



Carbon Cost Internalization in Mining Operations: A Systematic Literature Review Toward an Activity-Based Framework for Limestone Quarry

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ABSTRACT

Carbon pricing is becoming increasingly relevant to mining because greenhouse-gas emissions may create additional operating costs through regulatory requirements, carbon-market transactions, or internal economic valuation. This systematic literature review examines how carbon costs have been defined, quantified, and incorporated into mining economics, with particular attention to the development of a research framework for limestone quarrying from land clearing to the crusher hopper. The literature search was conducted from April to June 2026, with the final search completed on 17 June 2026. ScienceDirect was used as the primary literature source and Google Scholar as a supplementary source. Duplicate records were checked using DOI and bibliographic information before title, abstract, and full-text screening against predefined eligibility criteria. Screening was conducted by the first author and subsequently reviewed by the second author. Of 50 peer-reviewed articles assessed, 40 were retained for descriptive classification and thematic synthesis. The main gaps concern limestone-specific applications, integration of land-use-change and operational emissions, and site-based operating costs. The proposed framework distinguishes regulatory carbon-tax obligations, market carbon-unit prices, internal or shadow prices, and hypothetical prices used for stress testing, with Indonesian values treated as scenario inputs rather than assumed quarry-specific liabilities.

1. INTRODUCTION

Mining has a twofold role in the low-carbon transition. Minerals and industrial rocks are essential inputs for infrastructure, energy systems, and economic development, while mining activities themselves generate greenhouse-gas (GHG) emissions through drilling and blasting, loading, haulage, electricity consumption, fuel use, explosives, and land-cover change. Growing regulatory and corporate attention to these emissions has encouraged the use of economic instruments that assign a monetary value to GHG emissions. In this context, carbon pricing is intended to internalize, wholly or partly depending on the instrument and its coverage, the climate-related externality associated with GHG emissions. It should not be interpreted as internalizing the broader environmental and social externalities of mining, which may also include biodiversity loss, impacts on water resources, local air pollution, land disturbance, and social effects.

The carbon-pricing literature has developed along two broad but analytically distinct strands. The first examines the effectiveness of carbon taxes and emissions trading systems

(ETSS) in reducing emissions at national, sectoral, or firm levels. The meta-analysis of Ahmad et al. (2024) finds that both instruments can reduce emissions. The authors report a larger average effect for carbon taxes, but the estimated effects vary substantially across countries and industries. British Columbia, Finland, Mexico, Colombia and Argentina have mixed empirical results, dependent on tax rates, sectoral scope, exemptions, institutional settings and adjustment horizons (Pretis, 2022; Mideksa, 2024; Muzzi Pinto Coelho Junior & Pereda, 2026). These findings describe the effectiveness of carbon-pricing policies in changing emissions and should not be interpreted directly as evidence of the financial exposure of an individual mining operation. Mine-level carbon-cost exposure instead depends on the monetary value assigned to emissions, the emissions covered, site-specific emission intensity, production characteristics, energy sources, and the operator's ability to adjust technology or operating practices.

The second strand develops techno-economic approaches in which monetary values assigned to emissions are incorporated into operating costs, block values, cut-off grades, ultimate pit limits, and project net present value (NPV). At this operational scale, the financial effect of carbon pricing cannot be separated

from mine configuration. For example, in a copper-cobalt mining case, Rijdsdijk and Nehring (2022) reported an increase of about 2% in mining cost at USD 30/tCO_{2e} and about 5% at USD 100/tCO_{2e}. The results also suggest that altering the energy source may have greater economic consequences than changing the assumed value of carbon. Similarly, Ulrich et al. (2022) found large differences in carbon-cost exposure across gold-mining operations, driven by variation in emission intensity and energy mix. Thus, identical carbon values may result in different financial consequences across mining operations.

At the operational level, haulage has received particular attention because truck fuel consumption is a major source of direct emissions in open-pit mining. Huo et al. (2023, 2024) demonstrated that using reinforcement-learning-based dispatching can reduce fuel-related emissions by reducing the idle time, queuing and inefficient assignments of equipment. In addition, Tokac et al. (2025) showed that fleet electrification can lead to reductions in emissions and operating costs, depending on conditions, but the benefits remain sensitive to the electricity mix and mine characteristics. These findings are relevant to limestone quarrying, where repeated loading and haulage cycles between the mining face and crusher make equipment productivity, haul distance, and fuel consumption important determinants of both operating cost and emission intensity.

Limestone nevertheless differs economically from metallic commodities. Its operational value is generally determined by chemical-quality requirements, feed continuity, haul distance, blending requirements, and integration with plant demand rather than by metal cut-off grade. Carbon-cost models based primarily on cut-off-grade adjustment or ultimate-pit optimization therefore cannot be transferred directly to limestone quarrying without modification. For cement-grade limestone, a more relevant question is how the monetary valuation of GHG emissions affects activity-level costs and the unit mining cost from land clearing to delivery at the crusher hopper.

The reviewed evidence indicates a clear mismatch between the limestone/quarry literature and studies that monetize mining-related GHG emissions. Of the 40 studies retained for synthesis, eight (20%) specifically examined limestone or quarrying contexts. These studies predominantly applied life-cycle assessment, environmental-impact assessment, emission inventories, or operational emission analysis. None of the eight directly incorporated a carbon price, shadow carbon price, or equivalent monetary value of GHG emissions into activity-level operating costs for limestone quarrying. Conversely, studies that explicitly integrated carbon pricing or environmental costs into mine-economic models were concentrated mainly in broader open-pit or metallic-mining contexts. This pattern indicates a specific evidence gap at the intersection of quarry-level emission accounting and mine-level carbon-cost internalization, particularly for an operational boundary extending from land clearing to the crusher hopper.

