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Future Risk from Current Sustainability Assessment Frameworks for the Resource Sector

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Abstract: This paper introduces a comprehensive sustainability assessment framework integrating Life Cycle Sustainability Assessment (LCSA) with Scenario Planning and Sensitivity Analysis, using the alumina industry as a case study. Current sustainability frameworks often focus narrowly on carbon emissions, neglecting broader environmental and social impacts, such as biodiversity loss, land rehabilitation, and social equity. By combining LCSA with forward-looking Scenario Planning, the proposed framework provides a multi-dimensional assessment, enabling industries to anticipate future challenges and adapt to technological, regulatory, and market changes. The analysis of Australia's alumina production under Net-Zero and Accelerated Net-Zero scenarios demonstrates significant decarbonisation potential, achieving up to 97% emission reductions while improving energy efficiency by 50%. Despite these advances, indicators like biodiversity preservation and social equity remain insufficiently addressed, underscoring the need for a more holistic, industry-specific approach. Future research directions include improving measurement methods for ecological and social indicators, exploring policy mechanisms to enhance adoption, and establishing partnerships with international bodies like the Aluminium Stewardship Initiative to ensure global adaptability. The increasing adoption of Environmental, Social, and Governance (ESG) methodologies highlights the need for comprehensive impact management and higher standards of governance. Although the proposed framework has notable strengths, its reliance on region-specific quantifiable indicators and simplified models limits its global adaptability. The proposed framework advocates for a mandatory, independent regulatory mechanism to drive balanced, transparent reporting, supporting industries in achieving transformative sustainability outcomes.

Keywords: life cycle sustainability assessment (LCSA); scenario planning; decarbonisation; alumina; sustainability framework

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1. Introduction

Alumina is a critical material for global aluminium supply chains looking to improve their products' or sectors' sustainable performance [1–4]. Aluminium is the second most widely used metal after iron, and its properties (i.e., lightweight, malleable, corrosion-resistant, and having the potential to be infinitely recycled) act as enablers for other sectors to reduce their carbon footprint [1–4]. Demand is rapidly growing in the transport, construction, and renewable technology sectors, as they seek to improve fuel efficiency, energy use, and emissions [1,4–7]. Producing aluminium requires the extraction of bauxite ore, and the refinement of the ore to produce alumina, which is then smelted to create aluminium [8].

Bauxite is the principal ore used to produce alumina [9,10], and is excavated through strip mining techniques [1], leading to 40–50 square kilometres of land being modified every year to produce aluminium globally [4]. Bauxite mining's surface-level nature and requirement of large land and water areas create impacts across forests, farmlands, rivers, and groundwater sources that also sustain local communities [1,7,11,12]. Approximately 85% of bauxite mined globally is refined into metallurgical-grade aluminium oxide (alumina) [13]. Australia is the largest global producer of bauxite, responsible for 28.2% of the output [14], with bauxite quality varying across the country, from lower-grade (27% alumina content) to average (49% alumina content) [15,16], resulting in alumina production sometimes requiring three to four tonnes of bauxite to produce one tonne of alumina, compared to the global average of two tonnes [2,15]. Alumina is produced by processing bauxite ore through the Bayer process [1,9,17,18]. In 2022, Australia was the second largest producer, responsible for 15% of global alumina production [19].

The industry now faces growing demands for improved sustainability practises from local communities, stakeholders, and regulators [20,21]. Traditional sustainability frameworks within the industry have predominately focused on carbon emissions, failing to fully account for other broader environmental impacts. While the techno-economic aspects of enabling decarbonisation are important (i.e., renewable energy adoption and low-carbon technologies), they should not outweigh other environmental impacts, such as biodiversity conservation, soil rehabilitation, and tailings and waste management [22–26]. Moreover, the voluntary nature of current frameworks does not always enable the assessment of future uncertainties, limiting their effectiveness towards long-term planning, future-focused impact management, and good governance practises. While common sustainability frameworks, like the Global Reporting Initiative (GRI) and the Sustainability Accounting Standards Board (SASB), have advanced many industries' approaches to addressing climate change, they are not comprehensive enough to help achieve many of the resource sector's longer-term environmental and social implications. These sustainability assessment challenges are further compounded by constantly evolving technological solutions and market dynamics. By way of example, the alumina industry, with its significant environmental footprint and socio-economic impact, provides a good example of a resource sector requiring a more comprehensive sustainability assessment framework that can adapt to evolving environmental and resource industry challenges and changing stakeholder expectations.

This paper proposes a sustainability assessment framework that integrates the Life Cycle Sustainability Assessment (LCSA) Framework methodology within Scenario Planning and Sensitivity Analysis to enable the industry to assess economic, social, and environmental impacts equally, without narrowing focus on one over the other. The LCSA Framework measures the sustainability of operations in a company by utilising the concepts of life cycle thinking and the triple bottom line—assessing not only economic impacts, but expanding to impacts on society and the environment over a product's lifetime [27–29]. This encourages stakeholder involvement and engagement, and identifies critical gaps that can influence long-term planning and mitigate shifting burdens to other stages of the product's lifecycle [27]. Combining assessments from each dimension (i.e., economic, social, and environmental) and utilising the same system boundaries (e.g., one tonne of alumina) relates interdependencies, while simultaneously assessing sustainability impacts [27,30].

Scenario Planning and Sensitivity Analysis complement the LCSA Framework by developing forward-looking perspectives on the alumina industry's potential sustainable pathways. By considering various energy sources, emerging technologies, and their implementation timing, this approach allows for the exploration of different potential futures and their corresponding impacts on the sustainability of operations [31]. The integration of these scenarios and LCSA Framework methodologies ensures that the assessment is comprehensive and dynamic, adapting to changes in technology, policy, and market conditions. This process was utilised for the Australian alumina industry.

This paper outlines the methods undertaken to combine the LCSA Framework and Scenario Planning methodology, the results observed through an analysis of the Australian alumina industry across Western Australia and Queensland, and a discussion of the benefits and limitations of this process.

2. Materials and Methods

This paper employs a dual-method approach that integrates the LCSA Framework with Scenario Planning and Sensitivity Analysis to assess the sustainable performance of the Australian alumina industry. The methodology is structured in two parts: developing the LCSA Framework to evaluate current sustainability performance, and the integration of Scenario Planning to explore potential pathways and their effects on the alumina industry's future sustainability performance.

2.1. Life Cycle Sustainability Assessment (LCSA) Framework

The LCSA Framework is a tool used to identify, predict, and evaluate potential sustainability impacts and barriers across three dimensions: economic, social, and environmental [27,30]. This approach attempts to address the limitations of existing carbon-focused frameworks by incorporating a broader range of indicators that relate the impacts across all three dimensions under the same system boundary (i.e., bauxite mining to the sale of alumina) and functional unit (i.e., one tonne of alumina). The selection of indicators underwent a two-stage process, a preliminary review of the literature and an industry questionnaire, to ensure that the final list of indicators enabled a holistic assessment [27,32–34].

This framework, while developed with a focus on the Australian alumina industry, has the potential to be adapted for broader geographic and industrial contexts. By leveraging global databases, such as the International Aluminium Institute's sustainability benchmarks, or region-specific studies, the framework can accommodate regional variations in energy grids, biodiversity priorities, and regulatory environments, for instance, as follows:

- Indicator Adaption*:* Economic indicators, such as export revenue and operating profit, can be modified to reflect local economic conditions, while environmental indicators, like carbon intensity and water consumption, can integrate data from global climate and energy initiatives (e.g., World Resources Institute or regional energy transition plans).
- Regional Thresholds*:* Threshold values for key performance indicators can be recalibrated using region-specific sustainability studies and industry data, ensuring relevance and applicability across geographic contexts.
- Scalability Across Industries*:* The framework can also be applied to other resource-intensive sectors, such as cement production or steel manufacturing, where carbon reduction, energy efficiency, and land rehabilitation are critical concerns.

