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Green Aluminum: Challenges and Opportunities for India

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Abstract: Aluminium is among the most recyclable materials on Earth, with nearly 75% of all aluminium ever produced still in use, a testament to its infinite recyclability without degradation in quality. However, the production of primary aluminium remains one of the most energy and carbon-intensive industrial processes, contributing nearly 2% of global CO_2 emissions, a figure comparable to the total emission of some large countries. In sharp contrast, recycled aluminium requires only 5% of the energy used in primary production and emits as little as 0.3 tonnes of CO_2 per tonne, offering a significantly lower environmental footprint. As global demand surges for low-carbon materials across sectors like construction, transportation, and electronics, Green Aluminium, has emerged as a strategic imperative for climate-smart industrial growth. Despite noteworthy progress by global leaders such as Norsk Hydro and Alcoa, India remains behind the curve. Currently, less than 10% of its aluminium can be considered green, primarily due to a coal-dominated power mix, underdeveloped recycling infrastructure, and the absence of a green certification standard.

This paper evaluates India's green aluminium readiness through comparative global benchmarking, domestic industry case studies, and a structural policy analysis. It identifies four critical levers for enabling the transition: scaling aluminium recycling, adopting round the clock renewable power, instituting a transparent carbon grading and labelling framework, and advancing technology and policy pathways, including CCUS, battery storage, and green hydrogen. The paper concludes with a central policy recommendation: that India must urgently define and adopt a national taxonomy for "Green Aluminium" as a foundational step toward aligning industrial policy, environmental goals, and export competitiveness in this vital sector.

INTRODUCTION

World production of primary aluminum, by country, 2023 (p)

Ranking	Country	Thousand tonnes	Percentage
1	China	41,000	58.90%
2	India	4,100	5.90%
3	Russia	3,800	5.50%
4	Canada	3,300	4.70%
5	United Arab Emirates	2,700	3.90%
6	Bahrain	1,600	2.30%
7	Australia	1,500	2.20%
8	Norway	1,300	1.90%
9	Brazil	1,100	1.60%
10	Malaysia	980	1.40%
	Other countries	8,180	11.80%
Total (rounded)		**69,560**	**100.00%**

Exhibit 1: Source https://natural-resources.canada.ca/

Aluminium is one of the most recyclable materials on Earth. Nearly 75% of all aluminium ever

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produced is still in use today, thanks to its ability to be recycled endlessly without any loss of quality. Yet, the production of primary aluminium remains one of the most energy- and carbon-intensive industrial processes, accounting for roughly 2% of global CO_2 emissions, comparable to the entire annual emissions of Germany. Producing one tonne of aluminium from bauxite can emit up to 14 tonnes of CO_2. Despite the clear environmental advantages of recycling, the world continues to rely heavily on primary aluminium, as underscored by global production patterns shown in Exhibit 1, where primary aluminium still constitutes a dominant share of total supply.

It is therefore critical that the world accelerates its transition towards Green Aluminium, which should ideally be defined as aluminium produced by meeting key sustainability parameters such as low carbon emissions, reduced water usage, high circularity, and effective waste utilisation. However, there is currently no universally accepted definition of green aluminium, though a widely used benchmark is a carbon footprint below 4 tonnes of CO_2 per tonne of metal produced. Basis this globally accepted benchmark we can define Green Aluminium as aluminium produced with a minimal environmental footprint, typically through the use of recycled inputs, renewable energy, or low/zero-carbon smelting technologies.

