \tag{1}$$
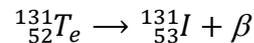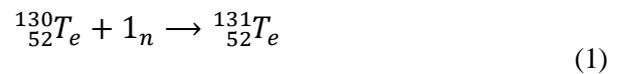
Tellurium oxide (TeO_2) is used as a target material to obtain I-131. Based on the Safety Analysis Report (SAR) in RSG-GAS so far, the assumptions used in calculating I-131 production in each reactor core channel are as follows:

- TeO_2 weight = 100 grams
- Irradiation time = 100 hours
- Cold delay time = 12 hours (length of time from EOI (End of Irradiation) to transportation process)
- The yield of the separation process is 65% using the dry distillation method, which is used to obtain an estimate of I-131 after separation with Te-131.

2.3. Cost-Benefit Analysis (CBA)

This study uses the CBA approach to assess the financial implications of the RSG-GAS and its supporting facilities revitalization project, which was subsequently dedicated to producing the I-131 radioisotope. CBA is a methodical approach to assessing potential benefits and associated costs over a certain investment period [25]. This method assesses whether the solution provided to the analyzed problem requires a greater cost or is comparable to the benefits obtained. In this process, the costs and benefits of the '*with the project*' scenario are identified and monetized, while compared with the counterfactual scenario ('*without the project*'), and each scenario's net present value (NPV) was calculated.

2.3.1. CBA Procedure

The CBA procedure is a framework consisting of seven steps, as shown in Figure 3.
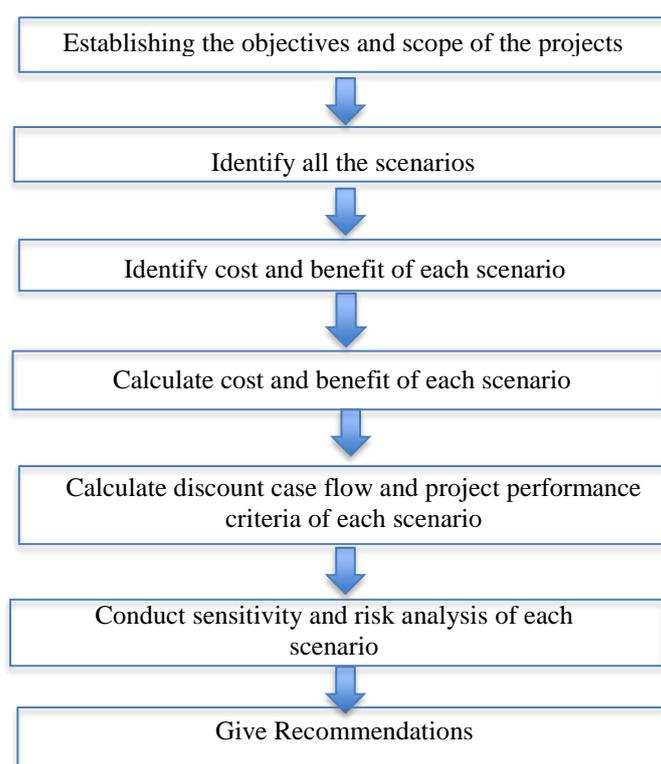

Figure 3. Steps in CBA

The seven steps in the CBA procedure can be described as follows:

- Step 1: Establishing the objectives and scope of the project.
  This is the most important stage in CBA because it determines the next steps. In this stage, methods such as brainstorming and discussions with experts in various fields related to the scope of the project scenarios are needed to explore their perspectives regarding the project scenarios.
- Step 2: Identify all the scenarios.
  The results of the brainstorming and discussion sessions are then translated into formulating alternative project scenarios.
- Steps 3 and 4: Identify and calculate the cost and benefit of each scenario.

In this stage, we identify and calculate all projected costs and revenues for each project scenario.

- Step 5: Calculate discounted cash flows and project performance criteria for each project scenario.

  In this stage, the cost and revenue projections identified and calculated in the previous step are input into the discounted cash flow model with a certain discount rate value. The results of this model are in the form of project performance indicators (NPV and Internal Rate of Return - IRR), which determine the feasibility of a project scenario to be implemented.

- Step 6: Conduct sensitivity and risk analysis on selected alternatives.

This stage is only carried out if deemed necessary.
- Step 7: Give recommendations
  In this stage, a series of recommendations is prepared, providing decision-makers with a comprehensive understanding of the financial feasibility of the project scenarios.

2.3.2. Incremental Approach

In this study, CBA compares the proposed scenario ('*with the project*') with the counterfactual scenario ('*without the project*'). Because it compares two scenarios, what is called an incremental value occurs, which shows the difference in NPV and IRR value between the two scenarios. That is why it is said that this CBA method uses an incremental approach. The incremental approach requires the following points [26]:
- First is the cash flow projection of the counterfactual scenario. In this scenario, no revitalization of RSG-GAS and its supporting facilities is carried out, so that the reactor operation is maintained in Business as Usual (BaU) conditions until the operational permit expires.

