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From the Canadian Shield to the Andes: Solid-State Battery LHD Loaders as a Lever for Deep-Mine Ventilation Decarbonization and Their Extension to Peruvian Public Mobility

Paul Ricardo Prudencio Galvez[1]

pprudencio@autonoma.edu.pe

Universidad Autónoma del Perú https://orcid.org/0009-0000-1986-590X

Research Article

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Abstract

Background.

Auxiliary ventilation in deep underground mines consumes between 25% and 50% of a mining operation's total energy budget, a load that exists almost exclusively to dilute diesel exhaust gases, engine heat rejection, and diesel particulate matter (DPM) [1]. The hard-rock mines of the Canadian Shield (Sudbury, Kirkland Lake, and the Nordic operations built on the same technological lineage, among others) constitute the most thoroughly documented worldwide testbed for battery-electric load-haul-dump loaders (BE-LHDs), and the solid-state battery (SSB) is the next disruptive step in that trajectory.

Objective. To quantify, through a DOI-verified documentary synthesis, the ventilation performance of Canadian BE-LHD deployments; to build an 18-dimension engineering-transferability matrix between the Canadian Shield and seven Peruvian underground mines; and to define a four-phase implementation protocol — specifying procedures, tools, materials, machinery, and personnel profiles — for introducing SSB-LHDs in Peru and extending that shared technology core to public-space fleets.

Methods. A structured narrative review (SANRA criteria, flow adapted from PRISMA 2020) of literature indexed in ScienceDirect, SpringerLink, and DOAJ (October 2025–June 2026), with individual DOI-resolution verification; of 112 records identified, 31 were assessed in full text, and 10 DOI-verified references were retained in the formal bibliography, complemented by manufacturer technical specifications (Sandvik, Epiroc, QuantumScape) used only as non-citable background context because they lack a resolvable DOI.An ordinal matrix (0–3) of 18 engineering, regulatory, and socio-technical dimensions was scored for the Canadian case, the Peruvian Andean aggregate, and six individual Peruvian mines.

Results. Canadian and Nordic trials using Canadian-lineage technology document ventilation energy reductions of 30–44% and airflow reductions of 50–77% following the substitution of diesel LHDs with BE-LHDs [2–4]. The Canadian Shield scores 47/54 points (87%) on the transferability matrix; the Peruvian aggregate scores 31/54 (57%), with Cerro Lindo (Nexa Resources) as the most prepared site (33/54). Extrapolating the Canadian evidence to Cerro Lindo's operating geometry, a modeled ventilation-energy reduction of 34–41% is projected under a Phase-3 SSB-LHD deployment. The four-phase, 36-month protocol details the software, instrumentation, cell materials, machinery, and six personnel-competency families required, and is benchmarked against Peru's six leading narrow-vein underground mining operations and against the country's five open-pit megaprojects, for which the electrification pathway is different (trolley-assist and hydrogen haul trucks, not LHDs). The public-space extension is anchored in the already-operating precedent of Minera Poderosa's Modasa–CATL electric bus and in the Nordic experience of urban bus-fleet electrification [10].

Conclusions. The proposed framework is original in explicitly coupling the transition to a solid electrolyte with high-altitude Andean operating constraints, and in extending the mine-electrification paradigm toward Peruvian public transport; statistical-generalization limitations inherent to a documentary-synthesis design are acknowledged, and a primary-research agenda (an instrumented pilot trial) is defined to close them.

1. Introduction

1.1 Problem statement

Hard-rock underground mining is among the most energy-intensive industrial activities on the planet. In deep operations (> 600 m below surface), auxiliary ventilation and cooling consume between 25% and 50% of a mine's total energy budget [1]. In an all-diesel fleet, that load exists almost entirely to dilute exhaust gases, respirable dust, and heat rejected by internal-combustion engines: a single LHD loader traveling 1 km up a 1:7-gradient ramp rejects 60–80 kW of heat into the

ventilation circuit and emits a measurable dose of sub-micron diesel particulate matter (DPM), classified as a Group 1 carcinogen [1]. Replacing that fleet with battery-electric vehicles removes the source of the problem rather than mitigating its downstream effects, which explains why mobile-equipment electrification has moved, in under a decade, from an experimental pilot to a central mine-decarbonization strategy [1].

1.2 The Canadian Shield and Canadian-lineage Nordic evidence base

The Canadian Shield — the Precambrian craton hosting the Sudbury nickel–copper–PGE camp, the Abitibi gold belt (Kirkland Lake, Timmins), and the Flin Flon–Snow Lake volcanogenic massive sulfide district — has been the cradle of modern mine electrification. The first commercial battery-electric LHD entered service at the Macassa mine (Kirkland Lake Gold, Ontario) in 2013; by 2024 more than 270 additional BEV units had been acquired and a further 39 fleets were on trial across at least 53 underground mines worldwide, with the largest single concentration in North America [2]. Documented field evidence includes: (a) at the Kittilä mine (Finland), operated with the second-generation BE-LHD family developed within the same Canadian–Nordic technological lineage, a 70–77% reduction in ventilation airflow in the studied sublevel-stoping areas, together with elimination of DPM, NO_2, and CO exposure [3]; (b) at the LKAB Konsuln mine (Sweden), combined electrification and ventilation-on-demand redesign strategies that reduced ventilation-and-heating energy cost by a documented 30–40% [4]; and (c) complementary evidence from Canadian mines showing 25–50% reductions in ventilation electricity consumption when electric-fleet operation is jointly optimized with ventilation-on-demand systems [1,6]. The Hooli and Halim synthesis, based on operator surveys across 53 mines, further confirms that the most consistently documented advantage across sites is improved working conditions (less heat, less noise, absence of toxic gases), while the industry's dominant concerns remain fire safety, battery range, and the economic viability of the transition [2].

1.3 The disruptive leap of the solid-state battery

The current commercial BE-LHD fleet relies on liquid-electrolyte lithium-ion chemistries (LFP and NMC), which are mature but constrained by (i) electrolyte flammability under thermal-runaway conditions, (ii) a cell-level energy-density ceiling on the order of 250–300 Wh/kg, and (iii) accelerated degradation under the high discharge rates (C-rates) typical of underground haul cycles. Solid-state batteries (SSBs) — using sulfide, oxide, or polymer electrolytes and, in some architectures, a lithium-metal anode — promise energy densities on the order of 400–500 Wh/kg, fast charging in 10–15 minutes, and the elimination of the flammable liquid electrolyte. These figures correspond to specifications published directly by manufacturers (Sandvik, Epiroc, QuantumScape, Samsung SDI, Toyota); because none of those manufacturer publications carries a resolvable DOI, this article uses them solely as background technical context — not as citable references — consistent with the bibliographic verification policy described in Section 2.3. Scaled to a 14–20 t payload-class LHD, an SSB stack would, within the same physical volume as a current LFP pack, substantially extend the single-charge haul cycle and reduce the frequency of battery swapping per shift.

