Economics

SUSTAINABLE DEVELOPMENT STRATEGY OF THE AZERBAIJAN ALUMINIUM INDUSTRY UNDER CBAM

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Abstract. This paper analyses the sustainable development strategy of Azerbaijan's aluminium industry under the EU Carbon Border Adjustment Mechanism (CBAM), entering full force in 2026, using Azeraluminium LLC as the reference unit. A Triple Bottom Line and Circular Economy framework is combined with Slack-Based Measure DEA, eco-efficiency index (EE), and AHP-weighted Composite Sustainability Index (CSI). Five country-level Decision Making Units are benchmarked: Norway, Canada, Russia, China, and Azerbaijan. Results show that Azeraluminium's CO_2 intensity (~6.2 tCO_2-eq/t) and eco-efficiency score ($\theta = 0.62$) expose approximately 20.7% of export revenue to CBAM charges. SBM-DEA slack analysis identifies a 38% CO_2 reduction potential through grid decarbonisation. The aggressive scenario - 400 MW renewable energy plus a 40,000 t/yr secondary aluminium complex - raises the EE index to 0.84 and reduces CBAM exposure to ~13.7%, with an estimated payback of 6-9 years. The scientific novelty is the first comparative SBM-DEA assessment of Azerbaijan's aluminium sector in a global benchmark framework combined with explicit CBAM financial quantification.
Keywords: *sustainable development, CBAM, aluminium, eco-efficiency, decarbonization.*

INTRODUCTION

Aluminium is indispensable in aerospace, automotive, construction, and energy applications owing to its combination of low density, corrosion resistance, and infinite recyclability. Global primary production reached 72 million tonnes in 2024 - roughly 40% above 2010 levels [1] – yet the sector accounts for approximately 3% of global industrial greenhouse gas emissions. Carbon intensity declined from 16.7 tCO_2-eq/t in 2020 to 14.8 tCO_2-eq/t in 2024, though progress is geographically uneven: Norway operates near 3.7 tCO_2-eq/t while India exceeds 18 tCO_2-eq/t.

The EU's CBAM will require importers to purchase certificates equal to the prevailing ETS carbon price - €60-75/tCO_2 in 2024, with projections above €100/tCO_2 by 2030 [2, pp. 45–60]. Azeraluminium LLC, the only fully integrated aluminium producer in the South Caucasus, produced 63,280 tonnes in 2024 (+72.1% year-on-year) [3]. Because ~90% of Azerbaijan's electricity is generated from natural gas, the company's CO_2 intensity exceeds the international "green aluminium" threshold of ≤4 tCO_2-eq/t, creating a direct CBAM financial exposure. This paper addresses three questions: how does Azeraluminium's eco-economic position compare with global benchmarks; what is the magnitude of the CBAM financial burden under different transformation pathways; and which trajectory optimises the eco-efficiency index within a realistic investment envelope?

THEORETICAL FRAMEWORK AND RESEARCH OBJECTIVES

Triple Bottom Line, Circular Economy and Eco-Efficiency. Triple Bottom Line (TBL) [4, pp. 70–95] frames corporate sustainability across economic, environmental, and social dimensions simultaneously. In metallurgy, these map to per-tonne production value, CO_2-eq emissions, and regional employment respectively. Elkington acknowledged in 2018 that TBL in practice often functions as a reporting tool rather than a driver of systemic change, and that its effectiveness requires integration with Circular Economy thinking. Kirchherr et al. [5] synthesised 114 definitions of the Circular Economy; aluminium is the paradigm material - recycled metal requires only 5-8% of primary production energy, achieving up to 95% emissions reduction [6].

Eco-efficiency was defined by WBCSD [7, pp. 37–38] as the ratio of product value to environmental impact. Korhonen and Luptacik [8] embedded it into DEA models with undesirable outputs, enabling cross-country *ceteris paribus* comparison. Haraldsson and Johansson [9] applied this methodology to aluminium electrolysis, quantifying that a 1 MWh/t reduction in energy intensity corresponds to 0.5-0.7 tCO_2-eq/t lower emissions - a figure directly informing the scenario modelling in this study.