- Second, the cash flow projection from the proposed scenario ('*with the project*'). This projection considers all financial and economic aspects of costs and benefits for the investment in the proposed scenario (here, we only consider financial costs and benefits).

- Finally, the incremental approach in CBA considers the difference between cash flows in the proposed scenario and in the counterfactual scenario.

Both incremental NPV and incremental IRR require cash flows from both scenarios and the project lifetime to be the same. The steps to obtain them are:

a. Calculate the net cash flow for each scenario ('with the project' scenario and the counterfactual scenario).
b. Calculate the difference in net cash flow between the two scenario options.
c. Calculate the incremental NPV and incremental IRR from the difference in net cash flow (Table 1 and Table 2). The 'with the project' scenario is said to be feasible if incremental NPV > 0 and incremental IRR > discount rate.

The NPV is calculated by the formula as follows:

$$NPV = C_0 + \frac{C_1}{(1+r)^1} + \cdots + \frac{C_N}{(1+r)^N} \quad (2)$$

where C is the net cash flow and r is the discount rate applied. At the same time, IRR is calculated by iterating over the value of r such that the NPV becomes zero.

Table 1. Net cash flow tabulation of both scenarios for calculating the incremental NPV

Scenario	Time Horizon					NPV
	T_0	T_1	T_2	…	T_N	
Counterfactual (A)	C_{A0}	C_{A1}	C_{A2}	…	C_{AN}	NPV_A
Proposed (B)	C_{B0}	C_{B1}	C_{B2}	…	C_{BN}	NPV_B
Incremental (I)	C_{I0}	C_{I1}	C_{I2}	…	C_{IN}	NPV_I

C: Net Cashflow

Table 2. Net cash flow tabulation of both scenarios for calculating the incremental IRR

Scenario	Time Horizon					IRR
	T_0	T_1	T_2	…	T_N	
Counterfactual (A)	C_{A0}	C_{A1}	C_{A2}	…	C_{AN}	IRR_A
Proposed (B)	C_{B0}	C_{B1}	C_{B2}	…	C_{BN}	IRR_B
Incremental (I)	C_{I0}	C_{I1}	C_{I2}	…	C_{IN}	IRR_I

3. METHODOLOGY

3.1. Research Method

This study was conducted following the flowchart, as shown in Figure 4. The study began with a literature review related to RSG-GAS, I-131 radioisotope production, and estimation of costs and benefits in both the counterfactual scenario and the 'with the project' scenario. Based on the literature

review that has been conducted, CBA is the most suitable method to assess the feasibility of the RSG-GAS and its supporting facilities revitalization for I-131 production. Therefore, the 'with the project' scenario is also called the I-131 Radioisotope Production Scenario. By using CBA, the value of the feasibility indicators (NPV and IRR) in both scenarios is obtained. These results can be input for stakeholders in policy formulation.
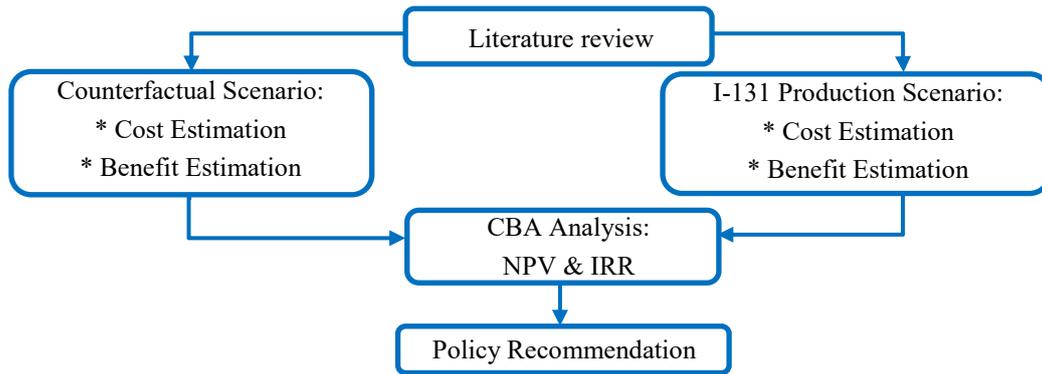
Figure 4. Research method

3.2. Data and Assumptions

3.2.1. Scenario Formulation

In this study, two scenarios were used, namely the Counterfactual scenario ('*without the project*') and the I-131 Radioisotope Production scenario as the proposed scenario ('*with the project*')

Counterfactual Scenario

This scenario is one in which RSG-GAS and its supporting facilities are not revitalized. It is assumed that the reactor operation refers to the production status in 2020. In this scenario, the reactor is operated for radioisotope and non-radioisotope production (topaz irradiation and demineralized water production). The timeline for this scenario spans from 2023 to 2030, as shown in Figure 5, after which the reactor stops operating due to the expiration of the operating permit.