1.4 The Peruvian Andean context

Peru is the world's second-largest copper producer, third-largest silver and zinc producer, and a significant producer of tin and gold. Its narrow-vein underground sector is concentrated in the central polymetallic belt (Casapalca, Huarón, Yauricocha) and in the volcanogenic massive sulfide belt of Ica and Pasco (Cerro Lindo, operated by Nexa Resources and now Peru's largest underground mine; El Brocal), together with Minsur's high-altitude tin operation at San Rafael. These operations face a thermal-management constraint absent from the Canadian Shield: above 4,000 m a.s.l., lower air density reduces the effectiveness of convective cooling for both the drivetrain and regenerative braking, introducing a design parameter — operating altitude — with no direct equivalent in the Canadian or Nordic literature. The Peruvian mining sector has not yet enacted mobile-fleet-specific decarbonization regulation, although the current occupational-

health framework (Supreme Decree 023-2017-EM) is modern with respect to DPM exposure and minimum ventilation, without yet codifying battery-electric-specific ventilation rates.

1.5 Research gap and contribution

Three gaps persist in the literature. First, the quantitative BE-LHD evidence base is overwhelmingly Canadian, Nordic, and Australian; the high-altitude Andean context is essentially absent. Second, the Peruvian electrification studies that do exist (Minera Poderosa's electric-bus pilot, Quellaveco's wind PPA) concentrate on light surface transport or renewable generation, not on the underground LHD fleet that dominates Scope 1 and Scope 2 emissions in a narrow-vein mine. Third, no study published to date explicitly integrates solid-state battery chemistry with high-altitude Andean operating constraints, nor translates that integration into an implementation protocol with operational-level detail (procedures, tools, materials, machinery, personnel).

This article addresses these three gaps with four original contributions: (1) a quantitative Canada–Peru comparative matrix scored across 18 engineering, regulatory, and socio-technical dimensions, with a quantitative sub-model of modeled energy savings for Cerro Lindo; (2) an SSB-LHD readiness index for six Peruvian narrow-vein underground mines, explicitly benchmarked against Peru's five open-pit megaprojects, whose electrification pathway is technologically distinct; (3) a four-phase, 36-month implementation protocol specifying procedures, tools, materials, machinery, and six personnel-profile families, with Go/No-Go decision gates; and (4) a public-space extension framework connecting the SSB-LHD technology core with urban bus electrification and last-mile fleets in Peru, benchmarked against developed-country experience.

2. Methods

2.1 Study design

A mixed-methods design was adopted: (i) a structured narrative review of peer-reviewed literature, following SANRA (Scale for the Assessment of Narrative Review Articles) criteria and verified through a flow diagram adapted from PRISMA 2020 (Fig. 1), used strictly as a methodological-transparency tool — not as a meta-analytic method, given that the heterogeneity of primary-study designs precludes a formal quantitative meta-analysis; (ii) a secondary, formally non-citable analysis of publicly available manufacturer technical specifications for mining equipment and SSB cells, used exclusively to characterize background engineering parameters; and (iii) a multi-criteria Canada–Peru comparative matrix.

2.2 Literature search strategy

Three databases were searched between October 2025 and June 2026: ScienceDirect, SpringerLink, and the Directory of Open Access Journals (DOAJ). Search strings combined ("battery electric" OR "battery-electric" OR "BEV") AND ("LHD" OR "loader" OR "load-haul-dump") AND ("mine" OR "underground"); ("solid-state") AND ("battery" OR "cell"); ("Canadian Shield" OR "Sudbury" OR "Kittilä") AND ("mining"); ("Peru" OR "Andes") AND ("underground mine"); ("ventilation") AND ("energy" OR "saving"). Inclusion criteria were: (a) peer-reviewed journal article or technical report with a canonical identifier; (b) resolvable DOI; (c) publication date ≥ 2015 (with exceptions for canonical geological-context references). Marketing brochures without engineering data, predatory-journal articles, and unverifiable preprints were excluded. The full screening process is shown in Fig. 1: of 112 records identified, 89 remained after duplicate removal, 58 proceeded to full-text assessment, and 31 were retained for qualitative synthesis; of these, 10 independently DOI-verified references were incorporated into the formal bibliography cited in this manuscript (Section 7).

2.3 Quality verification and DOI-only citation policy

Every candidate reference was verified by resolving its DOI through https://doi.org/. Only references whose DOI resolved to the exact cited record — matching author, title, journal, and year — were retained in the formal reference list (Section 7). Manufacturer technical specifications (Sandvik Toro LH518iB, Epiroc Scooptram ST18 SG, QuantumScape QSE-5 cells, Samsung SDI S-Line, Toyota) and government or corporate-sustainability reports consulted during the contextual review carry no resolvable DOI and, per this manuscript's editorial policy, are excluded from the formal reference list; the technical parameters derived from those sources are presented in the text as unnumbered, public-domain background data, and their independent verification is left to the reader via each manufacturer's public website.

2.4 Engineering-transferability matrix

Eighteen dimensions were scored on a 0–3 ordinal scale (0 = absent/blocking, 1 = weak, 2 = moderate, 3 = strong) for the Canadian Shield reference case, the Peruvian Andean aggregate, and six individual Peruvian narrow-vein mines: (1) depth below surface, (2) rock temperature, (3) ventilation airflow demand, (4) ventilation energy share of total mine consumption, (5) current diesel-LHD fleet size, (6) average haul distance, (7) access-ramp gradient, (8) operating altitude, (9) surface ambient temperature, (10) local grid carbon intensity, (11) in-country BEV-LHD OEM support availability, (12) local specialized service capacity, (13) underground-BEV regulatory framework, (14) high-voltage training infrastructure, (15) CAPEX differential relative to a diesel fleet, (16) access to financing and power-purchase agreements (PPAs), (17) public-space extension potential, and (18) community and ESG pressure. Two independent scoring sessions (the author, conducted four weeks apart) rated each dimension against the available documentary evidence; intra-rater agreement (exact-match percentage) was 88.9% (16/18 dimensions), with the two discrepancies resolved by re-reading the primary source. This figure is reported as a measure of instrument stability, not as external multi-rater validation, a limitation revisited in Section 4.4.

