British
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Government of India, Ministry of Power

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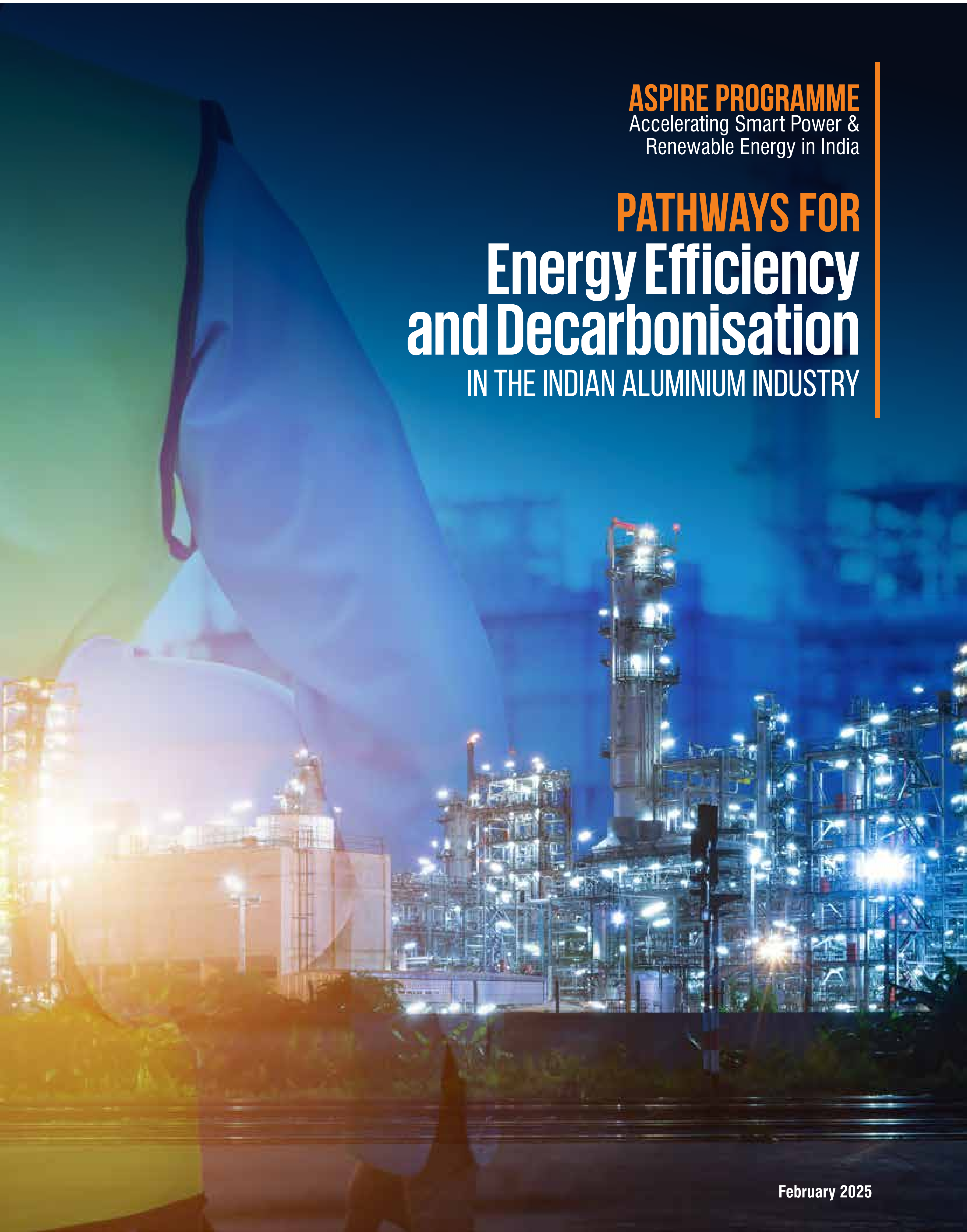

ASPIRE PROGRAMME
Accelerating Smart Power & Renewable Energy in India

PATHWAYS FOR Energy Efficiency and Decarbonisation IN THE INDIAN ALUMINIUM INDUSTRY