To demonstrate this scalability, future studies should include case studies from other industries and regions to illustrate the framework's versatility. For example, applying the LCSA to mining operations in South America or Africa could provide insights into biodiversity conservation strategies, while European case studies could highlight advancements in renewable energy adoption.

Assessing sustainability through all three dimensions enables a comprehensive understanding of industrial processes. By proposing a globally adaptable approach, the LCSA Framework encourages industries to tailor sustainability assessments to their specific socio-economic and environmental contexts, ensuring a more resilient and inclusive sustainability evaluation.

2.1.1. Preliminary Literature Review

Indicators were developed under a three-tier system: sustainability dimensions, impact categories, and key performance indicators (KPIs). The impact categories are the broad key areas of assessment under each dimension, while the KPIs describe specific, measurable impacts within each category [27]. The indicators shown in Table 1 were selected based on existing national and international literature, government and industry reports, and any relevant grey literature. This selection process incorporated global studies to ensure broader applicability, as follows:

1. Environmental and Social Life Cycle Assessments for the mining and metals sectors across various regions (e.g., Europe, Africa, South America).
2. Global Sustainability Assessments to capture the best practises and indicator benchmarks applicable across geographies.
3. Cross-Sector Indicators that align with international standards (e.g., Global Reporting Initiative, Sustainability Accounting Standards Board).

Table 1. Preliminary selection of KPIs.

Sustainability Dimension	Impact Categories		KPIs		Unit	References
Economic	EC-1	National Economic Benefits	EC-1.1	Contribution to Local Economy	\$AU/t	[35,36]
			EC-1.2	Export Revenue	\$AU/t	[37,38]
	EC-2	Company Economic Benefits	EC-2.1	Annual Carbon Reduction	t CO_2-e/t	[29,39,40]
			EC-2.2	Operating Profit	\$AU/t	[40,41]
Environmental	E-1	Atmosphere	E-1.1	Acidification Potential (AP)	kg SO_2-e/t	[30,42–49]
			E-1.2	Global Warming Potential (GWP)	kg CO_2-e/t	[30,32,42–44,47–49]
			E-1.3	Ozone Depletion (OD)	kg CFC/t	[42–47,49]
	E-2	Energy	E-2.1	Energy Intensity	GJ/t	[42–44,48,49]
			E-2.2	Renewable Energy Share	%	[39]
	E-3	Water	E-3.1	Freshwater Contamination	kg CTU-e/t	[43,45–47,50–53]
			E-3.2	Water Consumption	m^3 H_2O/t	[42–45,47]
	E-4	Land Use and Biodiversity	E-4.1	Bauxite Residue Land Utilisation	ha/t	[44]
			E-4.2	Bauxite Residue Re-Utilisation	t (BR)/t	[18,28,44,46]
			E-4.3	Natural Land Rehabilitation	ha/t	[30,45,47,52]
Social	S-1	Intra-Generational Equity	S-1.1	Investment in Local Community	\$AU/t	[54–56]
			S-1.2	Community Engagement	PSIA Scale	[57–61]
			S-1.3	Employment Generation	FTE/t	[29,54,56,57,60,62,63]
			S-1.4	Work Safety	Accident Rate per MWH	[54,55,57,60,63,64]

The indicators in Table 1 were chosen based on the following criteria [27,65,66]:

1. Relevance to Industry Goals**:** Indicators that align with key sustainability objectives, such as decarbonisation, energy efficiency, and freshwater management. For

example, E-2.1 Energy Intensity addresses the heavy energy demand in alumina production, particularly during steam generation.

2. Data Availability**:**
    a. Availability of Reliable Data*:* Indicators were selected based on robust, verifiable data from industry reports, scientific literature, and international databases.
    b. Avoiding Data Gaps*:* Indicators requiring data unavailable for all regions were excluded to maintain analytical consistency. For instance, while biodiversity loss is critical, data limitations often prevent detailed quantification.
3. Effectiveness in Measuring Sustainability**:** Indicators were selected based on their ability to deliver actionable insights into economic, social, and environmental performance. E-4.3 Natural Land Rehabilitation is crucial for post-mining ecosystems, as seen in Australian rehabilitation efforts.
4. Relevance to Future Scenarios**:** Indicators needed to be adaptable to scenario analyses and reflective of technological and policy changes over time. E-1.1 Carbon Intensity is an example that enables future-focused comparisons under varying decarbonisation pathways.

By leveraging global literature and region-specific studies, the indicator selection process allows for scalability. For example, while water consumption carries greater weight in arid regions like Australia, energy efficiency and emissions metrics may be prioritised in areas that are heavily reliant on fossil fuels.

The economic dimension evaluates the industry's financial contributions to local economies and its operational efficiency, expressed through export revenue, operating profit, and carbon reduction incentives. The environmental dimension encompasses emissions, energy usage, water impacts, and land usage, ensuring both local and global environmental concerns are addressed. Social indicators focus on community engagement, job creation, and worker health and safety, with the flexibility to adapt these metrics to diverse regional priorities.

Assessing the economic, environmental, and social dimensions allows for a holistic understanding of the alumina industry's sustainability performance. Examples like bauxite residue management (E-4.1) underscore the industry's need to address land use challenges, while employment generation (S-1.3) highlights its social contributions in rural areas.

2.1.2. Questionnaire

A targeted questionnaire was developed to validate and refine the preliminary indicator selection. Respondents included representatives from the government, industry, academia, and non-government organisations (NGOs), in order to capture a diverse range of expertise and perspectives. The selection criteria ensured that participants had direct experience or knowledge of the bauxite and alumina industries, as well as sustainability frameworks applicable across different regions [27,33,34].

The questionnaire was structured as follows:

1. Relevance and Importance: Participants rated the relevance and importance of each KPI on a 5-point Likert scale.
2. Indicator Suggestions: Participants could propose additional indicators that they believed were critical, but which were absent from the preliminary list.
3. Regional Context: Participants provided insights into how indicators might need to be adjusted for geographic or industrial differences, such as the following:
    a. Adding metrics for water stress in arid regions.
    b. Incorporating biodiversity monitoring for ecologically sensitive areas.

c. Addressing energy grid differences, such as reliance on renewable versus fossil fuels.

Out of the 52 invited participants, 20 provided responses: one from government, eleven from industry, four from academia, and four from NGOs. The feedback resulted in three key refinements:

1. Biodiversity Indicators: Metrics for biodiversity loss and native vegetation were added, which are particularly relevant to regions with significant land use pressures.
2. Global Applicability: Participants emphasised the need for region-specific thresholds and global benchmarks to enhance the framework's adaptability.
3. This study focuses on CO_2 emissions and omits NOx and SOx emissions from the final list of indicators. This change was made as the majority of participants did not view this as a priority for the alumina sector's environmental footprint; these indicators would be better placed in an LCSA of the aluminium smelting sector (due to its much larger fossil fuel energy intensity).

The final list of KPIs reflects a balance between universality (applicability across regions) and specificity (addressing regional priorities) (Table 2). Future studies should replicate this participatory process in other regions, to ensure that locally relevant indicators are incorporated while maintaining consistency with global sustainability standards.

