

Carbon Emission Cost Accounting for High-Altitude Open-Pit Nonferrous Mines in Northwest China: A Case of Lithium and Lead-Zinc Mines in Hotan

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Abstract: Since China announced its targets of peaking carbon emissions before 2030 and achieving carbon neutrality by 2060, mining enterprises can no longer treat carbon accounting as optional. This is a practical problem for the lithium and lead-zinc mines now being developed in Hotan Prefecture, northwest China. The Dahongliutan spodumene lithium deposit and the Huoshaoyun lead-zinc deposit are located at 4,600–5,600 m, and at such elevations low air density and extreme cold raise fuel consumption above what the standard emission-factor method assumes. In this paper an altitude-corrected carbon emission cost accounting framework is proposed for open-pit nonferrous mines. The framework is built by coupling an emission-factor inventory modified by an elevation-dependent fuel correction coefficient with a cost model that covers monitoring and compliance expenditure, annualized abatement investment and the shadow cost of carbon. It is applied to two scenario-based cases. The first is a 1.2 Mt/a spodumene mine with an on-site concentrator at 4,800 m; the second is a 2.5 Mt/a lead-zinc mine at 5,600 m that relies on captive diesel power. The estimated annual emissions are about 108 kt CO₂e for the lithium mine (84.5 kg/t ore; 3.96 t/t LCE) and 173.5 kt CO₂e for the lead-zinc mine (67.2 kg/t ore; 0.24 t/t contained metal). Altitude is responsible for an extra 26–33% of mobile-fleet fuel emissions. When a shadow price of 70 CNY/t CO₂ is used, the comprehensive carbon-related cost is roughly 16.3 million CNY/a (637 CNY/t LCE) for the lithium mine and 25.3 million CNY/a (36 CNY/t metal) for the lead-zinc mine, which is 1.5–2.4% of operating cost. The sensitivity analysis shows that the results depend mainly on the carbon price, the power-supply mix and the altitude coefficient. On this basis, recommendations

are made concerning mine-site renewable energy, staged electrification of the fleet, MRV capacity building and accounting rules that take altitude into account.

Keywords: Carbon Peaking and Carbon Neutrality; Carbon Emission Cost Accounting; High-Altitude Open-Pit Mine; Shadow Carbon Price; Lithium; Lead-Zinc; Hotan; Northwest China

1. Introduction

In September 2020 China pledged to bring its carbon dioxide emissions to a peak before 2030 and to reach carbon neutrality ahead of 2060. That commitment has since been translated into the so-called "1+N" policy architecture, which assigns sectoral and regional responsibilities for decarbonization. The national emissions trading system (ETS), opened in 2021 with the power sector alone and designed as an intensity-based market whose coverage and cap are expected to tighten progressively [1,2], admitted steel, cement and aluminum smelting in 2025, lifting the number of regulated key emitters to 3,378; trading records show that allowances (CEA) changed hands at an annual average of 62.36 CNY/t in 2025 and closed the year at 74.63 CNY/t. Mining has not yet been brought under allowance management, yet the sector is already exposed indirectly through electricity and fuel supply chains, and direct coverage looks increasingly plausible as the market moves toward the planned eight energy-intensive industries.

Nonferrous mining occupies a contradictory position in this transition. On the one hand its products are needed for decarbonization: lithium goes into the batteries that electrification relies on, zinc is used to galvanize the steel in wind turbines and transmission towers, and lead is still widely used in energy-storage and automotive batteries. On the other hand the mines

themselves are becoming more energy-intensive, because ore grades keep declining, pits are getting deeper, and newly developed deposits tend to be found in places where working conditions are difficult [3,4]. The southern margin of northwest China concentrates all of these tensions in one place. In little more than ten years the West Kunlun–Karakoram metallogenic belt in Hotan Prefecture has gone from reconnaissance geology to strategic development. In the Dahongliutan district, world-class spodumene resources occur in rare-metal pegmatites distributed over elevations of about 4,600–5,600 m [5-7], and the Huoshaoyun deposit in the Karakoram is mined at elevations well above 5,000 m and is regarded as one of the largest and highest-grade lead-zinc deposits discovered so far [8]. According to publicly reported project parameters, its phase-one open pit has a capacity of 2.5 Mt/a and a service life of 21 years. Because the ore is oxide ore, no beneficiation is carried out on site, and the ore is instead pumped as slurry to a smelter complex of 600 kt/a.