February 2025

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Contents

Abbreviations

Abbreviation	Definition
ABSTC	Aditya Birla Science and Technology Company
ACD	Anode Current Density
AGV	Automated Guided Vehicles
AP	Aluminium Pechiney Technology
ARENA	Australian Renewable Energy Agency
ASPIRE	Accelerating Smart Power and Renewable Energy in India
AWS	Amazon Web Services
BALCO	Bharat aluminium Company Limited
BAU	Business As Usual
BEE	Bureau of Energy Efficiency
BHC	British High Commission
BR	Bauxite Residue
CAGR	Compound Annual Growth Rate
CBA	Cost Benefit Analysis
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CEA	Central Electricity Authority
CHP	Combined Heat and Power
CII	Confederation of Indian Industry
CN	Commissioning Note
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
CPP	Captive Power Plant
DAC	Direct Air Capture
DC	Direct Current
DCs	Designated Consumers
DIP	Diversity, Inclusion and Belonging
DISCOMs	Distribution Companies
EE	Energy Efficiency
EEP	Energy Efficiency Project

Abbreviation	Definition
EGA	Emirates Global aluminium
EnMS	Energy Management System
EOR	Enhanced Oil Recovery
EPR	Extended Producer Responsibility
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FCDO	Foreign Commonwealth, and Development Office, Government of UK
FO	Fuel Oil
FY	Financial Year
GBP	British pound sterling (Great British Pounds)
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Gigajoules
GJ/Mt	Giga joules per metric tonnes
GoI	Government of India
HINDALCO	Hindustan aluminium Corporation Limited
IDEEKSHA	Industrial Decarbonisation and Energy Efficiency Knowledge Sharing Platform
IEED	Industrial Energy Efficiency and Decarbonisation
INR / ₹	Indian Rupees
ISTS	Inter State Transmission System
JLR	Jaguar Land Rover
JNARDDC	Jawaharlal Nehru aluminium Research Development and Design Centre
KPI	Key Performance Indicators
KTPA	Kilo Tonnes per Annum
MCL	Magnetic compensation loop
MGJ	Million Giga Joules
MMT	Million Metric Tonnes
MNRE	Ministry of New and Renewable Energy, Government of India
MPP	Mission Possible Partnership
MT	Metric Tonnes
MMT	Million Metric Tonnes
$MtCO_2$	Million Tonnes of Carbon Dioxide
mTOe	Million Tons of Oil Equivalent
MTPA	Million Tonnes per Annum
MU	Million Units
MVR	Mechanical Vapour Recompression
NALCO	National aluminium Company Limited

Abbreviation	Definition
OTS	Operator Training Simulator
PAT	Perform, Achieve and Trade
PPA	Power Purchase Agreement
PSP	Pumped Storage Plant
PV	Photo Voltaic
RE	Renewable Energy
REE	Rare Earth Elements
RPO	Renewable Purchase Obligation
RTC	Round The Clock
SEC	Specific Energy Consumption
SPCB	State Pollution Control Board
SPL	Spent Pot Lining
tCO_2-e/T	Tonnes of Carbon Dioxide Equivalent per Tonne of output
TOE	Tonne of Oil Equivalent
TRL	Technology Readiness Level
TWh	Terawatt-hour
UAE	The United Arab Emirates
UK	United Kingdom
USA	The United States of America
WAH	Women at Hindalco

Executive Summary

India is the world's second-largest producer of aluminium[1], contributing about ~6% to the global output. In 2023, the Indian aluminium market was valued at ~INR 941 billion (8.97 billion GBP) and is expected to grow at a CAGR of ~8% to 10% between 2024 and 2030[2]. Further, global aluminium demand is forecasted to grow by ~1.4 times and reach ~119 million tonnes in 2030[3] from ~86 million tonnes in 2020.

The Indian aluminium industry stands at a crucial juncture, navigating the intersection of surging demand and the urgent need to mitigate its environmental impact. The carbon intensity of India's aluminium manufacturing sector ranges between 16-20 tonnes of CO_2 equivalent per tonne (tCO_2e/t) of aluminium produced. The industry's substantial environmental footprint is driven by the intensive use of energy from captive thermal power plants, which poses a significant challenge to India's decarbonisation goals. Furthermore, the Indian aluminium industry is transforming into a competitive export-oriented industry, with aluminium exports growing at a CAGR of 15% over the last 5 years. Thus, considering global net-zero targets and developments such as CBAM, decarbonisation of the Indian aluminium industry is pertinent.

