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Integrated Green Mining Technology Package for Emission Reduction: A Design Science Approach in an Indonesian Open-Pit Mine

(Paket Teknologi Green Mining Terintegrasi untuk Pengurangan Emisi: Pendekatan Design Science pada Tambang Terbuka di Indonesia)

Hendra Sani ^{a,1,*}, **Syamsuddin** ^{a,2}

[a] *Engineering Study Program, Faculty of Engineering, Pejuang Republik Indonesia University, Makassar, 90233, Indonesia*

E-mail: [1]hendra.sani85@gmail.com; [2]Syamsuddin.hamzah71@gmail.com;

*Corresponding Author.
E-mail address: hendra.sani85@gmail.com (H. Sani).

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Abstract: *Mine decarbonisation studies still tend to evaluate electrification, energy efficiency, and renewable energy as separate interventions; therefore, evidence on integrated operational deployment remains limited, particularly for medium-scale open-pit mines in developing countries. This study evaluates whether an integrated green mining package can reduce Scope 1 and 2 emissions without undermining day-to-day operational reliability. Using a Design Science Research approach, the study developed and piloted a package consisting of trolley-assist haulage, battery-electric support vehicles, variable speed drives for dewatering pumps, an energy management system, and a solar PV–battery microgrid. Baseline and pilot performance were compared over two three-month periods using fuel logs, electricity meters, telematics, and PV/battery logger data. Emissions were calculated from activity data and IPCC-based emission factors, while renewable integration was assessed using HOMER Pro simulation. Diesel consumption declined from 4,000,000 L to 3,256,000 L (−18.6%), and purchased electricity decreased from 10,000 MWh to 9,060 MWh (−9.4%). The PV system generated 4,050 MWh, supplying about 30.9% of pilot-period electricity demand. Total Scope 1 and 2 emissions fell from 18,920 tCO_2e to 16,155 tCO_2e (−14.6%). The pilot also showed that electrification increased on-site electricity demand, making EMS coordination and renewable supply critical enabling conditions rather than optional add-ons. The novelty of this study lies in field-validating an integrated decarbonisation package instead of a single technology. The findings provide operational-scale evidence for medium-scale mines and support policies on electrification-ready microgrids, performance-based incentives, and standardised Scope 1 and 2 reporting.*

Keywords: *decarbonisation; mining; microgrid; renewable energy; battery-electric vehicles; Scope 1 and 2.*

Abstrak: *Studi dekarbonisasi tambang masih cenderung menilai elektrifikasi, efisiensi energi, dan energi terbarukan secara terpisah; sehingga bukti implementasi operasional yang terintegrasi masih terbatas, terutama untuk tambang terbuka skala menengah di negara berkembang. Penelitian ini mengevaluasi apakah paket green mining terintegrasi mampu menurunkan emisi Scope 1 dan 2 tanpa mengganggu keandalan operasi harian. Dengan pendekatan Design Science Research, penelitian ini mengembangkan dan menguji paket yang terdiri atas trolley-assist untuk haulage, kendaraan penunjang listrik baterai, variable speed drive pada pompa dewatering, energy management system, serta microgrid surya–baterai. Kinerja baseline dan pilot dibandingkan selama dua periode masing-masing tiga bulan menggunakan fuel log, meter listrik, telematics, dan data logger PV/baterai. Emisi dihitung dari data aktivitas dan faktor emisi berbasis IPCC, sedangkan integrasi energi terbarukan diuji menggunakan simulasi HOMER Pro. Konsumsi diesel turun dari 4.000.000 L menjadi 3.256.000 L (−18,6%), dan listrik yang dibeli dari jaringan turun dari 10.000 MWh menjadi 9.060 MWh (−9,4%). Sistem PV menghasilkan 4.050 MWh atau sekitar*

30,9% dari kebutuhan listrik selama periode pilot. Total emisi Scope 1 dan 2 turun dari 18.920 tCO_2e menjadi 16.155 tCO_2e (−14,6%). Pilot juga menunjukkan bahwa elektrifikasi meningkatkan kebutuhan listrik di lokasi, sehingga koordinasi EMS dan pasokan energi terbarukan menjadi syarat pendukung yang krusial, bukan pelengkap. Kebaruan penelitian ini terletak pada validasi lapangan atas paket dekarbonisasi yang terintegrasi, bukan teknologi tunggal. Temuan ini memberi bukti skala operasi bagi tambang skala menengah dan mendukung kebijakan microgrid siap-elektrifikasi, insentif berbasis kinerja, serta standardisasi pelaporan Scope 1 dan 2.