This gap is also methodological. Quarry-focused studies have established useful approaches for estimating emissions from extraction activities, fuel use, blasting, and processing, whereas mine-economic studies have demonstrated how carbon-related monetary values can affect operating costs, production planning, and project value. However, these two

lines of evidence remain weakly integrated for limestone quarrying. Land-use-change emissions are also commonly evaluated separately from recurring equipment-related emissions, while system boundaries vary considerably across studies. These differences complicate the development of a consistent activity-based model capable of linking site-specific emissions with operating costs.

Accordingly, this review has three objectives. First, it maps the concepts, methods, and findings of research on carbon pricing, GHG emissions, and mining economics. Second, it identifies the principal emission sources and operational factors governing carbon-cost exposure in open-pit mining. Third, it develops a research agenda and an activity-based framework for limestone quarrying within a land-clearing-to-crusher-hopper boundary. The review therefore examines the relationships among activity data, system boundaries, emission-estimation methods, forms of carbon valuation, economic indicators, sensitivity analysis, and technical decisions.

1.1. Conceptual Background

1.1.1. Carbon Pricing Instruments and Externality Internalization

Greenhouse-gas emissions represent an environmental externality because part of the climate-related damage associated with production is not reflected in private production costs or product prices. Carbon-pricing instruments seek to assign a monetary value to these emissions, most commonly through carbon taxes and emissions trading systems (ETSs). Their scope, however, is specifically related to greenhouse-gas emissions. Carbon-cost internalisation should therefore be distinguished from broader environmental-cost internalisation, which may additionally include biodiversity loss, impacts on water resources, local air pollution, land degradation, waste, and social externalities.

In their simplified theoretical forms, carbon taxes are commonly associated with greater certainty over the price of emissions, whereas ETSs are associated with greater certainty over the quantity of emissions allowed within the regulated system. These distinctions should not be interpreted as absolute characteristics of policies implemented in practice. ETS designs may incorporate price floors or ceilings, allowance banking, reserve mechanisms, and other market-stabilisation provisions that influence both allowance prices and available quantities. Carbon taxes may likewise include exemptions, differentiated rates, thresholds, rebates, or other adjustments that modify the effective price signal faced by regulated entities. The practical distinction between the two instruments therefore depends on their detailed policy design rather than on a strict separation between price certainty and quantity certainty. Their effectiveness is further influenced by the price level, sectoral and greenhouse-gas coverage, allocation arrangements, revenue use, enforcement, and complementary policies. A global expert survey reports relatively strong support for carbon taxation in unilateral policy settings, and border carbon-adjustments are often considered in relation to competitiveness concerns (Nesje et al., 2025).

For the purposes of this review, four forms of carbon valuation are distinguished. First, a statutory carbon-tax obligation represents an actual fiscal liability only where the

applicable legislation and implementing rules establish the taxable object, liable entity, tax base, applicable rate, taxation period, and payment mechanism. Second, a market carbon-unit price represents the observed transaction value of eligible carbon units and does not by itself establish a tax obligation. Third, an internal or shadow carbon price is an imputed value used by an analyst or organization to assess potential carbon exposure, compare technologies, or incorporate carbon-related risk into economic evaluation. Fourth, a hypothetical stress-test price is an assumed value used to examine the sensitivity of costs or investment outcomes under more stringent future carbon-price conditions.

Within this distinction, the IDR 30,000/tCO₂e value referenced in Indonesia's Harmonized Tax Law is not treated in this study as an operational carbon-tax rate applicable to limestone quarrying. Because no quarry-specific tax obligation has been established for the study context, the value is used only as a regulation-referenced shadow-price scenario for economic analysis. Its role is to provide a transparent Indonesian policy reference point for assessing potential carbon-cost exposure rather than to estimate an existing legal liability of a limestone-quarry operator.

It is also necessary to distinguish land-clearing emissions from recurring operational emissions because they arise from different processes and may be recognized at different times in an emissions inventory. Fuel-combustion emissions are associated with the period in which fuel is consumed, whereas carbon-stock losses from vegetation or soil are associated with the land-conversion event. This inventory treatment should remain separate from the subsequent financial treatment of those emissions.

For operational cost analysis, the monetized carbon-stock loss associated with a cleared area may additionally be expressed per tonne of recoverable limestone expected from that area. This treatment is used only as a production-normalized economic indicator and does not alter the timing or amount of emissions recognized in the GHG inventory. Recoverable limestone tonnage is used as the denominator because it represents the process-relevant output associated with the disturbed area. The resulting metric therefore provides a comparable unit-cost indicator for operational analysis but should not be interpreted as a formal emissions-allocation procedure under life-cycle assessment.

Accordingly, four analytical treatments should be kept distinct: (i) recognition and timing of land-use-change emissions in the emissions inventory; (ii) financial valuation of those emissions using a specified carbon value; (iii) normalization of the resulting monetary value per tonne of recoverable limestone for operational decision-making; and (iv) formal allocation procedures used in life-cycle assessment. Maintaining this distinction allows the emissions inventory to remain methodologically intact while providing an additional economic metric for evaluating carbon-cost exposure at the quarry level.