Aluminium is also a crucial metal given its use in growing sectors such as infrastructure, power cables, renewable energy, and electric vehicles. As India progresses towards achieving its net-zero target by 2070, it becomes essential to decarbonise the Indian aluminium industry.

1 Aluminum production top countries 2023 | Statista
2 India Aluminium Market Report Forecast Till 2030 (alcircle.com)
3 Travaux 52 paper (icsoba.org)

The focus of this report is on promoting energy efficiency and enabling decarbonisation in the Indian aluminium industry. The report aims to portray the landscape of the global and Indian aluminium sectors. The report presents a comparative assessment with global peers, key learnings based on a review and assessment of existing processes and leading practices, critical success factors for the accelerated net-zero scenario, and finally, a strategy for enhancing energy efficiency and enabling decarbonisation in the Indian aluminium industry. The report also enlists potential interventions for expediting the decarbonisation of the industry across major pathways. Additionally, the report seeks to identify specific policy measures that can facilitate and accelerate decarbonisation efforts. The key findings of the report are as follows:

Key findings

1. The Indian aluminium industry is globally competitive in terms of production and operational energy efficiency, accounting for about a 6% share in global production. Indian smelters demonstrate DC electricity consumption in the range of 12,900 to 14,500 kilowatt-hours per metric tonne (kWh/Mt), with an average of 13,322 kWh/Mt, whereas global counterparts exhibit a comparable spectrum of 12,500 to 15,500 kWh/Mt with a global average of 13,745 kWh/Mt.[4]

   The Indian aluminium industry is largely dependent on captive thermal generation with carbon intensity ranging between 16-20 tonnes of CO_2 equivalent per tonne of aluminium, resulting in higher emission intensity in comparison to global peers.

2. The Indian aluminium industry is transforming into a competitive export-oriented industry. The exports of aluminium produced in India have increased at a Compound Annual Growth Rate (CAGR) of ~14% in the last 5 years (2018 - 2022)[5]. To sustain the growth and comply with global developments such as the Carbon Border Adjustment Mechanism (CBAM), it is imperative to reduce emission intensity to permissible levels.

3. The increasing focus of governments, customers, and investors on a sustainable future, coupled with several carbon taxation policies such as CBAM has led to the development of a vast market for green aluminium, encouraging the production companies to decarbonise their operations.

   Green aluminium markets are emerging worldwide including Indian aluminium players. The companies are also partnering with independent international organisations to get relevant certifications for low carbon as well as recycled aluminium. Companies are also investing in producing green aluminium products such as low-carbon alumina, low-carbon

4 Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations
5 India Aluminum: Exports, 1995 - 2024| CEIC Data

aluminium and aluminium made with recycled content. ALCOA, Norsk Hydro, and Vedanta are already offering green aluminium products at premium prices. There is therefore a growing need for appropriate and widely accepted certification of green aluminium.

4. Adoption of energy efficiency measures is important for achieving the net-zero targets set by the Indian aluminium companies. Since aluminium production is an energy intensive process, the plants with an annual consumption of over 7,500 Tonnes of Oil Equivalent (TOE), have been notified as Designated Consumers (DC) under the Indian Energy Conservation Act 2001 and included in the PAT scheme which is being implemented by the Bureau of Energy Efficiency (BEE), Government of India.

   However, in the coming decade decarbonising the energy supply and adopting aluminium recycling are the two most important levers to decarbonise the aluminium industry.

   - The decarbonisation of the energy supply can happen either by switching to low-carbon sources of energy generation or by capturing emissions from captive power plants.
   - The recycling of aluminium presents both high economic and environmental prospects. Recycling aluminium uses only 5% of the energy used to produce aluminium and emits only 5% of the greenhouse gases. In the long term, recycled aluminium (secondary aluminium) is expected to play an important role in meeting the aluminium demand.

5. Integrating aluminium manufacturing units to low-carbon power sources is a critical step towards decarbonisation. The most established and reliable renewable energy source of green energy is hydropower. Hydropower offers a reliable electricity supply in comparison to other RE sources which is a prime requirement for aluminium smelting units. In 2021, Europe accounted ~93%, North America accounted ~95%, and South America accounted ~82% of the total power from hydropower to power smelting units.

   However, the case is entirely different for India as most smelting units are in the South-Eastern region while hydropower generation is mostly concentrated in Northern, Southern, and Western India. Indian Smelters are powered by fossil fuel-based captive power generating units against the European and American Smelter Units. Hirakud, Aditya and Vedanta units are located near Hirakud hydro power stations; however, they do not currently receive power from it.