Kata kunci: *dekarbonisasi; pertambangan; microgrid; energi terbarukan; kendaraan listrik berbasis baterai; Scope 1 dan 2.*

Introduction

The mining industry is under growing pressure to decarbonise because it is both energy-intensive and strategically important for supplying minerals required by the clean-energy transition. In operational terms, the main emission sources in many surface mines remain diesel combustion in haulage and auxiliary equipment (Scope 1), and purchased electricity or captive generation for pumping, workshops, processing, and support facilities (Scope 2). At the same time, mines cannot treat decarbonisation as a purely environmental exercise, because any energy transition that compromises production continuity, safety, or equipment availability will be rejected at site level (ICMM, 2021; IEA, 2023a; IEA, 2025).

Recent literature points to three major decarbonisation pathways. The first is equipment electrification, including trolley-assist systems and battery-electric vehicles. The second is process energy efficiency through automation, variable speed drives, and data-driven operational control. The third is the integration of renewable power and storage through mine microgrids. These pathways are individually well established in the literature; however, their operational interaction is less well understood. For example, renewable-energy studies often concentrate on sizing optimisation and reliability modelling; vehicle studies frequently examine life-cycle or powertrain comparisons; and efficiency studies usually target one subsystem at a time (Ellabban & Alassi, 2021; Igogo et al., 2021; Moussa Kadri et al., 2022; Balboa-Espinoza et al., 2023; Li et al., 2024).

That fragmentation is the real weakness in the literature. Treating electrification, efficiency, and renewables as isolated decisions may be analytically convenient, but it does not reflect how mines actually decarbonise. Electrification shifts demand from diesel to electricity. That shift then changes load profiles, raises the importance of supply quality, and increases the value of storage, dispatch control, and renewable integration. In other words, the decarbonisation problem is not additive; it is systemic. Recent reviews have increasingly recognised this point; yet operational evidence from integrated field deployment remains sparse, especially in medium-scale open-pit mines in developing-country settings, where budget constraints, outage risks, and workforce readiness are more acute than in heavily automated flagship sites (Amegboleza & Ülkü, 2025; Islami et al., 2025; Levesque, 2025).

The policy environment reinforces this need for integrated evidence. Indonesia and the wider ASEAN region are pursuing stronger energy-transition and efficiency agendas, but implementation quality depends on realistic pathways for electrification, dispatchable renewable power, and site-level energy management (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2024a, 2024b; ASEAN Centre for Energy, 2024). For mining companies, this means that decarbonisation roadmaps must combine technical feasibility, reporting discipline, and operational governance. A reporting framework without deployable site solutions is hollow; a technology pilot without credible measurement is just marketing.

This study addresses that gap by developing and piloting an integrated green mining technology package in a medium-scale Indonesian open-pit mine. The novelty lies in validating a package rather than a single intervention, and in doing so through a Design Science Research (DSR) process that produces a reproducible artifact: a sequence of baseline diagnosis, technology-package design, pilot implementation, and performance evaluation (Hevner et al., 2004; Peffers et al., 2007). The research question is straightforward: can an integrated package that combines process electrification, energy-efficiency controls, and on-site renewable energy reduce Scope 1 and 2 emissions while remaining operationally workable at pilot scale?

Accordingly, the objectives are threefold: (1) to diagnose the baseline energy and emissions profile of the mine; (2) to design and implement an integrated decarbonisation package that fits site constraints; and (3) to evaluate its effect on energy use and Scope 1 and 2 emissions. The paper contributes operational evidence, not a theoretical promise, and that distinction matters because mines fail on implementation, not on PowerPoint.

Methods

This study uses a Design Science Research approach combined with a single-site case study. DSR was chosen because the goal was not merely to observe existing practice but to design, implement, and evaluate a practical artifact capable of addressing a real operational problem. Following the logic of Hevner et al. (2004) and Peffers et al. (2007), the research proceeded through four stages: baseline diagnosis, package design, pilot implementation, and evaluation/refinement. The artifact produced by the study is therefore the integrated green mining package itself, together with its deployment logic and performance-measurement protocol.

