Sensitivity of Coal Reserve Economic Feasibility to Price Fluctuations: A Case Study of an Open-Pit Coal Mine in East Kalimantan, Indonesia

Arif Deswanda Cismawan
Master of Mining Engineering Study Program, Sriwijaya University, Indonesia

Eddy Ibrahim
Master of Mining Engineering Study Program, Sriwijaya University, Indonesia

Eddy Sutriyono
Master of Mining Engineering Study Program, Sriwijaya University, Indonesia

M. Taufik Toha
Master of Mining Engineering Study Program, Sriwijaya University, Indonesia

Maulana Yusuf
Master of Mining Engineering Study Program, Sriwijaya University, Indonesia

Rahmat Wahyudi Putra
Master of Environmental Science, Universitas Negeri Padang, Indonesia

Abstract: Coal price volatility is one of the most important factors affecting the economic feasibility of mining operations, particularly marginal coal reserves that are highly sensitive to changes in cost and revenue. This study evaluates the economic feasibility of marginal coal reserves under different coal price scenarios using a case study from an open-pit coal mine in East Kalimantan, Indonesia. The analysis applies a simplified discounted cash flow framework combined with operating margin analysis, critical price determination, and price sensitivity assessment. The results show that, at a base coal price of USD 43,97/ton, the project remains economically feasible, with an operating margin of USD 6,05/ton and a net present value of USD 82,91 million. However, a 20% decline in coal price results in a negative margin of USD 2,74/ton, making the project no longer economically feasible. The critical price was identified at USD 37,92/ton, representing the break-even threshold. The sensitivity analysis further demonstrates that the economic status of marginal coal reserves is dynamic and can shift from

Correspondents Author:
Arif Deswanda Chismawan, Master of Mining Engineering Study Program, Sriwijaya University, Indonesia
Email: arifdeswanda@gmail.com

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feasible to marginal or not feasible depending on market conditions. These findings highlight the importance of integrating price sensitivity into reserve evaluation and mine planning. The proposed framework provides a practical decision-support approach for reserve classification, production planning, and resource optimization under uncertain economic conditions. The main contribution of this study is the development of a practical techno-economic classification framework that links coal price variation with reserve feasibility status through the integration of critical price, operating margin, and break-even stripping ratio. This framework allows marginal reserves to be evaluated as dynamic economic entities rather than as fixed reserve categories under a single base-case price assumption.

Keywords: Marginal reserves, coal price sensitivity, economic feasibility, net present value, critical price.

Introduction

Coal remains one of the world's primary energy sources, particularly in developing countries where demand continues to increase. According to the International Energy Agency, coal continues to play a dominant role in electricity generation, especially in Asia, where it supports industrial growth and energy security. In addition, coal remains economically attractive due to its relatively stable supply chain and lower cost compared to alternative energy sources in certain regions (Guoxin et al., 2026). However, the coal market is characterized by significant price volatility driven by fluctuations in global demand, geopolitical instability, and the ongoing transition toward low-carbon energy systems (Jin & Xu, 2024). Recent studies have shown that coal prices can vary significantly within short periods, creating uncertainty in long-term mine planning and investment decisions (Lin & Lan, 2025). This volatility directly impacts the economic feasibility of mining operations, as profitability in open-pit coal mining is highly dependent on the balance between revenue and production costs (Bodiba, 2021). Furthermore, cost structures in surface mining are highly sensitive to operational factors such as stripping ratio, haulage distance, and fuel prices, which further amplify economic uncertainty (Kudzawu-D'Pherdd et al., 2026). Therefore, economic evaluation becomes a critical component in mine planning to ensure sustainable and profitable operations (Attwood, 2017).

One of the key challenges in coal mining is the management of marginal coal reserves, which are reserves that lie near the economic threshold of feasibility. These reserves are typically characterized by higher stripping ratios, lower coal quality, or less favorable logistical conditions, making them highly sensitive to economic parameters (Burmistrov et al., 2025). Marginal reserves are often excluded from mine planning due to uncertainty in their economic value and operational constraints (Hustrulid et al., 2013). However, fluctuations in coal prices can significantly alter the economic status of these reserves, shifting them from non-economic to economic categories or vice versa (Jamshidi & Osanloo, 2018). This phenomenon is particularly important in the context of resource optimization, where improper classification may lead to either premature abandonment of potentially valuable resources or inefficient allocation of mining capital (Carvalho & Dimitrakopoulos, 2024). Despite their strategic importance, marginal reserves are frequently treated as static entities in conventional resource evaluation approaches, leading to suboptimal resource utilization (Torries, 1998).

Previous studies have primarily focused on reserve estimation techniques or static economic evaluations based on fixed price assumptions. For example, traditional resource estimation methods emphasize geological modeling accuracy without integrating dynamic economic variables (Abzalov, 2016). While such approaches are essential for ensuring geological reliability, they do not reflect the economic uncertainty inherent in mining operations. Similarly, economic feasibility studies often rely on single-price scenarios, which fail to represent real market conditions and can lead to biased investment decisions (Tahernejad et al., 2018). More recent research has attempted to incorporate uncertainty through stochastic mine planning and simulation techniques; however, these approaches are often complex and require extensive computational resources (Avane et al., 2026). As a result, there remains a gap in practical and simplified methods that can capture the dynamic relationship between coal price fluctuations and reserve feasibility. In particular, limited studies have quantitatively analyzed how variations in coal prices influence the transition of marginal reserves between feasible and not feasible categories in a straightforward and applicable framework (Armstrong et al., 2020).