6. The low-carbon technologies in the aluminium sector are expected to play an important role in the decarbonisation journey of the Indian aluminium sector. However, based on declarations made by companies and stakeholder consultations, most of these technologies are expected to be commercially available to other players in the market in the next decade. For example, the following are some global emerging technologies in the aluminium industry:

   - Inert anode is a promising technology for reducing direct emissions. Inert anodes result in the production of oxygen instead of CO_2. However, different companies claim different timelines for commercialising the technology to other players in the market. ELYSIS has announced that their inert anode technology may become commercially available as soon as 2024, RUSAL has conducted an industrial pilot to produce a batch of lowcarbon aluminium, but a largerscale rollout is not anticipated until 2030. Additionally, Arctus aluminium believes it will have a commercialised cell in operation in 2025 and will sell its technology, starting in 2030.
   - Carbon capture and storage (CCS) is another important technology to capture direct emissions from the processes. Alvance aluminium Dunkerque, and Norwegian company Norsk Hydro – have recently announced that they are exploring options to use CCS for aluminium, with Norsk Hydro setting a goal of using CCS on a commercial scale by 2030, and Alvance is working in a consortium alongside Trimet, LRF (Rio

Tinto's research centre) and the Fives Group to evaluate the most economical way to capture carbon in aluminium smelters. The initiative is looking at amine technology to determine the feasibility of capturing flue gases directly versus the need to concentrate CO_2 for better capturing. Alvance is framing a pilot to be launched by 2024 in the hope of capturing up to 70% of emissions from the smelting process.6

- HalZero is a proprietary technology of Norsk Hydro which is based on converting alumina to aluminium chloride prior to electrolysis. Chlorine and carbon are kept in a closed loop, thus eliminating emissions of CO_2 and emitting oxygen instead. At Hydro's research and development laboratory in Porsgrunn, Norway, technologists have successfully tested and modelled the HalZero process. Furthermore, they are now verifying the technology on a test scale. The ambition is to produce the first aluminium batch using HalZero by 2025 and to reach industrial-scale pilot volumes by 2030.

> The Indian aluminium industry has scope to foster greater gender diversity while also marking a significant step in bridging the gender gap in the traditionally male-dominated metal metals industry, where women represent less than 10% of all workers in the sector between 2010 to 2015.
>
> There have been global and national companies which can act as a role model for other companies in promoting gender diversity, such as Vedanta. Vedanta Aluminium has female professionals comprising of over 22% of the total number of employees. Novelis, a subsidiary of Hindalco Industries Limited, targets increasing female representation to 30% in senior leadership positions by 2024[7]. Another example is Rio Tinto, which witnessed an increase in female representation from 22.9% to 24.3% and a further increase across all levels of the organisation, with senior leaders increasing from 28.3% to 30.1%, and operations and general support increasing from 16.2% to 17.7% due to their corporate policies.

7. The reporting of sustainability data by the aluminium players differs from player to player and country to country. This variation in reporting of data is influenced by several factors, including institutional structure, business operation, reporting framework selection, metric selection, data transparency, and technological variability. Consequently, the lack of uniformity hinders stakeholders, including investors, regulators, and consumers, from accurately assessing and comparing the sustainability performance of different aluminium players.

6 Hydrogen | Free Full-Text | LCA Analysis Decarbonisation Potential of Aluminium Primary Production by Applying Hydrogen and CCUS Technologies (mdpi.com)

7 Novelis to increase women representation to 30% in senior leadership positions by 2024, ETHRWorld (indiatimes.com)

Potential collaboration opportunities

Stakeholders in India have opportunities to collaborate with global institutions (including from the UK) such as The International Aluminium Institute (IAI), UK Research and Innovation (UKRI), Global Advanced Manufacturing Institute etc. on research and development projects focused on sustainable aluminium production, recycling, and new technologies.

Leveraging existing relationships and research collaborations can facilitate knowledge exchange and drive innovation. Adopting energy-efficient technologies, switching to cleaner fuels, and implementing best practices can significantly reduce emissions of the Indian aluminium industry. International companies (including from the UK) such as Hydro Aluminium, Emirates Global Aluminium (EGA), Alba, Rio Tinto, Altek, and Alvance have the potential to contribute to the Indian aluminium supply chain in the form of various technologies and processes.