1.1.2. Emission Inventories and System Boundaries

An emissions inventory links activity data to emission factors. Relevant activity data may include diesel consumption, electricity use, explosive tonnage, equipment hours, haul distance, cleared area, and changes in carbon stocks. Emission factors convert these activities into

individual GHG emissions, which are then expressed as CO₂e using global warming potentials (GWPs). CO₂ alone may not reflect the full emissions profile; non-CO₂ gasses should also be considered where relevant (Nong et al., 2021).

The resulting inventory is highly dependent on the choice of system boundaries. A pit-only boundary includes emissions from mining equipment and directly associated support activities. Mine-to-mill and full supply-chain boundaries progressively include processing, upstream inputs, external logistics and downstream activities. For this review, the core analytical boundary is defined as land-clearing-to-crusher-hopper.

The core boundary includes land clearing, topsoil and overburden handling, drilling, on-site blasting, loading, haulage, dozing and grading, routine road maintenance, dewatering, operational water use, workshop support where attributable, and feeding to the crusher hopper. Direct fuel combustion within these activities is treated as Scope 1, while purchased electricity used for operational support is treated as Scope 2. Contractor-operated equipment is included when it performs activities within the same operational boundary.

Upstream manufacture and transport of diesel, explosives, spare parts, and other consumables are excluded from the core case and may be treated separately as upstream Scope 3 emissions. Employee commuting, major infrastructure construction, reclamation and post-closure activities, crusher processing after hopper receipt, and external transport beyond the crusher are also excluded. These exclusions are intended to preserve a consistent quarry-level operational boundary for linking emissions with unit mining costs rather than to imply that the excluded sources are environmentally insignificant. The included and excluded processes, associated emission scopes, and boundary decisions are summarized in Figure 1.

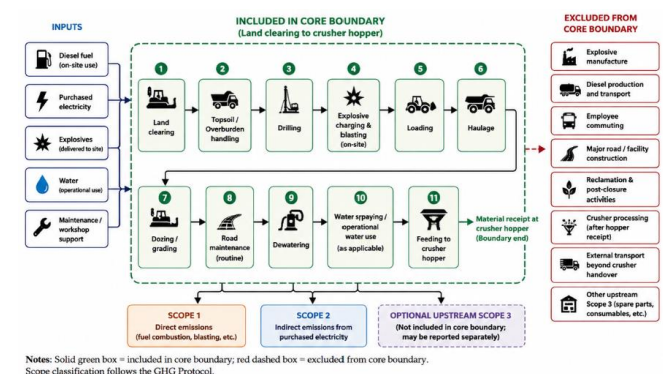


Figure 1 Proposed land-clearing-to-crusher-hopper system boundary for limestone-quarry carbon-cost assessment

2. METHOD

2.1. Review Protocol and Analytical Design

The review was structured using the Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) protocol (Paul et al., 2021), which organizes the review process into three sequential stages: assembling, arranging, and assessing. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., 2021) was used specifically as a reporting guideline to document study identification, duplicate checking, screening, eligibility assessment, exclusions, and final inclusion. The

corresponding study-selection process is presented in the PRISMA 2020 flow diagram (Figure 2).

The analytical design combined descriptive classification and thematic synthesis. The evidence was organized into three broad areas: (1) carbon-pricing policy design and effectiveness, (2) mining-related emissions and operational decarbonization, and (3) integration of carbon-related monetary values into mining economics and mine planning. Regulatory documents used to interpret the Indonesian carbon-policy context were treated as supplementary normative references and were not included in the peer-reviewed article dataset.

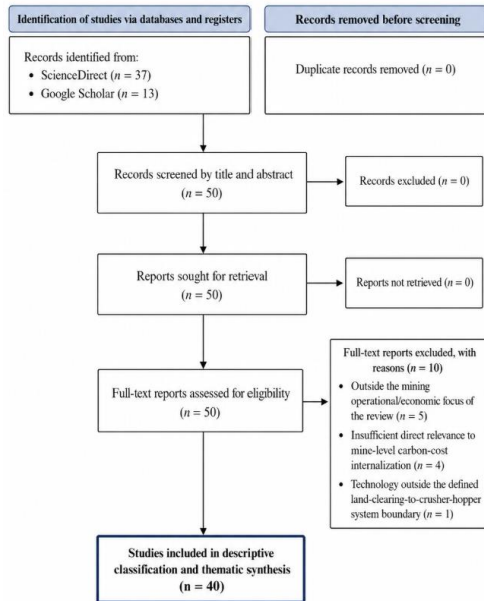


Figure 2 PRISMA 2020 flow diagram of study identification, screening, eligibility, and inclusion (search period : April – June 2026 ; final search date 17 June 2026)

2.2. Assembling: Information Sources, Search Strategy, and Identification

The literature search was conducted between April and June 2026, with the final search completed on 17 June 2026. ScienceDirect was used as the primary electronic literature source, while Google Scholar served as a supplementary source when successive searches increasingly retrieved studies that had already been identified.

A total of 50 peer-reviewed articles were identified during the search period. ScienceDirect contributed 37 articles, comprising six articles identified in April, ten in May, and twenty-one in June. Google Scholar contributed thirteen additional articles, comprising nine identified in May and four in June. Accordingly, six articles were identified in April, nineteen in May, and twenty-five in June.

A search strategy comprising of carbon-pricing, greenhouse-gas emissions, mining operations, economic evaluation and decarbonization terms was used. Core terms included “carbon price*”, “carbon cost*”, “carbon tax”, “emissions trading”, “internal carbon pric*”, and “shadow carbon price”, combined with mining-related terms such as “mining”, “mine”, “quarry”, “limestone”, “open pit”, and “mineral extraction”. These terms were further combined with

“operating cost”, “economic evaluation”, “mine planning”, “NPV”, “feasibility”, “emission*”, and “decarboni*”.