This study aims to evaluate the economic feasibility of marginal coal reserves under varying price scenarios. Specifically, the study assesses the economic performance of coal reserves using cost and revenue analysis, determines the critical coal price required to maintain economic viability, analyzes the sensitivity of reserve feasibility to price fluctuations, and classifies reserves into feasible, marginal, and not feasible categories. This approach reflects the increasing need for flexible mine planning strategies that can respond to market uncertainty and operational variability (Newman et al., 2010). Unlike conventional economic feasibility studies that primarily use discounted cash flow analysis as a static go/no-go investment tool, this study reframes the economic evaluation of marginal coal reserves as a dynamic reserve classification problem. The main contribution of this study is not the use of DCF or sensitivity analysis alone, but the integration of critical coal price, operating margin, and break-even stripping ratio into a practical decision-support framework for identifying feasibility transitions under changing market conditions.

In many feasibility studies, coal reserves are commonly classified as economically viable or non-viable based on a single base-case price assumption. Such an approach may overlook the fact that marginal reserves are highly conditional and may shift between feasible, marginal, and not feasible categories when coal prices change. This study addresses this limitation by explicitly linking price variation to reserve status, allowing the economic position of marginal reserves to be evaluated across several price scenarios rather than at one fixed point in time.

The novelty of the proposed framework lies in its ability to translate price sensitivity results into operational reserve classification. Instead of presenting sensitivity analysis only as a financial stress test, this study uses the results to define a transition zone between feasible and uneconomic reserves. This enables mine planners to identify the critical price level at which reserve status begins to deteriorate, the margin available before reaching break-even conditions, and the relationship between actual stripping ratio and break-even stripping ratio as a technical-economic control parameter.

While previous studies have contributed significantly to reserve estimation, economic evaluation, and uncertainty-based mine planning, their application to marginal reserve classification remains limited in two respects. First, static economic evaluations often fail to identify the transition point at which a reserve shifts from feasible to marginal. Second, advanced stochastic models, while analytically robust, may be difficult to apply during early feasibility screening when detailed probabilistic datasets are unavailable. This study addresses this gap by offering a simplified techno-economic framework that links price variation, operating margin, critical price, and BESR into an operational reserve classification process.

This approach provides a more applicable contribution for mine planning practice because it connects financial feasibility indicators with operational decision parameters. By combining NPV, operating margin, critical price, and BESR in one analytical sequence, the study offers a simplified but structured framework that can support production scheduling, pit prioritization, and resource optimization in projects where reserves are economically sensitive to commodity price fluctuations (Pirbalouti & Askari-Nasab, 2023). Therefore, the contribution of this study is positioned as a practical techno-economic classification framework for marginal coal reserves, rather than as a conventional financial feasibility assessment.

Research Methods

This study adopts a quantitative approach based on economic evaluation to assess the impact of coal price fluctuations on the feasibility of marginal coal reserves. Coal price volatility is a critical factor influencing mining project performance, particularly in coal-dependent economies where price uncertainty directly affects operational decision-making and long-term planning (Wang et al., 2024). The analysis was conducted using data derived from an open-pit coal mining operation in Indonesia, which employs a conventional truck and shovel system. In such operations, economic viability is highly sensitive to cost structure and commodity price dynamics, as profitability depends on the balance between stripping ratio, operational cost, and market price (Groeneveld et al., 2019).

The dataset used in this study consists of geological, operational, and economic parameters obtained from feasibility and cost evaluation reports. Geological data includes coal tonnage, coal quality (calorific value, ash content, and total moisture), and coal density, which are essential for defining reserve characteristics and are consistent with national reporting standards for coal resources and reserves (Badan Standardisasi Nasional, 2019). Operational data includes production cost components such as mining, hauling, crushing, processing, and port handling, all of which contribute to determining the economic threshold of coal reserves, particularly in marginal zones where small variations in cost significantly affect feasibility (Wicaksono & Sb, 2021). Economic parameters include coal selling price, total production cost, discount rate, and capital investment, which are commonly used in feasibility studies to evaluate project performance (Maleki et al., 2020).

The economic evaluation in this study was conducted using a simplified Discounted Cash Flow (DCF) framework. Revenue is calculated as the product of coal price and production volume, reflecting the standard economic model in mining where commodity price is the primary driver of revenue generation (Jaroni et al., 2019). Total production cost includes mining, processing, transportation, port handling, and royalty components, as cost estimation plays a crucial role in determining economic feasibility in open-pit mining systems (Rakhmangulov et al., 2022). The Net Present Value (NPV) is used as the primary indicator of economic feasibility, where a project is considered feasible if NPV is positive. NPV remains one of the most widely used indicators in mining project evaluation due to its ability to incorporate time value of money and long-term economic performance (Madziwa et al., 2023).

In addition to NPV, this study determines the critical coal price, defined as the minimum price at which total revenue equals total cost, resulting in a break-even condition. This threshold represents an important decision parameter, as it indicates the minimum market condition required for the project to remain economically feasible (Sidorenko et al., 2025). To capture the impact of price uncertainty, a sensitivity analysis is performed by varying coal price across multiple scenarios relative to the base price, including -30%, -20%, -10%, base case, +10%, and +20%. In this sensitivity analysis, coal price is treated as the primary variable, while production cost, stripping ratio, productivity, logistics cost, royalty structure, production volume, and capital expenditure are held constant under the base-case assumptions. This assumption is applied to isolate the effect of coal price changes on reserve feasibility. The term "dynamic" in this study refers to the reclassification of reserve feasibility according to changes in coal price and economic threshold, rather than to a probabilistic simulation model.