NET ZERO
CO2
CO2
CARBON CREDIT

01

Introduction

The Government of India's (GoI) climate targets demonstrate its firm commitment to accelerating the clean energy transition. In August 2022, India's Nationally Determined Contribution (NDC) was updated to reduce the emissions intensity of its GDP to 45% by 2030 from its 2005 level, increase the cumulative electric power installed capacity from non-fossil fuel-based energy resources to 50% by 2030, and achieve a net-zero economy by 2070[8]. Achieving these commitments would require deep decarbonisation efforts across all segments of the economy including from the manufacturing industry.

The manufacturing industry is the second-largest contributor of carbon dioxide (CO_2) emissions after electricity generation[9]. Within the manufacturing sector, the aluminium industry accounts for about 9% of total industrial emissions[10]. The total installed capacity to produce aluminium in India is about 4.1 million metric tonnes per annum (MMTPA) and about 9.2 MMTPA for alumina. In FY 2022-23 ~4.05 MMTPA of aluminium and ~7.6 MMTPA of alumina were produced in the country[11].

Aluminium undergoes a three-stage production process– (i) Mining of Bauxite, (ii) Refining of alumina from Bauxite and (iii) Smelting of alumina into aluminium. The process of refining and smelting are highly energy intensive and are responsible for approximately 90% of emissions in production.

The aluminium sector in India accounted for approximately 1.4%[12] of total energy consumed and contributed to approximately 10%[13] of total carbon emission reduction among energy-intensive industries during Perform Achieve and Trade (PAT) Cycle-I (2012-2015). However, despite this significant contribution,

8 pib.gov.in/PressReleaseIframePage.aspx?PRID=1987752
9 https://www.rbi.org.in/Scripts/bs_viewcontent.aspx?Id=4240
10 https://www.ghgplatform-india.org/industry-sector/
11 Sustainability Development Reports and respective companies' websites.
12 https://www.keralaenergy.gov.in/files/Resources/Aluminium_Sector_2018.pdf
13 https://beeindia.gov.in/sites/default/files/publications/files/Impact%20Assessment%202020-21_FINAL.pdf

there is currently no major national-level study on decarbonisation of the Indian aluminium sector, unlike existing studies for other energy intensive sectors such as iron, steel and cement. Additionally, internationally introduced carbon tariffs, such as the Carbon Border Adjustment Mechanism (CBAM), are expected to have a significant economic impact on India's aluminium exports. This highlights the importance of decarbonising the aluminium sector for India to meet its global climate change commitments and comply with international trade requirements such as the European Union (EU) CBAM and the upcoming UK CBAM.

The PAT scheme is being implemented by the Bureau of Energy Efficiency (BEE) to reduce Specific Energy Consumption (SEC) in energy intensive industries. The aluminium industry has been identified as a key focus sector under the PAT scheme under which targets are set for Aluminium plants for reduction of SEC. The Designated Consumers from aluminium sector have overachieved their targets during PAT Cycles I (2012-13 to 2014-15) & II (2016 to 2019) resulting in energy savings of 0.73 mTOe (~3.1 $MTCO_2e$) and 1.23 mTOe (~5.2 $MTCO_2e$) respectively. There are 12 aluminium units (DCs) covered under the Perform Achieve & Trade (PAT) scheme. According to the notification for PAT cycle VII, the total consumption of these 12 DCs was 13.30 mTOe. From PAT cycles I to IV, the aluminium sector has achieved a total energy saving of 2.13 mTOe and ~ 8 $mTCO_2e$ saved in total GHG emissions.

Considering the context of international carbon tariffs and India's climate change commitments, a study on the development of 'Pathways for Energy Efficiency and Decarbonisation in the Indian Aluminium Industry' is being conducted under the UK-India bilateral technical assistance programme – Accelerating Smart Power and Renewable Energy (ASPIRE) in association with the BEE. The ASPIRE programme is implemented by the Foreign Commonwealth and Development Office (FCDO), Government of UK in association with the Ministry of Power, Government of India.

1.1 Objectives of the study:

- Estimating emissions from the Indian aluminium industry and identifying leading practices on energy efficiency and decarbonisation being adopted by large aluminium companies across the globe.
- Preparing an energy efficiency and decarbonisation strategy for Indian aluminium industry.

