



ASMES - 2025

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Decarbonizing Vietnam's Open-Pit Coal Mining: A Life Cycle Case Study of Emissions and Mitigation Pathways

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ABSTRACT

Open-pit coal mining represents one of the most carbon-intensive activities in Vietnam's extractive industries, primarily due to diesel combustion in haulage fleets and fugitive methane emissions. This paper provides the first systematic Life Cycle Assessment (LCA) of greenhouse gas (GHG) emissions across five representative Vietnamese open-pit mines (Cao Son, Deo Nai-Coc Sau, Ha Tu, Na Duong, and Khanh Hoa), following the IPCC guidelines. Results indicate emission intensities ranging from 17 to 40 kg CO₂e per ton of coal, with haulage and methane contributing 40–50% and 30–45% of total emissions, respectively. Building on this baseline, we propose a three-pillar decarbonization framework: (i) energy efficiency optimization, (ii) fleet electrification with renewable integration, and (iii) methane capture and utilization. Scenario analysis suggests that integrated deployment could reduce sectoral emissions by 40–50% by 2030 and up to 70–80% by 2040, while generating co-benefits in fuel cost savings, energy self-sufficiency, and carbon credit potential. The findings provide critical insights for designing a low-carbon roadmap for Vietnam's coal sector and highlight future research needs in methane measurement, pilot technology demonstrations, and cross-sectoral integration to align with the national net-zero commitment by 2050.

Keywords: open-pit coal mining; greenhouse gas emissions; LCA; decarbonization; Vietnam; methane management; electrification.

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1. Introduction

The mining industry is among the most energy-intensive sectors globally, responsible for approximately 38% of industrial energy consumption and 15% of global electricity use (T. Igogo, et al, 2021). With rising demand for minerals and the steady decline of high-grade ores, energy consumption in the sector is projected to increase sharply—by about 36% by 2035 and potentially by 50% by 2050 (H. Abbaspour, 2022). Beyond its energy footprint, the industry contributes significantly to greenhouse gas (GHG) emissions, with estimates suggesting that mining activities account for 2–3% of total global CO₂ emissions (H. Legge, et al, 2021). This underscores the industry's crucial role in advancing global decarbonization efforts. Yet, fossil fuels continue to dominate its energy mix, with coal and oil making up around 62% of energy consumption, thereby sustaining high GHG emission levels (T. Norgate, N. Haque, 2010).

Within this broader context, open-pit coal mining epitomizes the scale and intensity of fossil resource exploitation. Characterized by fleets of heavy-duty haul trucks and large excavators, such operations generate substantial emissions through diesel combustion as well as fugitive methane released from coal seams. These emission “hot spots” place surface coal mining among the most carbon-intensive subsectors of global mining. Vietnam provides a salient case: while coal extraction remains central to national energy security, the sector faces mounting pressure to align with the government's 2021 pledge of achieving net-zero emissions by 2050 under the Paris Agreement. Delivering on this commitment requires targeted mitigation measures in mining, with a particular emphasis on curbing diesel-related CO₂ and methane leakage in open-pit operations.

This study examines GHG emissions from five representative open-pit coal mines in Vietnam—Cao Son, Deo Nai-Coc Sau, Ha Tu, Na Duong, and Khanh Hoa. Together, these operations represent a substantial share of national open-pit coal output, while also reflecting diverse geological conditions and equipment fleets. To quantify emissions, we integrate the Life Cycle Assessment (LCA) framework with the Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories. This approach enables the calculation of carbon dioxide equivalents (CO₂e) across major operational stages, namely drilling and blasting, loading, hauling, and auxiliary activities.

Based on these assessments, the paper advances a tripartite strategic framework for decarbonizing Vietnam's open-pit coal mines: (i) improving energy efficiency, (ii) electrifying equipment and incorporating renewable energy sources, and (iii) managing and utilizing coal mine methane (CMM). The potential emission reductions, investment requirements, and co-benefits of each strategy are evaluated. The analysis also considers how these strategies could be extended to other mining contexts—such as metal open-pit mines or underground operations—thereby informing a broader national pathway toward decarbonization in the extractive industries.

The paper proceeds as follows. The next section reviews the theoretical background and existing literature on GHG emissions in mining and current decarbonization strategies globally. The methodology section outlines the LCA-IPCC model employed and the data inputs specific to Vietnamese open-pit mines. Results and discussion present detailed estimates of CO₂e emissions across the selected mines, followed by a comparative evaluation

of the proposed strategies. Finally, the conclusion summarizes key findings and identifies directions for future research.

2. Literature Review

Recent studies highlight a growing trend among coal mining operations to integrate on-site renewable energy—such as solar photovoltaic (PV) and wind power—both to curb GHG emissions and to lower operational costs (Li, X., et al, 2024), (Dalvi, A. D., 2022). This shift aligns with global priorities that emphasize low-carbon energy sources and reduced dependence on coal.