CBAM and Sustainable Development Models. CBAM addresses carbon leakage by applying an ETS-equivalent carbon price to imported goods, combining Pigouvian taxation - internalising external costs - with market-based emission reduction incentives. The Environmental Kuznets Curve hypothesis is contested in aluminium because global trade has demonstrably shifted emissions rather than reduced them. Raworth's Doughnut Economics [10, pp. 38–45] provides a more applicable frame, balancing industrial decisions between a global carbon budget ceiling and a regional social minimum - directly relevant to Azerbaijan's industrial policy context.

METHODOLOGY

Quantitative Methods: MFA, EE Index and SBM-DEA. The study applies a four-stage mixed-methods design. In stage one, Material Flow Analysis [11, pp. 20–45] constructs a gate-to-gate mass balance for Azeraluminium over 2020-2024, encompassing the chain from bauxite input through electrolysis to semi-finished product output. In stage two, the eco-efficiency index follows the WBCSD formula [7, pp. 37–38]: $EE = V_{output} / (E_{CO_2} + \alpha \times W_{energy})$, normalised to [0,1] with Norway as the reference point. In stage three, a Slack-Based Measure DEA model [12] is applied with five Decision Making Units. Inputs are electricity (MWh/t), bauxite/alumina (t/t), and capital intensity (USD/t); desirable outputs are production volume and export value; undesirable outputs are Scope 1+2 CO_2 and water consumption. Norway and Canada define the frontier at $\theta = 1.000$.

Composite Sustainability Index and Scenario Modelling. Stage four constructs a Composite Sustainability Index using AHP weights: eco-efficiency (0.35), CO_2 intensity (0.30), energy intensity (0.20), and social indicator (0.15). Three scenarios are modelled for 2030: a baseline continuing the current energy mix; a moderate scenario adding 200 MW of renewables (reducing grid carbon intensity from ~430 to ~290 g CO_2/kWh); and an aggressive scenario combining 400 MW renewables, a 40,000 t/yr secondary aluminium complex, and waste-heat recovery. Data sources include the State Statistics Committee of Azerbaijan, UNIDO/EU4Environment [13], IAI [1], and annual sustainability reports from Norsk Hydro and Rio Tinto [14].

RESULTS AND DISCUSSION

Eco-Economic Profile of Azeraluminium and Global Benchmarking. Table 1 presents Azeraluminium's sustainability indicators over 2020-2024. The 2023 contraction (36,770 t) reflects a modernisation shutdown; the 72.1% recovery in 2024 marks the activation of expanded capacity. Energy intensity improved from 14.5 to 14.0 MWh/t - yet IAI's best available technology benchmark is 13.0 MWh/t [1], leaving a further 7% potential unrealised. The EE index rose from 0.57 to 0.62, confirming that economic value grew faster than environmental burden over the period. Figure 1 illustrates both trends simultaneously, making the 2023 disruption and subsequent recovery graphically apparent.

Table 1

Key sustainability indicators of Azeraluminium LLC, 2020-2024

Indicator	2020	2022	2023	2024	2025 Q1
Production (t)	~50,000	~52,000	36,770	**63,280**	15,500
Export (t)	n/a	68,263	74,502	**n/a**	18,800
Avg. export price (USD/t)	n/a	n/a	n/a	**2,448**	2,824
Energy intensity (MWh/t)[1]	14.5	14.3	14.2	**14.0**	n/a
CO_2 Scope 1+2 (tCO_2-eq/t)[2]	6.8	6.5	6.4	**6.2**	n/a
EE index[3]	0.57	0.59	0.60	**0.62**	n/a

[1] Author estimate based on IAI 2024 BAT range (13.2-15.7 MWh/t); n/a - data not available.
[2] Based on Azerbaijan grid carbon intensity (~430 g CO_2/kWh) and anode process emissions (~1.5 tCO_2-eq/t).
[3] WBCSD [7, pp. 37–38] formula; Norway as reference point.