The case study site is an anonymised medium-scale open-pit mine in eastern Indonesia. A single-site design was retained deliberately; it allows close observation of process interactions, equipment behaviour, operating constraints, and human factors that are usually diluted in multi-site surveys. The site is analytically useful because its major energy loads are typical of many surface mines: diesel-intensive haulage, continuous dewatering, workshop demand, and support-facility loads. The mine also uses a mixed electricity arrangement, which makes renewable integration and storage relevant in practice rather than only in simulation.

The technology package was not assembled arbitrarily. Trolley-assist was selected because ramp haulage was the most fuel-intensive segment and therefore the best candidate for immediate diesel substitution. Battery-electric support vehicles were chosen for short-duty-cycle activities that did not require full haul-truck replacement. Variable speed drives (VSDs) were installed on dewatering pumps because pump duty fluctuated, and the baseline operation relied on inefficient throttling and fixed-speed operation. An energy management system (EMS) was added because the package would otherwise create uncoordinated electrical loads and peak-demand risks. Finally, a solar PV–battery microgrid was introduced because electrification without lower-carbon electricity would merely shift emissions from diesel tanks to the grid. The implemented pilot configuration comprised trolley-assist on selected ramp segments, battery-electric support vehicles, VSD-equipped dewatering pumps, EMS-based load monitoring, and a 1.2 MWp solar PV plus 1.5 MWh battery system.

Data were collected for two consecutive operating windows: a three-month baseline period before implementation and a three-month pilot period after implementation. Quantitative data consisted of diesel fueling logs and stock reconciliation, main electricity-meter readings, PV inverter logs, battery-management-system records, and equipment telematics. Qualitative information was obtained through structured interviews with operators, maintenance staff, supervisors, and HSE personnel to capture implementation constraints and operating responses. A full techno-economic appraisal was not included in the present paper because the pilot duration was too short for a defensible life-cycle cost analysis, and several capital-cost items were confidential under the site agreement.

Energy and emissions were analysed using before–after comparison. Scope 1 and 2 emissions were estimated using the standard activity-data approach: $GHG = \Sigma(AD \times EF)$, where AD is activity data and EF is the relevant emission factor. Diesel emissions used a factor of 2.68 kg CO_2/L, while purchased electricity used a site-applied grid factor of 0.82 kg CO_2/kWh, in line with the reporting practice used at the site and IPCC-based accounting conventions (IPCC, 2006, 2019). Renewable integration and dispatch adequacy were checked in HOMER Pro using the measured site load profile, a one-hour time step, load-following dispatch, and a capacity-shortage constraint below 1% (Chisale et al., 2023; Ellabban & Alassi, 2021).

Data quality was controlled through timestamp harmonisation, cross-checking between fuel logs and stock balances, anomaly screening on load and PV generation, and spot audits of meter records. Missing data below 5% of observations were repaired by interpolation or forward filling at the native resolution; periods with more substantial gaps were excluded from before–after comparison. Because this is a pilot study using operational meters rather than research-grade laboratory instruments, uncertainty is reported conservatively as an indicative band derived from meter-class accuracy and factor variability. Under plausible combined uncertainty, the reported emissions reduction remains directionally robust. Detailed production-normalised intensities are not disclosed because the site's tonnage data are commercially sensitive under the non-disclosure agreement.

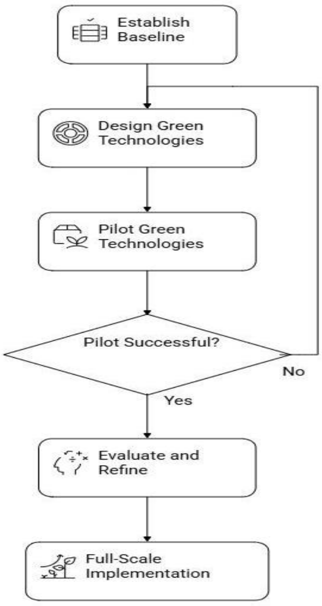

Figure 1. Stages of the DSR-based green mining process

Table 1. Summary of data sources, sampling intervals, and validation procedures

Data / variable	Source / instrument	Interval / period	Validation / QA-QC
Diesel consumption (L)	Fueling log and fuel-stock reconciliation	Daily; 3-month baseline and 3-month pilot	Check stock balance consistency; cross-check with telematics operating and idle hours
Purchased electricity (kWh)	Main incoming meter	15-minute to hourly; baseline and pilot	Meter audit; anomaly screening; reconciliation with utility records
PV generation (kWh)	PV inverter logger	5-15 minute; pilot period	Compare with installed capacity; check missing data; verify daily curve
Battery operation (kWh, SoC)	Battery management system	5-15 minute; pilot period	Validate SoC limits; reconcile charge-discharge energy; inspect alarm events
Equipment telematics	Telematics system	1-5 minute, aggregated daily	Outlier removal; time synchronisation; spot-check against shift logs
Operating activity	Dispatch and shift reports	Daily; baseline and pilot	Triangulate with monthly operations reports and field interviews