Table 2. Final list of KPIs.

Sustainability Objective	Impact Categories		KPIs		Unit
Economic	EC-1	National Economic Benefits	EC-1.1	Contribution to Local Economy	$AU/t
			EC-1.2	Export Revenue	$AU/t
	EC-2	Company Economic Benefits	EC-2.1	Annual Carbon Reduction	$AU/t
			EC-2.2	Operating Profit	$AU/t
Environmental	E-1	Atmosphere	E-1.1	Carbon Intensity	kg CO_2-e/t
			E-1.2	Global Warming Potential (GWP)	kg CO_2-e/t
	E-2	Energy	E-2.1	Energy Intensity	GJ/t
			E-2.2	Renewable Energy Share	MWh/t
	E-3	Water	E-3.1	Freshwater Contamination	kg CTU-e/t
			E-3.2	Water Consumption	m^3 H_2O/t
	E-4	Land Use and Biodiversity	E-4.1	Bauxite Residue Land Utilisation	ha/t
			E-4.2	Bauxite Residue Re-Utilisation	t (BR)/t
			E-4.3	Natural Land Rehabilitation	ha/t
			E-4.4	Clearing of Biodiversity and Native Vegetation	ha/t
Social	S-1	Intra-Generational Equity	S-1.1	Community Spending	$AU/t
			S-1.2	Community Engagement	PSIA Scale
			S-1.3	Employment	FTE/t
			S-1.4	Health and Safety	Accident Rate per MWH/t

2.2. Threshold Values

Threshold values were used to define and determine the targeted sustainability performance using a 5-point Likert Scale [27,34]. Minimum and maximum values for each KPI were determined by reviewing existing case studies, industry and government reports, international agreements, and articles on alumina sustainability relative to the Australian context. All threshold values were determined using the following methodology:

1. Minimum values were determined by following a combination of the following:
    a. Averaging reported values within current industry and government reports.

   b. Values reported in industry assessments of emerging low-emission technologies.
   c. Predicted values, based on market analysis and reports between 2025 and 2050.
2. Maximum values were determined by following a combination of the following:
   a. Averaging reported goal values within current industry and government reports.
   b. Maximum expected reduction potentials associated with the incorporation of renewable energy and low-emission technologies in current industry, government, and non-government organisation reports.
   c. Currently calculated annual emission reduction potentials reported in technology reports.
   d. Averages of goals from other operating countries whose approaches or performance match Australian operation goals.

All threshold values listed in Table 3 utilised the above dot points, alongside the references provided, to determine the values shown below.

Table 3. KPI threshold values.

KPI		Threshold Value		Reference
		Minimum	**Maximum**	
EC-1.1	Investment in Local Economy	$AU265.51	$AU521.71	[36,67–69]
EC-1.2	Export Revenue	$AU522.81	$AU553.13	[68–71]
EC-2.1	Annual Carbon Reduction	0.0 kg CO_2-e/t	26.92 kg CO_2-e/t	[37,72–74]
EC-2.2	Operating Profit	$AU62.33	$AU143.55	[75–79]
E-1.1	Carbon Intensity	760 kg CO_2-e	15.2 kg CO_2-e	[37,71,80–82]
E-1.2	Global Warming Potential (GWP)	700 kg CO_2-e	0.0 kg CO_2-e	[67,71,81,83,84]
E-2.1	Energy Intensity	10.5 GJ	4.6 GJ	[37,71]
E-2.2	Renewable Energy Share	0%	100%	[85]
E-3.1	Freshwater Contamination	0.233 kg CTU-e	0.155 kg CTU-e	[46,83]
E-3.2	Water Consumption	5.16 m^3	3.20 m^3	[67,71,83]
E-4.1	Bauxite Residue Land Utilisation	4.49×10^6 ha	3.82×10^6 ha	[67,86,87]
E-4.2	Bauxite Residue Re-Utilisation	0.0357 t (BR)	1.61 t (BR)	[86,88]
E-4.3	Natural Land Rehabilitation	5.02×10^5 ha	1.439×10^4 ha	[67,71]
E-4.4	Clearing of Biodiversity and Native Vegetation	3.86×10^5	1.93×10^5	[71,89]
S-1.1	Investment in Local Community	$AU0.06	$AU0.63	[35,36,67,90–92]
S-1.2	Community Engagement	0	+2	[93]
S-1.3	Employment Generation	4.81×10^4 FTE/t	1.255×10^3 FTE/t	[35,36,67,71,91,92]
S-1.4	Work Safety	4.8 TRAR	0.012 TRAR	[36,94–96]

All values above are representative per tonne of alumina production, except for S-1.2 and S-1.4. S-1.4 Work Safety; TRAR = Total Recordable Accident Rate per Million Hours Worked (MHW).

2.3. Scenario Planning and Sensitivity Analysis

Scenario Planning is a strategic tool that utilises various assumptions to determine future outcomes and impacts on operations. In the context of the alumina industry, Scenario Planning can identify potential risks and opportunities that may not be captured by traditional sustainability frameworks. Scenario Planning is also utilised to explore the potential futures of the alumina industry under different energy and technology mixes, aligning with the future risk focus increasingly demanded by ESG frameworks globally and in Australia [97–99]. This paper used the following methodology:

1. Key Variable Identification:
    a. Decarbonisation variables influencing the alumina industry were identified, including the availability and adoption of alternative energy sources, emerging technologies, and changes in policies and regulations.
2. Future-focused Scenario Development:
    a. A total of 34 sub-scenarios were developed—17 for Western Australia and 17 for Queensland—representing different combinations of the identified variables. These included varying levels of renewable energy integration and differing rates/types of technology adoption.
3. Scenario Types:
    a. Business-As-Usual (BAU): The continuation of current practises, with no additional decarbonisation efforts beyond publicised commitments.
    b. Net-Zero: The achievement of near-zero Scope 1 and 2 emissions by 2050, through incremental adoption of renewables and low-emission technologies.
    c. Accelerated Net-Zero: The rapid implementation of renewable technologies and advanced decarbonisation strategies to achieve the earliest possible reductions.
4. Data Collection and Analysis:
    a. Data were collected from primary and secondary sources, including industry reports, academic literature, and expert reviews. Threshold values for the KPIs were established based on available industry benchmarks.
5. Sensitivity Analysis:
    a. Sensitivity Analysis was conducted by manipulating key independent variables to explore their impacts on overall sustainability outcomes. This identified potential gaps and areas requiring improvement.
    b. For example, one sensitivity included was water consumption targets for 2030 and 2050, of a 15% reduction (5.16 m^3 to 4.4 m^3) and a further 25% reduction (down to 3.2 m^3), respectively. Sensitivity Analysis was conducted on water usage to predict how various operational changes (such as adopting water-efficient technologies or alternative processes) could contribute to the achievement of these targets.

2.4. Gap Analysis for Indicator Selection

While the LCSA Framework and Scenario Planning tools capture a wide range of sustainability impacts, they often prioritise indicators that can be easily measured, such as carbon emissions, energy use, or resource efficiency. This focus can lead to the underrepresentation of crucial social and environmental "ghost indicators", which include biodiversity preservation, cultural heritage, and community health. Despite their relevance, these indicators are frequently overlooked, due to challenges in data collection, measurement, and integration into traditional frameworks [100–102].