In 2020, there were 6 types of Radioisotopes produced by RSG-GAS, namely: I-131, Samarium-153 (Sm-153), Molybdenum-99 (Mo-99), Phosphorus-32 (P-32), Gadolinium-153 (Gd-153), and Lutetium-177 (Lu-177). However, in this study, it is assumed that only 4 types of Radioisotopes are produced, namely Sm-153, Mo-99, I-131, and P-32. This assumption is based on considering the unavailability of production cost data for Gd-153 and Lu-177. Sm-153, I-131, and Mo-99 are radioisotopes that are widely used for medical purposes, while P-32 is widely used in agriculture [27],[28].

The RSG-GAS radioisotope production in 2020 is shown in Table 3, referring to production data issued by the Center for Radioisotope and Radiopharmaceutical Technology (PTRR-BATAN) in 2020.

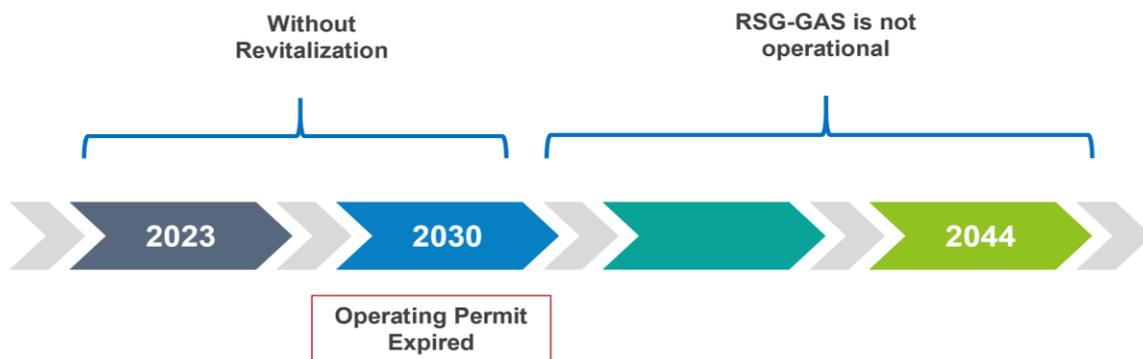**Figure 5.** Counterfactual scenario

Table 3. RSG-GAS's radioisotopes production in 2020

No	Radioisotope	Target	Total Radioactivity (mCi)
1	Sm-153	Samarium Oxide (Sm_2O_3)	349,622.34
2	Mo-99	Molybdenum Oxide (MoO_3)	23,730.17
3	I-131	Tellurium Oxide (TeO_2)	59,565.05
4	P-32	Sulfur	2,954.16

Non-radioisotope output (topaz irradiation and demineralized water production) is assumed to be one-third of the post-revitalization projection by the expert team of DPFK - BRIN. After revitalization, it is estimated that topaz irradiation will reach 1,500 kg and demineralized water production will reach 1,000 liters (if it is assumed that topaz irradiation and demineralized water production are still running after revitalization), so in the counterfactual scenario, topaz irradiation services are assumed to be 500 kg and demineralized water is assumed to be 350 liters, as shown in Table 4.

Table 4. RSG-GAS's non-radioisotope production in 2020

No	Product	Unit	Total
1	Topaz irradiation service	kg	500
2	Demineralized water	Liters	350

I-131 Radioisotope Production Scenario

This I-131 Radioisotope Production Scenario is a revitalization scenario, and after revitalization, RSG-GAS and its supporting facilities are fully dedicated to the production of I-131 radioisotope. I-131 radioisotope is a raw material used in the production of Oral I-131 and I-131 MIBG radiopharmaceuticals. This is based on the consideration of the high national demand for I-131 radioisotope, which is 2,869.35 Ci per year based on BAPETEN data as of February 19, 2022. This demand increases up to 3,099.54 Ci per year if the nuclear medicine facilities under construction in 6 hospitals are operational. In addition, it is also based on the consideration of the relatively longer half-life of I-131 (8 days) when compared to other medical radioisotopes (for example, Sm-153 with a half-life of 46.3 hours, Mo-99 with a half-life of around 66 hours, and Tc-99m with a half-life of around 6 hours).