A major strategic pathway identified in the literature is the electrification of heavy-duty mining fleets. Bao, H., et al. argued that prioritizing the electrification of large-scale mining equipment is fundamental to realizing the concept of an “all-electric mine,” free from direct fossil-fuel emissions (Bao, H., et al, 2023). Supporting this perspective, Biniaris et al. (2025) report that implementing trolley-assist systems in haulage operations can reduce CO₂ emissions by approximately 54–62% per ton of material moved when compared with conventional diesel-based haul cycles (Biniaris et al., 2025). Battery-electric haul trucks and hybrid solutions are also receiving increasing attention, though their current limitations in power density and charging infrastructure pose practical challenges.

Operational optimization constitutes another critical mitigation avenue. Improved dispatch scheduling of haul trucks, optimized crusher configurations, and other process refinements have been shown to enhance energy efficiency while lowering emissions (Biniaris et al., 2025). Nonetheless, several barriers remain. High capital requirements and the need for new energy infrastructure constrain rapid deployment, while battery technologies have yet to meet the heavy-duty requirements of ultra-class trucks (Bao, H., et al, 2023). Moreover, incomplete emissions data and the absence of consistent regulatory frameworks complicate the evaluation and benchmarking of decarbonization performance (Dalvi, A. D., 2022).

As emphasized in recent policy-oriented studies, the success of such interventions will depend not only on technological innovation but also on enabling environments that include supportive policies, targeted incentives, and coordinated investment (Li, X., et al, 2024), (Azadi, M., et al, 2020).

3. Methodology

3.1. Theoretical Basis and Rationale

Open-pit coal mining is energy- and material-intensive, with GHG emissions arising primarily from four sources: (i) diesel combustion in mobile and stationary equipment (drills, shovels, haul trucks, dozers), (ii) electricity consumption for electrically driven equipment and dewatering pumps, (iii) explosives detonation during drilling and blasting, and (iv) fugitive coal mine methane (CMM) released from coal seams during overburden removal and extraction. Prior evidence shows the mining sector accounts for ~2.7% of global energy use and ~10% of energy-related GHGs (Azadi, M., et al., 2020). Case studies indicate that, where seam gas content is appreciable, methane and diesel together dominate emissions—for example, at Pingshuo (China), CH₄ and diesel were ~46.7% and ~41.8% of

total mine emissions, respectively; similar patterns are reported in India (Bellois, G., 2022). Conversely, in low-gas settings, fuel and power consumption become the principal drivers.

Equipment configuration and production routing materially influence emission intensity. Fuel can represent ~30–32% of total energy inputs at open-pit sites (ICMM reports), reflecting the large duty cycles of haulage fleets (Figueiredo et al., 2023). Although each blast contributes a relatively small increment, annual explosives-related emissions can be non-negligible. Electricity-related emissions depend on grid intensity; for Vietnam's grid we adopt 0.6592 t CO₂/MWh (MONRE, 2024). Given the GWP₁₀₀ of CH₄ ≈ 25, even modest methane leakage materially elevates CO₂e. Consistent with IPCC classification, on-site methane is a Scope 1 source (Change, O. C., 2007).

Methodologically, we apply Life Cycle Assessment (LCA) to the mine-gate boundary (extraction and on-site handling to the mine gate). Downstream logistics, coal washing, and combustion are excluded (Scope 3) (Eggleston, H. S., et al, 2006). LCA enables consistent accounting of Scope 1 (diesel, CMM, explosives) and Scope 2 (grid electricity), with optional inclusion of upstream embodied emissions where data permit. Prior LCA studies in mining (Northey, Haque, & Mudd, 2013) demonstrate the utility of this approach to identify “hot spots” and benchmark emission intensities.

3.2. Study Sites and Data Sources

This study focuses on five representative open-pit coal mines in northern Vietnam: Cao Son (annual output ~4.5 Mt), Deo Nai–Coc Sau (combined output ~2.7 Mt), Ha Tu (~2.5 Mt), Na Duong (~1.2 Mt, lignite production for power generation), and Khanh Hoa (~0.4 Mt). The Quang Ninh mines (Cao Son, Deo Nai, Coc Sau, Ha Tu, and Khanh Hoa) primarily exploit anthracite under complex geological conditions, with high stripping ratios of 15–25 m³ of overburden per ton of coal. Na Duong, in contrast, produces lignite with lower stripping ratios of approximately 10–13 m³/ton.

The equipment fleets reflect the large scale and intensity of these operations, comprising dozens of large-diameter drills (127–250 mm), hydraulic shovels with bucket capacities of 5–12 m³, and truck fleets ranging from 20 to 100 tons in payload. For instance, Cao Son currently operates around 150 trucks, including 69 trucks in the 90–100 t class and 63 trucks of 55–60 t capacity. Ha Tu employs approximately 28 trucks at 91 t and 25 trucks at 55 t. These figures underscore the dominance of heavy-duty diesel-powered machinery, providing the baseline for emission quantification.

