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PAPER

Australia's greener path in a competitive global lithium supply chain

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Abstract

Lithium is vital for the decarbonization transition. With Australian mines supplying over 50% of global demand, building greener lithium mining in Australia is essential. Therefore, this study conducts a site-specific assessment of all seven Australian mine sites in the latest decade, examining factors such as ore yield, grade, mining costs, and emission intensity. Our analysis reveals that while Greenbushes is the lowest emitter, its limited lifespan, along with the planned expansions of other sites that have higher emission intensities, can significantly increase greenhouse gas emissions from the lithium supply in the future. To address the challenges of emissions and fluctuating lithium prices, Australia must make a sustainable strategic shift toward greater involvement in the downstream supply chain, including refining and manufacturing. A regional comparison with the Lithium Triangle highlights Australia's mining strength and potential to become a greener lithium producer by diversifying its energy mix with renewables, adopting advanced technologies for low-grade ore recovery, and implementing strong policy frameworks to support collaborative mid-sized and emerging projects. These approaches will strengthen Australia's role in the decarbonization transition, environmentally and economically.

1. Introduction

Lithium (Li) is essential for sustainable global energy transitions, particularly due to its role in Li-ion batteries for electric vehicles and grid storage [1]. It is sourced from two main types of deposits: (1) brines, predominantly found in Latin America's 'Lithium Triangle' (Chile, Argentina and Bolivia), and (2) spodumene extracted from Lithium–Cesium–Tantalum pegmatites, which are concentrated in Western Australia [2–4] and, more recently, the Northern Territory's Finniss mine [5]. Australia is the world's leading producer of spodumene, accounting for over 50% of global lithium supply and 79% of hard-rock lithium [6]. This dominance is driven by vast reserves, efficient extraction techniques, and proximity to key Asian markets. However, the lithium from hard-rock mining process is highly energy-intensive, generating approximately 9.6 tons of CO_2 equivalent per ton of lithium carbonate equivalent (LCE) and relying heavily on fossil fuels, which raises significant sustainability concerns [7].

To strengthen its position in the critical minerals sector, the Australian government introduced the critical minerals strategy [2023–2030] [8], aiming to expand the industry while positioning the country as a global leader in environmental, social, and governance (ESG) performance [9]. The strategy emphasizes building resilient supply chains, enhancing domestic processing capabilities, and leveraging critical minerals to support Australia's renewable energy ambitions. However, despite these commitments, a lack of comprehensive sustainability data raises concerns about the credibility of Australia's ESG claims. Without robust assessments, efforts to reinforce its supplier leadership and shape global sustainability standards may remain unverified.

Globally, the lithium supply chain faces numerous environmental challenges, including high carbon emissions, water consumption, land use issues, and potential ecological and social impacts [4, 10]. These issues are further exacerbated by geopolitical tensions and resource concentration, as over 80% of lithium battery materials are processed in China, Australia, and Chile [10–12]. Several studies highlight significant variations in the environmental impacts of lithium production depending on the extraction method and location. For instance, brine-based lithium production in Chile has a lower global warming potential compared to hard-rock extraction in Australia [13, 14].

Key studies by Schencker *et al* [10, 15] and Lagos *et al* [16] for Chile's Salar de Atacama, and by Kelly *et al* [4], Mas-Fons *et al* [3], and Khakmardan *et al* [14] for Australia's Greenbushes mine, have evaluated the environmental performance of battery-grade lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$) production [3, 4, 10, 14, 16]. These studies typically reflect best-case scenarios. However, few of them provide mine-by-mine quantitative assessments for Australian spodumene operations. In Australia, Li is domestically extracted and processed into spodumene concentrate, which is later shipped to China for refining [3, 12]. Since 2022, lithium hydroxide refining has been underway in Kwinana (Tianqi-IGO) and Kemerton (Albemarle) [17]. The Kwinana refinery initially aimed to produce 24 000 metric tons annually but faced operational and market challenges, leading to the suspension of expansion plans. Although the first processing train remains operational, it has not reached full capacity [18]. Consequently, this study does not assess the refining process in Australia, as refining remains economically uncompetitive compared to China due to significant differences in labor and operating costs. Instead, we evaluate the emissions associated with lithium refining in China [19].

To better understand the strategic competitiveness of Australia's Li mining sector, this study further aims to compare the life cycle impacts of lithium mining and production in Australia with those in Chile and Argentina, key countries within the Lithium Triangle, by unpacking the environmental consequences of different extraction methods and production routes. We employ a review of sustainability disclosures, coupled with the implementation of cradle-to-gate life cycle assessment (LCA), to evaluate and compare the environmental impacts of lithium production in Australia and the Lithium Triangle. By examining key aspects like spodumene concentrate production, ore grade, emissions intensity, and mining costs (i.e. the operational cost of producing spodumene concentrate or extracting lithium from brine) we aim to provide an improved understanding of the potential bottlenecks in Australia's lithium production at different mining sites and highlight the environmental trade-offs associated with distinct lithium production methods and locations. The findings of this research will not only contribute to the growing body of knowledge on sustainable lithium production but also provide crucial insights into the validity of Australia's leadership in the critical minerals sector.

2. Method

This study examines annual lithium production statistics in Australia, reported as spodumene concentrate production (SC 6% Li_2O), encompassing extraction, concentration, and the associated greenhouse gas (GHG) emissions from the concentration process. It also includes data on feed ore mining (where available) or reserve ore estimates, along with operating costs data.

The paper is organized into three parts (figure 1). First, we outline the data collection process and methods used to compile and communicate GHG emissions intensity reported by companies. Next, we present results and discussion, focusing on four key areas: emissions intensity and its relationship to ore grade, ore yield (amount of spodumene concentrated before refinery process), and mining costs, a comparison with lithium production in Argentina and Chile, and potential pathways for domestic refining. Finally, we conclude with key policy and industry implications.

Data were collected from annual company reports for seven mine sites in Australia—Greenbushes, Pilgangoora, Mount Marion, Mount Cattlin, Wodgina, Finniss, and Mount Holland, spanning the fiscal years 2017–2024. The starting point was chosen to align with Australia's rise as the global leader in lithium production. All collected data were systematically organized into a tabular database for analysis.

The growing importance of lithium and its rising demand has driven increased transparency around its production, and in the case of Australia, the availability of data on ore yield, ore grade, and GHG emissions in spodumene concentrate production enables a systematic investigation into the relationships between production cost-efficiency and emissions intensity. Additionally, a comparative assessment was conducted between hard rock spodumene mining in Australia and lithium extraction from brine deposits in the Lithium triangle. To ensure a comprehensive comparison, refining emissions and refining costs in China were incorporated, allowing for an evaluation of LCE as the final product.