Therefore, the framework is not intended to replace stochastic mine planning or Monte Carlo-based uncertainty analysis. Instead, it provides a simplified screening method that can be applied at the feasibility study stage when detailed probabilistic datasets may not yet be available. This distinction is important because the proposed framework is designed to support practical decision-making by identifying when a reserve moves from feasible to marginal or not feasible conditions under defined price scenarios. Sensitivity analysis is widely used in mining economic studies to evaluate the robustness of project feasibility under fluctuating market conditions (Tua & Wibowo, 2020).

For each price scenario, the operating margin and economic feasibility are recalculated, allowing the identification of changes in reserve status. The results are then used to classify reserves into three categories: feasible, marginal, and not feasible. This classification adopts a dynamic approach, where the economic status of reserves is not treated as fixed but changes according to external factors such as commodity price fluctuations (Cáceres et al., 2025). Such an approach aligns with recent developments in mining studies that emphasize adaptive decision-making and the integration of uncertainty into mine planning and resource management (Liu et al., 2024).

To ensure that the feasibility classification is applied consistently, this study defines three quantitative feasibility categories based on the operating margin relative to the base coal selling price. The operating margin is calculated as the difference between the coal selling price and the average production cost per ton. A reserve is classified as feasible when the operating margin is greater than 10% of the base coal selling price, indicating that the project has sufficient economic buffer to absorb moderate price or cost fluctuations. A reserve is classified as marginal when the operating margin is positive but equal to or less than 10% of the base coal selling price. This condition indicates that the project remains economically viable but has limited resilience to adverse market movements. In contrast, a reserve is classified as not feasible when the operating margin is equal to or below zero, meaning that the selling price is insufficient to cover the average production cost.

In this study, the base coal selling price is USD 43,97/ton. Therefore, the marginal threshold is set at an operating margin of up to USD 4,40/ton, equivalent to 10% of the base price. Under this classification rule, the -10% price scenario, which produces a positive margin of USD 1,65/ton, is categorized as marginal because the margin remains above the break-even point but below the minimum economic buffer required for a fully feasible classification. Conversely, the base-case scenario, with an operating margin of USD 6,05/ton, is classified as feasible because it exceeds the 10% margin threshold. Price scenarios that generate negative margins are classified as not feasible, as they indicate that the project would operate below its economic break-even level.

The overall analytical workflow consists of defining base economic parameters, calculating cost and revenue structures, determining the critical price, applying price sensitivity scenarios, evaluating economic performance, and classifying reserve feasibility dynamically. The framework does not quantify the probability of each price scenario; however, it provides a practical first-stage screening tool for identifying critical transition points before more data-intensive probabilistic analysis is conducted. This framework enables a more responsive and decision-oriented evaluation of marginal coal reserves, particularly under conditions of price volatility, and provides a practical basis for optimizing mine planning and resource utilization.

Results and Discussion

Coal price fluctuations represent a critical external variable that significantly influences the economic feasibility of mining projects, as coal prices are affected by global energy market dynamics, interest rates, exchange rates, and geopolitical risks. In addition, volatility in the coal market tends to be asymmetric and more pronounced during downward price movements, making price-decline scenarios highly relevant for evaluating the economic resilience of coal reserves. Therefore, the results of this study focus on assessing the extent to which price variations can shift reserve status from economically feasible to marginal or not feasible (Lyu et al., 2024).

Conceptually, a mining project should not be considered feasible merely because it is profitable at a given moment, but rather because it can remain feasible throughout one or more price cycles, including prolonged periods of low prices. Therefore, the findings of this study should not be interpreted solely as a snapshot of economic performance under base-case conditions, but as a measure of the resilience of coal reserves under price pressure (Moore & Friederich, 2021).

In mining feasibility studies, discounted cash flow (DCF) analysis remains the primary benchmark for evaluating whether a project should proceed, essentially representing a go/no-go decision point. However, such evaluation must be based on sufficient technical and economic parameters, including reserves, overburden, operational costs, selling price, recovery, and loss factors. Based on the project data provided, this study adopts this framework to assess the sensitivity of coal reserve feasibility in an open-pit mining operation in Indonesia (Kamel et al., 2023).Under base-case conditions, the project demonstrates strong economic indicators. The coal selling price (FOB vessel) is recorded at USD 43.97/ton, while the average production cost is USD 37.92/ton, resulting in an operating margin of USD 6.05/ton. From a financial perspective, the project yields an NPV of USD 82.907.245, an IRR of 30,98%, a WACC of 11,51%, a payback period of 5,48 years, and a profitability index of 2,74.

These figures confirm that, under base-case assumptions, the project remains economically feasible (Table 1).