In this study, the exclusion of certain ghost indicators was primarily due to limitations in data availability. Specifically, the data required to comprehensively assess indicators such as biodiversity, cultural heritage, and community health were not accessible due to non-disclosure agreement (NDA) requirements with Australian alumina producers. These agreements would restrict the sharing of proprietary operational data, which would have enabled a more detailed analysis. Additionally, the inability to publish results incorporating such data further constrained the scope of this assessment.

To address these gaps in future research, the following advanced methods are proposed to quantify ghost indicators effectively:

1. Ecological Indicators (Biodiversity and Habitat Loss):
    a. Leverage remote sensing data to monitor land use changes, habitat fragmentation, and vegetation loss. Tools like satellite imagery and Geographic Information Systems (GIS) can provide real-time assessments of biodiversity impacts.
    b. Apply ecosystem services valuation models to estimate the economic value of preserved biodiversity and natural habitats.
2. Social Indicators (Cultural Heritage and Community Impacts):
    a. Use participatory approaches, such as structured community surveys, to gather data on local perceptions of land degradation and cultural heritage disruptions.
    b. Develop qualitative-to-quantitative conversion frameworks that translate survey responses into measurable metrics for inclusion in the LCSA.
3. Integrated Modelling Techniques:
    a. Implement advanced ecological and social impact modelling techniques, such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) or Social Life Cycle Assessment (S-LCA) methodologies, to fill data gaps for these indicators.

By embedding these methodologies into the LCSA Framework and overcoming data-sharing barriers through partnerships or anonymised data-sharing protocols, the assessment can become more holistic. This approach enables a balanced evaluation of environmental, social, and economic dimensions. These additions not only enhance the comprehensiveness of sustainability assessments, but also align with broader Environmental, Social, and Governance (ESG) reporting requirements.

3. Results

3.1. Scenario Descriptions

Three scenarios were selected to evaluate the sustainability performance of alumina production in Western Australia and Queensland: Business-as-Usual (BAU), Net-Zero, and Accelerated Net-Zero. These scenarios span a 25-year window (2025 to 2050), aligned with Australia's national net-zero commitments [103]. Each scenario considers changes in production practises, energy systems, and technology adoption, to provide a forward-looking perspective on decarbonisation potential and sustainability performance.

3.1.1. Business-As-Usual (BAU)

The BAU scenario represents a continuation of current practises, with no additional decarbonisation efforts beyond publicly announced commitments. Key assumptions and characteristics include the following:

- Production Baseline:
    a. Western Australia: Total alumina production starts at 13.45 Mt per year, with a reduction from 2026 due to the close of Alcoa's Kwinana Alumina Refinery [104].
    b. Queensland: Production remains constant throughout the 25-year period.
- Energy Transition:
    a. Western Australia: Decommissioning of coal-fired power stations by 2030, transitioning to natural gas [105].
    b. Queensland: Decommissioning of coal-fired power stations by 2035 [106].
- Emissions Impact:

  a. Western Australia: Emissions decrease by 20%, from 9.65 Mt CO_2-eq to 6.56 Mt CO_2-eq, due to coal power reductions and declining production from the closure of the Kwinana Refinery.
  b. Queensland: Emissions decrease by 21%, from 5.23 Mt CO_2-eq to 4.30 Mt CO_2-eq.
- Technology Adoption: No new decarbonisation technologies are deployed in this scenario.

The BAU scenario provides a baseline against which to compare the incremental benefits of the Net-Zero and Accelerated Net-Zero pathways.

3.1.2. Net-Zero

The Net-Zero scenario focuses on achieving near-zero emissions by 2050 through incremental adoption of renewable energy and emerging low-carbon technologies. Key assumptions and stages in this scenario include the following:

- Stage 1: Energy Transition
  a. Western Australia: Coal-fired power stations are decommissioned by 2030.
  b. Queensland: Coal-fired power stations are decommissioned by 2035.
- Stage 2: Technology Implementation
  a. Mechanical Vapour Recompression (MVR): Retrofitting begins in 2030 and is completed within six years, significantly reducing energy demand by recycling process steam.
  b. Electric Calcination: Replacing fossil-fuel calcination with renewable electricity begins in 2040 and is completed by 2044.
- Energy Intensity:
  a. Energy intensity improves by 50% after renewable energy and technology implementation, reducing energy intensity from 10.47 GJ/t to 5.24 GJ/t.
- Renewable Energy Integration:
  a. Western Australia: Integration of 5 GW of renewable energy capacity.
  b. Queensland: Integration of 4 GW of wind energy.
  c. The South West Interconnected System (SWIS) and National Energy Market (NEM)'s renewable transitions follow the baseline assumptions from the Australian government's emission reduction reports [80,84].

The Net-Zero scenario highlights the potential for significant decarbonisation through a phased transition to renewable energy and the electrification of calcination processes.

3.1.3. Accelerated Net-Zero

The Accelerated Net-Zero scenario represents an ambitious pathway to achieve rapid decarbonisation by 2036–2040, exceeding the timelines of the Net-Zero scenario. Key assumptions and stages of this scenario include the following:

- Stage 1: Energy Transition
  a. Western Australia: Coal-fired power stations are decommissioned by 2030.
  b. Queensland: Coal-fired power stations are decommissioned by 2035.
- Stage 2: Technology Implementation
  a. Mechanical Vapour Recompression (MVR): Retrofitting begins in 2030 and is completed within six years.
  b. Electric Calcination (WA): Installation begins in 2036 and is completed by 2039.

  c. Hydrogen Calcination (QLD): Adoption begins in 2036, replacing natural gas with third-party renewable hydrogen, and is completed by 2039.

- Renewable Energy Integration:
  a. Western Australia: Integration of 6 GW of renewable energy capacity.
  b. Queensland: Integration of 4 GW of wind energy.
  c. The South West Interconnected System (SWIS) and National Energy Market's (NEM) renewable transitions follow the baseline assumptions from the Australian government's emission reduction reports [80,84].

The Accelerated Net-Zero scenario emphasises rapid technological deployment and increased renewable energy integration in order to achieve maximum decarbonisation potential. The adoption of hydrogen calcination in Queensland highlights the additional benefits of integrating alternative fuels into existing processes.

3.2. Scenario Analysis

The decarbonisation and sustainability performance results of the scenarios were compared graphically to assess where there were performance gaps and areas for improvement (Table 4).

Figures 1 and 2 depict the emissions intensities for alumina production in Western Australia and Queensland under three distinct scenarios: BAU, Net-Zero, and Accelerated Net-Zero. To ensure that the estimates of emission reduction are comprehensive for all stages in each scenario, the lifecycle emissions of all renewable energy technologies, such as solar and wind, were included. While these technologies are viewed as emissions-free during operation, their manufacturing and installation phases still emit CO_2.

Table 4. All scenarios' emission reduction percentages.