Global Overview – International Practices and Leaders in Green Aluminium

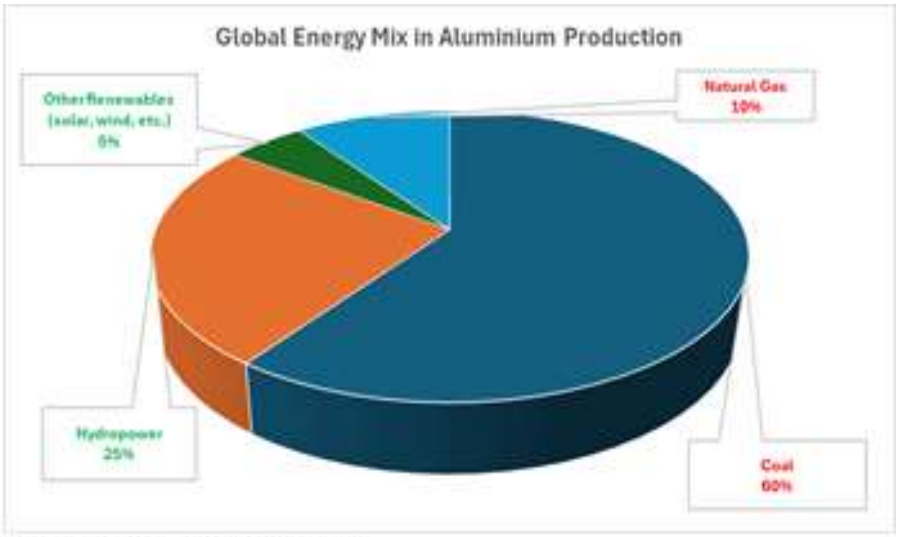

Exhibit 2: Source https://www.iea.org/

Around the world, leading aluminium producers and consumers are adopting strategies to reduce aluminium's carbon footprint. Key strategies include powering smelters with renewable electricity, expanding the use of recycled aluminium scrap, and advancing carbon-free smelting technologies, with approximately 30% of global aluminium production now powered by renewable energy sources (Exhibit 2.) The following are some examples of companies who are leading this transition.

Norsk Hydro (Norway) is a pioneer in this space, utilizing Norway's abundant hydroelectric power to produce aluminium with a carbon footprint one-fourth that of the industry average. Its "CIRCAL" product line uses at least 75% post-consumer scrap and is entirely powered by renewables. Hydro has committed to net-zero emissions by 2050.

Apple (United States), though not a producer, has influenced its supply chain by committing to 100% recycled or low-carbon aluminium in its products. It was the first to purchase carbon-free aluminium from the ELYSIS project, which uses hydroelectricity and inert anode smelting technology that releases oxygen instead of CO_2. Apple's MacBook and iPhone components now feature 100% recycled aluminium, avoiding over 6 million tonnes of CO_2 emissions in 2024 alone.

Ball Corporation (United States), a major manufacturer of aluminium beverage cans, uses about 70%

recycled content and powers many operations with renewable energy. It aims to reach 85% recycled content and 100% renewable-powered operations by 2030.

Emirates Global Aluminium (UAE) has introduced "CelestiAL," an aluminium line powered by solar energy, and "CelestiAL-R," which combines solar power and scrap to produce ultra-low-carbon aluminium. BMW is the first automaker to use this in its vehicles.

Other companies like Rio Tinto and Alcoa are scaling carbon-free smelting via the ELYSIS project, while Rusal and Hydro Quebec rely on hydroelectricity to deliver green aluminium. Global buyers such as Audi, BMW, and Coca-Cola are now demanding low-carbon aluminium, creating a "green premium" in the global market.