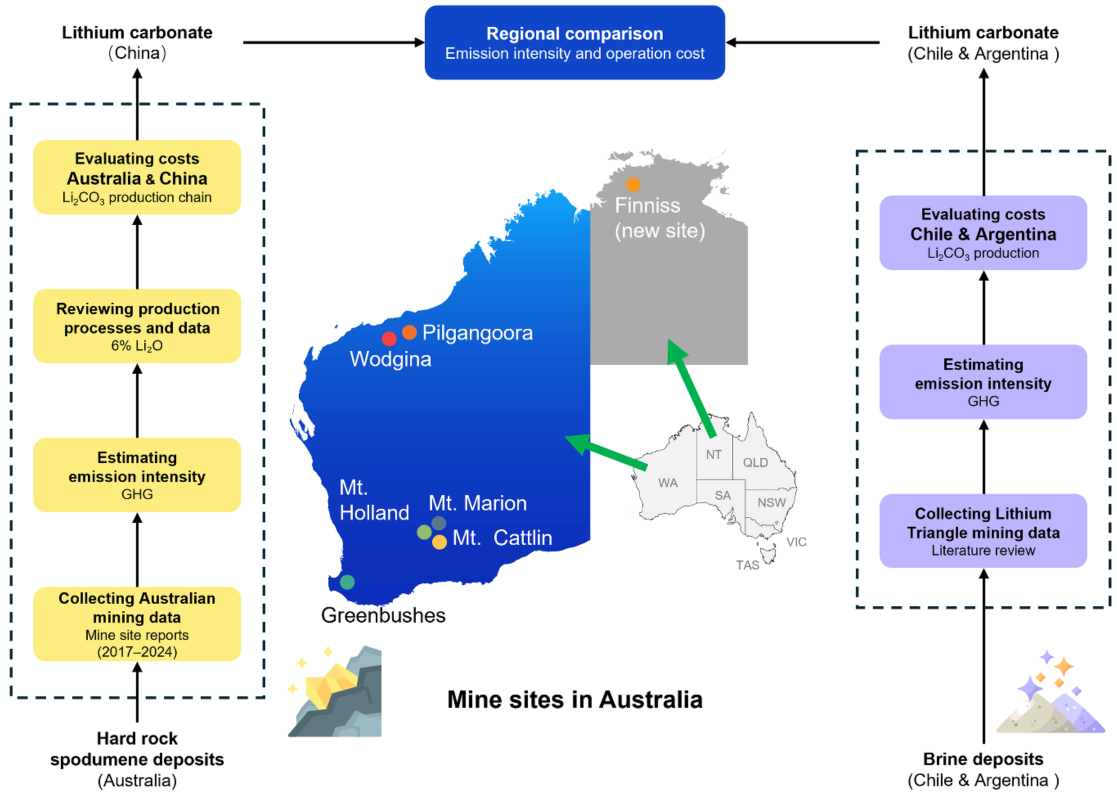

Figure 1. System definition and modeling framework. WA refers to Western Australia, NT to the Northern Territory, NSW to New South Wales, SA to South Australia, QLD to Queensland, TAS to Tasmania, and VIC to Victoria. Lithium extraction from hard rock spodumene in Australia is assessed across seven mine sites, evaluating operational costs, production yields, and GHG emissions, and evaluating emission intensity. A comparative analysis is conducted against lithium extraction from brine deposits in the Lithium Triangle, in terms of lithium carbonate (LCE, Li_2CO_3) production. This comparison considers both emission intensity and operating costs, with additional insights into the refining process in China.

2.1. Emission intensity (EI) assessment

GHG emissions data were collected and compiled from companies' sustainability reports, which follow either the Australian financial year or the calendar year, depending on data availability. Given that lithium mining operations generally maintain stable production levels, variations in reporting periods are unlikely to significantly affect annual emissions estimates.

Most companies began tracking and reporting their Scope 1 and Scope 2 GHG emissions through the National Greenhouse and Energy Reporting Scheme (NGERS) [20]. However, NGERS primarily provides corporate-level data without disaggregating emissions at the individual mine level. Moreover, not all lithium mining operations are subject to mandatory reporting, as some do not meet the scheme's thresholds.

To address these limitations, this study relies on the sustainability reports of individual mine sites, which typically disclose total GHG emissions in metric tons of carbon dioxide (t CO_2-e) but often do not distinguish between Scope 1 and Scope 2 emissions. While Scope 3 emissions are generally excluded from corporate disclosures, Australia is introducing mandatory Scope 3 reporting as part of its climate-related financial disclosure requirements [21]. This policy, set to take effect on 1 January 2025, will require large businesses and financial institutions to disclose climate-related risks, including supply chain emissions.

When sustainability reports provide emissions data for individual mines, those figures are used directly. In cases where companies report only aggregated emissions across multiple sites, mine-specific emissions are estimated based on relative production levels using company-reported data. A detailed breakdown of the GHG emissions data sources is provided in table S1 of the Supplementary Information.

The GHG emissions intensity for each mine is expressed in tons of CO_2-e per ton of annual spodumene concentrate production (6% Li_2O). This is subsequently converted to LCE using standard conversion factors. The EI is calculated using the following formula:

$$\text{GHG emission intensity} = \frac{\text{GHG emissions (Scope 1 + Scope 2)}}{\text{Annual production}}.$$

2.2. Lithium production and mining costs data collection

When available, the average reported head grade of ore processed annually was used. In cases where this data was unavailable, the average reserve ore grade for the corresponding year was assumed. Key mine sites—including Greenbushes, Pilgangoora, Mount Marion, and Mount Cattlin—have consistently reported production from fiscal year 2017–2024. Other sites, such as Wodgina, Finniss, and Mount Holland, began or resumed operations in 2022 and started reporting thereafter. All these mines are located in Western Australia, except for Finniss, which is in the Northern Territory (table S1).

Companies typically report spodumene concentrate grades ranging from 5.5% to 6% Li_2O as the final product. For consistency, this study assumes all production meets the 6% Li_2O threshold. Some sites that were expected to commence operations, such as Bald Hill and Kathleen Valley, suspended activities in 2023 due to market conditions, opting to scale back production or reduce costs [22, 23]. This study evaluates seven mine sites, six of which are currently in operation, as Mount Cattlin has been placed under care and maintenance [24].

Mine production data were obtained from company quarterly and annual reports, supplemented with information from the US Geological Survey and the Department of Energy, Mines, Industry, Regulation, and Safety from Australia [6, 25–27] (table S1). Production statistics were reported as annual production of spodumene concentrate (6% Li_2O) in tons and subsequently converted to LCE using standard conversion factors (table S2).

Mining operating costs were sourced from company financial reports and guidance documents for the relevant fiscal years. These costs cover expenditures related to mining, processing, and the concentration into spodumene concentrate production (SC6). Expenses such as shipping fees and state or private royalties are excluded from the assessment. While most mines report operating costs in Australian Dollars, some provide values in US Dollars. In cases where costs were reported in Australian Dollars, they were converted to US Dollars using the average foreign exchange rate published by the Reserve Bank of Australia [28]. The final values are presented in USD per ton of LCE.

To better understand emission patterns and operational efficiency, head ore grade, spodumene concentrate production, and cash operating costs were analyzed in relation to emissions intensity for each mine site. In particular, the comparison between cash operating costs and emissions intensity helped identify whether mines with high or low emissions per ton of production fall into the category of high- or low-cost operations. These insights were then used to make recommendations and conclusions regarding cost-effective and environmentally efficient mining practices. A detailed compilation of this data is provided in the Supplementary Data.

2.3. Statistical analysis

To explore the relationship between the spodumene concentration production variables and emissions intensity across the seven lithium mine sites in Australia, we performed a regression and correlation analysis. Key variables, including ore yield, ore grade, and emissions intensity, were transformed by applying a natural logarithm prior to modeling to improve linearity and normalize their distribution. Linear regression models with ANOVA were then applied to the transformed data to identify significant statistical relationships and potential drivers of emissions intensity. Based on our dataset, the best-fit curve, the exponential function, was selected among the linear function, logarithmic function, power function, etc.

2.4. Comparing hard rock spodumene in Australia and brine in Lithium Triangle

This study compares hard-rock spodumene mining in Australia and lithium brine extraction in Chile and Argentina in the Lithium Triangle—two dominant lithium production pathways—by evaluating their EI and operating costs.

In Australia, lithium is extracted from pegmatite deposits and concentrated into spodumene concentrate (6% Li_2O) at mine sites [1, 10]. Emissions are estimated based on energy consumption and processing requirements at seven operational sites, as reported in company disclosures (table S1). Since spodumene concentrate requires further refining—typically carried out offshore in China—to produce LCE or lithium hydroxide, this study calculates emissions associated with both transport and downstream processing to ensure a more comprehensive assessment.