3.3. Emission Accounting Framework

We constructed an annual GHG emission model for each mine, adopting a Life Cycle Assessment (LCA) approach aligned with the Intergovernmental Panel on Climate Change (IPCC) guidelines (Change, O. C., 2007), (Eggleston, H. S., et al, 2006). The system boundary was restricted to mining operations up to the point of coal delivery at the mine gate. Downstream processes, such as coal washing or combustion in power plants, were excluded (Scope 3). Both direct emissions from on-site fuel combustion and methane release (Scope 1), and indirect emissions from electricity consumption (Scope 2), were incorporated.

The general formulation is expressed as:

$$E_{CO_2e,mine} = \sum_k (M_k \cdot EF_k) \quad (1)$$

Where:

- $E_{CO_2e, mine}$: Total greenhouse gas (GHG) emissions of a mine, expressed in CO₂ equivalent (t CO₂e/year).
- M_k : The activity data or amount of energy/material consumed from source k (e.g., liters of diesel, MWh of electricity, tons of explosives, or cubic meters of methane released).
- EF_k : The emission factor associated with source k, representing the average GHG emitted per unit of activity (e.g., kg CO₂e per liter diesel, t CO₂e per MWh electricity, t CO₂e per ton explosives, kg CO₂e per cubic meter of CH₄).
- $\sum_k$: The summation over all major emission sources considered in the system boundary of the mine (diesel combustion, electricity use, explosives detonation, methane release).

3.4. Sources of Emissions

3.4.1. Diesel Consumption

Emissions from diesel combustion were estimated for each major equipment category (drills, excavators, haul trucks, bulldozers, and auxiliary generators). Fuel use was derived from equipment inventories, rated capacities, annual operating hours, and average consumption rates. For instance, a Caterpillar 777 haul truck (~96 t payload) consumes approximately 50–60 liters per hour, or ~1.5 liters per km depending on terrain, while a Komatsu PC1250 hydraulic excavator (~7 m³ bucket) consumes ~40 liters per hour. Total annual diesel consumption was then multiplied by the IPCC default emission factor of 2.68 kg CO₂ per liter (equivalent to 3.16 kg CO₂/kg of diesel, given a density of 0.84 kg/L). Trace emissions of CH₄ and N₂O from diesel combustion were included following IPCC defaults, though their CO₂e contribution is marginal (<1%).

3.4.2. Electricity Use

Some mines employ electrically powered equipment, including cable shovels (e.g., EKG 5 m³ and 8 m³ units), electric drills, and dewatering pumps. Electricity demand was calculated from equipment power ratings and operating hours, converted into annual consumption (MWh/year). Emissions were then estimated using Vietnam's grid emission factor of 0.6592 t CO₂/MWh (Ministry of Natural Resources and Environment, 2023). For example, a 250 kW electric drill operating 2,000 hours per year consumes ~0.5 GWh, resulting in ~336 t CO₂e annually.

3.4.3. Explosives

Emissions from blasting were calculated based on the consumption of ANFO (ammonium nitrate–fuel oil). Each ton of ANFO is estimated to release ~0.3 t CO₂e during detonation, primarily from CO₂ and N₂O formation. For instance, a mine consuming 1,000 t of ANFO annually would emit ~300 t CO₂e. While relatively minor compared to diesel and methane, explosives remain a necessary component of the emissions inventory.

3.4.4. Coal Mine Methane (CMM)

Methane release was estimated using emission factors per ton of coal extracted, due to the lack of site-specific measurements. Based on international data, default values were assigned: ~1 m³ CH₄/t for Cao Son, Deo Nai, and Ha Tu; 0.8 m³/t for Coc Sau (linked with Deo Nai); 0.5 m³/t for Na Duong; and 1.2 m³/t for Khanh Hoa. With a global warming potential (GWP100) of 25, this corresponds to ~16.7 kg CO₂e per cubic meter of CH₄.

Accordingly, methane contributes between ~8 and 17 kg CO₂e per ton of coal depending on mine conditions. Methane emissions were accounted for as continuous Scope 1 emissions, not assigned to any specific operational stage.

3.5. Emission Formulas for Key Stages

To quantify greenhouse-gas (GHG) emissions from open-pit mining operations, individual processes are disaggregated and assigned activity-based emission factors. Two critical stages—drilling & blasting and haulage—are highlighted below as representative “hot spots” of emissions within the mining life cycle.