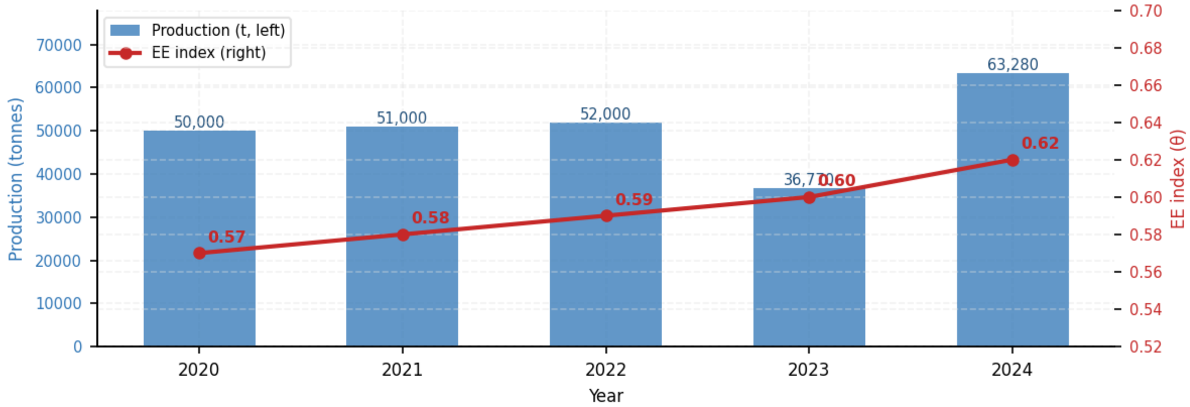

Figure 1. Azeraluminium LLC: production volume and eco-efficiency index dynamics (2020-2024)

Table 2 shows the SBM-DEA comparative profile. Norway and Canada sit on the efficiency frontier (θ = 1.000) through near-total reliance on hydropower. Azerbaijan ranks fourth at 0.62. China scores lowest (0.41) because despite relatively lean energy intensity its coal mix drives massive undesirable CO_2 output. Figure 2 plots these CO_2 intensity positions along a single axis, with the green aluminium threshold at 4 tCO_2-eq/t as a visual reference. Three strategic implications follow: Azerbaijan's energy intensity matches the world average, confirming competent process management; its CO_2 intensity (6.2 tCO_2-eq/t) is less than half the world average but remains well above hydropower leaders; and Rusal's ALLOW line (5.9 tCO_2-eq/t) is virtually identical to Azerbaijan's - both occupy the CBAM "middle-carbon" band [14].

Table 2

Comparative SBM-DEA sustainability profile of leading aluminium producers (2024)

Country / Producer	Output (Mt)	CO_2 (t/t)	Energy (MWh/t)	θ (DEA)	Dominant energy source
Norway (Hydro)	1.3	3.7	13.0-14.0	1.000	Hydropower ~100%
Canada (Rio Tinto)	3.3	<2.4	14.0-14.5	1.000	Hydropower ~100%
Russia (Rusal ALLOW)	3.8	5.9	14.5	0.89	Hydropower >90%
Azerbaijan	0.063	6.2	14.0	**0.62**	Natural gas ~90%
China (average)	43.0	16-20	13.4	0.41	Coal ~57%
World average	72.0	14.8	14.1	-	Coal 56.9% / hydro 31.3%