Revitalization is assumed to take 5 years (2024 - 2029), and after revitalization, the operation of RSG-GAS and its supporting facilities is estimated to be extended for 15 years (2030 - 2044). The continuation of operations will depend on the results of the BAPETEN audit later, which makes the timeline for the radioisotope production scenario shown in Figure 6.
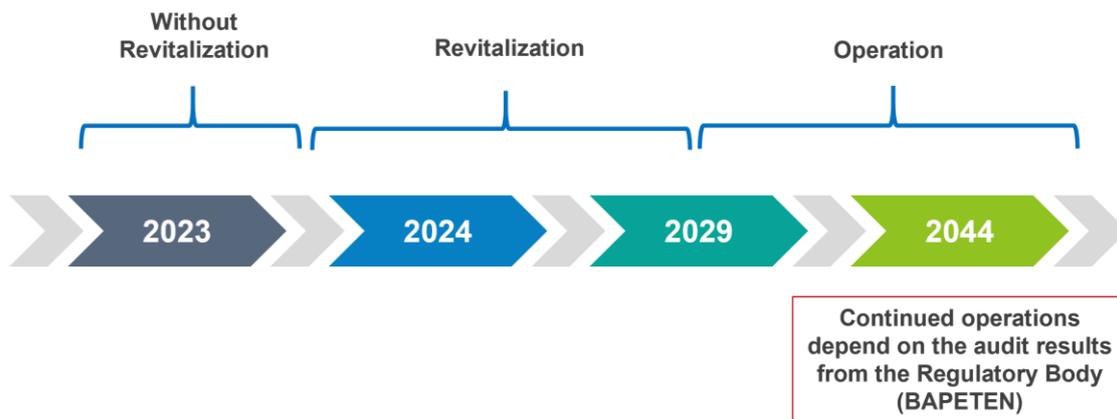

Figure 6. I-131 Radioisotope Production Scenario

In 2023, RSG-GAS has not been revitalized, so the production data for this year are assumed to be the same as those in the Counterfactual scenario. After revitalization, the facility is assumed to be dedicated to producing I-131 radioisotopes, without the production of non-radioisotope products (topaz irradiation and demineralized water production).

In this I-131 Radioisotope Production scenario, three categories of reactor operating capacity are simulated: 5 MW, 10 MW, and 15 MW. The variation of reactor capacities will affect the production capacity of the I-131 radioisotope. Based on calculations by the DPFK-BRIN team, the total TeO_2 sample irradiated per batch is 700 grams, which is divided by 100 grams per channel with a total of 7 channels used for irradiation (4 CIP channels and 3 IP channels). It is assumed that the reactor is operated for 32 weeks (32 batches) per year. Table 5 states the estimated activity of radioisotope I-131 for 3 reactor powers, which is later called operating capacities per batch.

Table 5. Estimation of I-131 radioisotope activity at 3 reactor operating capacities per batch

No	Irradiation Position	Operating Capacities (MW)	Neutron flux	Te-131 when EOI (Ci)	I-131 Activity with cold delay time 12 hours (Ci)*	Estimation of I-131 Activity acquired after separation (Ci)
1	CIP(D,7)	30	3.12E+14	37,038.01	92.24	59.96
		15	1.56E+14	18,519.00	46.12	29.98
		5	5.20E+13	6,173.00	15.37	9.99
2	CIP(E,6)	30	3.12E+14	37,038.01	92.24	59.96
		15	1.56E+14	18,519.00	46.12	29.98
		5	5.20E+13	6,173.00	15.37	9.99
3	CIP(E,7)	30	3.12E+14	37,038.01	92.24	59.96
		15	1.56E+14	18,519.00	46.12	29.98
		5	5.20E+13	6,173.00	15.37	9.99
4	CIP(D,6)	30	3.50E+14	41,549.05	103.4	67.21
		15	1.75E+14	20,774.52	51.73	33.62
		5	5.83E+13	6,920.88	17.23	11.20
5	IP: (G7)	30	2.36E+14	28,015.93	69.77	45.35
		15	1.18E+14	14,007.96	34.88	22.67
		5	3.93E+13	4,665.36	11.61	7.55
6	IP: (D9)	30	2.36E+14	28,015.93	69.77	45.35
		15	1.18E+14	14,007.96	34.88	22.67
		5	3.93E+13	4,665.36	11.61	7.55
7	IP: (B6)	30	2.36E+14	28,015.93	69.77	45.35
		15	1.18E+14	14,007.96	34.88	22.67
		5	3.93E+13	4,665.36	11.61	7.55

EOI: End of Irradiation

*) Calculation based on the link: https://www.wise-uranium.org/rnac.html

Since it is assumed that the reactor operates 32 batches per year, the total production of I-131 radioisotope per year for the three reactor operating capacities can be summarized in Table 6. The total production of I-131 radioisotope at reactor operating capacities of 5 MW, 15 MW, and 30 MW are 2.04 million mCi, 6.13 million mCi, and 12.26 million mCi, respectively. The existing national demand data for I-131 radioisotope released by BAPETEN as of February 19, 2022, is 2,869,351 Ci or around 2.9 million mCi. Thus, the production of I-131 radioisotope at 5 MW power capacity has been able to contribute around 71% of the estimated existing national demand. Meanwhile, the production of I-131 at 15 MW capacity doubles the estimated existing national demand, while at 30 MW power, it is more than 4 times the estimated national demand.