The report findings are expected to benefit Indian aluminium companies, policy makers, research institutes, and other relevant stakeholders. It will facilitate knowledge sharing between various stakeholders, such as aluminium companies and research institutes, thus helping them accelerate efforts towards achieving net-xero.

1.2 Structure of the report

The following section (section-2) provides an overview of the global and Indian aluminium industry landscape followed by section-3 which demonstrates an approach for developing an Energy Efficiency (EE) and decarbonisation for the Indian aluminium industry. Section 4 of the report briefly explains the manufacturing process of aluminium and provides an overview of the emissions generated from the Indian aluminium industry.

As a next step, a comparative assessment of Indian aluminium industry with global peers has been presented in sections 5 and 6. While section 5 provides a comparative assessment of the Indian aluminium industry with select global industries, section 6 provides some leading decarbonisation practices.

Having identified the leading practices in section 6, in section 7, the emissions from the Indian aluminium industry are estimated under two scenarios. Scenario 1 is a business-as-usual scenario and Scenario 2 assumes an aggressive reduction in emissions on account of greening the energy supply and adopting EE measures. Further, the section broadly outlines the interventions required to achieve decarbonisation pathway suggested in scenario 2.

Based on the review of existing processes and leading practices highlighted in the previous sections of this report, the "Decarbonisation strategy" section identifies four critical success factors for accelerated progression towards a net-zero aluminium industry. This section also outlines the suggestive interventions for accelerating decarbonisation of the Indian aluminium industry.

02

Overview of Aluminium Sector: Global and India

This section of the report presents an overview of the global and Indian aluminium sector, including market and production trends and key players. It also aims to provide a holistic understanding of the aluminium ecosystem and sets the ground for preparation of a framework for developing the pathways for energy efficiency and decarbonisation in the Indian aluminium Industry.

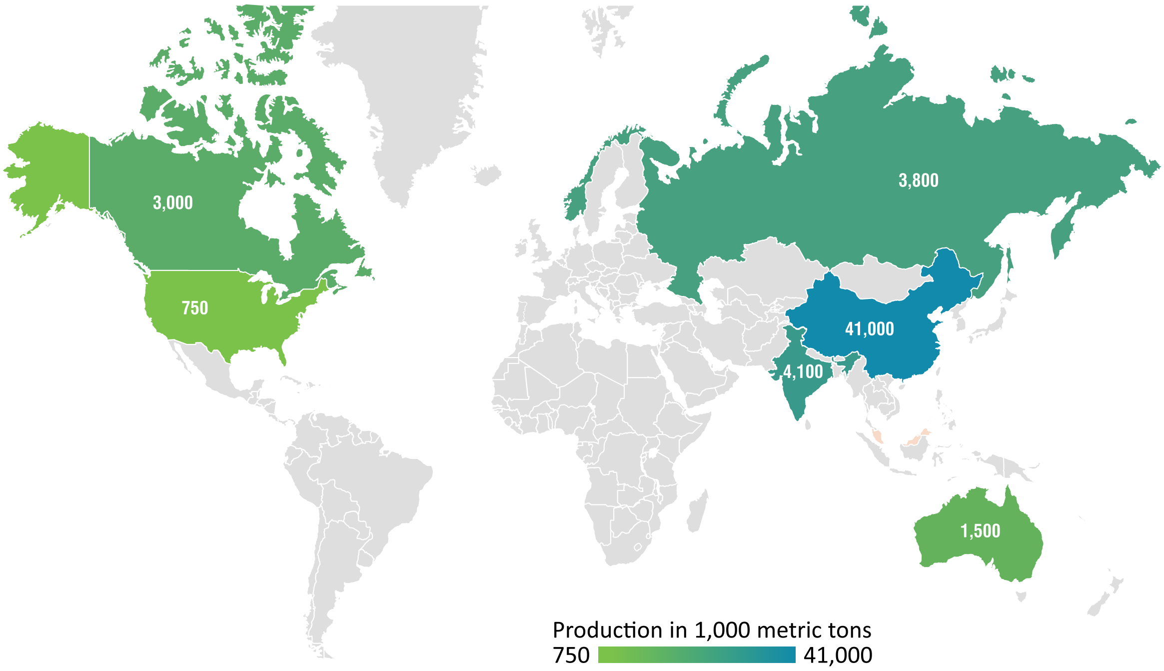
2.1 Global Landscape

In 2023, the global aluminium market size was ~INR 14 trillion[14] (GBP 130 billion) and is estimated to grow at CAGR of ~6% to ~INR 23 trillion (GBP 220 billion) by 2032[15]. Between 2019-2023, global production of primary aluminium witnessed a steady growth of ~3% (CAGR) from ~64 MMT to ~70 MMT[16].