Searches were conducted iteratively across three complementary areas: (1) carbon pricing and mining; (2) mining-related emissions, operating costs, and mine planning; and (3) limestone or quarrying and land-use-related emissions. The final search date of 17 June 2026 was used as the literature cut-off date for this review.

2.3. Arranging: Duplicate Checking, Eligibility, and Study Selection

Retrieved articles were compiled in a structured screening record. Manual duplicate checking was carried out with the use of Microsoft Excel. The DOI of each article was recorded and cross-checked to identify identical publications, followed by verification of titles and other bibliographic information where necessary. No duplicate publications were identified among the 50 retrieved records. Duplicate checking was treated separately from relevance screening. Publications addressing similar topics were not considered duplicates solely because of thematic similarity; instead, their eligibility was evaluated against the predefined inclusion and exclusion criteria presented in Table 1.

All 50 records underwent title and abstract screening and were subsequently evaluated for methodological and substantive relevance. Full-text assessment considered the study objective, sector or commodity, system boundary, emission sources, carbon-pricing or carbon-cost treatment, economic outcomes, and relevance to the review questions. Ten articles were excluded after eligibility assessment. Five were outside the mining operational or economic focus of the review, four did not provide sufficiently direct evidence for mine-level carbon-cost internalization, and one examined a technology outside the defined land-clearing-to-crusher-hopper system boundary. The individual exclusion reasons are documented in the study-selection record. Forty peer-reviewed articles were retained for descriptive classification and thematic synthesis.

The primary screening and eligibility assessment were conducted by the first author. The second author did not perform an independent parallel screening but conducted a final review of the selected study set and the resulting synthesis. The selection procedure is therefore reported as a single-reviewer screening process with subsequent author verification rather than as independent dual-reviewer screening.

Eligibility was assessed using predefined criteria covering source type, topical and operational relevance, outcomes, system boundary, language, accessibility, and publication period (Table 1).

Table 1 Article-selection criteria

Aspect	Inclusion Criteria	Exclusion Criteria
Source type	Peer-reviewed journal articles reporting relevant methods or results.	Editorials, abstracts, promotional documents, and non-peer-reviewed sources.

Aspect	Inclusion Criteria	Exclusion Criteria
Topic	Carbon pricing, GHG emissions, carbon/environmental costs, mine planning, decarbonization, quarrying, or related mining-policy studies.	Studies without a direct link to mining emissions, carbon-cost exposure, or mining economics.
Operational relevance	Mining/quarry activities, energy use, land-use change, fleets, or technologies relevant to the study boundary.	Processes outside the defined boundary with no transferable relevance.
Outcome	CO ₂ e emissions, carbon cost, operating cost, NPV, productivity, mitigation, or investment effects.	Outcomes without an identifiable emissions–economic relationship.
System boundary	Emission sources, activities, or scopes can be identified.	Boundary or emission sources cannot be determined.

These criteria were applied during screening and eligibility assessment, with exclusion decisions summarized in the PRISMA 2020 flow diagram.

2.4. Assessing: Data Extraction, Coding, and Thematic Synthesis

For each included article, information was extracted and coded according to bibliographic identity, publication year, country or geographical context, mining sector or commodity, system boundary, greenhouse-gas emission scope, emission sources, emission-estimation method, carbon-pricing instrument or carbon-valuation approach, carbon-price scenario, economic-evaluation method, outcome indicators, uncertainty treatment, mitigation strategy, methodological limitations, and relevance to limestone quarrying.

Methodological quality was evaluated qualitatively with respect to the transparency of research objectives, data sources, system boundaries, assumptions, validation procedures, uncertainty treatment, and reproducibility. Descriptive classification was used to identify publication patterns, thematic concentrations, commodity representation, and methodological approaches. Thematic synthesis was subsequently used to compare mechanisms, quantitative findings, methodological limitations, and recurring evidence gaps across studies.

Particular attention was given to the distinction between studies that quantified GHG emissions and those that assigned a monetary value to those emissions. Commodity-level coding was also used to evaluate the representation of limestone and quarrying within the evidence base. Of the 40 studies retained for synthesis, eight (20%) specifically addressed limestone or quarrying contexts; however, none of these eight directly incorporated a carbon price, shadow carbon price, or equivalent monetary valuation of GHG emissions into

activity-level quarry operating costs. These patterns were used to identify the evidence gaps underpinning the proposed research agenda rather than relying on publication frequency alone

3. RESULTS AND DISCUSSION

3.1. Descriptive Profile of the Included Studies

The final dataset comprises 40 articles published between 2016 and 2026. Thirty-five articles (87.5%) were published during 2023–2026, with the highest representation in 2025 ($n = 12$), followed by 2024 ($n = 11$). This concentration indicates that recent publications are strongly represented in the reviewed dataset. However, the pattern should not be interpreted as a definitive temporal trend for the wider field because it may partly reflect the selected information sources, search terms, search period, and screening procedure. Accordingly, the publication-year distribution is reported descriptively rather than as evidence of the growth rate of the research field.