Based on findings by Kelly *et al* [4] and Sun *et al* [29], approximately 15% of total emissions occur during the mining and concentration stage, while downstream refining accounts for about 85%. Shipping between Australia and China contributes only a small fraction—approximately 0.11%—of the total emissions, as highlighted by Khakmardan *et al* [1]. In this study, a conservative estimate assumes that 20% of total emissions occur within Australia, with the remaining 80% attributed to overseas transportation and refining.

In contrast, lithium production in Chile and Argentina relies on brine extraction, where lithium is recovered from evaporated saline solutions and directly processed into LCE at the production site. Since

Lithium Triangle's operations already report emissions at the LCE stage, a direct comparison with spodumene-based lithium is only possible after including additional refining emissions from China.

For Australian spodumene, this study first determines mine-site EI before incorporating emissions from freight and refining. For Lithium Triangle brine operations, emission data is sourced from LCA research studies and industry reports, as detailed in table S3. To ensure a balanced comparison, refining costs in China are also factored into the analysis.

To improve accuracy, this study distinguishes Chile and Argentina based on EI and brine operating costs, analyzing data from 2017 to 2024 and calculating average national values for emissions and operating expenses. The analysis focuses on the cash operating costs of LCE brine production, which include site-level expenditures such as brine management and lithium processing, while explicitly excluding royalties (table S4) [27].

By integrating these factors, this methodology provides a more accurate assessment of the environmental and economic impacts of both lithium extraction routes. The findings offer valuable insights into their sustainability and can inform policy development and industry decision-making.

3. Results

This section presents the findings of the assessment, covering the relationship between spodumene concentration production and CO_2 emissions, ore grade, and EI, and the mining cost relative to EI. It also includes an analysis of EI at individual mine sites and a comparison of mining costs and EI between production in Latin America and Australia.

3.1. EI in spodumene concentration

Since 2017, lithium production in Australia has grown significantly, increasing by more than 160% by 2024, with production exceeding 460 kt of LCE (measured as spodumene concentrate) [30–34]. This growth further solidifies Australia's position as the global leader in lithium production, with a global share of more than 40% [6]. Key mining sites contributing to this expansion include Greenbushes, Pilgangoora, Mount Marion, and Mount Cattlin. However, Mount Cattlin was placed into care and maintenance in 2024. Meanwhile, Wodgina, Finniss, and Mount Holland began operations and started reporting production from 2022 onward [5, 30, 33]. As of 2024, six mine sites remain in operation [22]. In contrast, some sites that were expected to commence operations, such as Bald Hill and Kathleen Valley, suspended their plans in 2023 due to market conditions, opting to scale back production or cut costs [22, 23, 35].

Most companies' sustainability reports emphasize total CO_2 emissions without distinguishing between Scope 1 and Scope 2 emissions. Since 2017, CO_2 emissions from spodumene concentration have surged nearly fourfold, reaching an astounding 750 kt of CO_2 by 2024 [30–34]. Between 2017 and 2022, many sustainability reports overlooked detailed emission categorizations, but reporting has gradually improved since 2022, particularly at Greenbushes and Pilgangoora. This significant rise in emissions underscores the need for greater transparency and accountability in sustainability reporting. Companies must adopt more detailed and standardized reporting practices to provide a clearer understanding of their environmental impact.

Emissions from mining and concentration processes vary significantly depending on the ore type. For lepidolite mines, emissions are reported at 4.03 $tCO_2-e\ t^{-1}$ LCE, whereas spodumene-based emissions are significantly lower at 1.08 $tCO_2-e\ t^{-1}$ LCE, with Scope 2 emissions being the primary contributor to this difference [36]. Figure 2 presents site-specific emission intensities for spodumene sources. Greenbushes has maintained consistent emissions throughout its operational history, averaging 1 $t\ CO_2-e-e\ t^{-1}$ LCE, with peaks observed in 2020 and 2021—likely due to COVID-19-related operational disruptions. In contrast, Pilgangoora has an outlier at 4.34 $t\ CO_2-e\ t^{-1}$ LCE, which aligns with its first full operational year, marking the establishment of baseline emission intensities. Mount Marion's emissions have shown a year-on-year increase. However, it is important to note that from 2022 onwards, its emissions have been officially reported for the first time. Prior to this, sustainability reports primarily reflected the overall emissions of its parent company, Mineral Resources, which operates both iron ore and lithium production.

Pilgangoora, Mount Cattlin, Mount Holland, and Finniss report emission intensities ranging between 1.6 and 1.9 $t\ CO_2-e\ t^{-1}$ LCE. Wodgina stands out with a significantly higher EI of 5.20 $t\ CO_2-e\ t^{-1}$ LCE, while Mount Holland falls in the lower quartile among Pilgangoora, Mount Cattlin, Mount Holland, and Greenbushes, with an average of 1.37 $t\ CO_2-e\ t^{-1}$ LCE. The average weighted emissions intensity across the studied mine sites in Australia during the analyzed period is around 2 $t\ CO_2-e\ t^{-1}$ LCE, aligning with information collected from existing literature (table Supplementary Data SD-1) [4, 14, 16, 37].

This site-based average aligns with the lower range of values found in prior LCA studies when analyzing solely on the mineral processing stage, which typically report emissions between 2 and 10 $t\ CO_2-e\ t^{-1}$ LCE

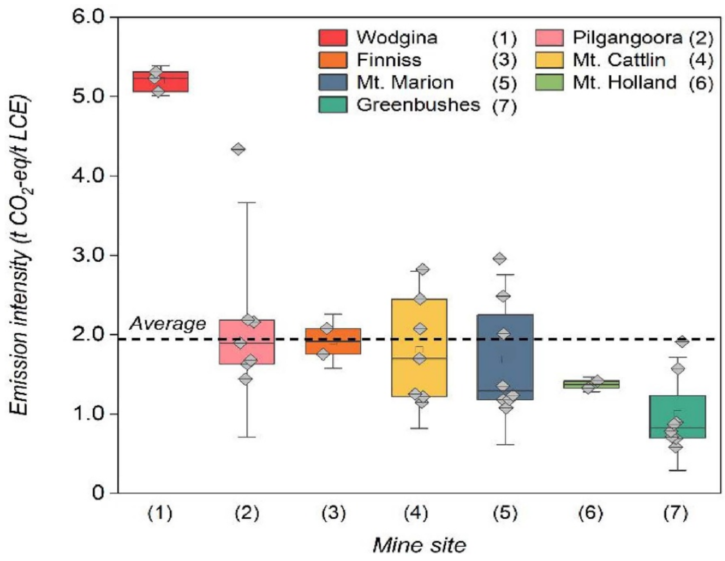

Figure 2. Emission intensity at Australian mine sites between 2017 and 2024. This figure presents interquartile ranges and mean values across seven mine sites, ranging from the highest-emission site, Wodgina, to the lowest-emission site, Greenbushes.

[4, 14, 16, 37]. The lower values reported in these studies often reflect data from Greenbushes, Australia's most efficient and high-grade lithium operation. However, such a focus can overlook the higher emission intensities of smaller and mid-sized operations, which are frequently excluded from site-specific evaluations and, consequently, from policy discussions. For instance, Kelly *et al* estimated an average of 2 t CO_2 e t^{-1} LCE for Australian operations, citing the heavy reliance on diesel and other fossil fuels during mining and processing activities [4]. Mas-Fon *et al* further emphasize the role of ore grade as a key determinant of EI, with higher-grade ore yielding lower emissions per ton of LCE due to reduced processing needs [3].