India's Aluminium Industry

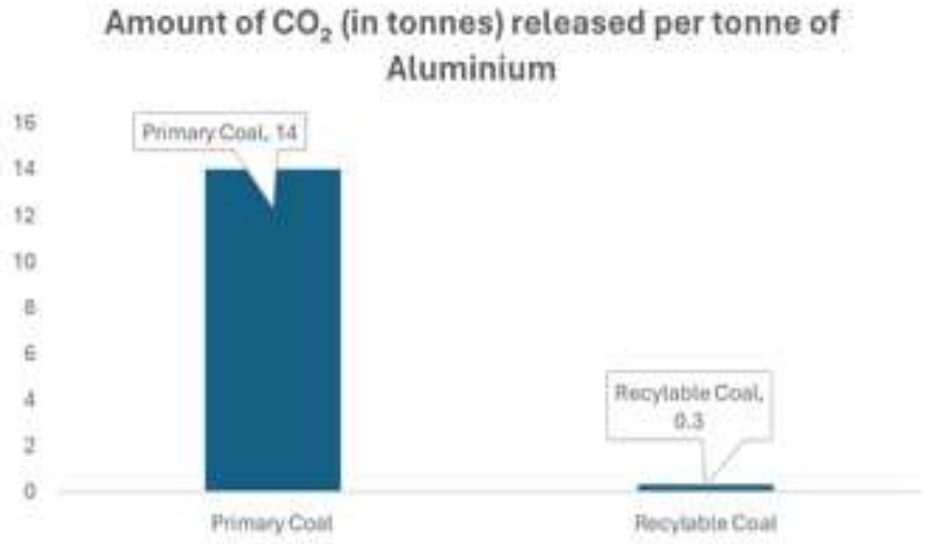

Exhibit 3: MRAI. *"India's Growing Low Carbon Aluminium..."* AlCircle, Nov. 2023.

India is the world's second-largest producer and third-largest consumer of aluminium. Domestic production is around 4 million tonnes and projected to grow to 10 million tonnes by 2030. However, per capita consumption remains low compared to global averages, indicating large potential for future growth.

Most Indian smelters are powered by captive coal-fired plants, resulting in some of the highest carbon footprints globally, up to 14 tonnes of CO_2 per tonne of aluminium. In contrast, recycled aluminium in India emits as little as 0.3 tonnes per tonne, revealing enormous potential for low-carbon growth through recycling (Exhibit 3.)

Challenges for Green Aluminium in India

As of now, India does not have a standardized certification system to quantify the exact percentage of aluminium production that qualifies as green aluminium even as defined for the purpose of this paper. However, based on available data and industry practices, it is estimated that less than 10% of India's aluminium output can be considered green aluminium. The three largest factors contributing to the low share of green aluminium are:

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1. High Reliance on Coal-Based Power:

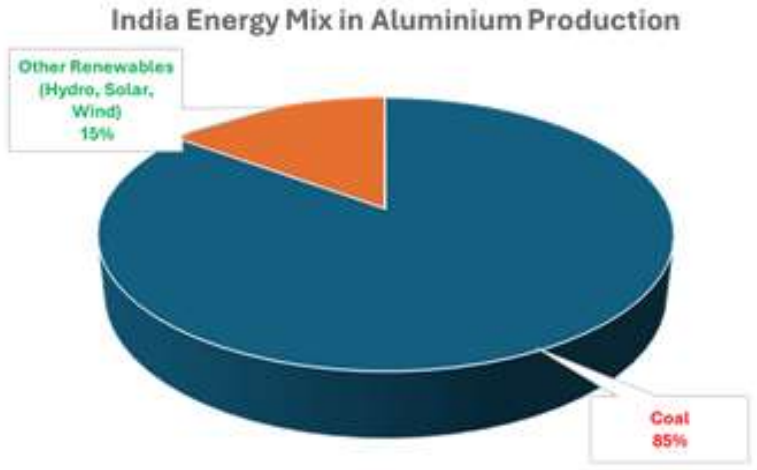

Exhibit 4: Source www.pv-magazine-india.com

India's aluminium industry remains heavily dependent on coal-fired power, (Exhibit 4,) which is one of the most carbon-intensive sources of energy. This reliance significantly increases the carbon footprint of aluminium produced in the country, making it difficult to classify as "green." Aluminium smelting is an energy-intensive process, with electricity accounting for up to 40% of production costs. In India, most primary aluminium producers operate captive coal-based power plants to ensure uninterrupted supply, as aluminium smelters require continuous, round the clock electricity.

2. Limited Recycling Infrastructure:

While aluminium is inherently recyclable and can be reused infinitely without losing quality, India's recycling ecosystem remains underdeveloped compared to global benchmarks. As of recent estimates, only around 30% of the aluminium used in India comes from recycled sources, significantly lower than in countries like Germany or the U.S., where recycling rates exceed 70–80%. One of the primary challenges is the limited availability of clean, sorted aluminium scrap within the domestic market. India lacks a widespread, formal scrap collection and segregation system. Much of the aluminium waste is processed in the informal sector, which lacks modern recycling facilities and environmental safeguards. As a result, high-quality, certified scrap suitable for industrial-grade recycling is in short supply.