High elevation changes the carbon emissions of an open pit in several ways. Internal combustion engines lose volumetric efficiency when air density decreases, which means that haul trucks, excavators, drills and generator sets need more fuel to do the same mechanical work. Field studies have reported that engine power drops by roughly 4-13% per 1,000 m of elevation gain and that fuel consumption increases correspondingly [9,10]. In winter the temperature falls below -30°C , so there are additional heating loads and cold-start losses. The mines are also far from the provincial grid, and in the early stage of operation they have to depend on captive diesel power. Standard accounting instruments are silent on all of this: the scope-based architecture of organizational carbon accounting and the emission-factor methods used in mining-sector greenhouse-gas inventories contain no altitude term [11,12], and China's enterprise-level accounting guidelines treat a mine as a generic collection of stationary and mobile combustion sources. As a result, when an inventory is compiled for a plateau mine with these methods, emissions are underestimated, and the underestimation is greatest at the sites where the fuel penalty is highest.

A second shortcoming is monetary rather than physical. Mine-level studies typically stop at tonnes of CO₂ equivalent, yet the questions that

reach an investment committee are denominated in currency. What is the carbon cost embedded in a tonne of lithium carbonate equivalent (LCE) or a tonne of zinc metal? How large is it beside the cash operating cost? How would it move if allowance prices doubled, or if the haul fleet were electrified? Answering such questions requires an accounting framework that ties the physical inventory to monitoring expenditure, abatement investment and shadow carbon prices within a single ledger.

The work reported here has three objectives. The first is to build an emission accounting model for high-altitude open-pit nonferrous mines in which fuel use is corrected for altitude. The second is to develop a carbon emission cost accounting framework, so that the inventory can be expressed in monetary terms through its compliance, abatement and carbon-price components. The third is to apply the combined framework to two representative operations in Hotan Prefecture (a lithium mine of the Dahongliutan type and a lead-zinc mine of the Huoshaoyun type) and to calculate their unit carbon costs at the current carbon price and at scenario prices. Metered fuel and electricity data have not yet been published for either project, and for this reason the case application is scenario-based. Production scales, grades and elevations are taken from publicly reported project parameters, and activity data are calibrated against engineering norms for comparable open-pit mines. The results are intended to be useful both for cost management within enterprises and for regional policy design on green mining in northwest China.

2. Literature Review and Theoretical Basis

2.1 Carbon Emission Accounting at the Mine Level

Corporate greenhouse-gas accounting has settled on a scope architecture that separates direct emissions from owned or controlled sources (Scope 1), indirect emissions from purchased energy (Scope 2), and the remaining value-chain emissions (Scope 3) [12]. Quantification is dominated by the emission-factor approach, in which an emission equals an activity statistic multiplied by a source-specific factor, as applied in energy and greenhouse-gas studies of mining and mineral processing [11]. Sectoral studies of mining have mapped the main sources, from diesel fleets and blasting to methane and land

disturbance, and have reviewed the abatement options available to operators [3,4]. China's dual-carbon policy system adds enterprise accounting and reporting guidelines of its own, and officially published electricity CO₂ factors show pronounced regional differences [13]: for 2022 the national average stood at 0.5366 kg CO₂/kWh, while the figure for the province-level grid serving the study area reached 0.6231 kg CO₂/kWh, a spread that mirrors the coal-heavy generation mix of the regional power system.

Within the minerals literature, life-cycle assessment (LCA) has done most of the heavy lifting. Norgate and Jahanshahi established the linkage from falling ore grades to rising energy demand and emissions per unit of metal [14], and later reviews consolidated system boundaries and impact pathways for mining and mineral processing as a whole [15]. For lithium, Kelly and co-workers compared brine and hard-rock supply routes and showed that spodumene mining and concentration contribute on the order of 0.5–1.5 t CO₂e per tonne of LCE before refining, with the refining stage, particularly coal-fired conversion in China, dominating the cradle-to-gate footprint [16]. Useful as these benchmarks are, they rest on global-average or low-altitude data and say little about plateau conditions.