Table 1 Main Economic Indicators under Base-Case Conditions

Parameter	Value	Unit
Coal Selling Price	43,97	USD/ton
Average production cost	37,92	USD/ton
Operating margin	6,05	USD/ton
Net Present Value (NPV)	82.907.245	USD
Internal Rate of Return (IRR)	30,98	%
Weighted Average Cost of Capital (WACC)	11,51	%
Payback Period	5,48	Years
Profitability Index	2,74	X

Despite the positive and relatively high base-case NPV, the literature emphasizes that deterministic NPV essentially compresses all future uncertainties into a single present value. This implies that a positive NPV under base-case conditions does not necessarily guarantee robustness against price fluctuations, as conventional NPV does not explicitly capture how incremental changes in price influence investment decisions. Therefore, the interpretation of results in this study is extended through price-based sensitivity analysis (Chandra & Hartley, 2024). Before evaluating price scenarios, it is essential to examine the project's cost structure. Based on the provided data, the total direct cost (pit-to-vessel) is USD 19.10/ton, while the average life-of-mine (LOM) production cost is USD 37.92/ton. The most significant cost components include total overburden removal at USD 16.47/ton, coal processing and transportation to anchorage at USD 10.79/ton, barging at USD 6.64/ton, and government royalties at USD 3.27/ton. This structure indicates that the primary cost pressure lies in material handling and logistics rather than coal extraction itself (Table 2).

Table 2 Pit-to-Vessel Cost Structure and Base Production Cost

Cost Component	Value	Unit
Overburden Mining (Mining Cost)	2,52	USD/ton
Overburden Overhaul	0,00	USD/ton
Coal Getting	1,16	USD/ton
Coal Hauling (Pit to Inpit ROM)	2,37	USD/ton
Coal Haul Road Maintenance	0,58	USD/ton
Coal Haul Road Toll Fee	0,95	USD/ton
Regional Government Royalties	3,26	USD/ton
Total Mining Cost	**8,32**	**USD/ton**
Coal Crushing & Loading	2,47	USD/ton
Surveyor	0,35	USD/ton
Total Crushing Cost	**2,82**	**USD/ton**
Coal Barging to Transhipment Point	6,64	USD/ton

Stevedoring	1,08	USD/ton
Shipping Document	0,10	USD/ton
Coal Handling and Treatment	0,15	USD/ton
Total Port Cost	**7,97**	**USD/ton**
Total Direct Cost	**19,10**	**USD/ton**
Total Overburden Removal	16,47	USD/ton
Coal Mining	1,16	USD/ton
Coal Transportation to Jetty Stockpile	2,37	USD/ton
Coal Haul Road Maintenance	0,58	USD/ton
Coal Haul Road Toll Fee	0,95	USD/ton
CSR	0,07	USD/ton
Coal Processing and Transport to Anchorage	10,79	USD/ton
Mine Rehabilitation	0,46	USD/ton
Government Royalty	3,27	USD/ton
G&A and Other Expenses	1.75	USD/ton
HSE	0,05	USD/ton
Average Coal Production Cost per Ton (FOB Vessel)	**37.92**	**USD/ton**
Coal Selling Price per Ton (FOB Vessel)	**43,97**	**USD/ton**

These findings are consistent with modern open-pit mining theory, which identifies stripping ratio, haulage cost, and material movement as the dominant drivers of economic performance. As open-pit operations deepen, increases in stripping ratio and haul distance can significantly escalate costs, with transportation becoming one of the largest operational cost components. Consequently, price sensitivity in this project must be interpreted alongside sensitivity to material movement costs (Shamsi et al., 2025). From a techno-economic reserve perspective, the project contains 69,25 million tons of coal reserves, 441.4 million bcm of overburden, and a stripping ratio of 6,37 bcm/ton. The project also reports a Break-Even Stripping Ratio (BESR) of 8,95 bcm/ton. This indicates that the project still maintains an economic margin of 2,58 bcm/ton below the BESR, or approximately 28,83% lower than the break-even threshold. Operationally, this position is significant as it indicates that the base reserves remain within acceptable economic limits (Table 3).

Table 3 Technical-Economic Reserve Parameters

Parameter	Value	Unit
Coal reserves	69,25	million tons
Overburden	441,40	million bcm
Actual stripping ratio	6,37	bcm/ton
Break-Even Stripping Ratio (BESR)	8,95	bcm/ton
Difference from BESR	2,58	bcm/ton
Headroom to BESR	28,83	%

This finding aligns with previous studies showing that stripping ratio is one of the most influential variables affecting capital cost and net present value. The relationship between coal price, stripping ratio, BESR, and operating margin provides a deeper explanation of why the reserve status changes across price scenarios. In open-pit coal mining, the stripping ratio determines the amount of overburden that must be removed for each ton of coal produced. As the stripping ratio increases, the production cost per ton also increases, thereby reducing the operating margin. Under base-case conditions, the actual stripping ratio of 6,37 bcm/ton remains below the BESR of 8,95 bcm/ton, indicating that the reserve is still economically mineable. However, this condition is valid only under the assumed coal price and cost structure.

At the base coal price of USD 43.97/ton, the project generates an operating margin of USD 6,05/ton, with a critical price of USD 37.92/ton. This indicates that the project has a downside buffer of only 13,76% from the base price. When the coal price declines by 10%, the margin decreases to USD 1.65/ton. While the margin remains positive, the project enters a marginal condition because the economic buffer becomes very narrow. At a 20% price reduction, the selling price falls below the critical price, producing a negative margin of -USD 2.74/ton. This means that the revenue generated per ton of coal is no longer sufficient to cover the average production cost.