Year	Aluminium Scrap Imports (Tonnes)	% of Recycled Aluminium from Imports	Domestic Recycling Status	Key Observations
2009–2010	~340,000	~70%	Highly informal, limited infrastructure	Imports dominate due to poor domestic collection systems
2016–2017	~930,000	~90%	Still largely unorganised, slow policy support	Surge in imports; demand for secondary aluminium grows
2019–2020	~1.35 million	~85–88%	Slight improvement in collection and awareness	India becomes world's largest aluminium scrap importer

Exhibit 5: Delhi Policy Group – India's Aluminium Industry Pathways for Aatmanirbharta

To bridge this gap, Indian recyclers have increasingly turned to scrap imports, particularly from the Middle East, the U.S., and Europe. However, this has triggered a policy tug-of-war. Primary producers argue that cheap scrap imports hurt the domestic primary aluminium industry and have lobbied for higher import duties. In contrast, recyclers and sustainability advocates demand duty-free access to imported scrap, emphasizing that it enables a circular economy and significantly lowers carbon

emissions. Exhibit 5 demonstrates the continued heavy reliance of imported scrap for the Aluminium recycling industry in India.

This policy ambiguity not only discourages investment in large-scale recycling infrastructure, but also leads to uncertainty in pricing, planning, and capacity-building across the recycling sector. Without a coordinated, supportive policy framework that favours recycling, through incentives, duty exemptions, and infrastructure investment, India will struggle to meaningfully scale up its green aluminium output.

3. Absence of Green Certification and Transition Barriers to Clean Power

One of the major roadblocks to scaling green aluminium production in India is the absence of a formal green certification framework. While several Indian aluminium producers have taken individual steps toward sustainability, such as integrating recycled content or investing in renewables, there is no unified system to independently verify, label, or promote low-carbon aluminium. This absence results in three key disadvantages:

- Domestic customers, especially B2B buyers, cannot distinguish between low-carbon and conventional aluminium.
- Exporters lose competitiveness in global markets where certified green materials are increasingly preferred.
- Producers lack market-based incentives to invest in emissions-reducing technologies, since their efforts cannot be verified or monetized.

In contrast, multiple international frameworks have emerged:

- **European Union**: Producers can apply for Environmental Product Declarations (EPDs) and must comply with the Carbon Border Adjustment Mechanism (CBAM), which mandates disclosure of embedded carbon in imports.
- **United States**: The Aluminium Stewardship Initiative (ASI) certifies producers on environmental, social and governance (ESG) criteria, including lifecycle carbon performance.
- **Canada and Norway**: Producers like Rio Tinto and Hydro publish product-specific carbon intensity metrics, with branded offerings such as Hydro CIRCAL, made from 75% recycled content and verified emissions below 4 kg CO_2/kg aluminium.
- **Japan**: The Japan Aluminium Association promotes eco-labelling, especially for packaging and construction use.

Beyond certification, transitioning to greener sources of power remains economically challenging for Indian producers. A study by the Council on Energy, Environment and Water (CEEW) highlights that shifting from captive coal plants to round the clock (RTC) renewable power is currently less viable economically, especially for older smelters built around integrated coal infrastructure. These plants cannot be shut down or retrofitted overnight, even if newer greenfield facilities can adopt clean energy pathways from inception. The Economic Survey of India (2024–25) also notes this limitation, underlining that any green transition in hard-to-abate sectors like aluminium will require a phased strategy, supportive policy incentives, and infrastructure readiness.

Without a national carbon grading and labelling standard, perhaps led by the Bureau of Indian Standards (BIS) or in collaboration with ASI even the most sustainable Indian producers cannot credibly claim “green” status in domestic or global markets. Establishing such a framework, alongside transitional support for energy-switching, could unlock green premiums, draw ESG investment, and position India’s aluminium sector as a global leader in sustainable manufacturing.

Green Aluminium Opportunities in India

India’s aluminium sector, though currently coal-heavy, has both the technical capacity and policy momentum to transition toward green aluminium. The dual levers of recycling and renewables offer a

credible path forward. The following two case studies illustrate how leading players are already putting this transition into practice through impactful initiatives.