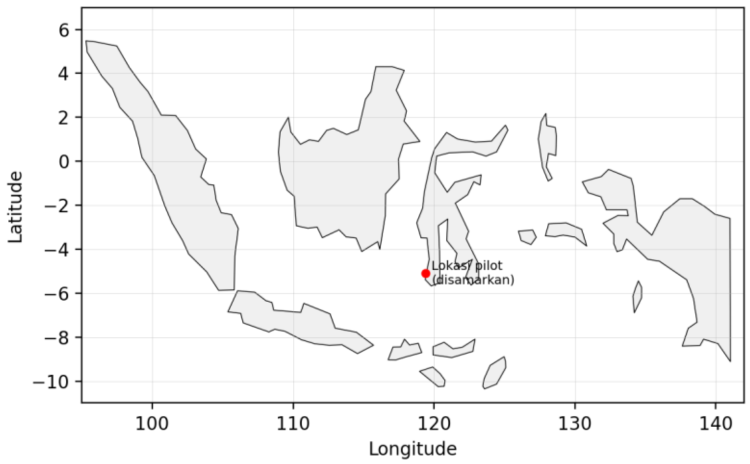

Figure 2. Anonymised provincial-scale study location

Results

Baseline diagnosis confirmed that diesel-based haulage and dewatering were the dominant energy users. During the three-month baseline period, diesel consumption was 4,000,000 L and purchased electricity was 10,000 MWh. After the pilot package was implemented, diesel consumption fell to 3,256,000 L and purchased electricity fell to 9,060 MWh. At the same time, the solar PV system generated 4,050 MWh during the pilot period.

A more careful reading of these numbers reveals an important operational point. Pilot-period total electricity demand was 13,110 MWh (purchased electricity plus PV generation), which is 31.1% higher than baseline purchased electricity. This increase is not a failure; it is the expected consequence of substituting part of the diesel-based workload with electrified processes. The decarbonisation effect therefore came from two simultaneous shifts: reduced diesel dependence and partial replacement of additional electric demand with on-site renewable generation.

Using the applied emission factors, Scope 1 emissions declined from 10,720 tCO2e to 8,726 tCO2e, while Scope 2 emissions declined from 8,200 tCO2e to 7,429 tCO2e. Total Scope 1 and 2 emissions therefore fell from 18,920 tCO2e to 16,155 tCO2e, equivalent to a 14.6% reduction. Based on conservative assumptions about meter accuracy and factor variability, the estimated reduction is best interpreted with an indicative uncertainty band of roughly ±2–3 percentage points. That band does not change the overall conclusion: the integrated package produced a meaningful downward shift in operational emissions.

The HOMER-based dispatch check indicated that the selected PV-battery configuration was adequate for partial renewable penetration under the pilot load profile and that storage materially improved solar utilisation and peak-load management. Interviews with operations and maintenance personnel identified three enabling conditions for stable performance: EMS coordination to avoid poorly timed coincident loads, preventive maintenance for electrical components and battery systems, and operator training to accommodate new charging, dispatch, and control routines.

Table 2. Before–after energy and emissions performance

Indicator	Baseline	Pilot	Change	Interpretation
Diesel consumption	4,000,000 L	3,256,000 L	-18.6%	Direct reduction from partial haulage electrification and lower idle intensity
Purchased electricity	10,000 MWh	9,060 MWh	-9.4%	Grid dependence fell despite added electric loads
On-site PV generation	0 MWh	4,050 MWh	New supply	Renewables supplied part of the electrified load
Total site electricity	10,000 MWh	13,110 MWh	+31.1%	Electricity demand rose as diesel work shifted to electric systems