These findings show that BESR should not be interpreted as a static technical limit. When coal prices decrease, the allowable economic stripping ratio also declines, meaning that coal blocks with higher stripping ratios may no longer be economically mineable. Conversely, when coal prices increase, the BESR expands and allows higher-cost blocks to be included in the mine plan. Therefore, the economic pit limit is dynamic and responds directly to changes in coal price. This explains why marginal reserves can shift from feasible to marginal or not feasible even when the geological reserve remains unchanged.

The integration of coal price, stripping ratio, BESR, and operating margin therefore provides a more robust basis for reserve classification. Coal price defines the revenue potential, stripping ratio defines the physical cost burden, BESR defines the maximum economically acceptable mining limit, and operating margin measures the remaining economic buffer. The interaction among these variables confirms that the feasibility of marginal coal reserves is not fixed, but changes according to market conditions and technical-economic constraints. This supports the main argument of the study that marginal reserve evaluation should adopt a dynamic framework rather than relying solely on a single base-case feasibility assessment. Thus, although this study focuses on price sensitivity, it is essential to recognize that reserves with higher stripping ratios are more likely to become uneconomic under declining price conditions (Zhang et al., 2020).

The sensitivity results should also be interpreted with caution because the scenarios isolate coal price changes while assuming that other cost components remain constant. In real mining operations, declining coal prices may occur simultaneously with cost escalation caused by higher fuel prices, longer hauling distances, increasing stripping ratios, lower equipment productivity, or changes in logistics and royalty obligations. Under such conditions, the economic margin would be compressed from both sides: revenue would decline while the production cost and break-even threshold would increase. Therefore, the transition from feasible to marginal or not feasible conditions could occur earlier than indicated by price-only sensitivity results.

From an investment perspective, the project is not merely a short-term operational model but one that involves substantial upfront capital expenditure. The total CAPEX is recorded at USD 30.290.692, consisting of USD 24.118.845 in fixed assets and USD 6.171.847 in intangible assets. Therefore, price sensitivity must be evaluated not only at the unit margin level but also in terms of the project's ability to sustain cash flow, recover initial investment, and maintain a positive net present value (Table 4).

Table 4 Capital Expenditure (CAPEX) Summary

Component	Value (USD)
Buildings and Supporting Facilities	24.118.845
Mining Property / Intangible Assets	6.171.847
Total CAPEX	**30.290.692**

The project's free cash flow profile indicates that its value is generated over a long operational horizon rather than being concentrated in early years. Accordingly, price sensitivity should be interpreted as affecting the entire project lifecycle rather than just short-term operating margins (Table 5).

Table 5 Annual Free Cash Flow to Firm (FCFF)

Year	FCFF (USD)
2024	19.013.365
2025	27.114.060
2026	4.888.355
2027	16.897.700
2028	23.384.720
2029	22.246.778
2030	22.741.610
2031	24.523.617
2032	33.356.699

2033	32.827.323
2034	32.132.298
2035	31.549.355
2036	31.149.932
2037	30.536.059
2038	19.395.664
Total FCFF	**269.725.974**

For the purposes of this study, sensitivity analysis serves as a screening tool to assess the immediate response of the project to price variations. The literature suggests that sensitivity analysis is widely used to evaluate the impact of parameter changes on NPV and IRR. In this study, price sensitivity analysis is considered appropriate as the primary objective is to identify transitions in feasibility status (feasible–marginal–not feasible) (Ronyastra et al., 2023). The Free Cash Flow to Firm (FCFF) profile represents the project's cash-generating capacity over the life of mine (LOM). As shown in Table 5 and Figure 1, the project maintains positive FCFF throughout the production period, with cumulative FCFF reaching USD 269.73 million. However, a notable decline occurs in 2026, when FCFF decreases to USD 4.89 million after reaching USD 19,01 million in 2024 and USD 27,11 million in 2025. Based on the available project data, this decline is mainly related to the early-stage capital burden and the operational transition phase. The project requires total CAPEX of USD 30.29 million, consisting of USD 24,12 million in fixed assets and USD 6.17 million in mining property or intangible assets. The concentration of these investment requirements in the early project period suppresses free cash flow in 2026, although the project still generates positive operating cash flow.

The decline in 2026 should therefore be interpreted as temporary cash flow compression during the development and ramp-up stage, rather than as an indication of long-term economic weakness. This interpretation is supported by the subsequent recovery of FCFF to USD 16.90 million in 2027, followed by a more stable upward trend until the project reaches its peak FCFF of USD 33.36 million in 2032. The overall FCFF pattern is consistent with a typical open-pit mining project cycle, which commonly includes early capital deployment, operational stabilization, peak productivity, and gradual decline toward the end of mine life. Accordingly, the temporary reduction in 2026 does not undermine the base-case feasibility of the project, but it indicates that annual cash flow behavior needs to be assessed together with aggregate indicators such as NPV, IRR, and payback period.