Case Study 1: Hindalco's Green Aluminium Push

Hindalco Industries, part of the Aditya Birla Group, has emerged as a frontrunner in India's green aluminium transition by combining large-scale recycling with investments in renewable energy. As the country's largest aluminium producer and the parent company of Novelis, the world's leading recycler of flat-rolled aluminium. Hindalco is uniquely positioned to lead on sustainability.

One of its key initiatives is the development of closed-loop recycling systems through Novelis, which processes over 2 million tonnes of aluminium scrap annually. Domestically, Hindalco is expanding its recycling footprint with plants like the one at Hirakud (Odisha), reducing dependence on energy-intensive primary aluminium and significantly lowering carbon emissions.

In parallel, Hindalco has made a bold move into renewable energy integration. In partnership with Greenko, the company is developing a 375–400 MW round the clock renewable energy project that combines solar, wind, and pumped hydro storage. This project is expected to cut over 680,000 tonnes of CO_2 emissions per year and will supply clean power to Hindalco's smelters, displacing coal-based captive power.

The company has publicly committed to reducing its carbon intensity from ~19.6 tonnes to below 4 tonnes of CO_2 per tonne of aluminium, a significant shift that aligns with global green aluminium benchmarks. It is also targeting 30% renewable energy use by 2030.

Hindalco's strategy reflects a well-integrated approach, building domestic circularity through scrap recycling while securing reliable, clean energy for its smelting operations. These investments not only enhance competitiveness in global markets increasingly demanding low-carbon materials but also set the template for other Indian producers to follow. Hindalco's case demonstrates that the pathway to green aluminium is not aspirational but already underway with scale, ambition, and measurable impact.

Case Study 2: Indian Railways – Aluminium Coaches

Indian Railways, the world's fourth-largest rail network, is setting a new precedent for public sector

sustainability through the introduction of lightweight aluminium coaches. Traditionally reliant on heavy steel coaches, the Railways is transitioning to aluminium-bodied alternatives that are more durable, energy-efficient, and environmentally friendly.

Manufactured at Modern Coach Factory (MCF) in Rae Bareli and Integral Coach Factory (ICF) in Chennai, the new aluminium coaches are 15–20% lighter than their steel counterparts. This reduction in weight translates into lower fuel consumption for diesel trains and reduced electricity use for electrified routes, ultimately cutting lifecycle carbon emissions by over 30% per coach.

What makes this transition even more significant is the sourcing of aluminium from recycled inputs, enabled by suppliers like Hindalco and Jindal Aluminium. Recycled aluminium consumes just 5% of the energy required to produce primary aluminium, drastically lowering the material's carbon footprint. Moreover, manufacturing plants involved in coach production are increasingly integrating solar power, thereby greening the production process itself.

The aluminium coaches also offer superior corrosion resistance and longer service life, extending coach life cycles from 25 to 35 years, which further amplifies sustainability gains. With fewer maintenance needs, Indian Railways also stands to benefit from long-term cost efficiencies.

Although the initial cost of aluminium coaches is higher, the Railways has acknowledged their superior total cost of ownership. As a result, it has initiated plans to increase aluminium coach production from hundreds to thousands per year, with a long-term goal of transitioning at least 25% of its passenger fleet to aluminium by 2030.

This case illustrates how a legacy public sector entity can accelerate material innovation and sustainability, paving the way for greener transport infrastructure across India.

Solutions and Opportunities

A) Boost Aluminium Recycling:
India's aluminium industry currently recycles only about 30% of its total aluminium, a figure significantly lower than the 70–90% recycling rates seen in many developed economies. A key bottleneck is the limited and inconsistent supply of clean, high-quality aluminium scrap within the country. To address this gap, India must take two parallel steps. First, enable duty-free imports of certified aluminium scrap; and second, formalize its domestic scrap collection ecosystem. These measures are essential to meet the growing demand for low-carbon aluminium and reduce dependence on energy-intensive primary production.

Currently, imported aluminium scrap faces a 2.5% basic customs duty, with calls from some primary producers to increase this further to protect domestic output. However, removing or reducing this duty for clean and certified scrap would lower input costs for recyclers, increase the availability of secondary aluminium, and enable the scalable production of low-carbon aluminium. For the industry, this would translate into lower production costs, better utilization of recycling capacity, and improved competitiveness, especially in sectors like automotive, construction, and packaging, where low-carbon sourcing is becoming vital. Economically, this shift could save billions in energy imports annually, reduce dependency on mined bauxite, and cut greenhouse gas emissions substantially, given that recycled aluminium uses 95% less energy than primary production.