Scenario	Western Australia	Queensland
BAU	20%	21%
Net-Zero	91%	97%
Accelerated Net-Zero	96%	97%

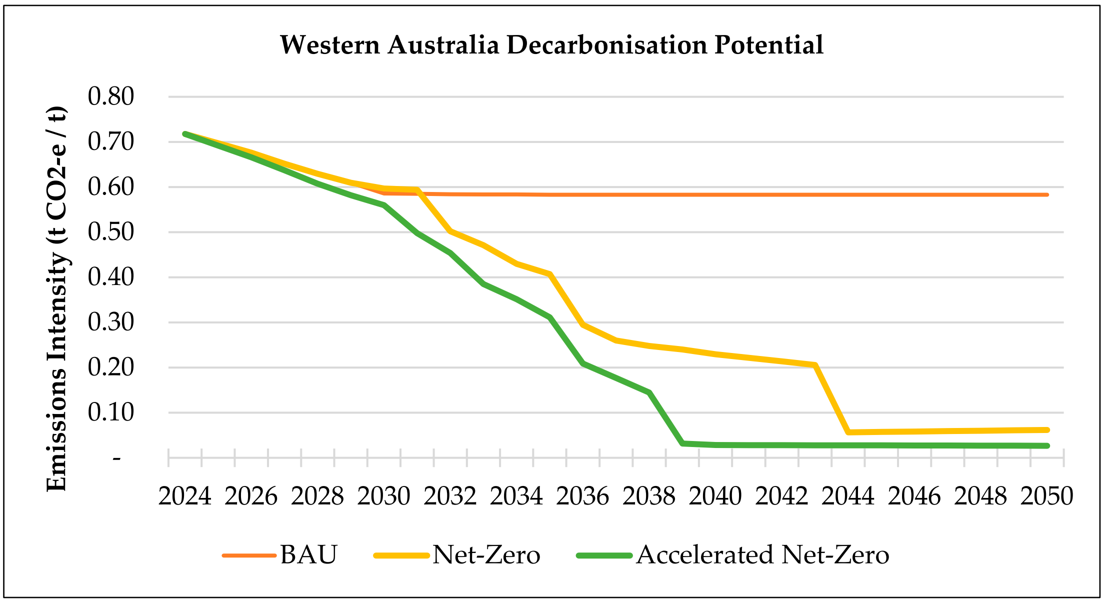

Figure 1. Western Australia's emissions intensity.

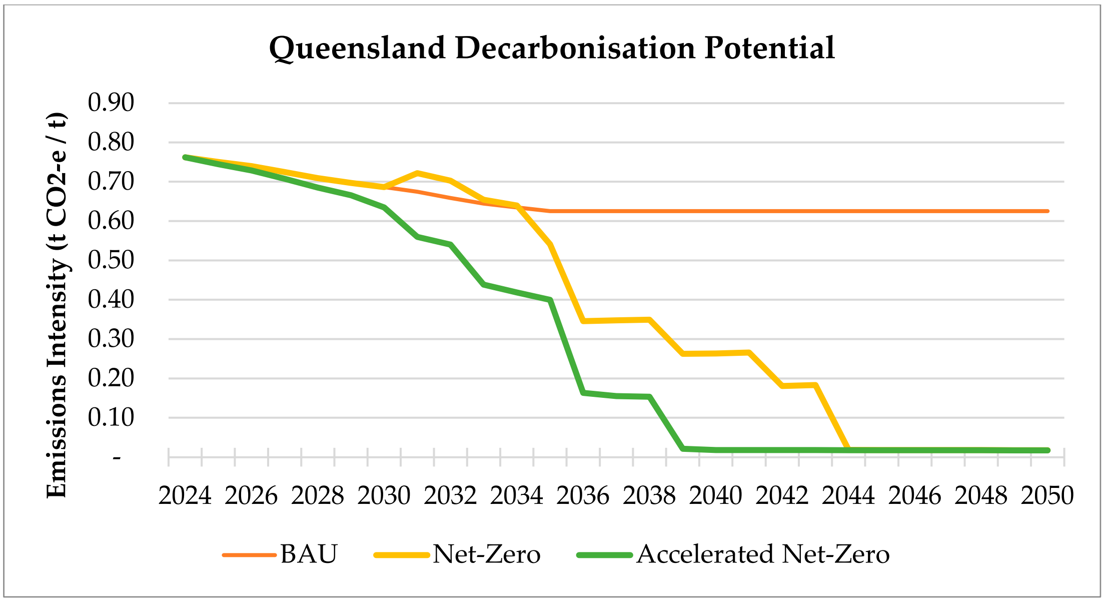

Figure 2. Queensland's emissions intensity.

3.2.1. BAU

Analysis of the Western Australia BAU scenario in Figure 1 demonstrates that the closure of coal-fired power stations and the Kwinana Alumina Refinery would reduce emissions by 20%, and total annual emissions from 9.65 Mt CO_2eq to 6.56 Mt CO_2eq. In Figure 2, the Queensland BAU scenario in Figure 2 demonstrates that the closure of coal-fired power stations would reduce emissions by 21%, and total annual emissions from 5.23 Mt CO_2eq to 4.30 Mt CO_2eq.

3.2.2. Net-Zero

The Western Australia Net-Zero scenario assesses the closure of coal-fired power stations, the installation of 5 GW of renewables (2 GW solar, 3 GW wind), and the combination of MVR and electric calcination. This would reduce emissions by 91%, and total annual emissions from 9.65 Mt CO_2eq to 0.69 Mt CO_2eq. Much of the emission reduction is attributed to MVR's ability to recycle steam output through the refinery process in combination with electric calcination, improving the energy efficiency from 10.47 GJ/t to 5.24 GJ/t.

The Queensland Net-Zero scenario assesses the closure of coal-fired power stations, the installation of 4 GW of wind turbines, and the combination of MVR and electric calcination. This would reduce emissions by 97%, and total annual emissions from 5.23 Mt CO_2eq to 0.12 MtCO_2eq. In 2031 and 2032, total emissions increase due to an increased reliance on grid energy, which relies more heavily on thermal coal. As with Western Australia, MVR and electric calcination improve energy efficiency by 50%.

3.2.3. Accelerated Net-Zero

The Western Australia accelerated Net-Zero scenario assesses the accelerated decarbonisation of the South West Interconnected System (SWIS) and the installation of 6 GW of renewables (2 GW solar, 4 GW wind), alongside MVR and electric calcination. This would reduce emissions by 96%, and total annual emissions from 9.65 Mt CO_2eq to 0.29 Mt CO_2eq.

The Queensland accelerated Net-Zero scenario accelerates decarbonisation of the grid, the installation of 4 GW of renewables, and the combination of MVR and hydrogen calcination. This would reduce total emissions by 97%, and total annual emissions from 5.23 Mt CO_2eq to 0.12 Mt CO_2eq.

The data illustrate a clear trend towards reduced emissions intensity with the adoption of renewable energy integration and electrifying process technologies. In Western Australia, the BAU shows a small emission reduction of 20%, which increases significantly to 91% in the Net-Zero scenario, and further to 96% in the Accelerated Net-Zero scenario, reflecting the substantial impact of accelerated innovation. Similarly, Queensland starts with 21%, improving to 97% under both the Net-Zero and Accelerated Net-Zero Scenarios. The negligible difference between the Net-Zero and Accelerated Net-Zero scenarios for Queensland indicate that the general and accelerated improvements in Queensland have the potential to achieve close to its maximum decarbonisation potential.

3.3. LCSA Analysis

The following LCSA indicators were assessed using this model: EC-1.2 Export Revenue, EC-2.1 Annual Carbon Reduction, EC-2.2 Operating Profit, E-1.1 Carbon Intensity, E-2.1 Energy Intensity, E-2.2 Renewable Energy Share, E-3.2 Water Consumption, E-4.1 Bauxite Residue Land Utilisation, E-4.3 Natural Land Rehabilitation, E-4.4 Clearing of Biodiversity and Natural Land, and S-1.3 Employment Generation. The remaining indicators were not assessed, as specific data were required, and could not be obtained due to the Australian refiners' confidentiality requirements.