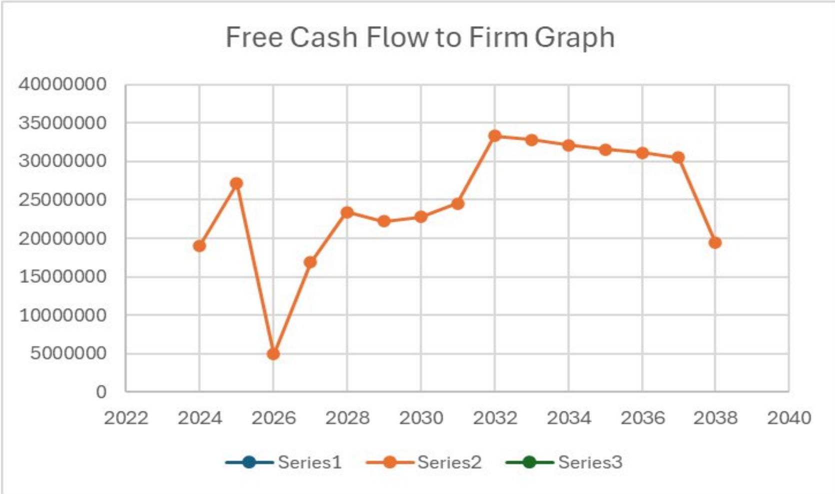

Figure 1 Free Cash Flow to Firm Graph

Following the cash flow compression in 2026, the project enters a more stable phase between 2027 and 2031, with FCFF ranging from approximately USD 16 million to USD 24 million. This pattern suggests improved operational stability, better cost control, and a more balanced production profile. The project reaches its strongest financial performance in 2032, when FCFF exceeds USD 33 million, before gradually declining from 2033 onward as the mine approaches its later production stage. This decline may be associated with increasing stripping requirements, longer haulage distances, and the progressive depletion of more economically favorable reserves. The FCFF profile reflects a typical life-of-mine pattern, beginning with early investment and operational ramp-up, followed by stabilization, peak production, and gradual decline toward mine closure. Although the project maintains positive cash flow throughout the mine life under base-case conditions, its relatively narrow operating margin indicates exposure to coal price fluctuations. A decline in coal price would directly reduce revenue and compress FCFF, potentially accelerating the transition from feasible to marginal conditions. Based on a base coal price of USD 43.97/ton and an average production cost of USD 37.92/ton, the project's critical price is USD 37.92/ton, representing the operating break-even point where the margin equals zero. This means that the project has a downside buffer of only USD 6.05/ton, or 13.76% of the base price. Such a limited buffer indicates that the project remains moderately vulnerable to price declines, where even a moderate reduction in coal price could shift the reserve into a marginal zone (Table 6).

Table 6 Critical Price and Economic Buffer of the Project

Parameter	Value
Base coal selling price	43,97 USD/ton
Base production cost	37,92 USD/ton
Critical price	37,92 USD/ton
Absolute buffer above break-even	6,05 USD/ton
Relative buffer to base price	13,76%

Although this study applies a deterministic sensitivity framework, the results should be interpreted within a broader uncertainty context. Coal price movements are not fixed-step changes, but stochastic outcomes influenced by global demand, energy policy, geopolitical risks, exchange rates, and fuel substitution dynamics. Therefore, the price scenarios used in this study represent practical stress-test points within a wider range of possible market conditions. The base-case result shows that the project remains feasible at a coal price of USD 43.97/ton, with a production cost of USD 37.92/ton and an operating margin of USD 6.05/ton. However, this margin provides only a 13.76% buffer above the critical price. From an uncertainty perspective, this indicates that the project has limited resilience against downward price movements. A positive base-case NPV should therefore not be interpreted as a guarantee of robust feasibility, particularly for marginal reserves that are highly sensitive to small changes in market price.

The most critical uncertainty zone occurs between the base price and the critical price. At a 10% price reduction, the project enters a marginal condition with a remaining margin of only USD 1.65/ton, while a 20% price reduction results in a negative margin of USD 2.74/ton. This narrow transition range suggests that moderate price volatility could create a meaningful risk of feasibility deterioration. Accordingly, the -10% scenario should be treated as an early warning threshold rather than merely a lower-price assumption.The critical price of USD 37.92/ton can also be interpreted as a probabilistic decision boundary. Prices above this level support positive margins, whereas prices below this threshold weaken the economic justification for extracting marginal reserves. In practical mine planning, this threshold may serve as a trigger for adaptive decisions, such as delaying high stripping-ratio blocks, prioritizing lower-cost mining areas, improving hauling efficiency, or revising the production sequence to preserve cash flow during unfavorable market conditions.

Future studies may assign probability distributions to coal price, production cost, stripping ratio, hauling cost, and royalty assumptions to estimate the likelihood of positive NPV, negative NPV, and marginal reserve transition. Nevertheless, the simplified framework remains valuable as an initial screening tool because it identifies the critical price threshold and clarifies the price range where reserve status changes from feasible to marginal or not feasible.

The relationship between coal price and operating margin demonstrates a strong linear sensitivity. A reduction of 20% in coal price results in a negative margin of -2.74 USD/ton, indicating that the project becomes economically infeasible. A further decline to 30% leads to substantial losses of -7.14 USD/ton (Figure 2). The feasibility classification reveals a clear transition from economically feasible to marginal and subsequently to not feasible conditions as coal prices decrease. The transition zone occurs between a 10%–20% price reduction, indicating a narrow economic buffer for marginal reserves (Figure 3).