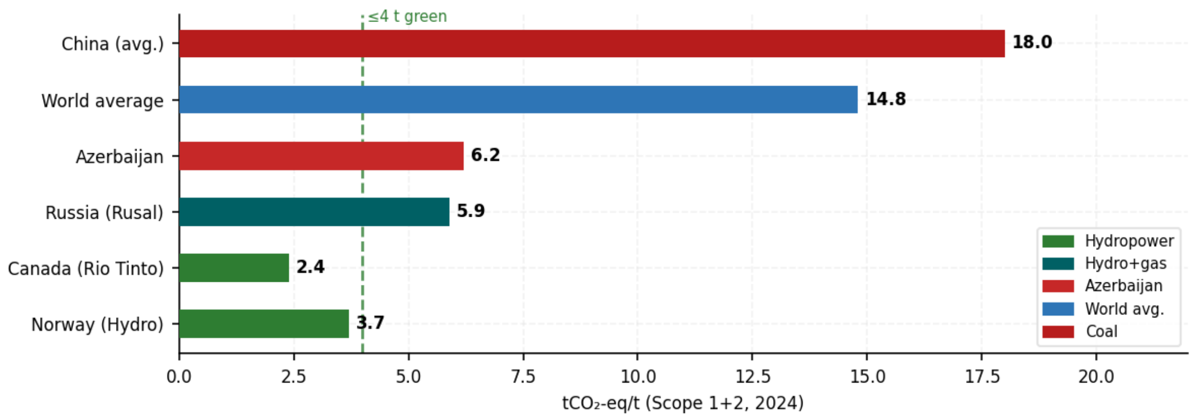

Figure 2. Global CO_2 intensity comparison by country and producer (tCO_2-eq/t, 2024)

Table 3 and Figure 3 present the AHP-weighted CSI results. Azerbaijan's CSI of 0.74 meaningfully exceeds its DEA θ of 0.62, reflecting the company's regional employment contribution - the social dimension partially compensates for the CO_2 intensity deficit visible in the radar chart.

Table 3

Composite Sustainability Index with AHP weights

Criterion	AHP weight	Norway	Canada	Azerbaijan	China
Eco-efficiency (DEA θ)	0.35	1.00	1.00	0.62	0.41
CO_2 intensity	0.30	0.96	0.99	0.79	0.27
Energy intensity	0.20	0.88	0.85	0.86	0.87
Social indicator	0.15	0.85	0.88	0.72	0.68
CSI (composite)	**-**	**0.94**	**0.95**	**0.74**	**0.52**

Figure 3. Composite Sustainability Index radar chart across four criteria (2024)

CBAM Financial Impact and Strategic Outlook. Table 4 and Figure 4 quantify the CBAM exposure under each scenario. At current CO_2 intensity (6.2 tCO_2-eq/t) and an ETS price of €75/tCO_2, the CBAM charge reaches ~€465/t - approximately 20.7% of the 2024 average export price of USD 2,448/t [3]. The aggressive scenario reduces CO_2 intensity to 4.1 tCO_2-eq/t and CBAM exposure to ~13.7% of export price. The required capital investment of USD 350-500 million [14] generates annual CO_2 reductions of ~340,000 t plus a market premium of USD 50-100/t from European buyers for approaching the "green aluminium" threshold; on this basis the payback period is estimated at 6-9 years.

Table 4

CBAM financial burden across scenarios: current and 2030 projections

Indicator	Current (2024)	Baseline (2030)	Moderate (2030)	Aggressive (2030)
Renewable energy addition	0 MW	0 MW	200 MW	**400 MW**
EE index (θ)	0.62	0.65	0.74	**0.84**
CO_2 intensity (tCO_2-eq/t)	6.2	6.0	4.8	**4.1**
Annual CO_2 reduction (kt)	-	~13	~180	**~340**
CBAM charge (EUR/t)	~465	~450	~360	**~308**
Share of export price (%)	~20.7	~20.0	~16.0	**~13.7**