Figures 3 and 4 present spider diagrams that illustrate the sustainability performance of alumina production for Western Australia and Queensland, respectively, under the BAU, Net-Zero, and Accelerated Net-Zero scenarios. The diagrams use a 5-point Likert scale, where 1 represents the lowest performance, and 5 indicates optimal performance, across key sustainability indicators.

- Western Australia (Figure 3):
    a. The Net-Zero scenario demonstrates substantial improvements in energy intensity, water consumption, and carbon intensity compared to BAU.
    b. The Accelerated Net-Zero scenario further improves carbon intensity and renewable energy share, reflecting the benefits of faster technology adoption.
    c. Bauxite residue land utilisation and clearing of biodiversity show limited progress, underscoring the need for more targeted ecological interventions.
- Queensland (Figure 4):
    a. Both the Net-Zero and Accelerated Net-Zero scenarios achieve significant improvements in emissions intensity and energy efficiency.
    b. Natural land rehabilitation and employment generation remain relatively unchanged, highlighting limitations in addressing broader sustainability impacts.

Figures 3 and 4 emphasise that while decarbonisation metrics (e.g., carbon intensity and energy efficiency) improve substantially under Net-Zero and Accelerated Net-Zero scenarios, other critical environmental and social indicators exhibit limited progress. This highlights the need for a holistic sustainability framework that addresses ecological and social dimensions alongside carbon reduction efforts.

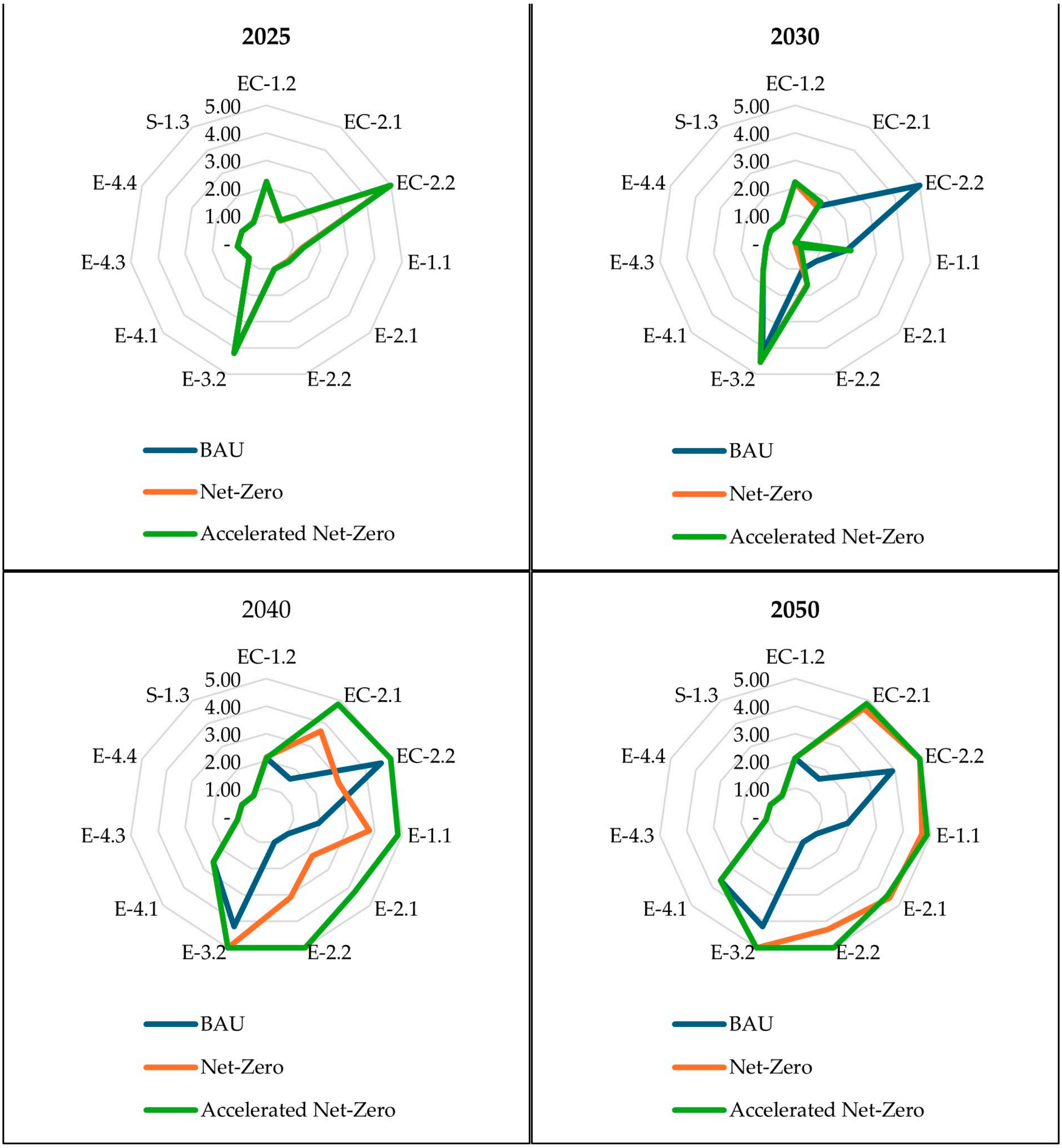

Figure 3. Western Australia's alumina production sustainability performance. EC-1.2 Export Revenue; EC-2.1 Annual Carbon Reduction; EC-2.2 Operating Profit; E-1.1 Carbon Intensity; E-2.1 Energy Intensity; E-2.2 Renewable Energy Share; E-3.2 Water Consumption; E-4.1 Bauxite Residue Land Utilisation; E-4.3 Natural Land Rehabilitation; E-4.4 Clearing of Biodiversity and Native Vegetation; S-1.3 Employment Generation.