3.5.1. Drilling and Blasting

$$E_{\text{drilling+blasting}} = M_{\text{diesel,drilling}} \cdot EF_{\text{diesel}} + M_{\text{electricity,drilling}} \cdot EF_{\text{electricity}} + M_{\text{explosives}} \cdot EF_{\text{explosives}} \quad (2)$$

In which:

- $E_{\text{drilling+blasting}}$: Total greenhouse gas (GHG) emissions (in CO₂ equivalent) from drilling and blasting per year (unit: t CO₂e/year).
- $M_{\text{diesel,drilling}}$: Diesel consumption for drilling machines (unit: liters/year or kg/year).
- EF_{diesel} : Emission factor of diesel fuel (kg CO₂e/liter or kg CO₂e/kg). According to IPCC, ≈ 2.68 kg CO₂e per liter of diesel.
- $M_{\text{electricity,drilling}}$: Electricity consumption for electric drills (unit: MWh/year).
- $EF_{\text{electricity}}$: Emission factor of the electricity grid (t CO₂e/MWh). In Vietnam ≈ 0.6592 t CO₂e/MWh.
- $M_{\text{explosives}}$: Amount of explosives consumed (unit: tons/year).
- $EF_{\text{explosives}}$: Emission factor of explosives (t CO₂e/ton). For ANFO, ≈ 0.3 t CO₂e per ton of explosives.

3.5.2. Haulage

$$E_{\text{haulage}} = \sum_{i=1}^{N_{\text{vehicle types}}} (N_{\text{vehicles},i} \cdot FC_i \cdot EF_{\text{diesel}}) \quad (3)$$

Where:

- E_{haulage} : Total greenhouse gas (GHG) emissions (in CO₂ equivalent) from the transportation stage in the open-pit mine (unit: t CO₂e/year).
- i : Index for each vehicle type (e.g., 55-ton trucks, 100-ton trucks).
- $N_{\text{vehicle types}}$: The number of different categories of haul trucks used in the mine.
- $N_{\text{vehicles},i}$: The number of trucks of type i operating in the mine (unit: vehicles).
- FC_i : Annual diesel fuel consumption per vehicle of type i (unit: liters/year or kg/year). This can be calculated as:

$$FC_i = \text{Fuel consumption rate} \left(\frac{\text{liters}}{\text{hour}} \text{ or } \frac{\text{liters}}{\text{km}} \right) \cdot \text{Operating time or distance per year}$$

- EF_{diesel} : Emission factor of diesel fuel (unit: kg CO₂e/liter). According to IPCC, ≈ 2.68 kg CO₂ per liter of diesel burned.

This summation framework accounts for fleet heterogeneity by disaggregating trucks by size and duty cycle. Larger trucks with higher payloads but longer haul distances typically dominate fleet emissions, making haulage the single largest emission source in most open-pit operations.

3.6. Emission Intensity Metrics

In addition to total annual emissions (t CO₂e/year), we calculated emission intensity, expressed as kg CO₂e per ton of coal extracted. This normalization facilitates inter-mine comparisons and benchmarking against international case studies.

3.7. Sensitivity Analysis

To address uncertainties in methane emissions, we performed sensitivity tests across three scenarios: (i) low gas content (0.5 m³/t), (ii) baseline assumptions (1.0–1.2 m³/t), and (iii) high gas content (2.0 m³/t). This approach follows the Tier 1 methodology of the IPCC, while highlighting the need for direct measurement campaigns in future work.

4. Results

4.1. Data Collection and Baseline Estimation

Equipment inventories and operational statistics for the selected mines were obtained from annual reports of Vinacomin and supplementary records provided by the Vinacomin Institute of Mining Science and Technology. These datasets, consolidated in the “Inventory of production and equipment in Vietnamese coal mines,” detail the number and categories of primary machinery deployed in open-pit operations. To complement official records, interviews were conducted with mine engineers to approximate average annual operating hours, which were estimated at ~5,000 hours for haul trucks, ~4,500 hours for excavators, and ~3,000 hours for drilling rigs. Fuel consumption rates were derived from mine design handbooks and manufacturer specifications. Although operational conditions inevitably introduce deviations from theoretical benchmarks, the model framework allows recalibration once measured data (e.g., Vinacomin’s specific fuel consumption norms) become available.

Based on these inputs, baseline emissions were calculated for the year 2023 under a business-as-usual (BAU) scenario. Subsequent mitigation scenarios were then constructed in alignment with the three strategic pillars: (i) efficiency improvements, (ii) electrification and renewable integration, and (iii) methane capture and utilization. Each scenario represents a plausible level of technology adoption by target years (2025 or 2030). For instance, the efficiency scenario assumes a percentage reduction in fuel consumption through improved fleet management; the electrification scenario considers partial replacement of diesel trucks with electric alternatives and solar PV supplying a share of electricity demand; and the methane management scenario assumes recovery of a specified fraction of fugitive CH₄. For each case, the model recalculates total CO₂e emissions and compares them against the baseline to assess abatement potential.

4.2. Baseline Emissions Across Mines

Table 1 summarizes the key characteristics of the five mines and their estimated baseline CO₂e emissions in 2024.