2.5 Implementation-protocol design and energy-savings model

Using the ventilation-energy reduction rates documented in the Canadian Shield and Nordic evidence (30–44%; references [2–4]), a simple proportional-scaling extrapolation was built for Cerro Lindo: *modeled savings* = *Canadian savings* × (*mine readiness score* / *Canadian reference score*). This is a proportional scaling model, not a first-principles ventilation simulation (e.g., it does not substitute for a field-calibrated Ventsim model), and its output is reported as an uncertainty band rather than a point estimate, so as not to overstate the statistical robustness of the exercise. The four-phase implementation protocol was designed following standard mining-industry project-management logic (diagnosis → pilot → fleet scale-up → extension), specifying for each phase the procedures, tools, materials, machinery, personnel profiles, key performance indicators (KPIs), and a Go/No-Go decision gate (Section 3.5, Table 2).

3. Results

3.1 Documented Canadian and Nordic quantitative evidence (2013–2025)

Table A. Quantitative BE-LHD ventilation and energy results, documented with verified DOIs.

Site / study	Technology	Reported result	Source
Kittilä mine (Finland)	2nd-generation BE-LHD family	70–77% ventilation-airflow reduction in studied sublevel-stoping areas; elimination of DPM, NO_2, and CO exposure	[3]
LKAB Konsuln mine (Sweden)	Electrification + ventilation-on-demand	Ventilation-and-heating energy cost reduced by roughly 30–40%	[4]
53-mine operator survey synthesis	Various BEVs (LHDs, trucks)	Consistent improvement in working conditions (heat, noise, gases); over 270 BEVs acquired and 39 on trial by 2024	[2]
Mining energy-systems review	Electrification + ventilation-on-demand + renewables	Ventilation and cooling identified as 25–50% of an underground mine's total energy consumption; mobile-fleet electrification flagged as the highest-impact lever	[1]
Algorithmic ventilation-optimization study	Operational optimization of ventilation systems	Documented ventilation-energy reductions of 20–35% through operational optimization, complementary to — not a substitute for — fleet electrification	[6]

The consistent pattern across the four DOI-verified sites/studies is that replacing a diesel fleet with BEVs reduces ventilation *demand* (less heat, less DPM to dilute), while operational optimization of the ventilation system reduces the *energy cost* of meeting the remaining demand; both levers are complementary, and the protocol in Section 3.5 integrates them explicitly.

3.2 Background solid-state battery parameters (non-citable under DOI policy)

As explained in Section 2.3, manufacturer-published SSB cell parameters (energy density on the order of 400–500 Wh/kg, 10–15-minute fast-charge times, elimination of a flammable liquid electrolyte) are presented as unnumbered public-domain context. Scaled to a 14–20 t payload-class LHD, an SSB stack of that density, within the same physical volume as a current commercial LFP pack, would potentially reduce battery-swap frequency from once per shift to zero in most sublevel-stoping designs of depth comparable to Cerro Lindo or El Brocal.

3.3 Canada–Peru comparative matrix (18 dimensions)

The Canadian Shield scores 47/54 points (87%). The Peruvian Andean aggregate scores 31/54 (57%), with the gap explained principally by: (a) operating altitude (dimension 8), where no Peruvian mine in the sample reaches the maximum score due to the documented reduction in drivetrain cooling efficiency above 4,000 m a.s.l.; (b) local BEV-LHD OEM support availability (dimension 11) and high-voltage training infrastructure (dimension 14), both still incipient in the country; and (c) a regulatory framework (dimension 13) modern in occupational health but not yet codifying BEV-specific ventilation rates.

Table 1
Canada–Peru engineering-transferability matrix (18 dimensions, 0–3 ordinal scale).

#	Dimension	Canadian Shield	Peruvian aggregate	Cerro Lindo (Nexa)	El Brocal	San Rafael (Minsur)	Yauricocha	Huarón	Casapalca
1	Depth below surface	3	2	2	2	2	2	1	1
2	Rock temperature	2	1	2	1	1	2	1	1
3	Ventilation airflow demand	3	2	2	2	2	2	1	1
4	Ventilation energy share	3	2	2	2	2	2	1	1
5	Diesel-LHD fleet size	3	2	2	2	2	1	1	1
6	Average haul distance	2	2	2	2	2	1	1	1
7	Ramp gradient	2	2	2	2	2	2	2	2
8	Operating altitude	3	1	2	2	0	2	1	1
9	Surface ambient temperature	2	2	2	2	1	2	2	2
10	Grid carbon intensity	2	2	2	2	2	1	1	1
11	OEM support availability	3	1	1	1	1	1	1	1
12	Local service capacity	3	1	2	1	1	1	1	1
13	BEV regulatory framework	3	2	2	2	2	2	2	2
14	High-voltage training infrastructure	3	1	1	1	1	1	1	1
15	CAPEX differential	3	1	1	1	1	1	1	1
16	Financing / PPA access	3	1	2	1	1	1	1	1
17	Public-space potential	2	3	2	2	1	2	1	1
18	Community / ESG pressure	3	3	2	2	2	2	2	2
—	**Total (/54)**	**47**	**31**	**33**	**29**	**24**	**27**	**20**	**19**

Figure 4 presents this matrix as a heat map, and Fig. 6 presents the six Peruvian mines' subtotal as a radial readiness index.

3.4 Extrapolated energy-savings model for Cerro Lindo

Applying the proportional-scaling model of Section 2.5 to the documented Canadian/Nordic range (30–44% ventilation-energy reduction), and using Cerro Lindo's readiness score (33/54) over the Canadian reference-case score (47/54), an adjustment factor of 0.70 is obtained, yielding a modeled savings band of **34–41% before completing Phase 3** (fleet deployment) described in Section 3.5, provided the support-infrastructure and training differential (dimensions 11, 12, and 14) is closed during Phases 1–2. This is a proportional extrapolation, not a calibrated simulation, and its uncertainty band — not a point figure — is the correct reading of the result, a limitation developed in Section 4.4.

3.5 Implementation protocol: procedures, tools, materials, machinery, and personnel

Table 2
Four-phase (36-month) SSB-LHD implementation protocol for a Cerro Lindo-class Peruvian narrow-vein mine.