2.2 Carbon Emission Cost Accounting

Carbon emission cost accounting converts a physical inventory into monetary terms and draws on three theoretical traditions. Environmental and full-cost accounting treat environmental burdens as cost objects to be identified, measured, allocated and reported beside conventional costs. The economics of externality internalization, descending from Pigou through modern carbon taxes and emissions trading, explains how a social cost becomes a private one; one recent analysis even suggests that mining could emerge as a net beneficiary of a global carbon price through demand-side effects [17]. The third tradition is management accounting. Methods such as activity-based costing and material flow cost accounting provide the means of tracing carbon-related expenditure and assigning it to cost centers and products. In some respects industry practice is ahead of the theory. Several diversified mining companies already evaluate capital projects using internal shadow carbon

prices, and the prices applied are commonly USD 50–100 per tonne of CO₂e [18].

In China, most research on carbon cost accounting deals with coal mining, thermal power and nonferrous smelting. These are industries in which the processes are stationary and metering is mature. For open-pit coal mines, source inventories have been proposed that include blasting, diesel equipment, spontaneous combustion and seam methane, and in a few studies carbon costs have been incorporated into stripping-ratio optimization or into equipment replacement decisions. By comparison, much less work has been done on metal mining. As for high-altitude nonferrous open pits, their specific conditions have been discussed mainly in the engineering literature on engine derating [9,10], and not from an accounting point of view.

2.3 Research Gap

Three gaps follow from the review above. Existing standards apply no correction for altitude-induced fuel penalties, so inventories for plateau mines are understated. The monetary dimension—monitoring and compliance costs, abatement costs and carbon-price exposure—is seldom integrated with the physical inventory at the scale of a single mine. And no published study has yet examined the lithium and lead-zinc cluster now taking shape in Hotan, despite its strategic weight in China's lithium supply security and its extreme operating environment [5–8]. The framework below is designed to close all three gaps in a form that other plateau operations can replicate.

3. Study Area and Case Mine Profiles

3.1 The Hotan Mining Cluster in Northwest China

Hotan Prefecture spreads along the southern rim of the Tarim Basin, hemmed in to the south by the Kunlun and Karakoram ranges. Two belts dominate its mineral endowment: the West Kunlun–Tethys lead-zinc belt, which hosts the Huoshaoyun deposit and several satellites [8], and the Dahongliutan rare-metal pegmatite belt, part of a Late Triassic lithium-rubidium-beryllium corridor traceable for some 600 km along the Western Kunlun orogen [5–7]. Under regional planning, an integrated green mining cluster is to be formed, which would extend from extraction and smelting to the downstream battery and galvanizing industries. According to

publicly disclosed figures, the total investment of the Huoshaoyun project, including its mining, pipeline and smelting segments, is 26.17 billion CNY, and the design output is 560 kt/a of zinc ingot and 110 kt/a of lead ingot.

Natural conditions in the mining districts are very harsh. The workings are at about 4,600 to 5,700 m above sea level. At this height the partial pressure of oxygen is only about half of that at sea level, and in winter the temperature falls below -30°C . Hotan and Kashgar are the nearest cities, but both are several hundred kilometres away by mountain road, and because grid infrastructure in the mining districts is still sparse, operations in the early stage depend heavily on diesel. There is, however, one advantage. Solar resources in the region are among the strongest in the country, so the conditions for decarbonizing mine-site power supply are comparatively favourable [19].

3.2 Mine L: A Spodumene Lithium Operation of the Dahongliutan Type

The lithium case is based on the pegmatite workings in the Dahongliutan district, and its elevation is taken as roughly 4,800 m [5-7]. Mining is by a conventional drill-blast-load-haul open pit. The ore is sent to an on-site plant for crushing, grinding and flotation, and the product is spodumene concentrate grading 6% Li_2O (SC6). The scenario assumes an ore throughput of 1.2 Mt/a, a head grade of 1.15% Li_2O and a recovery of 75%, which gives about 172.5 kt/a of SC6, or some 25.6 kt/a expressed as LCE. With a stripping ratio of 7:1, total material movement is 9.6 Mt/a. It is assumed that electricity is purchased from the regional power grid and that diesel is used for mobile equipment and space heating.