Table 1. Characteristics and estimated baseline CO₂e emissions of major open-pit coal mines in Vietnam (2024)

Mine	Output (Mt/year)	Stripping ratio (m ³ /t)	No. of trucks (≥50 t)	CO ₂ e emissions (kt/year)	Intensity (kg CO ₂ e/t coal)
Cao Son	4.50	~15.0	~150	150–180	~33–40
Deo Nai–Coc Sau	2.70 (combined)	~16.2	~130	90–100	~35–37
Ha Tu	2.50	~24.8	~70	80–90	~32–36
Na Duong	1.20	~12.7	~30	20–30	~17–25
Khanh Hoa	0.45	~11.2	~30	10–15	~25–35

Note: CO₂e estimates are based on assumed methane emission factors of 1 m³/t for Cao Son, Deo Nai, and Ha Tu; 0.8 m³/t for Coc Sau; 0.5 m³/t for Na Duong; and 1.2 m³/t for Khanh Hoa. Fuel consumption was derived from manufacturer and design benchmarks, with adjustments reflecting average utilization

4.3. Observed Patterns

The results indicate clear contrasts between absolute and intensity-based emissions:

Large-scale mines such as Cao Son and Deo Nai–Coc Sau generate the highest absolute emissions (150–180 kt CO₂e/y and 90–100 kt CO₂e/y, respectively), driven by high production volumes and large material movement requirements.

Ha Tu, despite moderate production, exhibits the highest stripping ratio (~25 m³/t), resulting in elevated emission intensity (~32–36 kg/t).

Na Duong has the lowest absolute emissions (20–30 kt/y), reflecting both its smaller scale and lower stripping ratio.

Khanh Hoa, though very small in output (~0.45 Mt/y), shows comparatively high intensity (~25–35 kg/t), attributed to thin, deep, and geologically complex seams that raise haulage requirements and methane release factors.

These baseline results establish the reference against which the potential of alternative mitigation strategies—efficiency improvements, electrification, and methane capture—will be evaluated in the scenario analysis.

5. Discussion and Analysis

5.1. Carbon Emission Structure in Open-Pit Coal Mining

Detailed calculations indicate that greenhouse-gas (GHG) emissions in Vietnamese open-pit coal mining are heavily concentrated in two sources: diesel combustion for haulage and fugitive methane release. This pattern is consistent with international case studies. Table 1 illustrates the average contribution of major emission sources across the five mines investigated.

5.2. Haulage (trucks transporting overburden and coal)

Haulage is the largest contributor, responsible for ~40–50% of total CO₂e emissions per mine. The underlying reason is the continuous operation of large truck fleets consuming tens of millions of liters of diesel annually. At Cao Son, for instance, ~12–15 million liters of diesel are burned each year by ~150 trucks, producing ~33–40 kt of CO₂. Haulage-related emissions scale with both the stripping ratio and haul distance: mines with higher

overburden volumes or longer uphill hauls to waste dumps show disproportionately higher haulage emissions. This explains why Ha Tu, despite its moderate production, records some of the highest per-ton intensities due to its exceptionally high stripping ratio.

5.3. Drilling and blasting.

This stage contributes only ~5–10% of total CO₂e. Diesel or electric-powered drills consume fuel, while explosives generate emissions through detonation chemistry. In Quang Ninh, most drills (e.g., CBII-250, Furukawa) are electric, consuming ~2–4 GWh per mine annually—equivalent to ~1.5–3.0 kt CO₂e. Explosive use adds several hundred tons CO₂e. While non-negligible, this share is far lower than haulage.

5.4. Loading (excavators and shovels).

Emissions from excavation are estimated at ~10–15% of totals. Diesel-powered shovels consume ~200,000–300,000 liters annually per unit, whereas electric shovels (e.g., EKG rope shovels) draw on grid electricity. Mines such as Cao Son, operating ~13 electric shovels, reduce direct diesel use but offset this by drawing carbon-intensive electricity from Vietnam's coal-dominant grid. Overall, however, loading remains less emission-intensive than haulage, owing to its stationary operating mode and shorter duty cycles.

5.5. Ancillary operations (dozers, graders, pumps, light vehicles).

These collectively contribute ~3–5% of CO₂e. Dozers (e.g., Caterpillar D8/D10, Komatsu D155) consume significant fuel individually, but their small fleet size limits aggregate impact. Pumping and auxiliary diesel generators add marginal emissions. Despite their modest direct share, auxiliary operations influence overall efficiency—for example, poor road maintenance by graders increases truck fuel consumption.

5.6. Methane emissions (CMM).

Methane is a substantial but uncertain source, contributing an estimated 30–45% of total CO₂e, depending on seam gas content. Under the baseline assumption of ~1 m³ CH₄ per ton of coal, methane contributes ~40% of mine-level CO₂e. In shallow, degassed seams, this may fall below 10%, while in deeper or gas-rich deposits (e.g., parts of Cao Son or Khanh Hoa), methane could account for half of total emissions. International evidence (e.g., China, India) confirms that open-pit methane emissions can rival those from underground mines when thick, gassy seams are exploited. Given the lack of direct measurements in Vietnam, these estimates should be treated as preliminary, underscoring the need for targeted field campaigns.