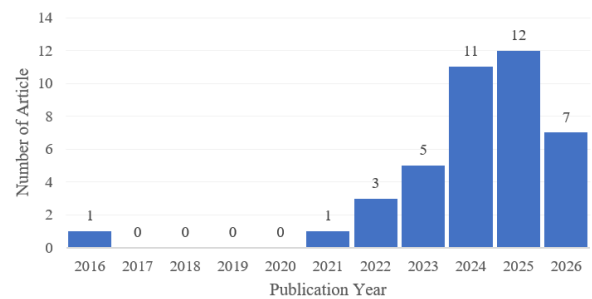


Figure 3 Distribution of Articles by Publication Year

Thematic coding identified several clusters across the 40 included studies. The cluster labelled “Cost Internalization and Mine Planning” includes studies addressing carbon-related economic evaluation, environmental-cost integration, mine planning, and related decision models. Membership in this broader cluster does not imply that every study directly monetized GHG emissions. Within this group, five studies provided the most direct evidence of incorporating carbon or environmental monetary values into mine-economic or planning models. The distinction between broad thematic membership and direct carbon-cost integration is maintained throughout the synthesis.

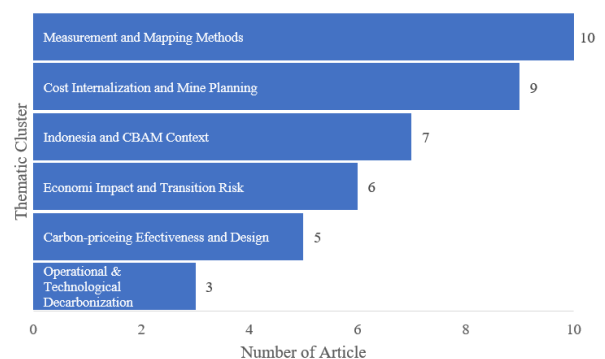


Figure 4 Distribution of Articles by Thematic Cluster

The included studies employed a diverse range of methodological approaches. Modeling and simulation were frequently used, including system dynamics, computable general equilibrium (CGE), TIMES, LEAP, discrete-event simulation, mixed-integer programming, and real-options analysis. Empirical and econometric research provided evidence on implemented carbon-pricing policies. Review and synthesis research mapped technological, policy and corporate responses. This methodological diversity broadens the range of evidence considered in the review but also limits direct comparison across studies because the units of analysis, assumptions, and system boundaries differ.

3.2. Effectiveness and Design of Carbon Pricing

The literature provides only limited consensus on the most effective instrument. Ahmad et al. (2024) find that both carbon taxes and ETS reduce emissions but carbon taxes have a stronger average effect. However, the results from macro-level analyzes can not be directly extrapolated to individual mine sites. Their relevance at the operational level depends on several site-specific factors, including the carbon price, the scope of emissions covered, opportunities for energy substitution, institutional conditions, and the availability of suitable technologies.

Ex post studies report heterogeneous effects across jurisdictions. Pretis (2022) found reductions in transportation emissions in British Columbia without a similarly large change in aggregate emissions, whereas Mideksa (2024) found stronger effects in Finland. The evidence from Mexico, Colombia and Argentina is also mixed. These outcomes are not directly comparable because the studies differ in policy design, sectoral coverage, exemptions, implementation periods, enforcement conditions, energy structures, and broader macroeconomic settings. Carbon-tax rates therefore represent only one component of the observed policy effect and should not be interpreted as the sole explanation for cross-country differences.

Evidence from the European Union Emissions Trading System (EU ETS) indicates that reducing emissions does not necessarily lead to lower profitability or job losses. Dechezleprêtre et al. (2023) find that the scheme reduced emissions by about 10% in the first phase of the scheme's implementation, with no significant negative effects on firm performance. However, Ma et al. (2024) found that an ETS can increase labor costs by changing skill requirements. Carbon internalization may therefore appear not only as a cost per tonne of CO₂e but also as organizational, data-management, specialist-labor, and process-change costs.

How revenues from carbon are used also influences policy acceptance and outcomes. Carl and Fedor (2016) find that the use of carbon-pricing revenues varies across instruments and jurisdictions, including green expenditure, taxpayer transfers and general government revenue. In a mining context these findings suggest rather than demonstrate that revenue recycling could potentially support low-carbon capital investment or transition measures. Thus, this type of application must be taken as an author inference, which requires an assessment by the particular sector, and not as a conclusion established by the mining studies reviewed.

The broader carbon pricing literature addresses the effectiveness of instruments in relation to tax or allowance

design, revenue recycling, distributional effects, corporate responses and complementary environmental policies (Ahmad et al., 2024; Carl & Fedor, 2016; Coelho Junior & Pereda, 2026; Dechezleprêtre et al., 2023; Faeni et al., 2026; Le Moigne et al., 2026; Ma et al., 2024; Mideksa, 2024; Nesje et al., 2025; Nobanee & Ullah, 2023; Pretis, 2022; Wang et al., 2024). The studies suggest treating the carbon price as a policy option and not as a constant that can be transferred universally.

3.3. Emission Sources and Operational Decarbonization in Mining

Mining-technology reviews identify drilling, blasting, loading, haulage, auxiliary equipment, conveying, crushing, and beneficiation as emission sources. Within a land-clearing-to-crusher-hopper boundary, the most relevant sources are land clearing, topsoil or overburden movement, fuel consumed by drills, explosives, loading equipment, haul trucks, graders, dozers, water trucks, pumps, and generators, together with electricity used by pit facilities. Haulage emissions are often dominant, but this must be verified with site data because haul distance, road grade, payload, idle time, and crusher location are decisive.