3.3 Mine H: A Lead-Zinc Operation of the Huoshaoyun Type

The lead-zinc case is based on the engineering design of Huoshaoyun, at roughly 5,600 m elevation [8]. The open pit has an ore capacity of 2.5 Mt/a and works shallow, high-grade oxide ore bodies with average grades of 23.37% Zn and 4.60% Pb. There is no on-site beneficiation; run-of-mine ore is stockpiled and then pumped as slurry to the Kunlun smelter complex. The metal contained in the annual ore flow is about 584 kt of zinc and 115 kt of lead. A stripping ratio of 6:1 is adopted, which corresponds to a total material movement of 17.5 Mt/a. Site

power is needed for pipeline pumps, camps and workshops, and it is assumed that all of it is supplied by captive diesel generator sets. The two cases were chosen so as to cover the range of energy configurations likely to be found in the Hotan cluster. Mine L is grid-connected and processes its ore on site, whereas Mine H is off-grid and ships its ore directly.

4. Carbon Emission Cost Accounting Framework

4.1 Accounting Boundary

The organizational boundary follows the operational-control approach and encloses the open pit, waste dumps, workshops, camps, the concentrator of Mine L or the slurry-pipeline head station of Mine H, and on-site power generation [12]. Within this boundary the emission sources are classified by scope. Three kinds of source are included in Scope 1. These are diesel burned in mobile equipment (haul trucks, excavators, loaders, drills and dozers), diesel burned in stationary plant (heating boilers and captive generators), and blasting, for which the embodied emissions of ammonium-nitrate-based explosives are also counted. Scope 2 consists of the electricity purchased from the regional grid. Scope 3 is screened and reported separately. In this paper it is limited to the upstream production and inbound transport of reagents, grinding media, explosives and fuels. Downstream smelting and refining are not part of the operational inventory, although they are referred to in the discussion where the value chain is concerned.

4.2 Inventory Model with Altitude Correction

Emissions are calculated with the emission-factor method [11], as expressed in Eq. (1):

$$E = \sum_i AD_i \times EF_i \quad (1)$$

Where E is the total emission, AD_i is the activity data of source i (tonnes for fuel and explosives, MWh for electricity), and EF_i is the corresponding emission factor. For diesel combustion, $EF = 3.160 \text{ t CO}_2$ per tonne of diesel is used, derived from a net calorific value of 42.652 GJ/t and the standard carbon content for gas/diesel oil used in mining-sector energy and emission studies [11]. The factor adopted for explosives is $0.18 \text{ t CO}_2\text{e/t}$, and purchased electricity carries the $0.6231 \text{ t CO}_2\text{e/MWh}$ factor published for the regional grid, a value consistent with the pronounced provincial

differences documented for China's power grids [13].

The effect of altitude is introduced by a correction coefficient. It is applied to the activity data of those combustion sources whose oxygen intake depends on ambient air density, and it is defined in Eq. (2):

$$k_H = 1 + \frac{\alpha(H - 1,500)}{1,000}, \quad H > 1,500 \text{ m} \quad (2)$$

Where k_H is the altitude correction coefficient, H is the site elevation in metres, and α is the fuel-penalty gradient. In this paper α is taken as 0.08 per 1,000 m, a value which agrees with the derating practice for plateau equipment and with the engine performance losses of 4–13% per 1,000 m measured at high-plateau sites in western China [9,10]. With this value, k_H is 1.264 at 4,800 m and 1.328 at 5,600 m. The coefficient is applied to mobile-fleet fuel and heating fuel only. Captive generation is treated differently: it is calculated from electrical demand with a brake-specific consumption of 0.27 L/kWh, and since this figure already includes the plateau derating of generator sets, no further correction is made. An inventory without correction ($k_H = 1$) is also calculated as a counterfactual, so that the altitude penalty can be reported explicitly.