Figure 1 illustrates a conceptual mapping of emission sources and corresponding mitigation strategies in Vietnam's open-pit coal mining operations. The left-hand side highlights the dominant emission “hot spots,” namely diesel combustion in haulage fleets and fugitive methane release from coal seams. These sources account for nearly 80–90% of total CO₂e emissions across the studied mines. On the right-hand side, tailored decarbonization measures are presented, including fleet electrification and renewable integration to replace diesel, as well as methane capture and utilization technologies to address fugitive CH₄. This visualization emphasizes the need for an integrated approach: targeting both energy-related and non-energy-related emissions simultaneously to achieve

substantial reductions. By linking sources with solutions, the figure underscores the rationale for the proposed three-pillar strategy, which combines efficiency improvements, electrification, and methane management into a unified decarbonization pathway. In Summary, two emission “hot spots” clearly dominate the profile of open-pit coal mining: Diesel combustion in haulage and heavy mobile equipment, and fugitive methane release from coal seams. Other sources—electricity use, explosives, and auxiliary equipment—are relatively minor but remain relevant for incremental efficiency gains. Future mitigation strategies must therefore focus on these two dominant sources while leveraging indirect reductions through technology upgrades.

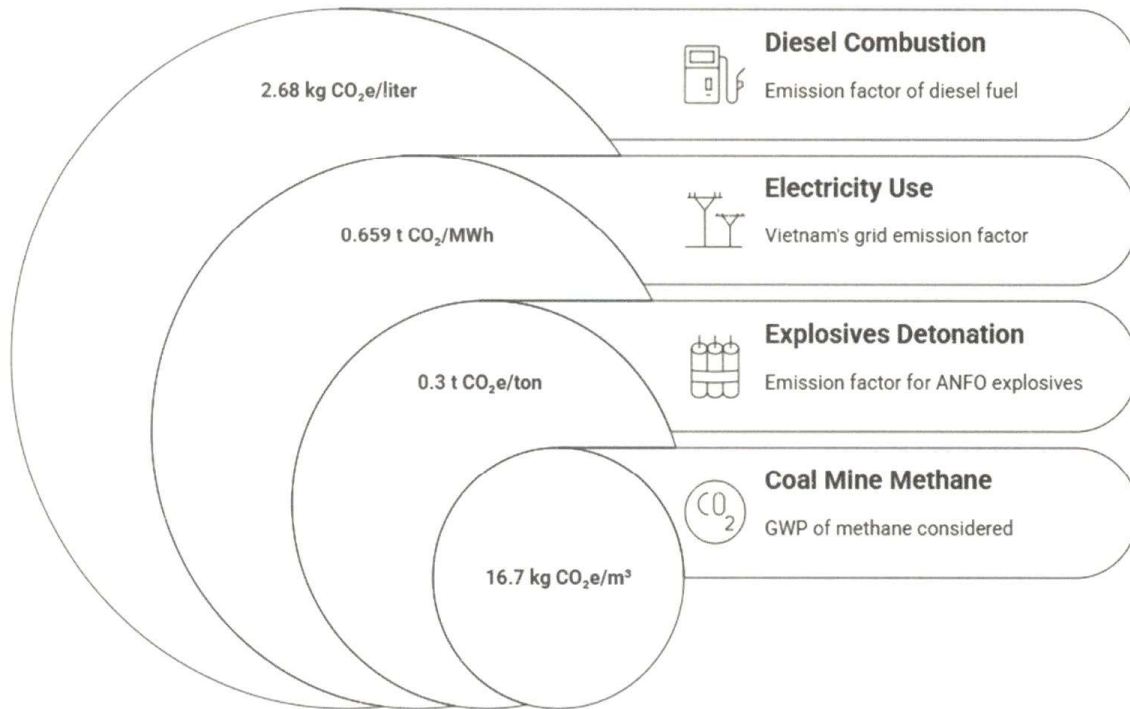


Figure 1. Emission Sources and Solutions for Vietnam's Open-Pit Coal Mines

6. Proposed Mitigation Strategies and Effectiveness Assessment

6.1. Three-Pillar Framework for Vietnam's open pit mining industry

Based on emission-source analysis, a three-pillar decarbonization strategy is proposed for Vietnam's open-pit coal sector: Energy efficiency improvement, Electrification with renewable integration, and Methane management and utilization (CMM).

Each pillar targets a distinct emission hotspot and, when deployed in combination, provides a robust pathway toward deep decarbonization.

(i) Energy Efficiency Improvement

This pillar aims to reduce energy demand per unit of production by optimizing operations and upgrading existing systems. Key measures include:

Process optimization: Transition from fully truck-dependent systems to integrated in-pit crushing and conveying (IPCC) solutions, reducing truck kilometers and diesel use. For example, semi-mobile crushers coupled with conveyor belts have demonstrated ~30%

lower haulage costs and proportional emission reductions in deep open-pits such as Shuichang (China).

Fuel and equipment management: Routine maintenance, tire-pressure control, and anti-idling dispatch systems reduce diesel waste. Real-time fleet management platforms can cut unnecessary truck waiting times and avoid empty runs.