Indicator	Baseline	Pilot	Change	Interpretation
demand				
Scope 1 emissions	10,720 tCO2e	8,726 tCO2e	-18.6%	Consistent with fuel-use reduction
Scope 2 emissions	8,200 tCO2e	7,429 tCO2e	-9.4%	Lower purchased electricity offset higher total electric demand
Total Scope 1+2	18,920 tCO2e	16,155 tCO2e	-14.6%	Net operational decarbonisation at pilot scale
Renewable electricity share	0%	30.9%	+30.9 pp	Share of pilot-period electricity demand supplied by PV

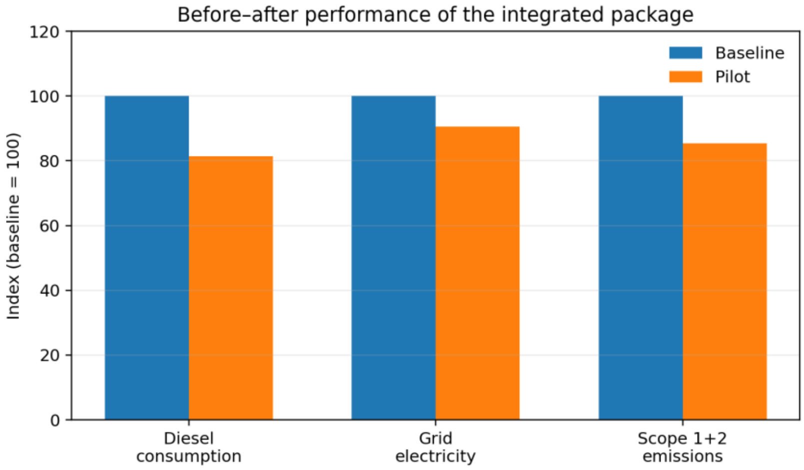

Figure 3. Before–after performance indices (baseline = 100)

Because not every subsystem was separately instrumented for causal decomposition, component-level contributions are interpreted qualitatively rather than overstated with false precision. Even so, the operational pattern is clear. Trolley-assist on ramp haulage delivered the strongest diesel-saving effect because it targeted the most energy-intensive segment of the mine's duty cycle. Battery-electric support vehicles contributed a smaller but still meaningful reduction by displacing diesel in shorter and more predictable auxiliary tasks. VSD-equipped dewatering pumps reduced avoidable electricity waste by matching motor output more closely to variable pumping requirements. The EMS did not itself create large direct emissions savings, but it functioned as a system integrator by smoothing peaks, sequencing flexible loads, and protecting microgrid stability. The PV-battery microgrid then displaced part of the electricity that would otherwise have been purchased from the grid and helped absorb the added load created by electrification.

Table 3. Qualitative contribution of individual package components

Component	Main operational role	Primary decarbonisation mechanism	Observed contribution/ limitation
Trolley-assist haulage	Electrifies high-load ramp segments	Displaces diesel in the most fuel-intensive duty cycle	Largest direct fuel-saving effect; limited to electrified segments
Battery-electric support vehicles	Replaces diesel in short auxiliary tasks	Cuts diesel consumption in predictable support operations	Meaningful but smaller contribution because only the support fleet was electrified
VSD on dewatering pumps	Matches motor output to variable pumping demand	Reduces avoidable electricity waste from fixed-speed operation	Stable efficiency gain; benefit depends on inflow variability
Energy management	Coordinates loads, storage, and dispatch	Avoids peak demand and improves system control	Mainly an enabling technology; indirect but

Component	**Main operational role**	**Primary decarbonisation mechanism**	**Observed contribution/ limitation**
system	timing		essential contribution
PV + battery microgrid	Supplies low-carbon electricity and buffers variability	Displaces purchased electricity and supports electrification	Key for turning higher electric demand into net emissions reduction

Discussion

The results matter less for their headline percentage than for what they reveal about implementation logic. The pilot did not simply cut fuel and add solar panels. It altered the site energy architecture. That is precisely why the integrated-package perspective is more useful than isolated-technology analysis. Studies on renewable integration in mining repeatedly show that hybrid systems can improve reliability and reduce emissions, but they often stop at optimisation or scenario modelling (Ellabban & Alassi, 2021; Moussa Kadri et al., 2022; Li et al., 2024). Studies on mining electrification likewise demonstrate emissions benefits, but many focus on life-cycle comparison or technology substitution without showing how a mine actually manages the new electrical demand created by electrification (Balboa-Espinoza et al., 2023; Ključnikov et al., 2023; Magdalena et al., 2025). This study helps close that operational gap by showing that the enabling technologies—especially EMS and on-site renewable supply—are not peripheral to electrification; they are part of the same system solution.