It is important to note that previous LCA-based assessments [1, 4, 14, 37, 38] have estimated the cradle-to-gate EI of hard-rock lithium extraction to range from 9.6 to 20.4 t $CO_2-e\ t^{-1}$ LCE, encompassing both mining and downstream refining stages. In contrast, this study analyzes reported Scope 1 and Scope 2 emissions directly sourced from company sustainability reports, which adhere to the NGERS [20, 30–34]. These emissions are tied specifically to the production of spodumene concentrate (6% Li_2O) at the mine site level, excluding refining. This difference explains the lower average emissions observed in this study (approximately 2 t $CO_2-e\ t^{-1}$ LCE, compared to up to 20.4 t $CO_2-e\ t^{-1}$ LCE reported in full cradle-to-gate LCAs).

3.2. Ore grade, ore yield, and EI in spodumene concentration

To assess the relationship between ore features and EI, a multivariable regression was initially conducted using ore grade and ore yield as independent variables. However, the model did not yield statistically significant results ($p = 0.14$), and the individual p-values for ore yield ($p = 0.91$) and ore grade ($p = 0.20$) further indicated a lack of explanatory power. A collinearity assessment revealed a strong positive correlation between ore grade and ore yield ($r = 0.77$), suggesting that their interdependence may be affecting model performance. Consequently, separate regression analyses were conducted to isolate the individual effects of each variable on EI (tables S5–S8).

In figure 3(a), the relationship between ore grade (expressed as % Li_2O) and EI across seven mine sites is presented. The results show that mines with higher ore grades tend to produce spodumene concentrate with lower CO_2 emissions per ton processed. Regression and correlation analyses confirm that this inverse relationship is statistically significant ($p < 0.05$) (table 1). The data follows an exponential function trend, with highly consistent regression equations across the different mining sites evaluated.

Figure 3(b) examines the association between ore yield (expressed in LCE) and GHG EI. Mine sites were grouped according to production scale: Greenbushes represents a large-scale operation (average >155 kt LCE/year), Pilgangoora, Mt. Marion, and Mt. Holland are mid-scale (around 50 kt yr^{-1}), with Mt. Holland classified as a new project initiated in 2023. Meanwhile, Mt. Cattlin, Wodgina, and Finniss are classified as small-scale operations, producing between 8–22 kt yr^{-1}, with Wodgina and Finniss also commencing operations in 2023.

Results indicate that large-scale operations, particularly Greenbushes, show the lowest emission intensities, while mid- and small-scale projects exhibit comparatively higher emissions per ton of spodumene

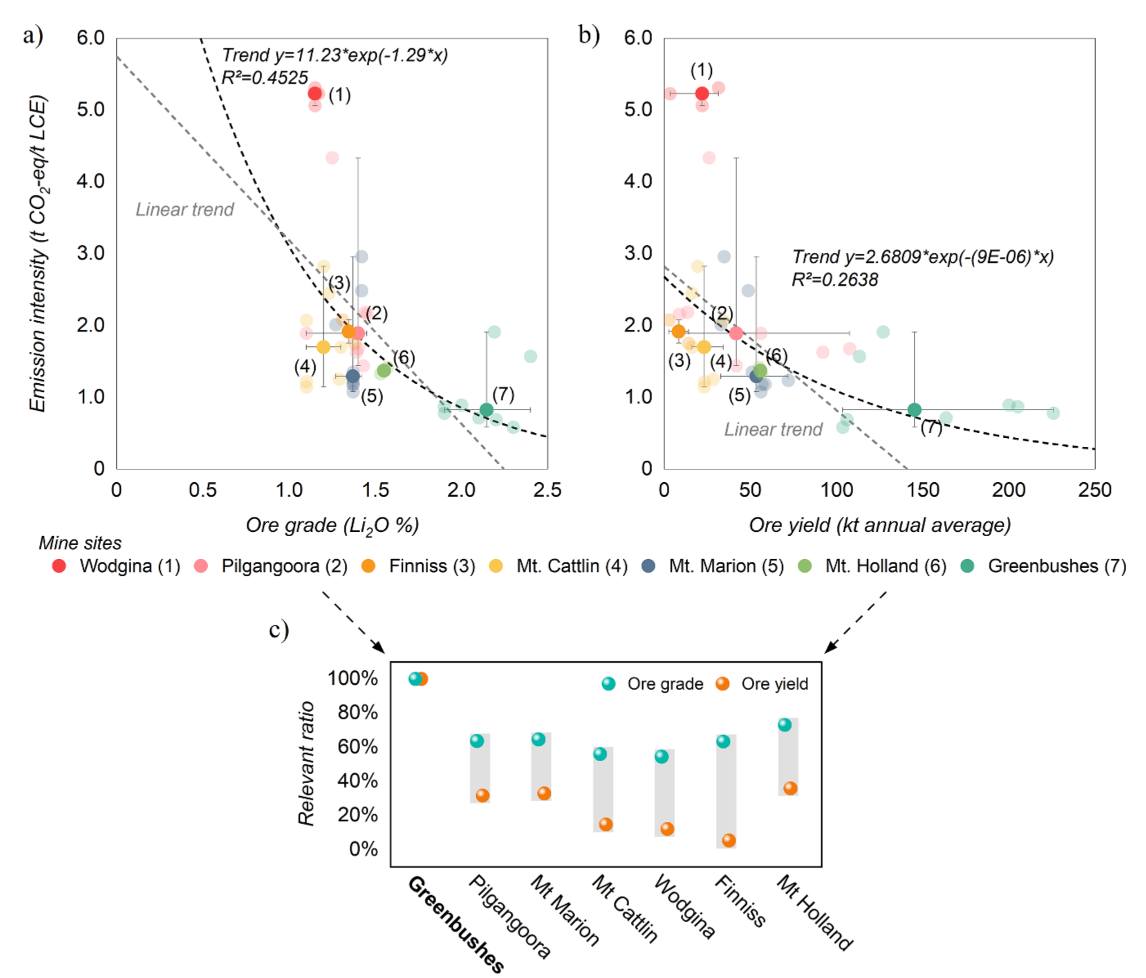

Figure 3. (a) Ore grade mining and (b) Ore yield vs. emission intensity at seven Australian mine sites. In both cases, data points present interquartile ranges and mean values for each mine site. The trend line equation for (a): $y = 11.23^{*}\mathrm{e}^{-(1.29x)}$ and (b): $y = 2.68^{*}\mathrm{e}^{-(9\times10-06^{*}x)}$. (c) Relationship between ore grade and ore yield. Assessment to evaluate the correlationship between ore grade and ore yield.

Table 1. Regression analysis results for ore grade vs. GHG emission intensity.

Statistics	All Data
Pearson correlation coefficient (R)	0.787
Coefficient of determination (R^2)	0.620
Adjusted R^2	0.544
Standard error	0.383
F statistic	8.155
Statistical significance (p)	0.036

Note: F statistics represent the variation between mean values in each mine site.

produced. The regression analysis between ore yields and emissions intensity does not yield a statistically significant relationship ($p > 0.05$) (table 2). This suggests that, based on current data, we cannot confidently conclude that ore yield alone has a significant effect on EI.

Based on these findings, these results indicate that while ore grade plays a meaningful role in determining emission outcomes, its close relationship with ore yield complicates interpretation in a multivariable context. Therefore, ore grade was retained as the more robust and interpretable predictor. Figure 3(c) summarizes the interplay between ore grade, ore yield, and GHG EI. In the best-case scenario represented by Greenbushes—characterized by high ore grade and high ore yield—the lowest emission intensities are observed. This trend holds for most sites, except for Wodgina and Finniss, both of which are new operations and exhibit relatively high emission intensities (5.20 and 1.92 $tCO_2-eq\ t^{-1}$, respectively). These anomalies suggest that while ore grade has a robust influence in EI, operational maturity and scale may introduce additional variability or uncertainty in emission performance among newly commissioned projects.