Table 6. Total production of I-131 radioisotope per year (32 batches) at three reactor operating capacities

No	Capacity (MW)	Total production of I-131 radioisotope (mCi)
1	5	2,041,936
2	15	6,130,384
3	30	12,260,144

3.2.2. Costs Data

In both the Counterfactual scenario and the I-131 Radioisotope Production scenario, the initial investment in the construction of RSG-GAS and its supporting facilities for radioisotope production is considered as sunk costs or ignored because these costs will not change regardless of the choice taken. Therefore, only the investment costs for revitalization and production costs are considered in both scenarios.

Costs Data in Counterfactual Scenario

The costs in this scenario are only operational costs, which include production costs per product type (radioisotopes, topaz irradiation, and demineralized water), fuel costs, and maintenance costs. The production costs of radioisotopes include raw material costs, direct labor costs, and production overhead costs, as stated in Table 7.

The production cost of each type of radioisotope and the non-radioisotope production cost were referred to the calculation of the DPFK-BRIN team. Table 8 states the total production cost in the counterfactual scenario.

Table 7. Taxonomy of the production cost of radioisotopes

No	Cost component for radioisotopes production
1	Raw material costs
	- Target preparation material
	- Post-irradiation process material
	- Process material
	- Quality control material
	- Cleaning agent
	- etc.
2	Direct labor costs
	- Personal protective equipment (PPE)
	- Administration
	- Labor cost
	- Work permit cost
3	Overhead production costs
	- Production facility cost
	- Irradiation cost/ Capsule batch
	- Operational cost for supporting facility
	- Certification and licensing cost
	- Waste disposal cost
	Total cost of production = cost 1 + cost 2 + cost 3

The RSG-GAS fuel is Uranium-235 (U-235), which is in the form of a fuel bundle consisting of 40 standard fuel elements and 8 control fuel elements. Based on information obtained from DPFK-BRIN during a visit to RSG-GAS, the reactor has a 24-month fuel burn-up cycle, with fuel elements replaced every 3 months. Every 3-month cycle, 5 standard fuel elements and 1 control fuel element are replaced. The price of 1 unit of standard fuel element is around IDR 0.95 billion, while the price of 1 unit of control fuel element is around IDR 1.2 billion. Thus, every 3 months, there is an expenditure of IDR 5.95 billion for fuel refueling, or around IDR 23.8 billion per year. Because the reactor operates at 15 MW (half full capacity), the fuel cost in the counterfactual scenario is assumed to be around ½ of the total fuel cost, which is IDR 12 billion. Maintenance costs are assumed based on a calculation by the DPFK-BRIN team, which is around IDR 5 billion. So, the total operational cost of RSG-GAS in the counterfactual scenario is around IDR 20.97 billion, as listed in Table 9.

Table 8. Production cost in the counterfactual scenario

Item	Unit	Quantity	Unit cost (IDR)	Total (IDR)
Radioisotope products				
• Product 1: Sm-153	mCi	349.622,34	7,816.73	2,732,903,609
• Product 2: Mo-99	mCi	23.730,17	8,000	189,841,360
• Product 3: I-131	mCi	59.565,05	12,974.56	772,830,206
• Product 4: P-32	mCi	2.954,16	8,000	23,633,280
Non-RIRF products				
• Product 5: Topaz	kg	500	500,000	250,000,000
• Product 6: Demineralized water	liters	350	500	175,000
Total production cost in the counterfactual scenario				3,969,383,454

Note: IDR = Indonesian Rupiah

Table 9. Operational cost in the counterfactual scenario

No	Items of operational cost	Total (IDR)
1	Production cost	3,969,383,454
2	Fuel cost	12,000,000,000
3	Maintenance cost	5,000,000,000
	Total operation cost in the counterfactual scenario	20.969.383.454

Costs Data in I-131 Radioisotope Production Scenario

In this scenario, the RSG-GAS and its supporting facilities revitalization project is carried out, and after revitalization, the reactor is fully dedicated to the production of I-131 radioisotope. Therefore, the costs incurred in this scenario include the investment cost for revitalization and operational costs, where operational costs include the production costs of the I-131 radioisotope, fuel costs, and maintenance costs. The estimated investment cost for revitalization is IDR 320 billion, consisting of IDR 300 billion for the revitalization of RSG-GAS and IDR 20 billion for the revitalization of supporting facilities which is dedicated for radioisotope production, as shown in Table 10. It is assumed that the investment withdrawal is flat during the revitalization period (IDR 64 billion per year). During the revitalization period, the reactor is assumed to be in a shutdown state so that there is no production.