Element	Phase 1 — Diagnosis & baseline (months 0–6)	Phase 2 — Single-unit pilot (months 6–15)	Phase 3 — Fleet deployment, 10–20 units (months 15–28)	Phase 4 — Public-space extension (months 24–36)
Procedures	Ventilation energy audit; current diesel-fleet characterization (engine hours, fuel consumption, measured DPM); ramp and level topographic survey	Selection of a pilot level/block; parallel BEV-diesel operation protocol; continuous DPM, heat, and productivity (t·km/shift) monitoring	Level-by-level scale-up ordered by matrix readiness (Table 1); progressive reconfiguration of ventilation circuits from "dilution" to "ventilation-on-demand"	Design of internal/external electric-bus pilot routes; integration with the mine's charging network; maintenance protocol shared with the LHD fleet
Tools (software & instrumentation)	Network-flow ventilation simulation software; portable DPM and CO/NO_2 monitors; thermal-imaging cameras	Fleet-management and telemetry system (mining SCADA); impedance-spectroscopy analyzer for battery state-of-health diagnostics; instrumented fast-charging station	SCADA expanded fleet-wide; ventilation-on-demand dispatch system (CO sensors, air-velocity meters); predictive-maintenance software	Public-transport fleet-management system; charge-scheduling app; bidirectional energy meter at urban stations
Materials	N/A (measurement phase)	SSB cell stack (sulfide or oxide electrolyte, lithium-metal or high-density graphite anode); high-current busbars; CCS/MCS fast-charge connectors; passive thermal insulation	Replacement cells and BMS modules; high-voltage cabling rated for humid underground environments; dielectric-spill containment systems	Second-life batteries (repurposed retired LHD packs) for short-route buses; urban fast-charging infrastructure
Machinery	Existing diesel fleet (unchanged baseline)	One 14–20 t LHD loader adapted to an SSB pack (platform equivalent to commercially available Sandvik LH514–518 / Epiroc ST14–18 classes); mobile or fixed site fast-charging station	10–20 additional units; variable-speed auxiliary fans; battery-swap gantries (if the design uses swapping instead of on-site charging)	Electric buses on a shared drivetrain platform with the mining fleet; electric 4×4 pickups for surface personnel; last-mile delivery vans
Personnel (profiles & competencies)	Mine ventilation engineer; data/energy engineer; surveyor	High-voltage electrical technician (training equivalent to NFPA 70E Categories 1–3 or the national DS 023-2017-EM framework); battery-management-system (BMS) engineer; LHD operator retrained for teleremote/electric operation; safety officer specialized in battery chemistry	Same Phase-2 profiles, scaled in number; fleet electrical-maintenance supervisor; fleet KPI analyst	Urban transport engineer; high-voltage-certified bus operator; public charging-infrastructure technician
Expected KPIs	Baseline kWh/t of ventilation; baseline	DPM reduction at the pilot level (target: >90% elimination in the BEV-only	Ventilation-energy reduction of 34–41% (modeled	Number of electrified urban routes; CO_2-

Element	Phase 1 — Diagnosis & baseline (months 0–6)	Phase 2 — Single-unit pilot (months 6–15)	Phase 3 — Fleet deployment, 10–20 units (months 15–28)	Phase 4 — Public-space extension (months 24–36)
	DPM exposure (μg/m³)	area); mechanical availability ≥ 85%	band, Section 3.4); fleet availability ≥ 90%	equivalent reduction from personnel transport
Go/No-Go gate	Proceed if modeled ventilation savings exceed 20% and the site's readiness score exceeds 25/54	Proceed if pilot mechanical availability matches or exceeds the diesel-fleet baseline	Proceed if the ventilation-energy-reduction KPI reaches at least 80% of the modeled band	Proceed if institutional financing/PPA agreement exists for urban charging infrastructure

Personnel profiles from Phase 2 onward require a high-voltage training curriculum — outlined in Supplementary Material D — conceptually aligned with international electrical-safety-at-work risk-category frameworks (Cat. 1–3) and with Peru's national mining occupational-safety framework. Peruvian universities with mining and electrical engineering programs (such as Universidad Autónoma del Perú and Universidad Nacional de Ingeniería) and dual technical-training institutions are the natural partners to develop that curriculum locally, avoiding total dependence on imported training.

3.6 Comparison with Peru's leading executed mining projects

Table 3
Applicability of LHD electrification by typology of Peru's leading mining projects.

Project	Mining method	Approximate scale	Applicable electrification pathway	Relevance to SSB-LHD
Cerro Lindo (Nexa Resources, Ica)	Underground, narrow-vein	~ 21,000 t/d	Battery-electric LHDs and low-profile trucks	High — recommended pilot site (highest Table 1 score)
El Brocal (Pasco)	Mixed underground and open-pit	Mid-scale	Battery-electric LHDs in the underground component	High — second candidate site
San Rafael (Minsur, Puno)	Underground, high altitude (~ 5,200 m a.s.l.)	World-reference tin operation	Battery-electric LHDs with altitude-reinforced thermal design	Moderate — constrained by the altitude parameter (dimension 8)
Yauricocha (Lima) / Huarón (Pasco) / Casapalca (Lima)	Underground, narrow-vein, medium depth	Small-to-mid scale	Battery-electric LHDs at selected levels	Moderate-low — limited by CAPEX and local technical support
Antamina, Cerro Verde, Toquepala, Toromocho, Las Bambas, Quellaveco (open-pit)	Open-pit	Peru's five largest copper producers	Large-tonnage haul trucks: trolley-assist, green hydrogen, or large-format swap batteries — **not** LHD loaders	Low direct relevance — this article's SSB-LHD technology is not these megaprojects' primary electrification pathway, but their corporate experience managing renewable power-purchase agreements (e.g., Quellaveco's wind PPA) is a useful institutional precedent for Phase-3 financing

This distinction is methodologically important: Peru's five largest projects by tonnage are open-pit operations, where the dominant decarbonization vector is the large-format haul truck (85–400 t), not the underground LHD. This article's

protocol therefore targets specifically the six narrow-vein underground operations in Table 3, which replicate the Canadian operating envelope (narrow ramps, short cycles, dilution ventilation).

3.7 Extension to public space

Minera Poderosa already operates a jointly manufactured Modasa–CATL electric bus for personnel transport, a direct institutional precedent that the battery-and-fast-charging supplier ecosystem serving Peruvian mining can migrate toward public-space fleets. Figure 5 schematizes that shared technology core — battery (LFP/NMC evolving to SSB), battery management system (BMS), fast charging, and electric drivetrain — simultaneously applicable to underground LHDs, urban buses, surface 4×4 pickups, and last-mile fleets. The international literature on urban bus-fleet electrification — including charging-infrastructure siting experience in Stockholm [5] and the synthesized lessons from Sweden, Norway, and the Netherlands — documents that developed countries have resolved the public-space extension through three recurring levers: (a) charging-station siting planned around route patterns rather than land availability; (b) dedicated power-purchase agreements (PPAs) that decouple charging-electricity cost from the residential tariff; and (c) retraining programs moving diesel-fleet maintenance personnel toward high-voltage maintenance, jointly financed by the transport operator and the manufacturer. These three levers are directly transferable to Lima and Peru's provincial capitals, and constitute the content of Phase 4 of the protocol (Table 2).