Huo et al. (2023) showed that the reinforcement learning based dispatching can reduce the emissions of haulage by more than 30% at the same production level. Their follow-up study shows that smart dispatching can be a cheaper short-term strategy than fleet electrification or carbon capture and storage (CCS). The results support the view that the emissions baseline has to be set according to the actual performance of the system and not only the rated fuel consumption of the individual machines.

In some scenarios, battery-electric trucks could reduce emissions substantially, according to Tokac et al. (2025). Electrification may nevertheless shift emissions from Scope 1 to Scope 2 when electricity remains carbon intensive. Comparisons between diesel and electric fleets must therefore use consistent boundaries, including charging-station demand, charging efficiency, and the grid emission factor.

Explosives-related emissions and land-use change receive less attention. Nong et al. (2021) emphasize the importance of including non-CO₂ GHGs. In Indonesia, the regulations specify activity data and emission factors and recognize energy, industrial processes and land use as relevant sectors. This allows the development of an inventory structure that distinguishes recurring operational emissions from changes in carbon stock due to new clearings.

The operational evidence base also comprises emissions-estimation methods, fleet-energy reviews, dispatch models, technology comparisons, and activity-level inventories (Al Nuaimi et al., 2025; Huo et al., 2023, 2024; Mesa et al., 2025; Nong et al., 2021; Onifade et al., 2024; Tokac et al., 2025). Together these studies support the use of measured activity data and equipment-specific operating parameters in addition to generic production coefficients.

3.4. Integrating Carbon Cost into Mining Economics

Five studies provide the core evidence for evaluating cost-internalization mechanisms in mining. Table 4 summarizes the most relevant quantitative findings.

Rijdsijk and Nehring (2022) provide direct evidence that cost increases are not uniform across the project cost structure. For them, mining costs were more sensitive than processing costs, but dependence on electricity drove the longer-term outcome. The work of Agosti et al. (2023) and Mirzehi and Moradi Afrapoli (2024) demonstrate that the cost of carbon should not be simply added after the mine plan is finalized. Carbon cost in block values or objective function can influence mining sequences, tonnage, and NPV risk.

Activity-based costing is a feasible approach to integrate emissions into the cost analysis for an active limestone quarry. Costs and emissions are first estimated for each stage of the operation and then combined to determine the overall unit mining cost. This approach is better suited to limestone quarrying than cut-off-grade optimization, as operational decisions are generally driven by raw-material quality, blending requirements, equipment productivity, haul distance, and the specifications of material delivered to the crusher.

The five studies providing the most direct mine-economic evidence were those that directly linked monetized environmental or carbon-related effects to mine planning, operating costs, project value, or production decisions: Agosti et al. (2023), Badakhshan et al. (2023), Mirzehi and Moradi Afrapoli (2024), Rijdsijk and Nehring (2022), and Ulrich et al. (2022). This narrower set should be distinguished from a broader thematic cluster on cost internalization and mine planning which also contains studies with indirect or conceptual economic relevance. For analytical clarity, the framework separates gross carbon valuation from compliance-related adjustments and mitigation expenditure. Gross carbon valuation is calculated as assessed emissions multiplied by the selected carbon value. Where applicable, compliance exposure may then be adjusted for eligible allowances or offsets and supplemented by MRV and transaction costs. Mitigation expenditure is reported separately because it represents an investment or operating response intended to reduce future emissions rather than a direct component of the carbon-price liability itself.

Table 2 Key Quantitative Findings from Mining Studies

Study	Object	Scenario/ Approach	Main finding
(Ulrich et al., 2022)	Cross-country gold mining	USD 50 and USD 100/tCO ₂ e	The financial impact of carbon pricing can vary considerably depending on the emissions intensity of the operation and the composition of its energy supply. For this reason, carbon cost per unit of production provides a useful indicator for comparing the effects across different mining operations or operating scenarios.

Study	Object	Scenario/ Approach	Main finding
(Rijdsijk & Nehring, 2022)	Copper-cobalt mine; Scopes 1-2	USD 30 and USD 100/tCO ₂ e	Mining cost increased by approximately 2% at USD 30/t and 5% at USD 100/t; power-source changes may have a larger effect than the carbon rate.
(Agosti et al., 2023)	Ultimate-pit-limit optimization	Carbon tax incorporated into block value	Carbon pricing affects NPV, economic tonnage, and emissions; slope-profile optimization can improve the economic-environmental trade-off.
(Mirzehi & Moradi Afrapoli, 2024)	Open-pit iron ore; drilling to crushing	USD 15-60/tCO ₂ e	The environmental-cost-minimization scenario reduced emissions by approximately 10% with an adjusted-NPV reduction of about 4%.
(Badakhs han et al., 2023)	Open pit and block caving	Monetization of environmental cost per tonne	Externalities can be expressed as unit costs, but the value must not be equated with carbon cost because it includes non-carbon impacts.

3.5. Decarbonization Technologies and Decision Thresholds

Mitigation strategies can be divided into: operational efficiency, electrification, fuel switching, renewable energy, changes in material handling systems, carbon capture and offsets. Equipment idle time can be reduced, haul roads can be better maintained, dispatch systems can be optimized, payload utilization can be increased, and fleet size can be affected by actual production requirements. These measures generally require less capital than large-scale technology replacement and can often be implemented as initial steps in the decarbonization process.

Electrification can reduce Scope 1 emissions, but the total cost of ownership and the emission factors of electricity must be analyzed. Biodiesel provides a transition path for existing diesel equipment, but life-cycle reductions depend on feedstock, blending level, and policy. Renewable energy is more directly applicable to pumps, workshops, lighting, conveyors and charging loads. CCS is less relevant for quarry emissions as the main sources are mobile rather than concentrated stacks.