Table 10. Investment cost for revitalization

Installation	Detail	Proposed budget (IDR)
RSG-GAS Reactor	• Modernize Analog I & C system to Digital	190,000,000,000
	• Revitalize RadMon System	60,000,000,000
	• Refurbish electrical equipment (5 installations)	50,000,000,000
Total 1		300,000,000,000
Radioisotope production (Supporting facilities)	• Revitalize RadMon System	10,000,000,000
	• Replace the larger radiation filter the stack	10,000,000,000
Total 2		20,000,000,000
Total investment cost for revitalization		320.000.000.000

The production cost of the I-131 radioisotope is assumed using the calculation from the DPFK-BRIN expert team, which is IDR 13,043.06 per mCi. In addition to affecting production capacity, the operation of RSG-GAS to produce I-131 radioisotope at 3 different capacities (5 MW, 15 MW, and 30 MW) will also affect the amount of fuel costs. In the Counterfactual scenario, the reactor is assumed to be operated at 15 MW, with a total fuel cost of IDR 12 billion per year. Therefore, the fuel cost for reactor operations with 5 MW and 30 MW capacities is around IDR 4 billion and IDR 23.8 billion, respectively. The operational costs for the three reactor operating capacities are the sum of the production costs of the I-131 radioisotope, fuel costs, and maintenance costs, as stated in Table 11. Operational costs are assumed to remain constant throughout the lifetime of the project.

Table 11. Operational cost of the I-131 radioisotope production scenario at three reactor operating capacities

No	Operating Capacity (MW)	Fuel cost (IDR)	Maintenance cost (IDR)	Production cost			Total operational cost (IDR)
				Production quantity (mCi)	Production cost (IDR/mCi)	Total production cost (IDR)	
1	5	4,000,000,000	5,000,000,000	2,041,936	13,043.06	26,633,090,021	35,633,090,021
2	15	12,000,000,000	5,000,000,000	6,130,384	13,043.06	79,958,955,096	96,958,955,096
3	30	23,800,000,000	5,000,000,000	12,260,144	13,043.06	159,909,771,324	188,709,771,324

3.2.3. Revenues Data

Revenues Data in Counterfactual Scenario

The selling price of radioisotopes and irradiation service tariff in both scenarios are based on the Non-Tax State Revenue (PNBP) tariff stated in the Regulation of the Minister of Finance No. 185/PMK.02/2021 concerning Types and Tariff of Non-Tax State Revenue, which fluctuates at BRIN.

Revenue in the counterfactual scenario is calculated by multiplying the production quantity in this scenario by the PNBP tariff of each product. The PNBP tariff is assumed to remain constant throughout the project lifetime. The estimated total revenue in the counterfactual scenario is presented in Table 12. RSG-GAS revenue in the counterfactual scenario is around IDR 5.03 billion per year.

Table 12. RSG-GAS's revenue in a counterfactual scenario

Item	Quantity Unit	Quantity	PNBP unit	PNBP Tariff (IDR)	Total Revenue (IDR)
Radioisotope products:					
• Product 1: Sm-153	mCi	349,622.34	IDR/ mCi	7,000	2,447,356,380
• Product 2: Mo-99	mCi	23,730.17	IDR/ mCi	8,000	189,841,360
• Product 3: I-131	mCi	59,565.05	IDR/ mCi	12,000	714,780,600
• Product 4: P-32	mCi	2,954.16	IDR/ mCi	60,000	177,249,600
Non-RIRF product:					
• Product 5: Topaz	kg	500	IDR/ kg	3,000,000	1,500,000,000
• Product 6: Demineralized water	liters	350	IDR/ liter	1,000	350,000
Total revenue in the counterfactual scenario					5,029,577,940

Revenues Data in the I-131 Radioisotope Production Scenario

Meanwhile, the revenue in the I-131 Radioisotope Production scenario is obtained from the result of multiplying the estimated total production of I-131 radioisotope at each reactor operating capacity with the PNBP tariff for I-131 radioisotope based on the Regulation of the Minister of Finance No. 185/PMK.02/2021 which is IDR 12,000 per mCi and is assumed to remain the same throughout the project lifetime. The estimated revenues from RSG-GAS at the three reactor operating capacities (5 MW, 15 MW, and 30 MW) are stated in Table 13, which are IDR 24.5 billion, IDR 73.56 billion, and IDR 147.12 billion, respectively.

Table 13. Total revenue of RSG-GAS for the production of I-131 radioisotope at three reactor operating power capacities

No	Operating Capacities (MW)	Total production of I-131 radioisotope (mCi)	PNBP tariff (IDR/mCi)	Total Revenue (IDR)
1	5	2,041,936	12,000	24,503,232,000
2	15	6,130,384	12,000	73,564,608,000
3	30	12,260,144	12,000	147,121,728,000

4. RESULTS AND DISCUSSION

4.1. Project Performance Results on Three Reactor Operating Capacities

The project performance indicator results from the I-131 Radioisotope Production scenario at each reactor operating capacity were then compared with the project performance results for the Counterfactual scenario, as stated in Table 14 - 16. The discount rate used is 3.25%, referring to the long-term interest rate of Government bonds (SUN). The incremental value represents the difference between the performance indicator values for the I-131 radioisotope production scenario ('with the project') and the counterfactual scenario ('without the project').