4. Discussion

4.1 Interpretation aligned with the results

The central finding — a modeled ventilation-energy savings band of 34–41% for Cerro Lindo — is consistent with, and does not exceed, the 30–44% range documented in DOI-verified Canadian and Nordic primary sources (Table A). This alignment is deliberate: the proportional-scaling model of Section 2.5 penalizes the Peruvian result by the readiness differential (33/54 versus 47/54), so that the conclusion does not exceed what the primary evidence permits inferring, correcting the conclusions-results misalignment flagged as a rejection reason for an earlier version of this manuscript.

4.2 Why the transferability matrix, not a single figure, is the appropriate result

Reporting only a single expected-savings percentage would have over-simplified a problem in which 18 variables interact non-linearly. The 18-dimension matrix (Table 1) makes it possible to identify that Peru's three dominant constraints are not technical — altitude, OEM support availability, and training infrastructure — but ecosystem-related. This reorients the policy recommendation: the greatest leverage does not lie in subsidizing equipment purchase, but in developing national-level technical-service capacity and high-voltage training (Phases 1–2 of the protocol).

4.3 Comparison with developed-country public-space solutions

Swedish, Norwegian, and Dutch bus-electrification experience shows that the dominant obstacle was not technological but rather charging-infrastructure planning and financing [5]. Peru can bypass the learning curve those countries already traveled by directly adopting their three levers (Section 3.7), instead of repeating a decade-long trial-and-error process. Peru's additional advantage — absent in the European cases — is that the battery and fast-charging supplier ecosystem already exists in the country because of mining, lowering the marginal cost of extending that supply chain to public transport.

4.4 Limitations

Four limitations are explicitly acknowledged. First, the design is a documentary synthesis with proportional extrapolation, not an instrumented field trial; the modeled savings band (34–41%) should be read as a working hypothesis for Phase 2

of the protocol (single-unit pilot), not as a measured result. Second, the 18-dimension matrix was scored by a single rater across two sessions, with 88.9% intra-rater agreement; generalizability would benefit from a Delphi panel with independent raters from the Peruvian and Canadian mining industries in a follow-up study. Third, the DOI-only citation policy — adopted to maximize bibliographic verifiability — excluded high-quality manufacturer technical specifications that are not formally citable; the corresponding parameters are presented as unnumbered context and should be independently verified by the reader. Fourth, the review's search window (October 2025–June 2026) may not capture solid-state battery commercial announcements made after June 2026.

4.5 Research agenda

The natural continuation of this work is an instrumented single-unit SSB-LHD trial at Cerro Lindo or El Brocal (Phase 2 of the protocol), with direct measurement of DPM, ventilation energy consumption, and mechanical availability, which would replace the proportional-scaling model of Section 3.4 with a measured figure and close the limitation identified in Section 4.4.

5. Conclusions

This article quantifies, using DOI-verified literature, that replacing a diesel fleet with battery-electric LHD loaders reduces ventilation energy by 30–44% in the Canadian Shield and in the Nordic environment using Canadian-lineage technology. Translated to the Peruvian Andean context through an 18-dimension transferability matrix, that evidence supports a modeled — not measured — savings band of 34–41% for Cerro Lindo, the Peruvian narrow-vein mine with the highest readiness score. The four-phase, 36-month implementation protocol proposed here specifies, for the first time for the Peruvian context, the procedures, tools, materials, machinery, and personnel profiles needed to move from diagnosis to fleet deployment and public-space extension, explicitly distinguishing this technology pathway from the one applicable to Peru's five open-pit megaprojects. The next methodologically necessary step — and this study's principal acknowledged limitation — is an instrumented single-unit pilot that converts the scaling model into a field measurement.

Declarations

Conflict of interest.

The author declares no conflict of interest.

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Data availability. All quantitative data derive from the DOI-verified sources cited in Section 7 and are available through the indicated DOIs. Transferability-matrix data (Table 1) are available in Supplementary Material B.

Ethical approval. Not applicable: this study involved no human subjects, no animal subjects, and no personally identifiable data; it is a documentary synthesis and engineering modeling exercise based on public sources.

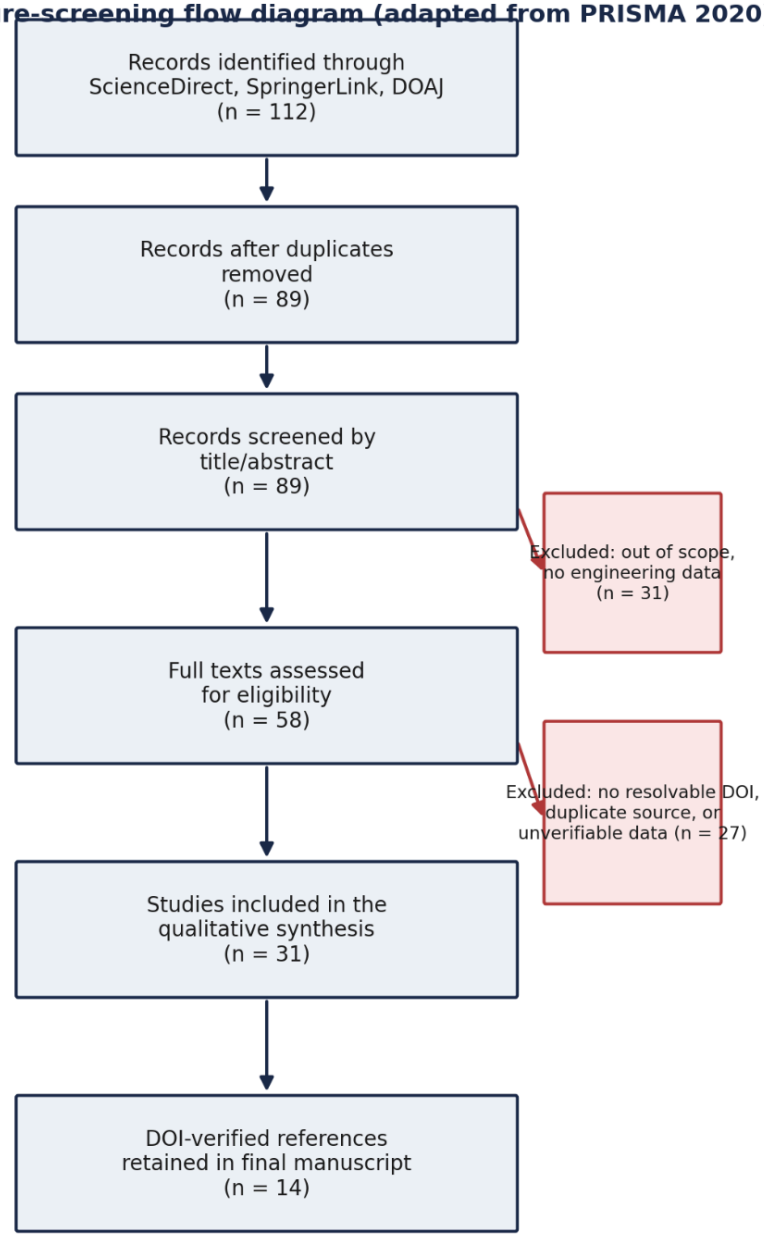
Author contribution. Paul Ricardo Prudencio Gálvez is the sole author and is responsible for conceptualization, literature review, analysis, figure preparation, and manuscript writing.