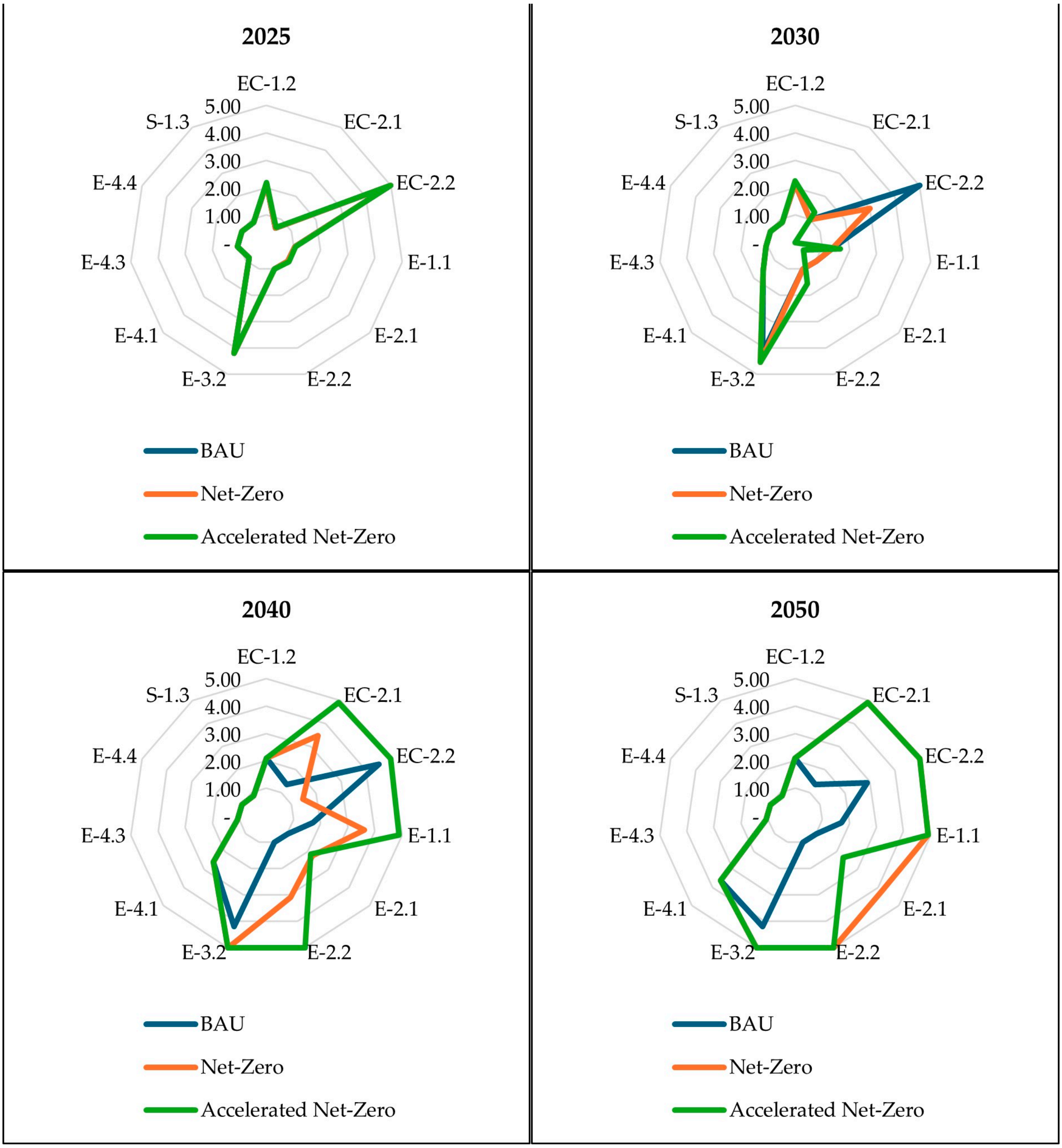

Figure 4. Queensland's alumina production sustainability performance. EC-1.2 Export Revenue; EC-2.1 Annual Carbon Reduction; EC-2.2 Operating Profit; E-1.1 Carbon Intensity; E-2.1 Energy Intensity; E-2.2 Renewable Energy Share; E-3.2 Water Consumption; E-4.1 Bauxite Residue Land Utilisation; E-4.3 Natural Land Rehabilitation; E-4.4 Clearing of Biodiversity and Native Vegetation; S-1.3 Employment Generation.

4. Discussion

4.1. Benefits of the Framework

The integration of the LCSA and Scenario Planning frameworks facilitates a comprehensive, multi-dimensional assessment of sustainability performance. By combining environmental, economic, and social indicators across the production lifecycle, these tools offer a forward-looking perspective on potential pathways for decarbonisation, technological innovation, and broader sustainability gains.

The key benefits of this framework are its capacity to achieve the following:

- Quantify Immediate and Long-Term Impacts*:* Beyond carbon emissions, the framework captures a broader range of indicators, such as energy intensity, water consumption, and economic performance. For instance, under the Accelerated Net-Zero scenario, Queensland achieves a 97% reduction in carbon emissions, while improving energy efficiency by 50%.
- Support Informed Decision-Making*:* Scenario Planning enables companies to anticipate risks and opportunities associated with emerging technologies, regulatory changes, and market shifts. This framework enhances their ability to align operations with global climate targets, such as the Paris Agreement.
- Improve Operational Sustainability*:* The adoption of technologies like MVR and electric/hydrogen calcination demonstrates tangible benefits, including reduced energy demand, improved process efficiency, and water savings.
- Perform Cost–Benefit and Risk Assessment*:* A detailed cost–benefit analysis highlights the practical implications for industry adoption:
    a. Electric Calcination: An estimated reduction cost of $30–50 per tonne of CO_2 mitigated, offering significant energy efficiency improvements and lower operational costs compared to fossil fuel alternatives.
    b. Hydrogen Calcination: While achieving similar decarbonisation outcomes, the cost of this is higher ($60–90 per tonne of CO_2 mitigated), due to challenges in hydrogen production, storage, and transport. However, hydrogen calcination provides greater flexibility for energy-intensive operations, and aligns with evolving hydrogen infrastructure.
    c. Risk Consideration: Industry adoption of these technologies carries financial risks related to capital investment, operational disruption, and reliance on emerging energy markets. Additionally, technological maturity and regional energy availability may limit implementation timelines.
    d. Such assessments allow industries to prioritise investments in emission reduction technologies based on cost-effectiveness, feasibility, and scalability.
- Enhanced Stakeholder Engagement*:* By assessing impacts across social and economic dimensions alongside environmental indicators, companies can better engage stakeholders, including local communities and regulatory bodies, fostering trust and transparency.

Furthermore, the forward-looking nature of this framework allows industries to address future challenges proactively, supporting a structured transition to low-carbon operations while identifying critical sustainability gaps. The comparative analysis of scenarios highlights where investments in emerging technologies yield the most significant performance improvements while balancing economic considerations.

4.2. Limitations of the Framework

While the integration of the LCSA and Scenario Planning provides a more holistic assessment, several limitations restrict the framework's ability to deliver a fully comprehensive sustainability evaluation:

1. Data Availability and Accessibility:
    a. The exclusion of key environmental and social "ghost indicators", such as biodiversity loss, cultural heritage, and community health, is primarily due to insufficient or unavailable data. For this study, the requirement for NDAs with alumina producers restricted access to proprietary operational data, limiting the evaluation of critical impacts.

   b. Mitigation: Future research should incorporate anonymised data-sharing protocols and leverage advanced tools, like remote sensing for ecological assessments, and structured community surveys for social indicators. Collaborations with independent research bodies and public–private partnerships can facilitate broader data collection efforts.

2. Carbon-Centric Focus:
   a. While this framework successfully measures decarbonisation performance, its emphasis on carbon emissions and energy metrics risks overshadowing equally significant issues, like land rehabilitation, bauxite residue management, and social equity. The selective improvement of easier-to-quantify indicators raises concerns about “cherry-picking” sustainability wins.
   b. Mitigation: Developing integrated models, such as multi-criteria decision analysis (MCDA), would ensure balanced consideration of environmental, social, and economic dimensions. Incorporating long-term ecological and social monitoring systems will help to address these under-represented indicators.
3. Simplified Modelling Assumptions:
   a. The scenario analysis relies on simplified assumptions about technology adoption rates, renewable energy integration, and operational changes. This approach may fail to capture dynamic factors, like fluctuating market prices, policy uncertainties, and geopolitical risks.
   b. Mitigation: Enhancing model complexity through Sensitivity Analysis and dynamic system modelling would improve the robustness of scenario outcomes. For instance, iterative modelling techniques can identify key sensitivities in cost and performance assumptions, allowing more accurate future projections.
4. Limited Geographic Scope:
   a. The framework’s reliance on Australian-specific data and assumptions limits its global applicability. Regional variations in energy grids, regulatory environments, and biodiversity priorities must be accounted for to enhance transferability.
   b. Mitigation: Further research can address this limitation through collaborations with international partners and comparative case studies across different geographic regions. Leveraging global datasets and region-specific benchmarks will improve adaptability and scalability. For example, partnerships with global organisations like the International Aluminium Institute could provide access to standardised data for broader applicability.