Yu et al. (2024) show that the preferred decarbonization pathway may change as carbon prices, available budgets and forecasted technology costs change. Future studies should therefore not only estimate the financial burden associated with emissions. They also need to know at what level of

carbon price it becomes more profitable to invest in a mitigation measure than to continue to pay carbon costs. This threshold can be defined as the switching price of carbon or the carbon price at break-even.

The wider technology literature discusses biodiesel pathways, renewable-energy integration, supply-chain decarbonization, socio-environmental trade-offs, and staged fleet transitions (Chen et al., 2026; Enemuo & Ogunmodimu, 2025; Islami et al., 2025; Negrete et al., 2024; Yu et al., 2024). These results suggest the need to balance short-term operational improvements with longer-term capital intensive technology replacement. Such comparison makes it possible to see which measures bring instant emission savings and which ones are more expensive but bring bigger long term savings.

3.6. Carbon Economic Value and CBAM in Indonesia

Power sector models show that higher carbon prices can generate larger emission reductions but additional investment is necessary (Sunanda et al., 2025b). Indonesian system-dynamics modeling also indicates that a rate of IDR 30/kg CO₂e works gradually and must be accompanied by energy-structure transformation and green investment (Rokhmawati et al., 2024).

The four regulations reviewed complete a policy chain. Indonesia has established the legal basis for carbon taxation through Law No. 7 of 2021 (Republic of Indonesia, 2021). Republic of Indonesia (2025), Presidential Regulation No. 110 of 2025 on Nationally Determined Contribution (NDC), carbon allocation, inventories, carbon economic value instruments, registries, and greenhouse-gas control. The technical rules concerning emissions trading, offsets, MRV, and carbon certificates are included in the Minister of Environment and Forestry Regulation No. 21 of 2022, provided that the provisions of this regulation do not contradict the newer Presidential Regulation (Republic of Indonesia, 2022). The trading of carbon units through the carbon exchange is governed by Financial Services Authority Regulation Number 14 of 2023, as amended by Financial Services Authority Regulation Number 10 of 2026.

CBAM does not create a direct carbon-tax obligation for an upstream limestone quarry solely because it supplies raw material to cement production. Its relevance is primarily indirect. First, CBAM obligations are in respect of covered imported products and embedded emissions under the relevant regulatory framework. Second, downstream cement producers may require more granular data on upstream emissions to support embedded-emissions calculations and product-level reporting. Third, customers can incorporate data or decarbonization requirements through procurement or supply-chain policies. Consequently, quarry operators may face indirect commercial pressure to quantify and reduce emissions even where no direct CBAM liability applies at the quarry level.

The Indonesian and transition-policy literature further addresses CBAM exposure, carbon-tax scenarios, political-economy constraints, critical-mineral demand, green finance, energy security, and integrated carbon-market mechanisms (Do et al., 2026; Dong et al., 2025; D'Orazio, 2024; Fan et al., 2026; Firdausy et al., 2025; Massagony et al., 2025; Rokhmawati et al., 2024; Sunanda et al., 2025a, 2025b; Yang

et al., 2026; Ye & Chen, 2025). Although these studies are not quarry-cost models, they define the institutional and economic conditions under which shadow carbon pricing becomes relevant.

3.7. Main Synthesis

Findings across the studies support one principal conclusion: the economic effect of carbon internalization results from the interaction between the carbon price and emission intensity, rather than from price alone. Emission intensity is shaped by technology, energy mix, productivity, mine geometry and haul distance, material characteristics, and system boundaries. Emission benchmarks from other mines are therefore suitable only for comparison, not as substitutes for site-specific data.

The literature also distinguishes accounting effects from behavioral effects. In the short term, a shadow carbon price adds a cost to baseline emissions without changing operations. Over medium and long horizons, firms may respond through efficiency improvements, fuel switching, electrification, renewable energy, or offsets. The empirical model should separate these two stages to avoid assuming that a tax automatically reduces emissions.

For an operating mine, the cost baseline should be developed from actual operating expenditure or normalized cost data for each activity. Historical costs need to be adjusted to the selected analysis period and classified according to their sensitivity to emissions-related changes. Fuel and electricity consumption are directly linked to emissions, whereas the effects on labor, maintenance, monitoring, reporting, and verification (MRV), external verification, and data-management systems are generally indirect.

Including land clearing broadens the novelty of the study but also increases the risk of double counting. A loss of carbon stock must not be counted simultaneously as a land-use-change emission and as foregone future sequestration unless a clearly defined methodology is used. Reclamation activities cannot automatically be treated as carbon offsets. Their recognition requires a clearly defined baseline, evidence of additionality, assurance that the carbon benefits are permanent, a reliable monitoring, reporting, and verification (MRV) system, and certification under an applicable carbon standard.

3.8. Model Suitability for Limestone Quarries

Activity-based carbon costing appears well suited to the proposed operational boundary because it enables emissions and costs to be assigned consistently to individual quarry activities. The review does not establish its superiority over alternative costing or life-cycle frameworks through formal multi-criteria comparison; rather, its suitability derives from its compatibility with activity-level operating data and the land-clearing-to-crusher-hopper boundary. Each activity is assigned activity data, emission factors, CO₂e emissions, baseline cost, and carbon cost. Results are then expressed per tonne of limestone delivered to the crusher hopper. This structure enables hotspot identification, scenario comparison, and sensitivity analysis.