High-efficiency equipment: Replacement of outdated units with hybrid diesel-electric trucks or next-generation hydraulic shovels featuring regenerative braking can deliver 5–15% fuel savings.

Mine design optimization: Geotechnical approaches such as steep-slope mining, optimized haul roads, and reduced overburden volumes can translate directly into lower fuel demand.

Auxiliary management: Road maintenance and pit dewatering improve fleet efficiency by minimizing rolling resistance and delays.

Estimated impact. If implemented comprehensively, efficiency measures can cut diesel consumption by ~10–20%, equivalent to ~7–10% of total CO₂e emissions. Importantly, these interventions are low-capex, high-return—fuel savings directly reduce operating costs, which typically constitute ~30% of mine expenditure.

(ii) Electrification and Renewable Integration

This pillar represents the most transformative pathway, substituting fossil fuels with low-carbon electricity.

Mobile fleet electrification: Progressive adoption of electric and trolley-assist trucks can drastically reduce diesel use. Global trials (e.g., Palabora copper mine, South Africa) demonstrate 40–60% fuel savings on uphill hauls. Electric rope shovels and drills, already common in Vietnam, should be further expanded.

Fixed plant electrification: Prioritizing conveyors, crushers, and pumping systems over diesel-driven alternatives.

Renewable deployment at mine sites: Solar farms on waste dumps and wind turbines in reclaimed areas can supply part of mine demand. With solar irradiation in Quang Ninh averaging 3.5–4 kWh/m²/day, tens of MWp could be feasibly installed.

Fuel transition options: In the medium term, biodiesel or CNG could serve niche roles, though large haul trucks remain constrained by energy density; hydrogen or ammonia may emerge beyond 2040.

Estimated impact. If 50% of the truck fleet and all shovels are electrified by 2030, sector-wide emissions could fall by 20–25%, assuming current grid intensity. With a greener grid mix, reductions could exceed 50% by 2040–2050.

Investment profile. This pillar requires high upfront capital, with electric haul trucks costing 2–3× more than diesel units, plus infrastructure for charging/trolley lines. However, operational savings (~20–50% lower O&M) and potential policy incentives (e.g., renewable subsidies) strengthen long-term economics. Non-monetary co-benefits include reduced noise, dust, and occupational exposure.

(iii) Methane Management and Utilization (CMM)

Methane is both a potent GHG and a latent energy source. Strategies include:

Pre-drainage drilling and gas capture: Boreholes drilled in advance of mining can extract methane for power generation or CNG use.

On-pit methane capture: Installation of collection pipes and localized flaring systems reduces fugitive release.

Safety and monitoring: Continuous methane sensors in pits and spoil piles mitigate explosion risks and enable responsive control.

Estimated impact. Capturing 50% of fugitive methane could cut total mine CO₂e emissions by ~20%, given methane's current ~40% share of the emission profile. In gas-rich seams, potential abatement could reach ~30–40%.

Economic benefits. At ~10 million m³/year methane recovery, on-site generation could yield 35–40 GWh annually, sufficient for self-supply with surplus export potential. Carbon credits add financial upside.

Table 2. Summarizes the comparative attributes of the three pillars.

Criteria	(i) Energy Efficiency	(ii) Electrification & Renewables	(iii) Methane Management (CMM)
Scope of impact	Diesel savings across all stages	Eliminates diesel, reduces grid reliance	Direct abatement of fugitive CH ₄
CO ₂ e reduction potential	10–15% (max ~20%)	20–30% by 2030, >50% long term	10–20% (up to 40% in gas-rich seams)
Investment needs	Low to moderate	High (fleet + infrastructure + renewables)	Moderate (drilling, compressors, gensets)
Economic benefit	Strong—fuel savings	Mixed—OPEX savings offset by CAPEX	Moderate—power generation, carbon credits
Short-term feasibility	High	Low (pilot phase)	Medium
Long-term potential	Moderate	Very high	High
Challenges	Operational discipline	Capital intensity, grid stability	Geological uncertainty, safety

6.2. Integrated Roadmap

Figure 2 illustrates the proposed three-pillar decarbonization roadmap for open-pit coal mining in Vietnam. The left-hand side highlights the major strategic pillars—energy efficiency, electrification and renewable integration, and methane management—each addressing distinct emission sources. These pillars converge into an integrated decarbonization pathway that progressively reduces greenhouse gas emissions. The roadmap identifies clear milestones: a 40–50% reduction in CO₂e emissions by 2030, 70–80% by 2040, and the achievement of near net-zero operations by 2050. This conceptual framework underscores the complementary nature of the strategies, where early gains from efficiency improvements support longer-term transformations through electrification and methane recovery.