By addressing these limitations through further research, advanced modelling, and collaborations, the framework can evolve into a globally relevant tool for sustainability assessment. This would enable industries to identify broader risks, mitigate unquantified environmental and social impacts, and develop adaptive pathways for achieving transformative sustainability outcomes.

4.3. The Next Generation of Sustainability Frameworks

4.3.1. Unaddressed Environmental and Social Impacts

Although the integration of the LCSA and Scenario Planning provides a structured approach to sustainability performance assessment, the frameworks’ predominant focus on decarbonisation leaves several critical environmental and social impacts inadequately addressed. These gaps are partly due to limitations in data availability, which constrained the ability to comprehensively evaluate some indicators during this study. Addressing these limitations requires both methodological advancements and enhanced access to diverse datasets.

Biodiversity and Habitat Preservation

- Incorporate biodiversity monitoring programmes that utilise remote sensing and field-based studies, to measure habitat quality and species richness in areas impacted by alumina production.
- Introduce mandatory post-mining rehabilitation plans with specific, measurable targets for biodiversity restoration.
- Employ ecological valuation tools to estimate the benefits of preserved rehabilitated habitats.

Cultural Heritage and Indigenous Rights

- Develop cultural heritage impact assessment protocols that involve Indigenous communities in decision-making processes, ensuring their rights and traditions are respected.
- Use GIS-based mapping to identify and monitor culturally significant sites within mining areas, integrating these insights into planning and mitigation efforts.

Social Equity and Community Health

- Conduct longitudinal community surveys to track changes in local perceptions of well-being, land use, and economic opportunities resulting from industrial activities.
- Use health impact assessments (HIAs) to evaluate long-term health risks associated with air and water pollution from alumina production. These assessments should inform mitigation strategies and policy interventions.

Integrated Reporting

- Develop a multi-criteria decision analysis framework to weigh and integrate findings from ecological, social, and economic assessments. This approach ensures that "ghost indicators" receive equal consideration, alongside traditional sustainability metrics.

By embedding these methodologies and leveraging global partnerships, the framework can address these unquantified impacts, transitioning from a predominantly carbon-centric approach to a truly comprehensive sustainability assessment model. This evolution not only supports the alumina industry's transition to sustainability, but also strengthens its applicability to global contexts by prioritising community and environmental well-being.

Current sustainability reporting in the alumina industry is driven by GHG protocols, such as the Greenhouse Gas Protocol (GHG Protocol) and Australia's National Greenhouse and Energy Reporting (NGER) Scheme [107–109]. While these initiatives play an important role in mitigating climate change, they often sideline other equally important sustainability aspects, including biodiversity and social equity. International efforts like the Convention on Biological Diversity (CBD) and Australia's Threatened Species Strategy underscore the ongoing challenges in adequately measuring and addressing biodiversity impacts, which are poorly reflected in many sustainability frameworks today [110–113].

4.3.2. Enhancing Global Adaptability

The current LCSA and Scenario Planning frameworks primarily rely on Australian-specific data and thresholds, which limits their transferability to other regions and industries. To overcome these limitations, the framework should be adapted for broader global contexts using the following approaches:

- Global Data Integration*:* Incorporate international datasets, such as those from the International Aluminium Institute, World Resources Institute, or regional environmental agencies, to recalibrate KPIs and thresholds.
- Case Studies Across Regions*:* Conduct comparative studies in regions such as South America, Africa, and Asia, where resource-intensive industries face unique biodiversity, water, and social challenges, such as in the following examples:
    a. South America: Addressing biodiversity loss from mining in the Amazon basin using ecological restoration techniques.
    b. Europe: Assessing the success of renewable energy transitions in energy-intensive industries.
    c. Africa: Evaluating community health and economic impacts in mining-dependent rural areas.
- Scalability Across Sectors*:* Extend the framework's applicability to other resource sectors, such as cement, steel, or rare earth metals, where similar environmental and social challenges persist. These industries can benefit from insights into decarbonisation, energy efficiency, and social equity.

By addressing these limitations through international collaboration, regional studies, and methodological advancements, the integrated LCSA and Scenario Planning framework can evolve into a globally applicable tool for sustainability assessment. This approach ensures that industries worldwide can adopt the framework to identify sustainability risks, mitigate unquantified environmental and social impacts, and align operations with region-specific sustainability goals.

The next generation of sustainability frameworks must embrace adaptability, transparency, and inclusiveness to address global sustainability challenges comprehensively. This evolution will ensure transformative progress across industries and geographies, advancing sustainability as a shared global priority.

5. Conclusions

The integration of the Life Cycle Sustainability Assessment (LCSA) framework with Scenario Planning and Sensitivity Analysis presents a robust, forward-looking approach to sustainability assessment for the alumina industry. This research demonstrates that significant decarbonisation benefits can be achieved through renewable energy adoption and advanced technologies like mechanical vapour recompression (MVR), electric calcination, and hydrogen calcination, achieving up to 97% emission reduction and 50% improvements in energy efficiency under the Net-Zero and Accelerated Net-Zero scenarios. By assessing economic, social, and environmental dimensions simultaneously, the framework identifies critical sustainability performance gaps and informs adaptive, forward-thinking decision-making.

Despite these advances, limitations persist:

1. Carbon-Centric Focus*:* The current emphasis on decarbonisation risks neglecting broader environmental and social challenges, such as biodiversity preservation, land rehabilitation, and cultural heritage protection.
2. Data Accessibility*:* Limited access to industry-specific and ecological data restricts comprehensive assessment, particularly of critical "ghost indicators".
3. Regional Scope*:* The reliance on Australian-specific data reduces the global adaptability of the framework.

Future Research Direction

1. Enhanced Measurement Methods for Ecological and Social Indicators:
    a. Develop advanced biodiversity monitoring tools, such as remote sensing and GIS-based habitat assessments.
    b. Use participatory methods, like structured community surveys and cultural heritage mapping, to quantify social impacts.
    c. Integrate advanced models, like Social Life Cycle Assessment (S-LCA) and ecosystem valuation frameworks, to address under-represented impacts.
2. Global Adaptability and Transferability:
    a. Leverage international benchmarks and global datasets (e.g., International Aluminium Institute, UNEP Life Cycle Initiative) to standardise indicators and regional thresholds.
    b. Conduct comparative case studies in regions such as South America, Africa, and Europe to account for geographic variations in biodiversity priorities, resource availability, and energy grid dynamics.
    c. Extend the framework to other resource-intensive sectors (e.g., cement, steel) to demonstrate scalability and broader applicability.
3. Policy and Regulatory Mechanisms:
    a. Advocate for the establishment of a mandatory, industry-specific sustainability framework, overseen by independent regulatory bodies, to ensure consistent, transparent reporting.
    b. Propose policy incentives, such as government subsidies or tax credits, to encourage the adoption of advanced decarbonisation technologies and biodiversity preservation initiatives.
    c. Foster partnerships with international organisations like the Aluminium Stewardship Initiative to drive global implementation and alignment with best practises.

By pursuing these actionable research directions, industries can address current limitations, improve resilience to future challenges, and align with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs). The evolution of sustainability frameworks to include biodiversity preservation, cultural heritage protection, and social equity alongside decarbonisation will enable resource-intensive industries, such as the alumina production industry, to achieve genuine, transformative sustainability outcomes. This holistic approach ensures long-term environmental, economic, and social resilience, advancing global sustainability priorities.

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