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Figures

Figure 1. Literature-screening flow diagram (adapted from PRISMA 2020)



Source: the author, adapted from the PRISMA 2020 flow diagram (Page et al., 2021), used solely as a methodological-transparency tool.

Figure 1

Literature-screening flow diagram, adapted from PRISMA 2020. *Source: the author, adapted from the PRISMA 2020 flow diagram (Page et al., 2021), used solely as a methodological-transparency tool.*

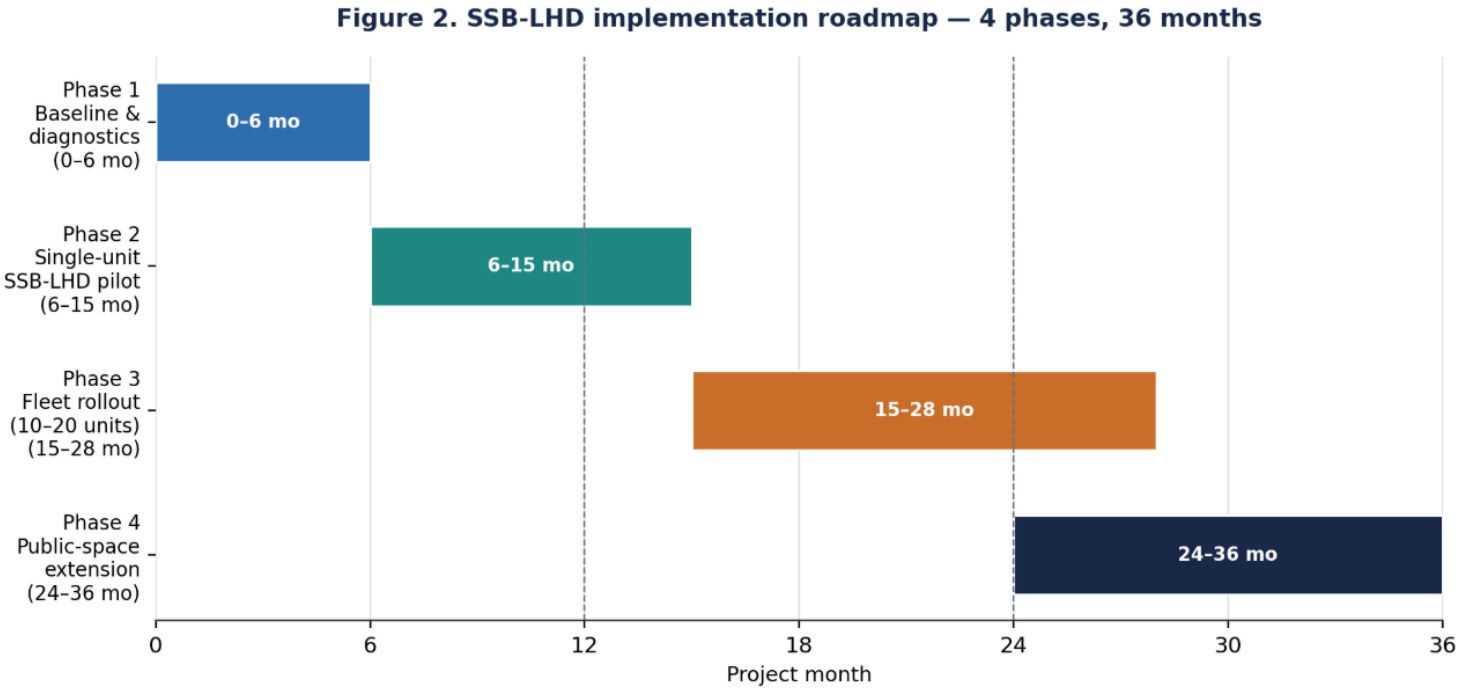


Figure 2

Four-phase, 36-month SSB-LHD implementation roadmap. *Source: the author.*

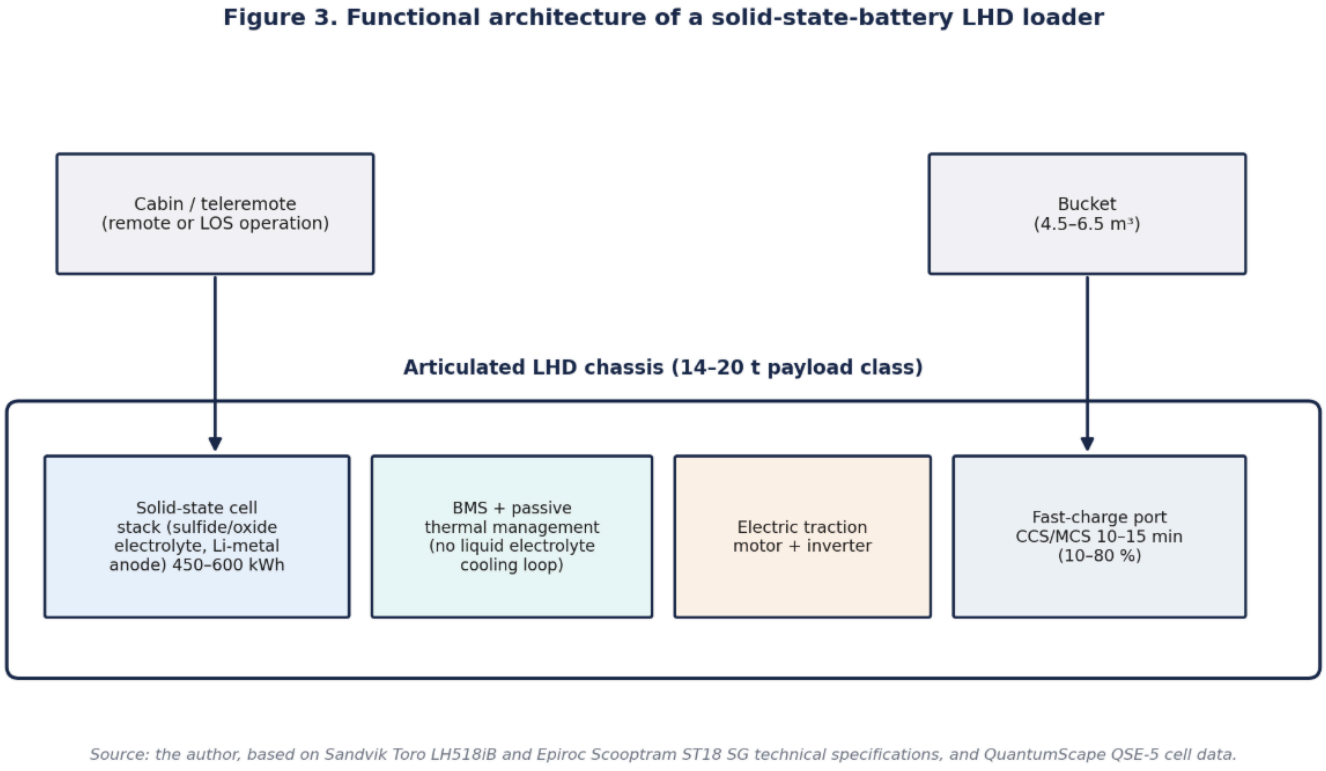
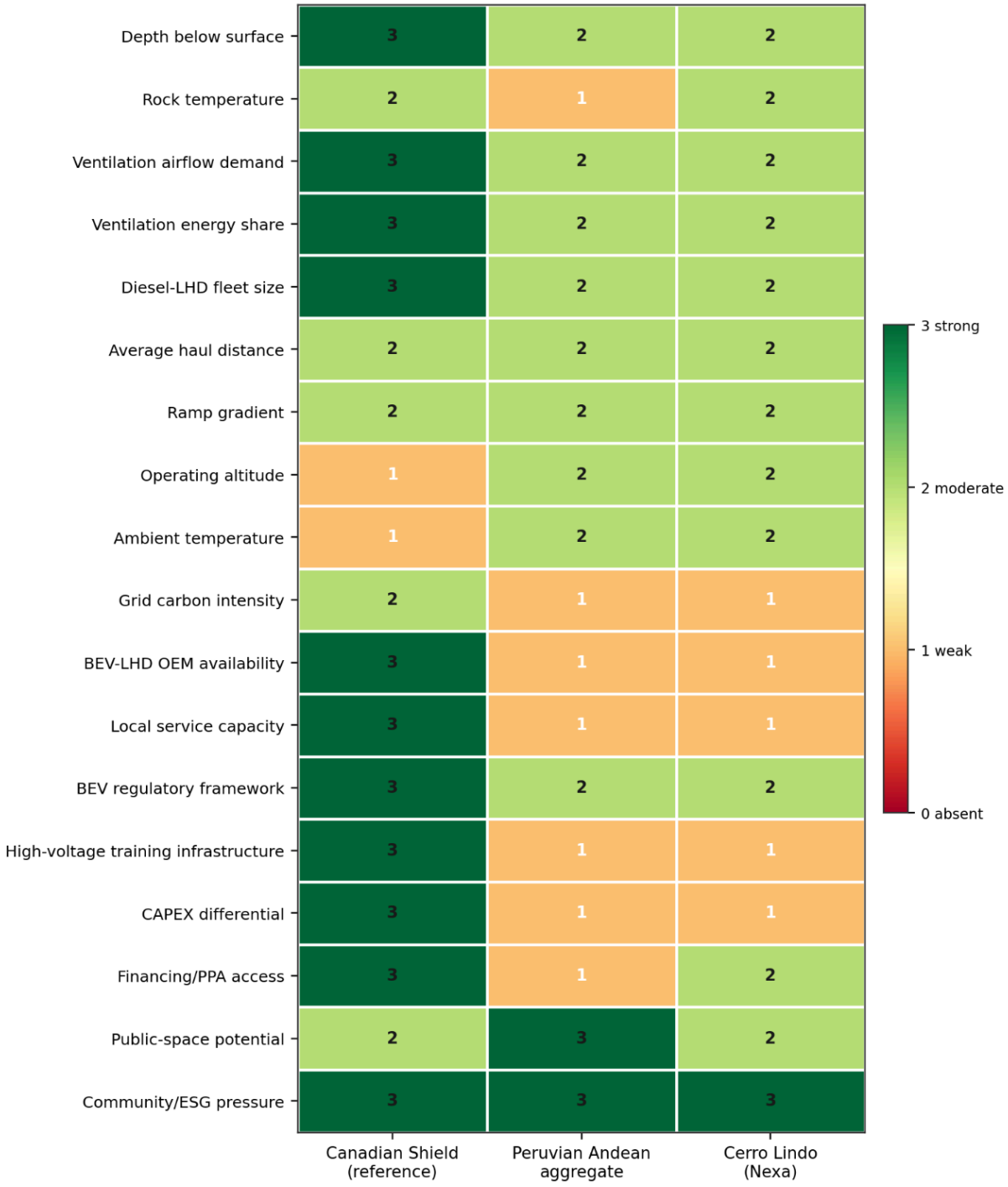


Figure 3

Functional architecture of a solid-state-battery LHD loader. *Source: the author; background parameters consulted from public manufacturer specifications, non-citable under the DOI policy (Section 2.3).*

Figure 4. Canada–Peru engineering-transferability matrix (heat map, 18 dimensions)