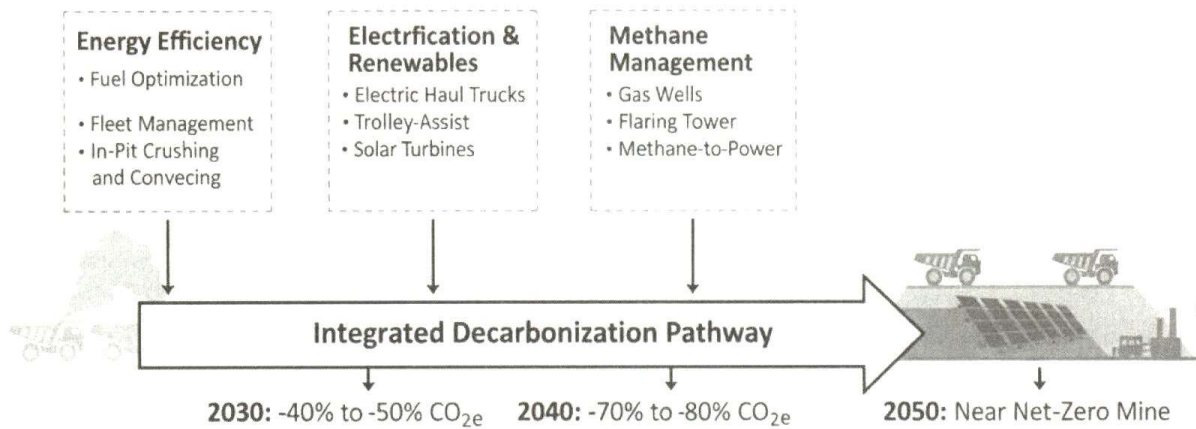


Figure 2. Conceptual roadmap of three-pillar decarbonization strategies for Vietnam's open-pit coal mining industry

7. Conclusion and Future Works

This study provides the first systematic quantification of greenhouse gas (GHG) emissions from open-pit coal mining in Vietnam, applying a Life Cycle Assessment (LCA) framework aligned with IPCC guidelines. Results from five representative mines demonstrate that emissions are dominated by two “hot spots”: (i) diesel combustion in haulage and heavy mobile equipment, which accounts for approximately 40–50% of CO₂e, and (ii) fugitive methane release from coal seams, contributing on average 30–45%. Other sources—including electricity consumption, explosives, and ancillary operations—are comparatively minor but remain relevant for incremental efficiency gains. Estimated emission intensities range from 17 to 40 kg CO₂e per ton of coal, depending primarily on stripping ratio and seam gas content. These findings align with international evidence, underscoring the urgency of targeted abatement in Vietnam's surface mining sector.

Building on these results, the paper advances a three-pillar decarbonization strategy: (i) energy efficiency improvement through optimized operations, fuel management, and advanced equipment; (ii) electrification and renewable integration to substitute diesel with low-carbon electricity; and (iii) methane management and utilization (CMM) to capture, flare, or valorize CH₄. Scenario analysis indicates that a combined implementation of these measures could reduce emissions by 40–50% by 2030 and 70–80% by 2040, positioning the sector on a viable trajectory toward net-zero by 2050. In addition to climate benefits, these interventions can deliver economic co-benefits through fuel savings, renewable self-supply, and potential carbon credit revenues.

Nevertheless, several challenges remain. Data limitations—particularly regarding methane release rates and actual fuel consumption—introduce uncertainty into baseline estimates. High capital requirements and limited infrastructure constrain rapid deployment of electrification technologies, while regulatory ambiguities surrounding methane ownership and utilization hinder large-scale CMM projects. Policy support, financial incentives, and clear legal frameworks will therefore be essential to enable wide-scale adoption.

Future research should address these gaps through:

- Field measurements and model calibration – Direct monitoring of methane emissions, fuel consumption, and equipment duty cycles to refine emission factors for Vietnamese conditions.
- Extended LCA boundaries – Incorporating other environmental dimensions such as particulate matter, NO_x, and water impacts, and expanding to full coal value chains, including transport, washing, and combustion.
- Technology assessment and pilots – Demonstration projects on trolley-assist haulage, battery-electric trucks, solar PV on waste dumps, and methane-to-power systems to generate empirical performance and cost data.
- Cross-sectoral integration – Evaluating synergies between mining and energy systems, for example, co-locating power plants with carbon capture and storage (CCS) near coal mines to utilize low-quality coal while mitigating downstream emissions.
- Application to other mining contexts – Adapting the LCA-IPCC framework to underground coal mines (where methane and ventilation electricity dominate) and to metal open-pits (where diesel and grid electricity prevail). These comparative studies would allow tailored decarbonization roadmaps across the extractive industries.

In conclusion, the decarbonization of Vietnam's open-pit coal mines represents both a challenge and an opportunity. While the sector remains carbon-intensive, the combination of efficiency improvements, electrification, and methane management provides a feasible and scientifically grounded pathway to achieve deep emission reductions. With robust data, enabling policy frameworks, and targeted pilot projects, the coal mining industry can make a significant contribution to Vietnam's national commitment to net-zero by 2050.

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