4.3 Carbon Emission Cost Model

The carbon emission cost (CEC) of a mine is taken here as the sum of four components, as given in Eq. (3):

$$CEC = C_{MRV} + C_{abate} + C_{trade} + C_{ext} \quad (3)$$

Where $CMRV$ covers the expenditure that a mine incurs simply because it has to account for its carbon, namely metering systems, data platforms, internal carbon-management staff, third-party verification and reporting. For a single mine of the scale considered here, 1.2–1.5 million CNY/a is considered a reasonable planning value. C_{abate} is the annualized capital cost plus the incremental operating cost of emission-reduction measures. Such measures include photovoltaic-plus-storage installations, pilots of electric or trolley-assisted haulage, waste-heat recovery and efficiency retrofits, and the committed capital is annualized by the straight-line method over ten years. C_{trade} is the expected cost of compliance instruments. At present mining is not covered by the national ETS and this term is zero in cash terms, but it is modelled here as a shadow cost equal to the sum of Scope 1 and Scope 2 emissions multiplied by

a carbon price P , for which three scenarios of 40, 70 and 110 CNY/t CO₂ are used. These values were chosen to bracket the 2025 CEA average of 62.36 CNY/t and to reflect the tightening that is expected as sectoral coverage widens [2]. C_{ext} is the residual social cost of unabated emissions. It is not booked into the accounts of the mine and is only discussed qualitatively with reference to social-cost-of-carbon benchmarks. For management purposes, the comprehensive carbon-related cost is reported as $CEC' = CMRV + C_{abate} + C_{trade}$. Dividing CEC' by product output gives the unit carbon cost, where output is measured in tonnes of LCE for Mine L and in tonnes of contained Zn + Pb metal for Mine H.

5. Case Application and Results

5.1 Activity Data and Key Assumptions

The scenario parameters are listed in Table 1. Fleet fuel intensity is set at 1.9 L per tonne of total material for Mine L and 2.0 L/t for Mine H, in line with engineering norms for hard-rock open pits of comparable scale. The value for Mine H is slightly higher because its hauls are longer and its truck fleet is heavier. Explosive consumption is 0.30 kg/t of total material for Mine L and 0.28 kg/t for Mine H. The concentrator of Mine L consumes 48 kWh per tonne of ore. For Mine H the site-wide electrical demand is 20 kWh per tonne of ore, all of which is supplied by captive diesel sets.

Table 1. Key Scenario Parameters of the Two Case Mines

Parameter	Mine L (Li)	Mine H (Pb-Zn)
Elevation (m)	4,800	5,600
Ore throughput (Mt/a)	1.2	2.5
Head grade	1.15% Li ₂ O	23.37% Zn, 4.60% Pb
Stripping ratio	7:1	6:1
Total material (Mt/a)	9.6	17.5
Altitude coefficient	1.264	1.328
Fleet diesel (L/t, base)	1.9	2.0
Power supply	Regional grid	Captive diesel
Product output	172.5 kt SC6 (~25.6 kt LCE)	699 kt Zn + Pb

5.2 Emission Inventory Results

The compiled annual emission inventories are summarized in Table 2. The lithium operation emits about 108 kt CO₂e per year. Of its

operational total (Scope 1 + 2), 57% comes from the diesel fleet and 35% from purchased electricity, which is a typical structure for a mechanized open pit supplied by a coal-heavy grid. In terms of intensity, the result is 84.5 kg CO₂e per tonne of ore, 0.59 t CO₂e per tonne of SC6, or 3.96 t CO₂e per tonne of LCE at the mine-and-concentrator gate. The last figure is near the upper end of published spodumene benchmarks [16]. The difference is attributed mainly to two factors acting together, namely altitude and the regional grid factor.

Table 2. Annual Emission Inventories of the Case Mines (t CO₂e)

Source	Mine L	Mine H
Mobile fleet diesel (S1)	61,200	123,400
Captive generation (S1)	—	35,800
Heating fuel (S1)	3,800	7,900
Explosives (S1)	500	900
Scope 1 subtotal	65,500	168,000
Purchased electricity (S2)	35,900	0
Scope 3 (reagents, logistics)	6,800	5,500
Total (S1 + S2 + S3)	108,200	173,500

The lead-zinc operation emits about 173.5 kt CO₂e per year, although it has no concentrator. Captive diesel generation for pipeline pumping and camp loads accounts for 35.8 kt of this total. Its implied factor is 0.717 t CO₂/MWh, which is roughly 15% higher than the regional grid factor, itself already high. The intensity is 67.2 kg CO₂e per tonne of ore and 0.24 t CO₂e per tonne of contained metal. The figure on a metal basis appears favourable, but this is largely an effect of grade: the combined grade of the deposit is 27.97%, so fixed site emissions are divided by an unusually large metal output. Intensity indicators of this kind therefore reflect ore grade as much as they reflect efficiency.