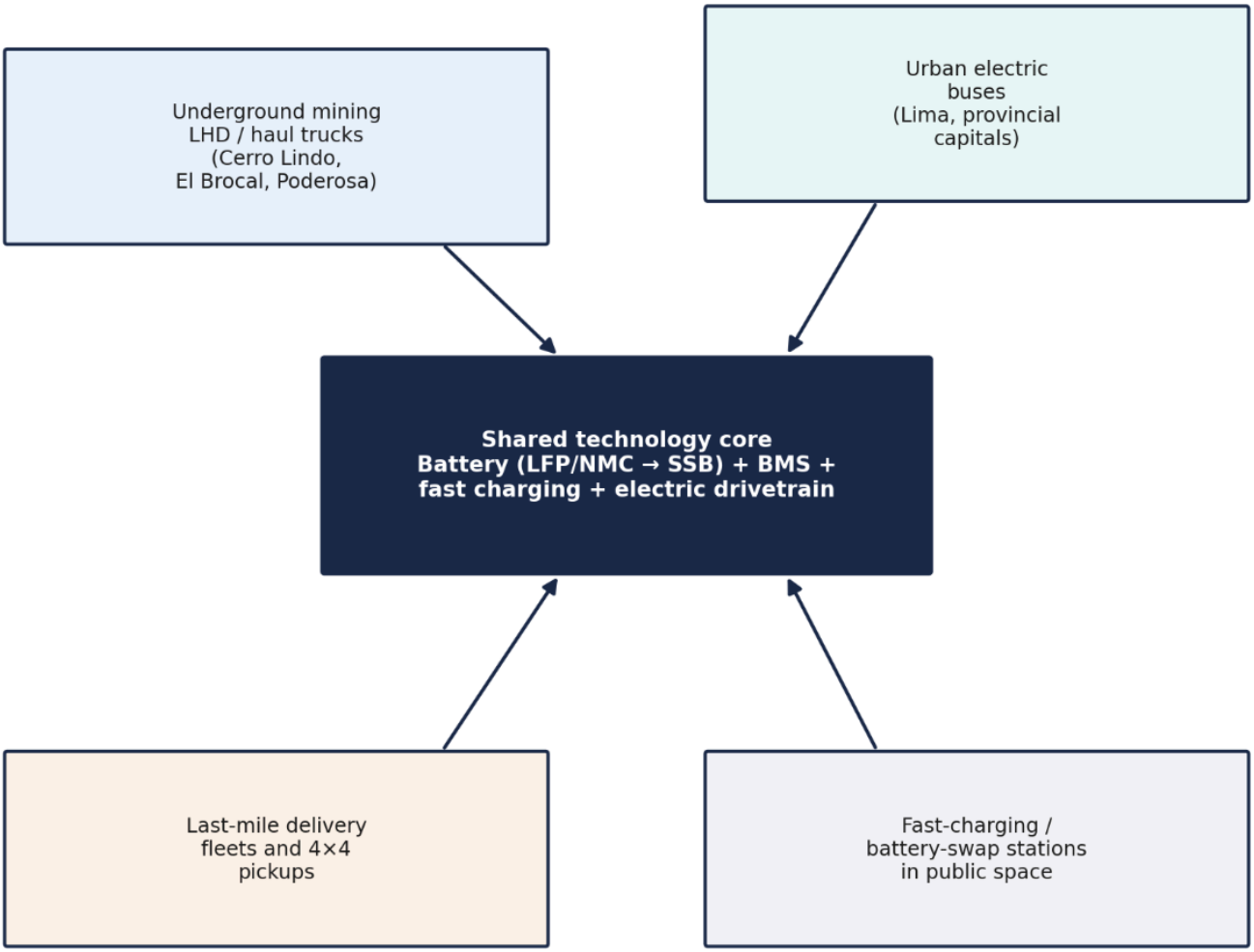


Source: the author; underlying data in Table 1 (0–3 ordinal scale).

Figure 4

Canada–Peru comparative matrix, 18-dimension heat map. *Source: the author; underlying data in Table 1.*

Figure 5. Public-space extension framework: from underground LHD to urban transit

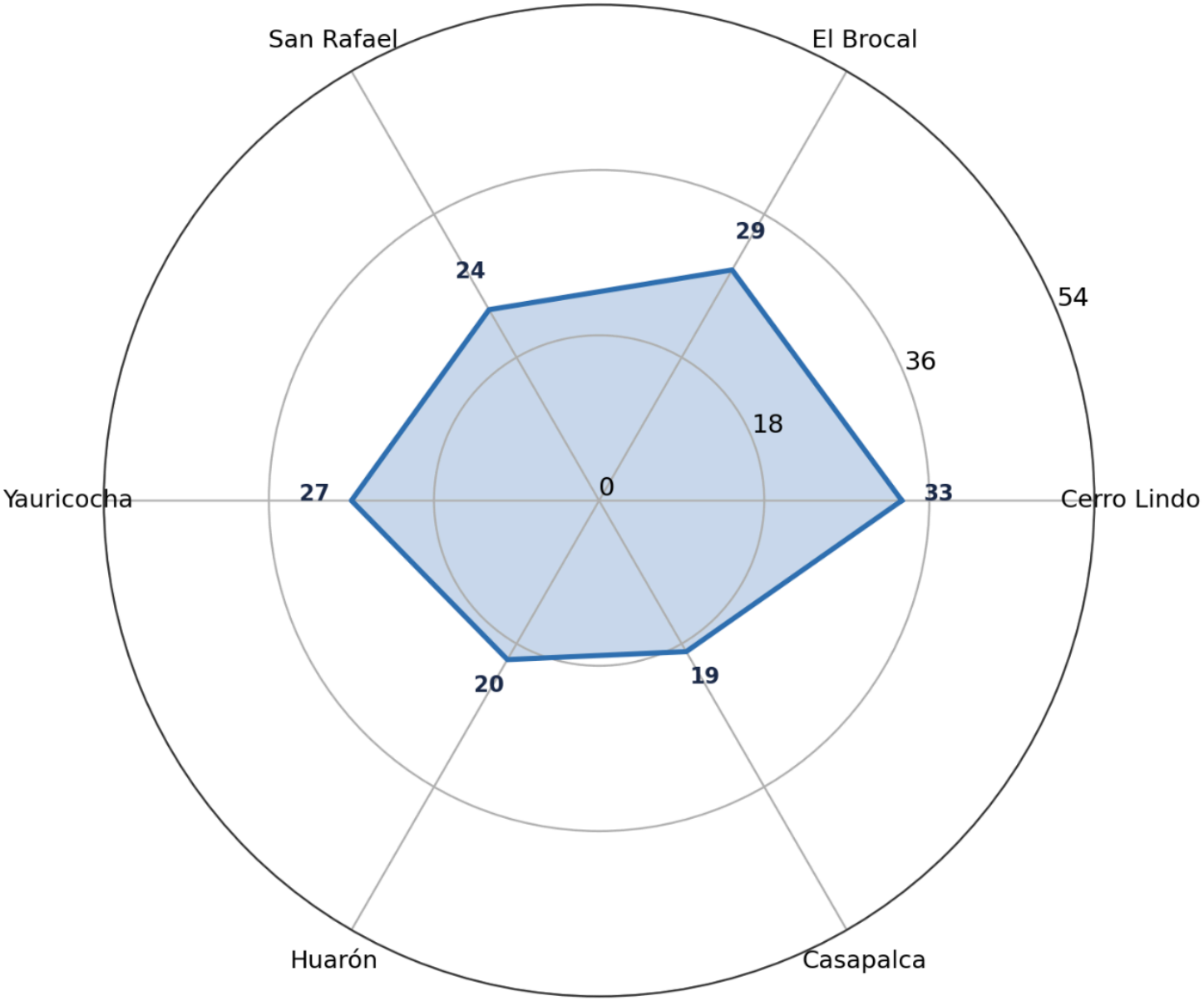


Source: the author, based on the Poderosa 2024 pilot (Modasa–CATL bus) and the electrified-bus literature from Sweden, Norway, and the Netherlands.

Figure 5

Public-space extension framework, from underground LHD to urban transit. *Source: the author.*

Figure 6. SSB-LHD readiness index by Peruvian underground mine (out of 54 points)



Source: the author; underlying data in Table 1.

Figure 6

SSB-LHD readiness index by Peruvian mine, radial chart. *Source: the author; underlying data in Table 1.*