Based on Table 14 - 16, it is known that the counterfactual scenario is considered unfeasible, as indicated by the negative NPV Value (IDR -114.32 billion), and therefore, no IRR value is obtained. Meanwhile, the I-131 radioisotope production scenario is also considered unfeasible at the three reactor operating capacities, as indicated from the negative NPV (IDR -418.17 billion at 5 MW; IDR -540.72 billion at 15 MW and IDR -722.51 billion at 30 MW) and from the negative incremental NPV relative to their counterfactual scenario (IDR -303.85 billion at 5 MW; IDR -426.40 billion at 15 MW and IDR -608.19 billion at 30 MW).

Table 14. Results of I-131 radioisotope production scenario (at 5 MW) vs counterfactual scenario

Performance Indicator	I-131 production scenario (at 5 MW)	Counterfactual scenario	Incremental
NPV (Million IDR)	-418,171.73	-114,320.28	-303,851.44
IRR	N/A	N/A	N/A

Table 15. Results of I-131 radioisotope production scenario (at 15 MW) vs counterfactual scenario

Performance Indicator	I-131 production scenario (at 15 MW)	Counterfactual scenario	Incremental
NPV (Million IDR)	-540,720.30	-114,320.28	-426,400.02
IRR	N/A	N/A	N/A

Table 16. Results of I-131 radioisotope production scenario (at 30 MW) vs counterfactual scenario

Performance Indicator	I-131 production scenario (at 30 MW)	Counterfactual scenario	Incremental
NPV (Million IDR)	-722,514.39	-114,320.28	-608,194.11
IRR	N/A	N/A	N/A

The incremental NPV is the result of subtracting the NPV of the I-131 radioisotope production scenario from the NPV of the counterfactual scenario. The value of this unfeasible project is simply very understandable, considering that the PNBP tariff for the I-131 radioisotope used as the basis for the selling price is lower than the estimated production cost of the I-131 radioisotope carried out by the team from DPFK–BRIN, IDR 12,000 per mCi and IDR 13,043.06 per mCi, respectively. Therefore, it is

necessary to conduct a sensitivity analysis to determine the minimum PNBP tariff for the I-131 radioisotope production so the scenario can be considered feasible to be implemented. The results of this sensitivity analysis can then be used by the government to reconsider the PNBP tariff for I-131 radioisotope.

4.2. Sensitivity Analysis of I-131 Radioisotope Production Scenario

Sensitivity analysis was conducted on the PNBP tariff of I-131 radioisotope. The current basic tariff based on Regulation of the Minister of Finance No. 185/PMK.02/2021 is IDR 12,000 per mCi. In this analysis, the PNBP tariff will be varied from IDR 15,000 to 35,000 per mCi for each reactor operating capacity (5 MW, 15 MW, 30 MW). The results of the sensitivity analysis of the increase in PNBP tariff on project performance at the three reactor operating capacities are seen in Tables 17-19.

Table 17. Sensitivity of PNBP tariff increase to the project performance of the I-131 radioisotope production scenario (at 5 MW)

No	PNBP tariff (IDR/ mCi)	Performance Indicator	
		NPV (Million IDR)	IRR
1	12,000	-418,171.73	N/A
2	15,000	-356,961.75	N/A
3	20,000	-254,945.13	-12.2%
4	25,000	-152,928.50	-3.5%
5	30,000	-50,911.88	1.4%
6	35,000	51,104.74	4.9%

Table 18. Sensitivity of PNBP tariff increase to project performance of I-131 radioisotope production scenario (at 15 MW)

No	PNBP tariff (IDR/ mCi)	Performance Indicator	
		NPV (Million IDR)	IRR
1	12,000	-540,720.30	N/A
2	15,000	-356,953.21	N/A
3	20,000	-50,674.72	1.4%
4	**25,000**	**255,603.77**	**10.4%**
5	30,000	561,882.27	16.3%
6	35,000	868,160.76	21.0%

Table 19. Sensitivity of PNBP tariff increase to project performance of I-131 radioisotope production scenario (at 30 MW)

No	PNBP tariff (IDR/ mCi)	Performance Indicator	
		NPV (Million Rp)	IRR
1	12,000	-722,514.39	N/A
2	15,000	-354,998.91	N/A
3	**20,000**	**257,526.90**	**10.4%**
4	25,000	870,052.71	21.1%
5	30,000	1,482,578.52	28.4%
6	35,000	2,095,104.32	34.1%

Based on Table 17-19, RSG-GAS operated at 5 MW capacity could be feasible for I-131 radioisotope production if the PNBP tariff was IDR 35,000 per mCi, marked by a positive NPV (IDR 51.10 billion) and an IRR greater than the discount rate (4.9% > 3.25%). While at 15 MW capacity, the project is already feasible at the I-131 radioisotope PNBP tariff of IDR 25,000 per mCi, marked by a positive NPV (IDR 255.60 billion) and an IRR greater than the discount rate (10.4% > 3.25%). And at 30 MW capacity, the project is already feasible at the I-131 radioisotope PNBP tariff of IDR 20,000 per mCi indicated by a positive NPV (IDR 257.53 billion) and an IRR greater than the discount rate (10.4% > 3.25%).