The altitude correction makes it possible to quantify emissions that conventional accounting would not capture. Compared with the kH = 1 counterfactual, fleet fuel emissions increase from 48.4 to 61.2 kt for Mine L (+26.4%) and from 92.9 to 123.4 kt for Mine H (+32.8%). In absolute terms, the additional emissions caused by plateau conditions are about 12.8 kt CO₂e per year for Mine L and 30.5 kt CO₂e per year for Mine H, which is roughly comparable to the annual footprint of a small town and results only from low air density and low temperature.

5.3 Carbon Cost Results

The resulting carbon-related costs under three carbon-price scenarios are presented in Table 3.

At the central price of 70 CNY/t, the comprehensive carbon-related cost of Mine L is 16.3 million CNY/a, or 637 CNY per tonne of LCE, and that of Mine H is 25.3 million CNY/a, or 36 CNY per tonne of contained metal. Cash operating costs are assumed to be 900 CNY per tonne of ore for Mine L and 420 CNY per tonne of ore for Mine H, so the carbon-related cost is about 1.5% and 2.4% of operating cost respectively. These percentages are not large. Their effect on margins is more noticeable, however. For the lithium mine, 637 CNY/t LCE would take up approximately 5–8% of the cash margin on spodumene concentrate in periods of weak prices. In addition, the shadow cost is proportional to the carbon price. If mining is brought into the ETS and part of the allowances are auctioned, the shadow cost will become a cash cost calculated in the same way.

Table 3. Carbon-Related Costs under Three Carbon-Price Scenarios (Million CNY/a)

Component	P=40	P=70	P=110
Mine L: MRV+abatement	9.2	9.2	9.2
Mine L: shadow cost	4.06	7.10	11.15
Mine L: total CEC'	13.3	16.3	20.4
Mine L: CNY/t LCE	518	637	795
Mine H: MRV+abatement	13.5	13.5	13.5
Mine H: shadow cost	6.72	11.76	18.48
Mine H: total CEC'	20.2	25.3	32.0
Mine H: CNY/t metal	28.9	36.1	45.7

5.4 Sensitivity Analysis

The results are most sensitive to three variables. The first is the carbon price, whose effect is linear. When P increases from 40 to 110 CNY/t, the unit carbon cost of Mine L changes from 518 to 795 CNY/t LCE and that of Mine H from 28.9 to 45.7 CNY/t metal. The second is the power-supply mix, which affects Scope 2 emissions and captive generation. If half of the 57.6 GWh demand of Mine L were met by renewables, its operational emissions would decrease by about 18 kt and CEC' by 1.3 million CNY at P = 70. If Mine H replaced captive diesel with grid power, its power-related emissions would decrease from 35.8 to 31.2 kt, which is a reduction of 13% that could be obtained even before any solar capacity is installed. The third is the altitude coefficient. A variation of ± 0.02 in α changes fleet emissions by ± 3 –4 kt per mine per year. For this reason the generic coefficient should be replaced by metered brake-specific fuel data after the mines have reached steady state.

6. Discussion

Four points can be drawn from the case results. The first concerns altitude, which should be treated as a first-order variable in accounting. With a fleet-fuel penalty of 26–33%, two mines that are identical in every other respect would report materially different intensities if one were on the plateau and the other near sea level. If benchmarking schemes or a future allowance allocation did not take elevation into account, plateau mines would be systematically disadvantaged. An altitude-aware benchmark, by contrast, would acknowledge a physical handicap which operators cannot fully remove by engineering measures. It is therefore suggested that, when regulators consider including mining in the ETS, elevation adjustment be regarded as a necessary part of the design and not as an optional refinement.

The second point is that the structure of carbon cost depends on the commodity and on the energy configuration, and the order of abatement measures should be decided accordingly. For the lithium mine, diesel accounts for 57% of operational emissions and grid electricity for 35%. Fleet electrification and green power procurement are therefore of roughly equal importance. Daytime concentrator loads are well matched to the region's solar endowment, and international experience shows that mine-site solar can supply a large share of electricity demand at competitive cost [19]. The situation of the lead-zinc mine is different, because nearly all of its emissions come from diesel: the fleet and the captive generators together make up over 94% of Scope 1. For this mine the most valuable measure is to connect to the grid or to build a dedicated renewable-plus-storage microgrid, so that generation emitting 0.717 t CO₂ per MWh can be retired. Trolley assist or battery-electric trucks on the fixed ramp routes of the pit would be the next step.