The 14.6% reduction should also be interpreted with discipline. It is a strong pilot result, but not a magic number. It was achieved under partial electrification, limited renewable penetration, and a three-month operating window. The result would likely increase under longer deployment, broader fleet substitution, and deeper renewable coverage; equally, it could weaken if uptime discipline, maintenance quality, or dispatch coordination deteriorate. That is the real trade-off in mine decarbonisation: the problem is not whether low-carbon technologies exist, but whether operations can absorb the added complexity. Similar recent work emphasises that technological readiness alone is insufficient unless mines also resolve questions of investment sequencing, operational control, and workforce capability (Adedoja et al., 2025; Ghorbani et al., 2024; Islami et al., 2025).

The component-level pattern observed here is also consistent with other studies. Electrification of high-energy mobile equipment usually delivers the largest direct fuel savings, while energy-efficiency controls and process optimisation provide lower but more stable reductions across fixed systems. Renewable microgrids then determine whether those electrification gains translate into net emissions reductions or merely into higher electricity dependence (Igogo et al., 2021; Kalantari et al., 2022; Magdziarczyk et al., 2024; Qays et al., 2025). In that sense, the most strategically important finding is the increase in total site electricity demand during the pilot. That single result exposes the weakness of any decarbonisation roadmap that promotes electrification without simultaneously planning power quality, storage, and renewable dispatch.

From a scalability standpoint, the package is most transferable to mines that share four conditions: a large diesel burden in repeatable haul routes, significant pumping or ventilation loads, an electricity arrangement that can accommodate hybridisation, and a management team willing to institutionalise energy monitoring. Mines lacking those conditions may still benefit from elements of the package, but the effect will be smaller or more conditional. The practical implication is blunt: mines should stop searching for a universal silver bullet and instead build integrated decarbonisation sequences around their dominant loads.

The policy implications are equally direct. First, mine-site microgrids should be regulated and incentivised as enablers of industrial decarbonisation, not treated only as isolated power projects. Second, performance-based incentives are more useful than technology-prescriptive incentives because they allow sites to combine electrification, control systems, and renewables according to local constraints. Third, standardised Scope 1 and 2 reporting should be tightened so that operators cannot claim decarbonisation while simply shifting energy use across reporting boundaries. These points are particularly relevant in Indonesia and ASEAN, where electricity transition, industrial competitiveness, and mineral strategy are becoming increasingly intertwined (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2024a, 2024b; ASEAN Centre for Energy, 2024; IEA, 2023b).

Conclusion

This study developed and piloted an integrated green mining technology package that combines electrification, process energy-efficiency controls, and on-site renewable energy in a medium-scale Indonesian open-pit mine. Over a three-month pilot period, diesel consumption decreased by 18.6%, purchased electricity decreased by 9.4%, renewable electricity supplied about 30.9% of site demand, and total Scope 1 and 2 emissions fell by 14.6%.

The main scientific contribution is not the existence of any one component, since trolley-assist systems, VSDs, EMS platforms, and mine microgrids already exist in the literature. The contribution is the operational validation of these components as a coordinated package using a Design Science Research logic. The study therefore adds field-based evidence to a literature that too often remains fragmented across optimisation papers, subsystem studies, and technology-specific assessments.

Practically, the findings show that mine decarbonisation should be designed as a systems transition. Electrification without power-system redesign is incomplete; renewables without dispatch control are fragile; efficiency measures without integration logic leave savings on the table. Managers and policy makers should therefore treat mine decarbonisation as an implementation problem governed by sequencing, reliability, and measurement discipline.

The study has clear limitations: it is based on one site, a short pilot horizon, aggregate operational reporting, and activity-based emissions accounting. Future research should extend the pilot duration, compare multiple mine types, publish production-normalised indicators where confidentiality allows, and incorporate techno-economic and life-cycle analysis so that operational feasibility can be linked to capital allocation and long-term abatement cost.

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Conflict of Interests

The authors declare no conflict of interest. The collaborating mining company provided operational access under confidentiality arrangements but had no role in the research design, data interpretation, manuscript preparation, or decision to submit the article.

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