Table 2. Regression analysis results for ore yield vs. GHG emission intensity.

Statistics	All Data
Pearson correlation coefficient (R)	0.627
Coefficient of determination (R^2)	0.393
Adjusted R^2	0.272
Standard error	0.483
F statistic	3.240
Statistical significance (p)	0.132

Note: F statistics represent the variation between mean values in each mine site.

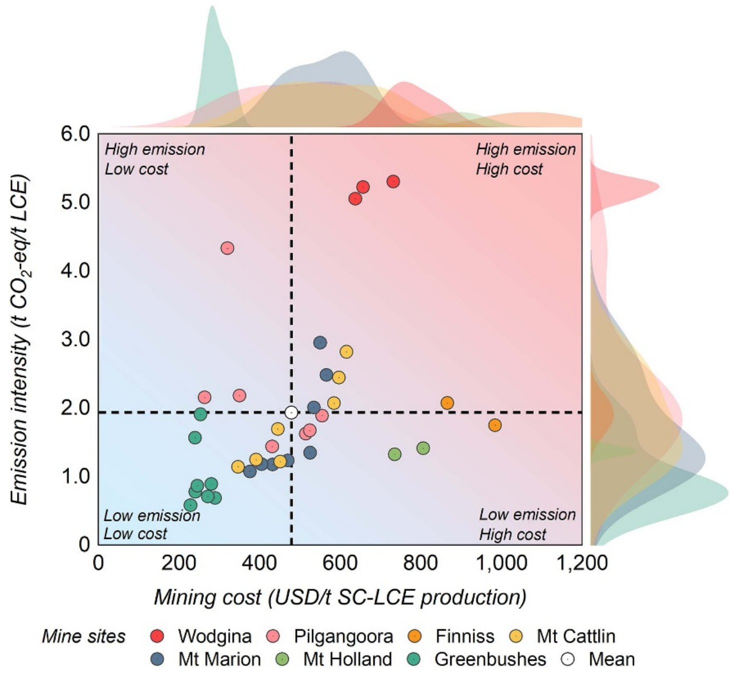

Figure 4. Mining cost vs. emission intensity of spodumene concentration (SC) at seven Australian mine sites. The curves illustrate the degree of centralization or decentralization of the data within the dataset. A more peaked curve suggests that the data points are concentrated around the mean, indicating centralization, while a flatter or more spread-out curve implies greater dispersion, reflecting decentralization. The figure is divided into four quadrants based on the mean emission intensity and mining cost for each mine site.

3.3. Production cost and EI assessment

Following the approach of Ulrich *et al* [39], figure 4 presents the mining cost per ton of spodumene concentrate at each assessed mine site in relation to its EI. The figure is divided into four quadrants based on the study's mean EI of 1.94 t CO_2-e t^{-1} LCE and production cost of 478.75 USD t^{-1} SC6. This classification facilitates the identification of mine sites based on whether they exhibit high or low emissions per ton of spodumene produced and whether they fall into high- or low-cost categories.

Greenbushes stands out as the most efficient site, characterized by both its low emissions and low costs. Its production costs are, on average, 255.71 USD t^{-1} SC6 with the lowest EI among all mine sites (1 t CO_2-e t^{-1} LCE), a trend that might be attributed to its high ore grade. Pilgangoora and Mount Marion have averagely similar production costs over the last year. Mount Marion production costs, averaging around 482 USD t^{-1} SC6 and EI of 1.69 t CO_2-e t^{-1} SC6, and Pilgangoora, while primarily in the low-cost category, shows a broader range of production costs, fluctuating between 207 and 524.25 USD t^{-1} SC6, with a mean value of 396 USD t^{-1} SC6. Its EI is close to the median, at 2.19 t CO_2-e t^{-1} SC6.

Mount Cattlin has undergone a significant shift over time. Initially positioned in the low-cost, low-emission quadrant, it later transitioned to the high-cost, high-emission category. Among the assessed mines, Mount Cattlin exhibits the most variable production cost values, fluctuating annually and reaching approximately 615.75 USD t^{-1} SC6 in 2023. This makes it the highest cost site among currently well-established production mines, such as Greenbushes, Pilgangoora, and Mount Marion. Its rising production costs and associated emissions may have contributed to its placement under care and maintenance in 2024.

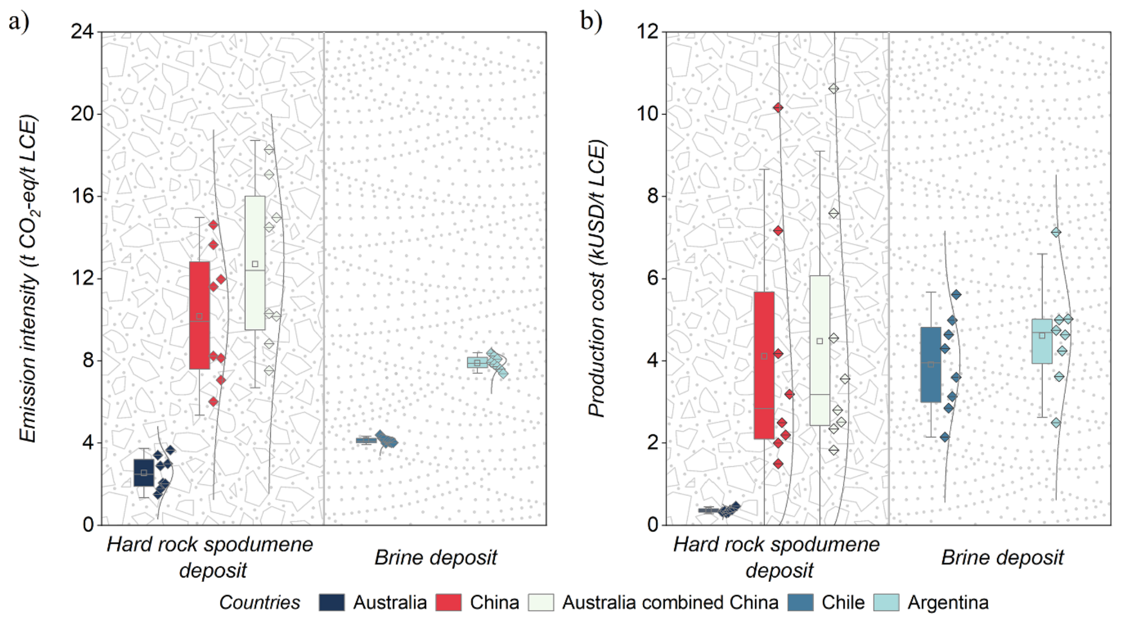

Figure 5. Comparison of (a) LCE emission intensity and (b) LCE mining costs from spodumene in Australia (refining in China) vs brine mining in Chile and Argentina. Australia and China are first presented separately to highlight their individual impacts and then together to show the combined effect on LCE emission intensity and mining costs. This allows for a comparison with the Lithium Triangle countries.

Among the high-cost, high-emission quadrant, Mount Holland exhibits the lowest EI (1.37 t $CO_2-e\ t^{-1}$ LCE on average), with an average mining cost of 771 USD t^{-1} SC6. Finniss, on the other hand, has the highest production cost, averaging 925.23 USD t^{-1} SC6, with an EI of 1.92 t $CO_2-e\ t^{-1}$ LCE. Wodgina, while having the lowest production cost among these three sites (averaging 676 USD/t SC6), also has the highest EI of all assessed sites, averaging 5.20 t $CO_2-e\ t^{-1}$ SC6.