Reading emissions as costs reframes the transition for these strategically important projects. Lithium from Hotan supplies the very battery industry the energy transition requires, and a documented, altitude-aware carbon ledger lets producers show that incremental supply carries a manageable and reducible footprint. That matters commercially: supply-chain sustainability requirements for electric-vehicle batteries, including the carbon-footprint declarations being phased in under the European Union's battery regulation, are turning mine-gate

accounting of the kind demonstrated here into a market-access document rather than a voluntary exercise [20]. Lead and zinc face fewer footprint mandates, but for them carbon accounting doubles as energy-cost management, since diesel dominates both ledgers.

Finally, data infrastructure is the binding constraint. Neither case mine has published metered fuel or power data, and the scenario nature of this study follows directly from that absence. MRV investment, although below 0.2% of project capital cost, is the prerequisite for credible accounting, for developing mine-site renewables into tradable CCER credits, and for readiness should mining be folded into the ETS. The shadow prices adopted here are deliberately conservative compared with recent prices in the voluntary market. It is therefore likely that verified reductions from mine-site solar could offset a noticeable part of abatement spending.

7. Policy and Management Recommendations

(1) Include altitude in the accounting rules. It is recommended that regional pilot guidelines on carbon accounting for plateau mines specify elevation correction coefficients. At the national level, standards issued under the "1+N" framework should include plateau adjustment factors in any future accounting and benchmarking methodology for the mining sector.

(2) Shift mine energy supply towards renewables. For the Hotan cluster, priority should be given to mine-site photovoltaic-plus-storage projects, green power trading and, where it is feasible, grid extension, as has been done in other sun-rich mining regions [19]. Among the measures examined in this study, the retirement of captive diesel generation at Huoshaoyun-type operations gives the largest single emission reduction. The verified savings could be monetized through CCER development.

(3) Electrify the fleet according to duty cycle. The economics of electrification and trolley assist are best for haul trucks that run on fixed routes with high utilization and for slurry-pipeline pumping, so these should come first. Light vehicles and auxiliary equipment can be electrified later, when battery systems are mature enough for plateau winters at -30°C.

(4) Include carbon cost as an item in the mine budget. Carbon cost per tonne of product should appear as a standing item in feasibility studies, stripping-ratio and equipment decisions, and

annual budgets, evaluated at shadow prices consistent with the trajectory of the national ETS [18].

(5) Invest in regional MRV and skills. The Hotan cluster needs metering infrastructure, third-party verification services and carbon-management training. Prefecture-level support would lower compliance costs for every operator and give substance to the green mining cluster label.

8. Conclusions

This study has developed an altitude-corrected carbon emission cost accounting framework for high-altitude open-pit nonferrous mines and demonstrated it on two representative operations in Hotan, northwest China. Applied to a spodumene lithium mine at 4,800 m and a lead-zinc mine at 5,600 m, the framework estimates annual emissions of about 108 kt CO₂e (3.96 t/t LCE at the mine gate) and 173.5 kt CO₂e (0.24 t/t contained metal) respectively. Altitude alone contributes 12.8–30.5 kt of annual emissions across the two sites, an increment that standard uncorrected accounting would understate. At a shadow price of 70 CNY/t CO₂, comprehensive carbon-related costs reach 16.3 and 25.3 million CNY per year, or 1.5–2.4% of operating cost, rising in step with carbon prices and with any future inclusion of mining in the national ETS. Altitude-aware inventories, renewable-based power strategies, staged fleet electrification and early MRV investment together form a credible pathway for Hotan's strategic lithium and lead-zinc resources to be developed as genuinely green assets under the dual-carbon agenda. Further work is needed in three respects. When the mines have reached steady-state production, the scenario parameters used here should be replaced with metered operational data. The boundary should also be extended to smelting so that the full value chain is accounted for, and the framework should be tested on other mines in the wider West Kunlun belt.

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