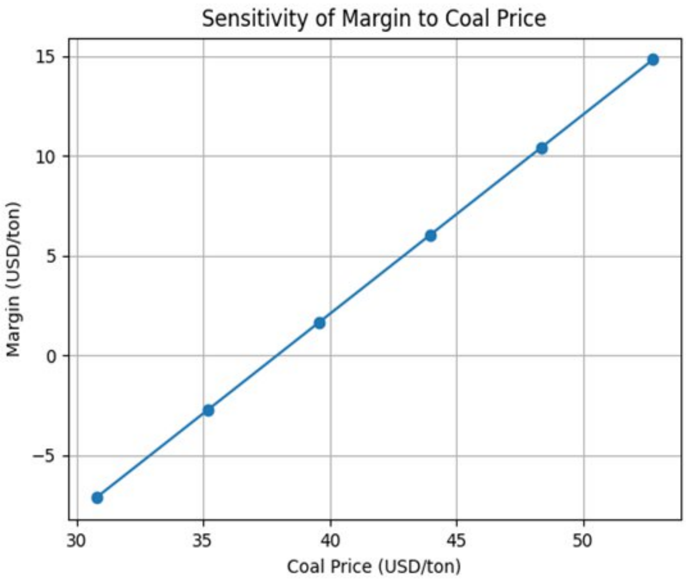

Figure 2 Sensitivity of Margin to Coal Price

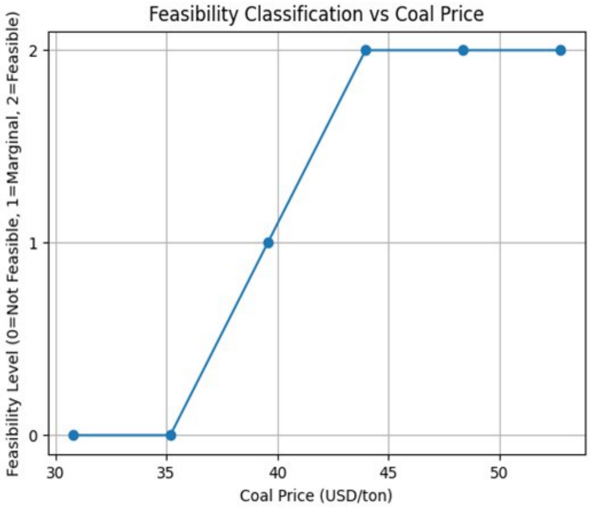

Figure 3 Feasibility Classification vs Coal Price

Similarly, the relationship between coal price and Net Present Value (NPV) shows a strong and nearly linear dependency, confirming that project viability is highly sensitive to market price fluctuations (Figure 4). At the base price, the project generates an NPV of approximately USD 82.9 million. However, as coal prices decline, NPV decreases significantly. At a 10% price reduction, the project remains feasible but with a reduced economic buffer, whereas further price reductions drive NPV into negative territory. The vertical dashed line in Figure 4 represents the critical price of USD 37.92/ton, corresponding to the operating break-even condition where the selling price equals the average production cost. This threshold serves as a key decision boundary. When prices fall below this value, the project transitions from feasible to not feasible, indicating that revenues are insufficient to cover both operational and capital costs.

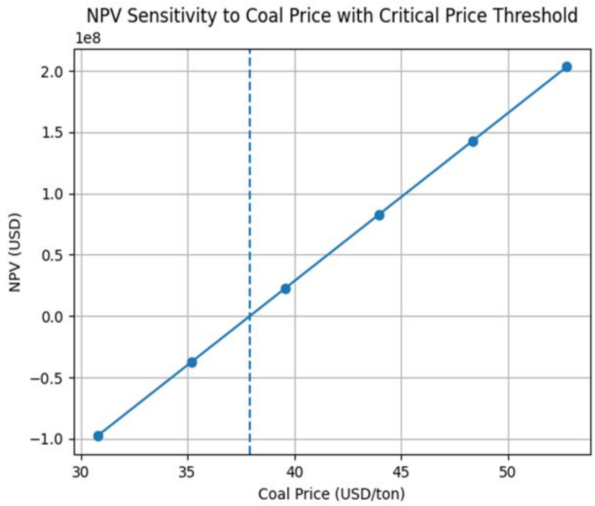

Figure 4 NPV Sensitivity to Coal Price with Critical Price Threshold

These results indicate that the economic feasibility of marginal coal reserves is not static but dynamically governed by price fluctuations. The relatively narrow gap between base price and critical price highlights the project's limited resilience to downward price movements. This finding underscores the importance of evaluating marginal reserves using dynamic economic thresholds rather than fixed classifications, as their feasibility can shift rapidly even under moderate price changes. Technically, this approach is consistent with the concept of ultimate pit economics, where price scenarios are tested progressively from low to high to identify economically feasible portions of the reserve. At low prices, only zones with favorable stripping ratios and geological conditions remain feasible, while higher-cost areas are excluded from economic consideration (Buelga Díaz et al., 2021).

The feasibility status in each price scenario is interpreted using the quantitative classification threshold defined in the methodology section, where margins above 10% of the base coal price are considered feasible, positive margins up to 10% are considered marginal, and zero or negative margins are considered not feasible. Based on the applied price scenarios, the results clearly demonstrate a progressive decline in feasibility. At a 30% price reduction, the project becomes not feasible with a margin of -USD 7.14/ton. At a 20% reduction, it remains not feasible with a margin of -USD 2.74/ton. At a 10% reduction, the project becomes marginal with a margin of USD 1.65/ton. At base and higher price scenarios, the project remains feasible (Table 7).