Considering that the operation of RSG-GAS after revitalization at 15 MW capacity has produced I-131 radioisotope approximately 2 times the estimated existing national I-131 radioisotope demand, plus if the new nuclear medicine facilities under construction in 6 hospitals are already operating (6,130,384 mCi Vs 3,099.54 mCi per year). It can be recommended that after RSG-GAS and its supporting facilities are revitalized, it can be fully dedicated to the production of I-131 radioisotope with an operating capacity of 15 MW. Excess production can be allocated for export.

This target can be said to be a moderate target, where the national demand for I-131 radioisotope is met and can even be exported, but the increase in PNBP tariff is still around 2 times the current PNBP tariff (IDR 25,000 vs IDR 12,000 per mCi). The issue with the PNBP tariff is that reconsidering the PNBP tariff will later affect the tariff of nuclear medicine services in hospitals. If the PNBP tariff is too high, it will ultimately burden the community as the patient of nuclear medicine services. The production option at 15 MW, of course, needs to be reviewed at a certain time, considering the potential increase in national demand for I-131 radioisotope in the coming years.

It should be noted that at the operating capacity of 15 MW and a PNBP tariff of IDR 25,000 per mCi, the IRR value is already 10.4%. This value is far above the set discount rate (3.25%). Therefore, a sensitivity analysis of the PNBP tariff was carried out at this 15 MW capacity with a range of PNBP tariff values of IDR 20,000 to IDR 25,000 per mCi, with each increase of IDR 1,000 per mCi, and then its effect on project performance indicators was observed. This is intended to see more precisely at what PNBP tariff the I-131 radioisotope production project scenario is considered feasible. The results of this PNBP tariff sensitivity analysis are stated in Table 20.

Table 20. Sensitivity of PNBP tariff increase (IDR 20,000 to 25,000 per mCi) to the project performance of the I-131 radioisotope production scenario (at 15 MW)

No	PNBP tariff (IDR/ mCi)	Performance Criteria	
		NPV (million IDR)	IRR
1	20,000	-50,674.72	1.4%
2	21,000	10,580.98	3.6%
3	22,000	71,836.68	5.6%
4	23,000	133,092.38	7.3%
5	24,000	194,348.08	8.9%
6	25,000	255,603.77	10.4%

Based on Table 20, at the operating capacity of 15 MW and I-131 PNBP tariff of Rp 21,000 per mCi, the 'with the project' scenario is already feasible as indicated by a positive NPV (IDR 10.58 billion) and IRR value > discount rate (3.6% > 3.25%). Thus, it can be recommended that after revitalization, RSG-GAS can be operated to produce I-131 radioisotope at a capacity of 15 MW and a minimum PNBP tariff of Rp 21,000 per mCi.

5. CONCLUSION

The results of this study indicate that the counterfactual scenario ('*without the project'*) is considered unfeasible, indicated by a negative NPV of IDR -114.32 billion. In the I-131 radioisotope production scenario, the project is also considered unfeasible at all three reactor operating capacities, indicated by negative NPV (IDR -418.17 billion at 5 MW; IDR -540.72 billion at 15 MW, and IDR -722.51 billion at 30 MW). Besides, the negative incremental NPV relative to their counterfactual scenario is shown (IDR -303.85 billion at 5 MW; IDR -426.40 billion at 15 MW, and IDR -608.19 billion at 30 MW). The unfeasible project performance in the I-131 radioisotope production scenario is due to the low PNBP tariff used as the basis for the selling price of I-131 radioisotope, which is IDR 12,000 per mCi, while the production cost of this radioisotope, according to the calculations of the DPFK-BRIN expert team, reaches IDR 13,043.06 per mCi. Sensitivity analysis of this I-131 radioisotope PNBP tariff on the I-131 radioisotope production scenario with an operating capacity of 15 MW shows that the project will be feasible at a minimum PNBP tariff of IDR 21,000 per mCi.

CRediT authorship contribution statement
Nuryanti: Writing – original draft, Methodology, Investigation, Funding acquisition, Data curation; **Mudjiono:** Writing – original draft, Methodology, Investigation; **Elok Satiti Amitayani:** Writing – review & editing, Methodology, Conceptualization, Investigation, Formal analysis; **Nur Hasanah:** Writing – editing, Investigation; **Nurlaila:** Investigation, Data curation, Project Administration; **Ewitha Nurulhuda:** Investigation, Visualization, Project Administration; **Rizky Firmansyah Setya Budi:** Writing – review, Validation, Conceptualization, Formal analysis; **Sufiana Solihat:** update the CBA model and interpreted the results; **Anis Rohanda:** Conceptualization, Methodology, Data; **Jupiter Sitorus Pane:** Writing – review & editing, Validation, Conceptualization, Investigation, Formal Analysis; **Imam Bastori:** Methodology, Conceptualization, Formal Analysis.

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