Along the top outer border of figure 4, the behavior of Greenbushes (in terms of mining operating costs) appears stable compared to other mine sites, particularly the more dispersed ones, such as Mount Cattlin and Mount Marion. On the right border of figure 4, Wodgina shows a higher concentration of emissions per ton, while Mount Holland, Greenbushes, and Mount Marion exhibit softer curves in the lower emission spectrum.

3.4. Comparison between brine in Latin America and hard rock spodumene in Australia

Figure 5(a) presents a significant advancement in our sustainability assessment of spodumene production in Australia. It compares this production to LCE production from brines in Latin America—specifically, in Argentina and Chile—over the period from 2017 to 2024. The analysis evaluates both the mining cost per ton of LCE and the associated EI at each production site, with Australian data derived as weighted averages from seven mine sites.

To enhance clarity, the results are organized based on the mean production cost and mean EI across all assessed sites. To ensure a fair comparison between brine extraction and hard rock mining, the analysis also considers the emissions and costs associated with refining the spodumene concentrate (6% Li_2O) into LCE. Because this refining process takes place in China, its emissions and costs are incorporated into a combined Australia + China estimate. This comprehensive approach provides a more accurate comparison of the environmental and economic impacts of lithium production across different extraction methods and regions. According to our data, the average EI is 8.2 t $CO_2-e\ t^{-1}$ LCE, and the average production cost is 4,830 USD t^{-1} LCE. For context, a 2024 Western Australian Government report indicates that the global average total cash cost is 9,714 USD t^{-1} LCE, while Lagos (2024) reports an average EI of 9.34 t CO_2-e per ton.

Since 2017, both countries appear to be reducing their emission intensities in LCE production, although rising production costs have been observed. Chile's average production cost is around 4,000 USD/t LCE, with costs gathered near this value. It is important to note that these figures for Chile do not include mobile royalties on lithium prices, which are beyond the scope of this analysis. In Argentina, the average production cost is approximately 4,441 USD t^{-1} LCE, with a clear inverse relationship between EI and production cost—lower emissions and higher operating costs. On average, Chile's EI is about 4.13 t $CO_2-e\ t^{-1}$ LCE, compared to Argentina's 7.90 t $CO_2-e\ t^{-1}$ LCE.

When focusing only on the spodumene concentration process in Australia, the operational cost averages around 570 USD t^{-1} SC6. This makes Australia competitive, as these costs are lower than the average values reported for Chile and Argentina (figure 5(b)).

In terms of EI (coupled with refining emissions), the average emissions from Greenbushes, Pilgangoora, Mount Marion, and Mount Cattlin reach 11.92 t $CO_2-e\ t^{-1}$ LCE, significantly higher than the averages in Chile and Argentina, which are 4.13 and 7.90 t $CO_2-e\ t^{-1}$ LCE, respectively (figure S1). However, when considering the lowest emissions recorded at Greenbushes, Mount Marion, and Mount Cattlin—7.23 t $CO_2-e\ t^{-1}$ LCE—these values fall within the range of Argentina's average EI. In all cases, Chile consistently demonstrates the best performance in terms of EI. By contrast, Wodgina, Finniss, and Mount Holland exhibit much higher emissions, with an average of 15.73 t $CO_2-e\ t^{-1}$ LCE—nearly four times higher than Chile's average and double that of Argentina.

4. Discussion

4.1. Achieving a low EI in Australia's lithium sector

Australia hosts the largest spodumene deposits globally, with total reserves estimated at 7 Mt of lithium (37.24 Mt LCE) [6]. Among Australia's lithium mines, Greenbushes stands out due to its exceptionally low EI and high production capacity, accounting for at least 51% of the country's spodumene concentrate output in 2024 [27]. The mine's high-quality ore, with an average grade of 2.4% Li, and its large-scale operations make it unparalleled in the Australian market, boasting an estimated 1.5 Mt of lithium reserves [40]. Other major spodumene deposits include Mount Holland (1.1 Mt Li; 1.5% Li), Pilgangoora (1.19 Mt Li; 1.19% Li), and Wodgina (1.25 Mt Li; 1.15% Li) [37, 41]. While Greenbushes' strategic importance is evident, the lack of comparable sites in terms of operational scale and ore quality poses a significant risk to the resource resilience of Australia's lithium industry.

The EI of Australian lithium mines varies considerably, with Greenbushes consistently reporting the lowest emissions. A key challenge lies in its projected lifespan of approximately 20 years [42]. While this provides a stable medium-term outlook for low-emission, low-cost production, it also raises concerns about the sustainability of lithium supply at current extraction rates. Mount Marion, with a similar lifespan and relatively low emissions as Greenbushes, appears to be following a comparable trajectory, gradually being overtaken by other mine sites with higher emissions. Mount Cattlin has already been suspended, despite an updated ore reserve estimate allowing continued mining until at least the 2027–28 financial year; its future remains uncertain [24]. The volatility of global lithium prices has also created uncertainty for small-scale and younger mining operations [43], for instance, Kathleen Valley, Bald Hill, and Finniss. As other mines with longer lifespans—such as Pilgangoora (34 years) [44], Wodgina (30 years) [45], and Mount Holland (50 years) [46]—ramp up production, their higher emission intensities (ranging between 1.37 and 2.2 t $CO_2{}^{-1}e\ t^{-1}$ LCE) are expected to contribute to an overall increase in Australia's average emissions intensity (table S9).

To ensure the long-term sustainability of its lithium industry while addressing these environmental challenges, according to our analysis, Australia should consider supporting its less mature and emerging lithium projects to strengthen overall supply. This should be accompanied by the implementation of a comprehensive policy framework that strengthens carbon reduction measures. Since most spodumene extraction and concentration occur onshore, ore concentration is a significant contributor to CO_2 emissions, largely due to the reliance on fossil fuels—diesel for ore mining and processing, and coal for refining 6% Li_2O concentrates [1, 4]. Australia thus has a unique opportunity to lead in sustainable mineral development. Despite the current average EI of approximately 2 t $CO_2-e\ t^{-1}$ LCE—expected to rise with increased output from higher-emission mines—the sector offers considerable potential for decarbonization.

Spodumene calcination—one of the most energy-intensive processes in lithium mining—poses a major challenge for emissions reduction [1, 41]. The adoption of electric kilns could reduce related emissions by up to 80% if powered by renewables [7, 47, 48]. Early signs of this transition are already visible. Greenbushes is exploring power purchase agreements for renewable electricity [49, 50] and the integration of solar, wind, and hybrid power systems in mining operations, as demonstrated by Pilgangoora's hybrid facility and Mount Holland's solar plant [33, 44], highlights the potential for emissions reduction through clean energy adoption [33, 44].

The use of biodiesel, supported by subsidies for oil plant-based alternatives, presents another viable emissions-reduction pathway. In addition, efforts to replace diesel with hydrotreated vegetable oil—a renewable diesel recognized under Australia's NGERS—are also gaining momentum [51]. Further opportunities lie in fleet electrification, automation, and digitalization of mining operations, which can simultaneously boost productivity and improve environmental performance [49, 52, 53].

While these technologies are promising, their implementation may still pose challenges, especially for newer or small-to-medium-scale mining operations. The high capital costs of low-emission technologies might create a competitive disadvantage for newer entrants. Policy interventions should prioritize financial support for technology adoption, research funding for process innovation, and incentives for renewable energy integration. New projects present a particular opportunity to incorporate the best available technologies from inception, avoiding the retrofit costs faced by established operations.