Table 7 Price Sensitivity of Margin and Feasibility Status

Price Scenario	Price (USD/ton)	Margin (USD/ton)	Status
-30%	30,78	-7,14	Not feasible
-20%	35,18	-2,74	Not feasible
-10%	39,57	1,65	Marginal
Base case	43,97	6,05	Feasible
10%	48,37	10,45	Feasible
20%	52,76	14,84	Feasible

The key interpretation of these findings is that the project has limited tolerance to price decline. While it remains feasible under base conditions, a relatively small price decrease of 13,76% is sufficient to reach the break-even point. This indicates that the economic safety margin is relatively narrow. From a mining decision-making perspective, the project is neither fragile nor fully resilient to price shocks, with the -10% scenario representing a critical warning zone requiring careful operational management. This conclusion is further supported by Indonesian studies on BESR, which show that stripping ratio limits are commonly used in industry practice to define economically mineable zones. In such cases, BESR serves as a threshold for pit design and block selection. In this study, the combination of actual SR (6,37 bcm/ton), BESR (8,95 bcm/ton), and critical price (USD 37.92/ton) indicates that price fluctuations are more likely to drive feasibility changes than short-term geometric adjustments of the pit (Saputra et al., 2014).

From a reserve classification perspective, these findings reinforce the argument that economic viability should not be treated as a static classification. Instead, reserve classification must consider the ability of the project to sustain economic returns across price cycles rather than relying on spot price conditions. The most important outcome of this study is therefore not merely that the project is currently feasible, but that its feasible reserves are conditional upon price, with a clear transition zone between 10% and 14% price reduction (Larkin & Ballantine, 2015).

The results demonstrate that the feasibility of coal reserves in the studied open-pit mine is highly sensitive to price fluctuations. While the project is economically feasible under base conditions, its economic buffer is limited. Moderate price declines are sufficient to shift the project into a marginal condition, while larger declines render it not feasible. Therefore, the practical novelty of this study lies in the integration of critical price, margin screening, and BESR into a simple yet operational framework for dynamically evaluating reserve feasibility, which can be directly applied in mine planning, pit optimization, and production scheduling. The empirical results of this study are derived from a single open-pit coal mine; therefore, the critical price, operating margin, and feasibility transition range should be interpreted as project-specific outcomes rather than universal benchmarks. Nevertheless, the proposed framework has broader applicability because its analytical structure can be transferred to other mining projects by recalibrating key technical and economic variables, such as coal price, production cost, actual stripping ratio, break-even stripping ratio, hauling distance, royalty structure, capital expenditure, and discount rate. Mines with different geological settings, cost structures, production scales, and market exposure can apply the same framework to determine their own economic thresholds and reserve classification boundaries. Thus, the generalizability of this study lies in the repeatability of the evaluation process, not in the direct transfer of its numerical results. This strengthens the practical value of the framework as a decision-support tool for identifying feasibility transitions in marginal reserves under varying market and operational conditions.

Conclusions

This study evaluates the sensitivity of coal reserve feasibility to price fluctuations in an open-pit coal mining operation using an integrated economic approach. The results demonstrate that the economic viability of coal reserves is highly dependent on market price conditions and cannot be treated as a static classification. Under base-case conditions, the project is economically feasible, as indicated by a positive NPV of USD 82,9 million, an IRR of 30,98%, and an operating margin of USD 6.05/ton. However, the economic buffer of the project is relatively limited, with a critical price of USD 37.92/ton, representing only a 13,76% margin below the base price. This narrow buffer indicates that the project is moderately sensitive to downward price movements.The sensitivity analysis reveals a clear transition in feasibility status as coal prices decline. At a 10% price reduction, the project remains economically feasible but enters a marginal condition with a significantly reduced margin. Further price reductions of 20% and 30% result in negative margins, rendering the project economically infeasible. These findings highlight that even moderate fluctuations in coal price can significantly alter the economic status of marginal reserves. From a techno-economic perspective, the project's stripping ratio of 6,37 bcm/ton remains below the break-even stripping ratio (BESR) of 8,95 bcm/ton, indicating that the reserves are still within an acceptable economic range under base conditions. However, the results also suggest that price fluctuations have a more immediate impact on feasibility compared to short-term changes in mining geometry, reinforcing the importance of incorporating price dynamics into reserve evaluation.

The novelty of this study lies in repositioning marginal reserve evaluation from a static financial feasibility assessment into a dynamic techno-economic classification process. By integrating critical price, operating margin, and BESR, the study demonstrates how reserve status can shift across feasible, marginal, and not feasible categories under different coal price scenarios. This provides a practical contribution to mine planning by allowing decision-makers to identify economic transition zones, anticipate price-driven reserve deterioration, and prioritize production strategies based on both financial and operational thresholds. This approach allows for a more adaptive classification of reserves into feasible, marginal, and not feasible categories based on prevailing market conditions. Practically, the findings provide a decision-support tool for mine planning and resource management, enabling operators to identify critical price thresholds, anticipate feasibility transitions, and optimize production strategies under uncertain market conditions. The study therefore emphasizes that economic feasibility in coal mining is inherently dynamic and should be continuously reassessed in response to price volatility. Future studies are recommended to incorporate probabilistic approaches such as Monte Carlo simulation to better capture uncertainty in price, cost, and operational parameters. Additionally, integrating spatial mine planning and block-level economic evaluation would further enhance the applicability of dynamic reserve classification in real mining operations.

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