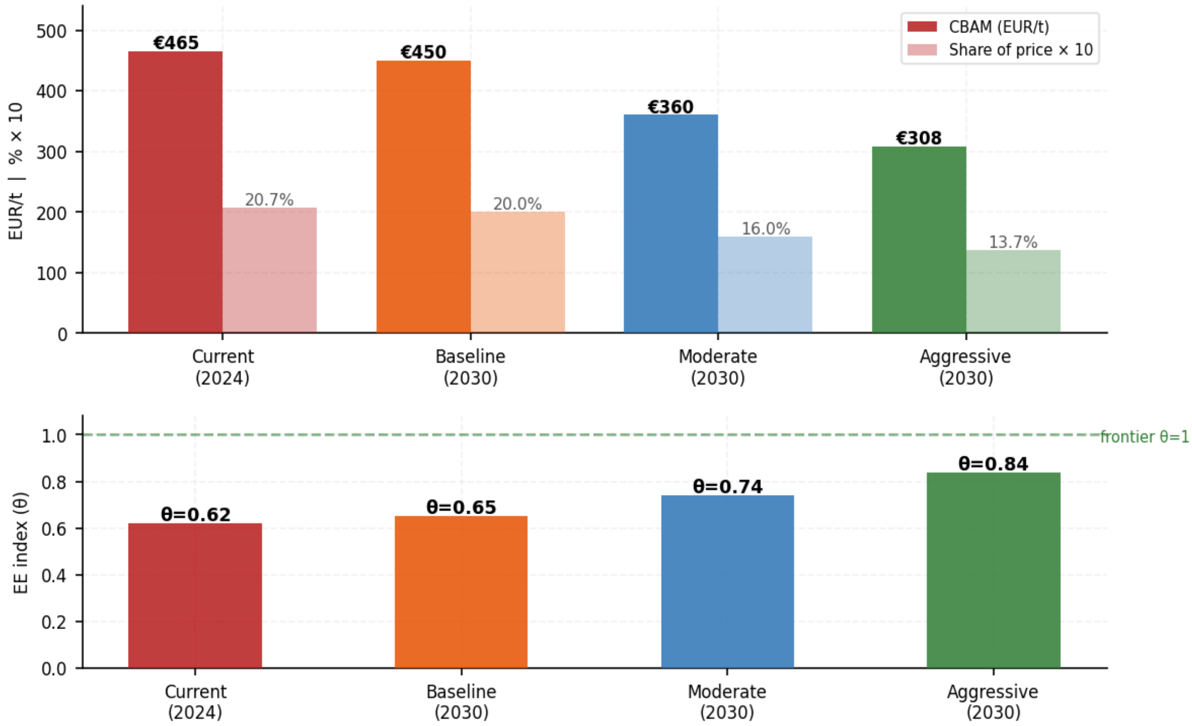

Figure 4. CBAM financial burden and EE index across scenarios (2024-2030)

CBAM's displacement of high-carbon Chinese production from EU markets creates an asymmetric opportunity for Azerbaijan: as a middle-tier producer, it is better positioned than coal-based competitors to capture market share - but only if the carbon profile improves sufficiently. UNIDO/EU4Environment [13] documents that Azeraluminium has already begun concrete planning in this direction, and the alignment between renewable energy investment and Azerbaijan's broader energy diversification agenda strengthens the policy case further [15].

CONCLUSION

Three principal findings emerge. First, Azeraluminium's CO_2 intensity (~6.2 tCO_2-eq/t) and eco-efficiency score (θ = 0.62) place it in a global middle tier that faces a CBAM charge equivalent to ~20.7% of export revenue from 2026. Second, SBM-DEA slack analysis reveals a 38% CO_2 reduction potential realisable through grid decarbonisation alone, without changes to production volume or process technology. Third, the aggressive scenario raises the EE index to 0.84, reduces CBAM exposure to ~13.7% of export price, and yields an estimated payback of 6-9 years.

Policy recommendations are: (i) integrate 400 MW of renewable energy by 2028; (ii) pursue ASI Performance Standard certification to access the green aluminium price premium in European markets; and (iii) build a "low-carbon Caspian aluminium" brand for Turkish, EU, and Japanese buyers. **Limitations** arise from restricted public access to plant-level data, requiring estimation of some indicators from international benchmarks. **Future research** should conduct plant-specific Life Cycle Assessment and integrate 2030 ETS price forecasts into the CBAM financial model. In sum, the sustainable development of Azerbaijan's aluminium industry is not an environmental aspiration but a near-term competitive imperative.

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