4.2. Relationship between ore grade/yield and EI in spodumene

An assessment of ore grade, ore yield, and GHG EI across Australian spodumene operations highlights how mineral quality, production scale, and operational maturity jointly influence environmental performance in the country's lithium mining industry. Among all mines, Greenbushes stands out as the most efficient, with the lowest GHG EI and highest ore yield, primarily due to its exceptionally high ore grade (>2% Li_2O), long operational history, and integrated infrastructure. These characteristics allow for optimized processes and economies of scale, which reduce energy use and emissions per ton of spodumene produced [13, 54].

Mid-sized operations (middle or small sites refer to ore yield operational scale, instead of deposit size) such as Mount Marion, Pilgangoora, and Mount Holland also demonstrate moderate emission intensities, with ore grades ranging between 1.2% and 1.6% Li_2O. In contrast, Wodgina and Finniss, both newer and operating at lower volumes, show significantly higher GHG intensities. Wodgina, despite its relatively low production of 19 kt LCE, exhibits a significantly higher EI (approximately 5 t $CO_2-e\ t^{-1}$ LCE). This might be attributed to operational disruptions, such as its suspension in 2019 and subsequent restart in 2022, as well as fluctuations in lithium market prices (75% drop from 2022 to 2024). According to the FY24 results report [30], this may be linked to the operation of Train 1 and Train 2, while Train 3 is still being prepared for commissioning and expected to begin production in mid-2023, subject to market conditions. Meanwhile, the construction decision for Train 4 remains pending [55].

Finniss, with the lowest reported ore grade (1.35% Li_2O) and only 14 kt of lithium yield in 2024, recorded 1.92 $tCO_2-e\ t^{-1}$, underscoring the challenges new, small-scale mines face in achieving environmental efficiency. Mount Holland achieved better emissions performance than Finniss despite also being a new entrant, largely because of its higher ore grade (1.6% Li_2O), larger scale (50 kt yield). This suggests that other variables—particularly ore grade and the maturity of operations—might play a more decisive role in shaping environmental outcomes.

As ore grades inevitably decline, established mine sites should find ways to maintain low emissions intensity and improve overall sustainability [7, 13]. While Australia currently benefits from high-grade deposits—particularly Greenbushes—this natural advantage is not infinite. As ore grades decline over time, the volume of material that must be extracted and processed increases, leading to higher energy demand and greater emissions [56, 57]. This trend underscores the growing energy intensity of lithium mining in Australia, where diminishing ore quality presents a long-term sustainability challenge [56].

Several innovative approaches show promise for addressing these challenges. Adopting advanced ore-sorting technologies—such as x-ray transmission and magnetic resonance [58]—can improve feed grade by selectively removing waste before processing, thereby reducing energy use and emissions. Such technologies are especially promising for mature mines where large volumes of lower-grade material must be processed efficiently [59]. The LieNA (Lithium Extraction from Non-conventional Assemblages) technology was developed through a partnership between Livium and Mineral Resources (MinRes). This innovative process eliminates the need for high-temperature spodumene conversion, one of the most energy-intensive steps in conventional hard-rock lithium extraction. Instead, this technology enables direct lithium extraction from fine spodumene particles, which are typically discarded in traditional operations due to their low recovery potential. By recovering lithium from lower-grade and fine material, it has demonstrated potential to improve yields by up to 50%, thereby extending the operational life of existing mines. This technology facilitates the processing of tailings and previously uneconomical ore, contributing to a more circular and efficient mining operation. y avoiding calcination and simplifying the overall extraction process, the technology significantly lowers energy demand and associated. The recent successful pilot and engineering studies for LieNA signal its readiness for commercial application, especially for operations seeking to maintain profitability and environmental performance amid declining ore grades [60, 61].

Additionally, increasing process integration and refining capacity on-site can enhance energy efficiency. By co-locating refining operations with mining—an approach being explored at Greenbushes and Mount Holland—operators can optimize throughput and lower overall environmental burdens.

These strategies are not mutually exclusive and must be pursued in tandem with national-level initiatives such as Australia's Net Zero Plan, the Net Zero Emission Mining Initiative, and the critical minerals strategy [9, 62]. These policies aim to position decarbonization as an economic opportunity rather than a cost burden, reinforcing Australia's role in sustainable lithium production. Given the country's dominance in global lithium supply, expanding operations like Pilgangoora and Wodgina should prioritize clean energy adoption to prevent further emissions growth [44].

While Australia's lithium sector currently benefits from high-quality resources and established operations, long-term sustainability will require proactive investment in innovative technologies and processes. The industry's ability to maintain its global leadership position depends on successfully transitioning from reliance on natural advantages to technology-driven efficiency improvements. By adopting advanced processing methods, integrating clean energy solutions, and aligning with supportive policy frameworks, Australian spodumene producers can continue to reduce emission intensities even as ore grades decline, ensuring environmentally sustainable production to meet growing global demand.

4.3. Australia's lithium industry building resilience

Greenbushes remains the cornerstone of Australia's spodumene production, benefiting from an unparalleled combination of high ore grades and large-scale operations. These attributes allow it to achieve the lowest mining and concentration costs in the country—approximately USD 256 t^{-1} SC6—and the lowest EI among all sites evaluated (figure 4). These operational strengths make Greenbushes highly resilient to fluctuations in the lithium market.

By contrast, spodumene concentration from lower-grade ores tends to be more energy-intensive. This results in higher mining costs, not only due to scale limitations but also because of lower recovery rates and the technical challenges inherent in hard-rock mining. For example, the Finniss project in the Northern Territory—currently the smallest in scale with a production capacity of 14 kt—reported the highest mining costs among Australian spodumene mines in 2024, at USD 925 t^{-1} SC6.

Volatility in lithium prices plays a critical role in determining mine operation decisions. When prices drop, mines may reduce output or temporarily shut down, affecting their profitability and long-term viability. While more mature and larger or mid-sized operations such as Greenbushes, Pilgangoora, and Mt Marion seem to be better positioned to weather such fluctuations, newer and smaller projects—including Mt Holland, Wodgina, and Finniss—are more vulnerable to disruptions. The sharp decline in lithium prices from 73 000 USD t^{-1} LCE in 2022 to 13 000 USD t^{-1} LCE in early 2024 has disrupted financial planning for several mining projects. For example, mines like Kathleen Valley, Bald Hill, and Wodgina have been particularly affected, experiencing multiple operational halts and restarts based on market conditions. With lithium prices falling again in 2024, Wodgina's production costs remain relatively high compared to more stable operations like Mount Marion.

Mines that undergo frequent operational suspensions often face increased production costs and emissions due to inefficiencies in restarting extraction and processing activities. For example, Wodgina's production costs are notably higher than those of Mount Marion, partly due to its temporary shutdown and subsequent reactivation. Restarting operations often involves recalibrating equipment, workforce realignment, and optimizing recovery processes, all of which contribute to increased expenses and carbon footprints.

To build resilience against such market instability and enhance long-term sustainability, one strategic direction is to increase domestic value addition through onshore lithium refining. Local refining can reduce transport-related emissions, enhance economic returns, and buffer Australia from geopolitical supply chain disruptions. This approach also aligns with Australia's critical minerals strategy and broader net-zero commitments [8].

However, the substantial capital investment required to develop refining and downstream infrastructure remains a major barrier—particularly for small and mid-sized mining companies. In response, we propose the formation of strategic alliances among these smaller actors as a pathway to overcome individual limitations and enhance collective competitiveness. For instance, smaller companies could focus on securing and supplying raw materials, while mid-sized companies—often with relatively greater financial capacity—could invest in shared refining infrastructure. Such collaboration would not only help distribute investment risks but also build long-term resilience and value capture within the domestic lithium supply chain. Although not geographically adjacent, operations such as Finniss, Wodgina, and Pilgangoora could potentially form alliances, as they are more regionally connected compared to more distant sites like Greenbushes in Southwestern Australia.