The primary denominator for the carbon-adjusted unit mining cost is the tonnage of limestone received at the crusher

hopper because it represents the process-relevant product output. Emissions from topsoil removal, waste stripping, or overburden handling, where such activities occur, should nevertheless remain included in the numerator because they are required to access the limestone resource. Their contribution should also be reported separately through activity-level emissions and, where relevant, supplementary indicators such as tCO₂e per total material moved or stripping-ratio-adjusted metrics. In quarry settings where no overburden is present, the framework should be applied only to the relevant site-specific activities, such as topsoil removal followed directly by limestone extraction.

Carbon-value scenarios should be defined by their economic role and source rather than by qualitative labels alone. The scenario set should distinguish: (1) a zero-price baseline; (2) a regulation-referenced shadow-price scenario; (3) an observed domestic carbon-market price reported with the instrument and observation date; and (4) hypothetical stress-test scenarios derived from explicitly cited external benchmarks. For each scenario, the analysis should report the nominal or real price basis, currency and exchange-rate assumption, base year, inflation treatment, escalation rate where applicable, market instrument, observation date, and source.

At a minimum, sensitivity analysis should cover the carbon price, diesel consumption, haul distance, payload, production, cleared area, initial carbon stock, electricity emission factor, and mitigation efficiency. Fuel price must be separated from

carbon price because the two may change independently. Their interaction is important to avoid attributing excessive explanatory power to carbon pricing alone.

3.9. Future Research Agenda

The research agenda follows the sequence: dominant finding → limitation → scientific consequence → research design. Table 3 presents research priorities that directly support future empirical studies of limestone mining.

The Indonesian context strengthens the relevance of this issue. Law of the Republic of Indonesia No. 7 of 2021 provides the legal basis for a carbon tax and establishes a minimum rate of IDR 30/kg CO₂e when the market carbon price is below that level. Presidential Regulation No. 110 of 2025 includes carbon allocations, emissions inventories, quotas, carbon trading, offset mechanisms, carbon levies, registry systems, and measurement, reporting, and verification (MRV) requirements in the scope of Indonesia's carbon economic value framework.

However, no operational sector-specific carbon-tax base, emissions quota or levy mechanism for limestone mining. Therefore, in the subsequent empirical analysis, the monetary value attributed to emissions should be considered a shadow carbon price for the purposes of internalization and scenario analysis, rather than an actual tax liability to be paid by the quarry operator.

Table 3 Literature gaps and future research agenda

Gap	Evidence	Scientific Consequence	Research Agenda
Sectoral	8/40 studies addressed limestone/quarrying; 0/8 directly monetized GHG emissions at quarry-cost level	Limited transferability of metal-mine carbon-cost models	Test activity-level carbon costing in operating limestone quarry
Boundary	Reviewed studies use pit-only, mine-to-mill, or cradle-to-gate boundaries	Unit cost and intensity estimates are not directly comparable	Apply explicit land-clearing-to-crusher-hopper boundary
Land use	Land-clearing and operational emissions are generally treated separately	Potential underestimation or double counting	Report inventory recognition and production-normalized indicators separately
Price	Studies use heterogeneous/static carbon values	Scenario results lack comparability	Define regulation-, market-, and stress-test scenarios transparently
Cost	Few studies integrate site operating cost with emissions	Limited evidence on unit-cost exposure	Combine activity data, CO ₂ e, baseline cost, and carbon valuation
Uncertainty	Sensitivity often emphasizes carbon price	Operational uncertainty remains under-characterized	Test diesel use, haul distance, payload, electricity factor, cleared area, carbon stock
Decision	Studies quantify impacts but rarely switching thresholds	Limited support for mitigation timing	Estimate break-even/switching carbon price
Policy	No quarry-specific liability established in reviewed Indonesian context	Regulatory values cannot be treated as actual liability	Separate legal obligations, market values, shadow prices, and stress tests

4. CONCLUSION

The literature suggests that carbon pricing has evolved from a macro-level policy instrument to a techno-economic

variable in mine planning and operations. The cost impacts are not only dependent on the carbon price but on emission intensity, energy mix, equipment productivity, haul distance, system boundaries and mitigation capability. Quantitative evidence from the metal mine sector reveals that the effect of

higher mining costs is relatively limited at low to medium prices but becomes larger in high-emission operations or where energy supply becomes more carbon intensive.

A key gap identified in the reviewed evidence is the limited integration of land-clearing emissions, operational emissions, and site-specific costs within limestone quarrying. Future research should apply activity-based carbon costing, disaggregate emissions from Scope 1, Scope 2, and land-use change, and evaluate results across a range of shadow carbon-price scenarios. Key outputs should include emissions intensity, carbon cost per tonne of production, percentage increase in mining costs, activities most strongly contributing to emissions, critical carbon-price threshold and points at which alternative mitigation measures become economically preferable.

As of the regulatory cut-off date used in this review (August 10th 2026), no quarry-specific carbon-tax obligation, emissions quota, or payment mechanism was identified for limestone mining within the Indonesian regulatory sources examined. Accordingly, the carbon values used in the proposed framework are treated as analytical shadow-price scenarios rather than as calculations of an existing quarry-specific legal liability. The right way to frame this is a carbon cost exposure and shadow price internalization analysis, with a minimum scenario of IDR 30,000/tCO₂e, a domestic market-price scenario and stress tests. The framework provides a solid analytical basis for the proposed empirical thesis and indicates a clear direction for future research on the development of carbon-pricing policies in the mining sector.

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