Simultaneously, India's largely informal scrap economy must be brought into the formal sector through structured policy interventions. This includes establishing reverse logistics systems, offering GST incentives or tax rebates to certified scrap collectors, and creating a national scrap traceability framework. These steps will enhance the availability of domestically sourced, high-grade scrap and reduce over-reliance on imports. The economic impact is equally promising: formalization would generate thousands of jobs in collection, sorting, and processing, strengthen India's circular economy, and reduce environmental degradation from unregulated scrap operations. If implemented effectively,

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these reforms could double or even triple India's aluminium recycling rate by 2030, laying the foundation for India to emerge as a global leader in green aluminium.

B) Accelerate Renewable Energy Adoption:

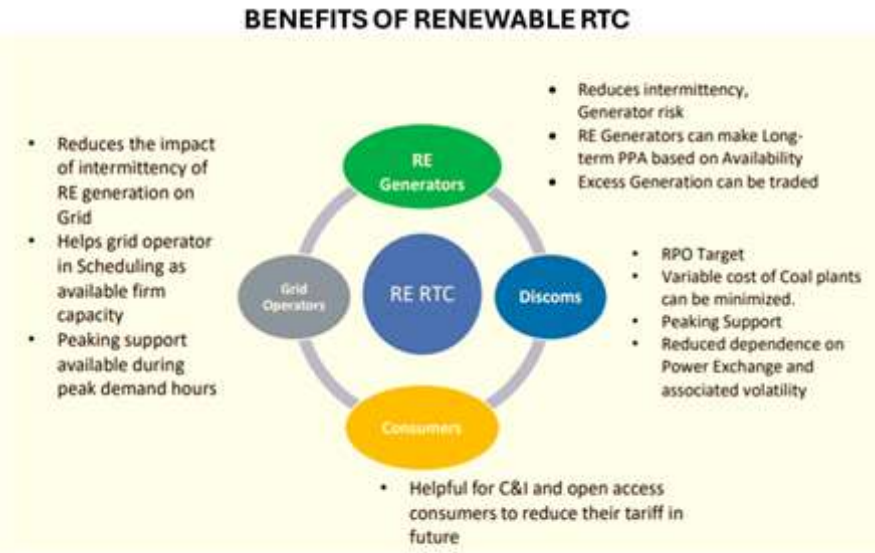

Exhibit 6: CENTRAL ELECTRICITY AUTHORITY 'Techno-Economic Analysis of Renewable Energy Round the Clock (RE-RTC) Supply ...'

Aluminium production is one of the most energy-intensive industrial processes, with electricity accounting for nearly 40% of total production costs. In India, over 80% of the electricity used by aluminium smelters comes from captive coal-based power plants, which results in some of the highest carbon footprints in the world, ranging between 17 to 20 tonnes of CO_2 per tonne of aluminium, compared to under 4 tonnes in low-carbon economies. This dependence on coal severely limits India's ability to produce green aluminium at scale and makes its exports vulnerable to carbon-based tariffs and regulations in global markets.

To overcome this, the government must incentivize aluminium producers to transition to round the clock (RTC) renewable power. RTC renewables combine solar, wind, and pumped hydro storage to provide the consistent 24/7 electricity required for aluminium smelters (Exhibit 6.) Supporting this transition will require a mix of policy measures, including interest subvention or viability gap funding for renewable projects, reduced open-access and cross-subsidy charges, the development of dedicated green energy corridors, and long-term power purchase agreements tailored for RTC supply in industrial clusters.

Shifting aluminium production to RTC renewables would dramatically reduce carbon intensity and open doors to carbon-sensitive export markets, particularly in Europe where mechanisms like the Carbon Border Adjustment Mechanism (CBAM) are being introduced. It would allow Indian producers to command a premium for green-certified aluminium and attract greater ESG-aligned investment. On a national level, the shift would enhance energy security, reduce dependency on coal imports, and contribute to India's target of 500 GW of renewable capacity by 2030. Additionally, it would spur rural development and job creation in the clean energy sector, making green aluminium not only an industrial imperative but also a strategic economic opportunity.