To facilitate such collaboration, government intervention through targeted financial mechanisms is critical. For example, the Green Energy major projects: Lithium industry support program, which supported downstream lithium upgrading in Western Australia. Expanding such programs—geographically (e.g. into the Northern Territory) and temporally (ensuring long-term funding)—could promote more inclusive regional development [63].

The recent passage of the Critical Minerals Production Tax Incentive in early 2025 marks another important step [64]. This scheme provides a refundable tax credit over 10 years, covering 10% of eligible costs for downstream mineral processing, including lithium refining. However, it excludes upstream mining and extraction activities. Consequently, for mining operations to benefit from this scheme, they must advance into refining stages—producing lithium hydroxide or carbonate on-site.

This requirement presents a challenge, particularly for operations with limited capital or technical capacity to manage vertical integration. While these initiatives aim to build a more robust and sustainable lithium value chain, their success should not be evaluated solely through economic or production metrics. Long-term sustainability also requires broader adoption of low-carbon technologies in both mining and refining, improved water and waste management, responsible land use practices, and well-planned mine closure and rehabilitation processes [65, 66].

Innovative projects are already paving the way. The collaboration between Pilbara Minerals and Calix Ltd, which aims to produce battery-grade LCE on-site, shows how co-located refining supported by solar and battery storage can reduce emissions and processing costs. The project is currently in its experimental phase and targets a 30% emissions reduction by 2030 [67].

Beyond technical innovation, these transitions offer an opportunity for job creation and workforce development. Investments in education and vocational training tailored to downstream processing are crucial. Lastly, ensuring the transparency and accountability of public incentives will require the establishment of robust ESG reporting mechanisms.

4.4. Australia's lithium needs a greener mining pattern to compete with Lithium Triangle

The demand for lithium has surged in recent years, prompting increased mining activities in key regions such as Australia, China, Chile, and Argentina. While both brine extraction and hard-rock mining are critical to meeting this demand, their economic and environmental implications differ significantly. In terms of EI, brine operations have consistently demonstrated better performance per ton of LCE (figure 5). However, beyond CO_2 emissions, these operations involve the extraction of large volumes of water from underground aquifers, resulting in significant water loss through evaporation and raising concerns about ecosystem impacts [1, 3, 68].

Our results indicate that the spodumene concentration process in Australia generates an average of 2 t $CO_2-e\ t^{-1}$ LCE. It has been mentioned that over 80% of emissions in LCE production from hard rock spodumene are associated with the refining process rather than the initial extraction [1, 4]. This underscores the significance of refining emissions, which, in the case of Australia, are primarily generated in China, where most of Australia's spodumene is processed.

Economically, the Lithium Triangle remains competitive in terms of brine mining operating costs per ton of final LCE. This advantage stems from the ability to process lithium brines directly into battery-grade chemicals at the source, whereas Australian spodumene must undergo an additional refining stage overseas, primarily in China. This adds not only to production costs but also to the carbon emissions. Although China currently controls around 60% of global lithium refining capacity, this dependency introduces strategic vulnerabilities for Australia, including geopolitical risk, potential carbon leakage, and limited value capture along the supply chain.

Despite China's commitment to integrating more renewable energy into its industrial processes, its refining sector remains a significant contributor to global emissions. Currently, China accounts for about 60% of the global lithium refining capacity. In recent years, many Chinese refining companies have accelerated the green transformation of the lithium refining industry. For example, China's two major lithium production companies, Tianqi Lithium and Ganfeng Lithium, have built factories in Sichuan Province, which is mainly hydropower, to ease the carbon EI of enterprises [69, 70]. In addition, the Chinese government has also introduced a series of carbon accounting and carbon trading policies, striving to promote carbon emission reduction from the economic level [71]. Australia could leverage China's shift toward renewable energy in lithium refining, potentially gaining an advantage if future supply chain agreements ensure lower-emission processing. Beyond this, trilateral collaborations could further support a more sustainable lithium supply chain. A strategic partnership combining Australia's raw material supply, China's processing expertise, and Japan's advanced battery manufacturing capabilities could accelerate advancements in refining technologies and EV battery development [72]. This aligns with the Australia-Japan Strategy for Cooperation in the Pacific, which strengthens critical minerals collaboration between the two nations [72, 73]. Deepening ties with Japan while maintaining trade relations with China would not only help Australia diversify its supply chain but also balance economic opportunities with geopolitical considerations.

Looking ahead, as noted in previous sections, Australia should transition beyond its current role as a raw spodumene exporter and develop a robust domestic refining industry. However, expanding refining capacity alone is not enough, particularly if powered by fossil fuels. The added refining stage remains an environmental challenge. Without the adoption of cleaner production technologies, domestic refining could significantly increase Australia's overall LCE emissions. To compete with the lower-emission profile of the Lithium Triangle, Australia should take the lead in developing near-zero-emission refining solutions.

Encouragingly, some emerging Australian refining plants are expected to be located closer to mining sites and powered by natural gas, which could reduce total emissions from mining and refining by up to 50% [74]. In the longer term, integrating renewable energy and green hydrogen into refining processes could further reduce the sector's carbon intensity [53]. Co-locating refining facilities with mines also offers economic advantages by cutting transport costs and enabling spodumene to be used at below-market prices, enhancing both cost-efficiency and sustainability, though price competitiveness with Chinese refiners remains a challenge.

Policy support will be essential to drive this transition. Introducing a decarbonization tax credit could incentivize the adoption of cleaner technologies and accelerate industry transformation. Moreover, Australia's strength in collaboration with partners looking for more clean suppliers, as an example, the European Union—particularly through the Critical Raw Materials Act—presents an opportunity to access new markets for responsibly sourced, low-emission lithium.

In addition to these measures and aligned with Australia's National Battery Strategy—which aims to position the country as a globally competitive producer of batteries and battery materials while securing its place in international supply chains—the government might also prioritize driving a battery circular economy [75]. This approach would address the urgent need to improve recycling infrastructure and policies, ensuring that end-of-life batteries are efficiently managed. Such a strategic framework would not only support sustainable lithium production but also reinforce Australia's role in the global energy transition [76].

In summary, while the Lithium Triangle currently enjoys an operational cost and emissions advantage, Australia has the potential to position itself as a leader in responsible lithium supply. Through strategic investments in clean refining, international cooperation, and policy frameworks, Australia can reduce its environmental footprint, strengthen supply chain resilience, and compete not only in volume but in sustainability.

5. Conclusion

This study examines the EI of hard rock spodumene lithium production at Australian mining sites from 2017 to 2024, along with the additional emissions from refining in China. Notably, Greenbushes stands out as the leading mine regarding ore yield, ore grade, and EI. As mining progresses, the declining ore grade increases extraction efforts, leading to higher GHG emissions and mining costs. Comparing LCE produced by the Australia-China supply chain with LCE produced in the Lithium Triangle, the latter has lower carbon emissions per ton of LCE; in contrast, the former has lower mining costs. By accelerating the adoption of renewable energy in mining operations, without neglecting the capabilities of small and medium-sized mine sites and strategic government support, and expanding domestic refining capacity, Australia can significantly reduce its carbon footprint, enhance its green mining performance, and reinforce its strategic position in the global lithium supply chain.

Data availability statement

The authors declare no competing financial interest.

All data that support the findings of this study are included within the article and supplementary materials.

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