C) Establishing a Carbon Grading and Labelling Framework

India currently lacks a standardized carbon grading and labelling system for aluminium, limiting its competitiveness in carbon-sensitive global markets. With mechanisms like the EU's Carbon Border Adjustment Mechanism (CBAM) mandating carbon disclosure, Indian aluminium exports are at risk. While evolving regulations like Renewable Purchase Obligations (RPO), the Carbon Credit Trading

Scheme (CCTS), and Extended Producer Responsibility (EPR) for non-ferrous metals are nudging the sector toward sustainability, none provide a unified green certification. A carbon labelling framework, administered by BIS or in partnership with global bodies like the Aluminium Stewardship Initiative, could classify aluminium based on its emissions (e.g., under 4 tCO_2 per tonne), renewable energy use, and recycled content.

Such certification would help producers access global green markets, attract ESG-linked investments, and earn green premiums. Domestically, it could guide procurement choices and raise consumer awareness. Globally, India can look to China's green aluminium certification and Norway's Hydro CIRCAL as models. A transparent, credible labelling system would incentivize decarbonization, boost export competitiveness and create market differentiation for Indian aluminium, enabling the country to transition from being a low-cost producer to a sustainability leader in the global aluminium value chain.

D) Technological and Policy Pathways for Decarbonization

Decarbonizing India's aluminium sector, a major industrial emitter, will require both enabling technologies and policy reform. The biggest opportunity lies in shifting from captive coal-based power to renewable electricity, supported by large-scale battery storage and hybrid projects. Round the clock renewable (RTC) power backed by pumped hydro or lithium-ion batteries can deliver stable power to energy-intensive smelters. Nuclear energy, as a clean baseload option, can also play a complementary role. However, transitioning from coal is constrained by sunk investments in captive plants and grid reliability concerns.

Carbon Capture, Utilization, and Storage (CCUS) offers a long-term solution to address residual emissions, especially from process-based CO_2 release during smelting. Alongside, emerging technologies like inert anodes and green hydrogen hold promise for deep decarbonization. On the policy front, instruments like the CCTS will price carbon intensity, while grid reforms and open access rules will enable industries to source green power flexibly.

Reports from NITI Aayog and CEEW confirm that green aluminium is feasible but capital-intensive, requiring over ₹2 lakh crore in additional investment. Targeted fiscal support, carbon pricing, procurement mandates, and green finance will be critical. With strategic planning and innovation, India can transform its aluminium sector into a green manufacturing powerhouse in the near future.

CONCLUSION

Aluminium demand in India is set to surge in tandem with the country's economic growth, infrastructure buildout, and transition to clean technologies. Currently, India consumes just 2.5 kg of aluminium per capita, far below the global average of 11 kg and China's 30+ kg, underscoring the immense headroom for expansion. As India aspires to become a global manufacturing hub and expand sectors like renewable energy, electric vehicles, railways, and construction, aluminium consumption is projected to grow from 4 million tonnes today to 10 million tonnes by 2030 alone.

However, if this growth continues on the current path, fuelled by captive coal power and minimal recycling, the climate consequences will be stark. With emission intensities as high as 20 tonnes of CO_2 per tonne of aluminium, the sector alone could contribute over 200 million tonnes of CO_2 annually by 2030, severely undermining India's net-zero targets and risking trade penalties under emerging carbon regulations like the EU's CBAM.

The solution lies in a multi-pronged strategy:

- Scale up aluminium recycling through duty-free scrap imports and formalizing domestic scrap flows
- Shift to round the clock renewable power for smelters
- Establish a carbon grading and labelling framework for domestic and export credibility
- Support decarbonization technologies such as battery storage, CCUS, and green hydrogen

But all these efforts need an anchor. Just as the Ministry of Steel introduced a Green Steel Taxonomy, the Government of India must urgently define what constitutes "Green Aluminium." A clear taxonomy is the essential first step to aligning policy, finance, industry, and international trade around a low-carbon future for Indian aluminium.

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