Figure 1 below illustrates the comparative primary aluminium production across countries in the year 2023. India was the world's second largest producer of aluminium, accounting for ~6% (~4.1 MMT) of total global production in 2023. Other leading producers include China, Russia, Canada, UAE, Bahrain, Australia, Norway and USA.[17]

14 Aluminium Market Share & Size | Global Statistics Report - 2032 (gminsights.com) (last accessed on 16th July)
15 https://www.precedenceresearch.com/aluminum-market
16 Primary Aluminium Production - International Aluminium Institute (international-aluminium.org) (last accessed on 7th May 2024)
17 Aluminium production top countries 2023 | Statista

Figure 1: Leading aluminium producing countries:



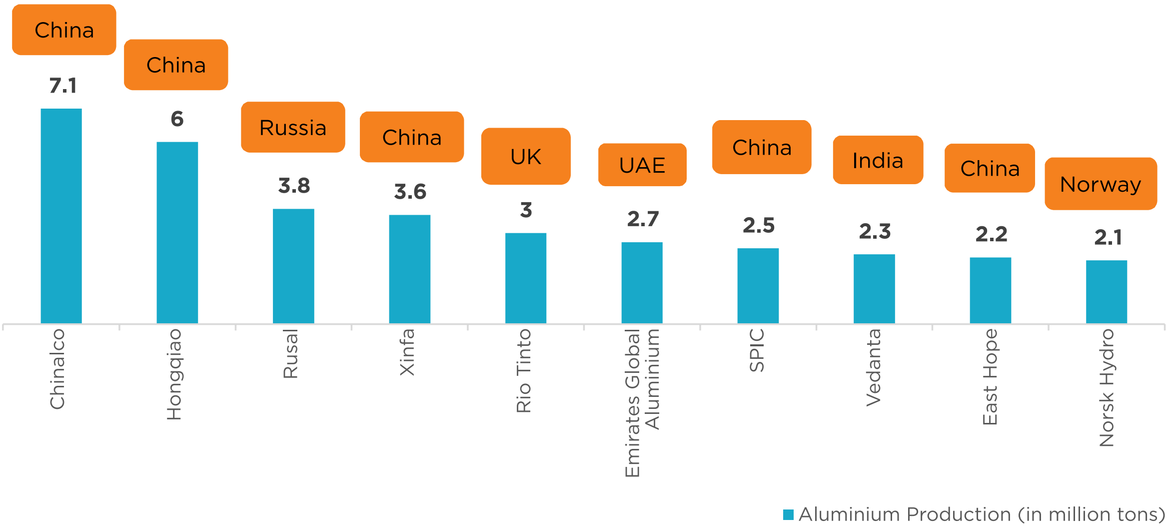
Source: Aluminium production top countries 2023 | Statista

Global aluminium demand is forecasted to grow by ~1.4 times to ~108 MMT by 2030[18] from ~78 MMT in 2020 with a CAGR of ~3%, while Indian aluminium demand is expected to reach ~9 MMT by 2030[19]. To meet the growing global demand, several countries in the Asia Pacific and the Middle East regions are anticipated to witness expansions in manufacturing capacity over the next five years.[20]

With around 7.1MMT of aluminium produced, Chinalco was the world's largest aluminium producing company in 2022[21]. Hongqiao, Rusal, and Xinfa were also ranked among the largest aluminium producers globally. UK based Rio Tinto holds the 5th position globally, while Vedanta group based in India holds the 8th position globally, contributing to about 2.3 MMT of global aluminium production. Figure 2 below represents the aluminium production of the top 10 aluminium producing companies in 2022[22].

18 Travaux 52 paper (icsoba.org)
19 Aluminium sector surging in India, but hampered by labour shortages, Hindalco executive says | Reuters
20 Travaux 52 paper (icsoba.org)
21 Primary aluminium global company production ranking | Statista
22 Primary aluminium global company production ranking | Statista, (last accessed on 16th April 2024)

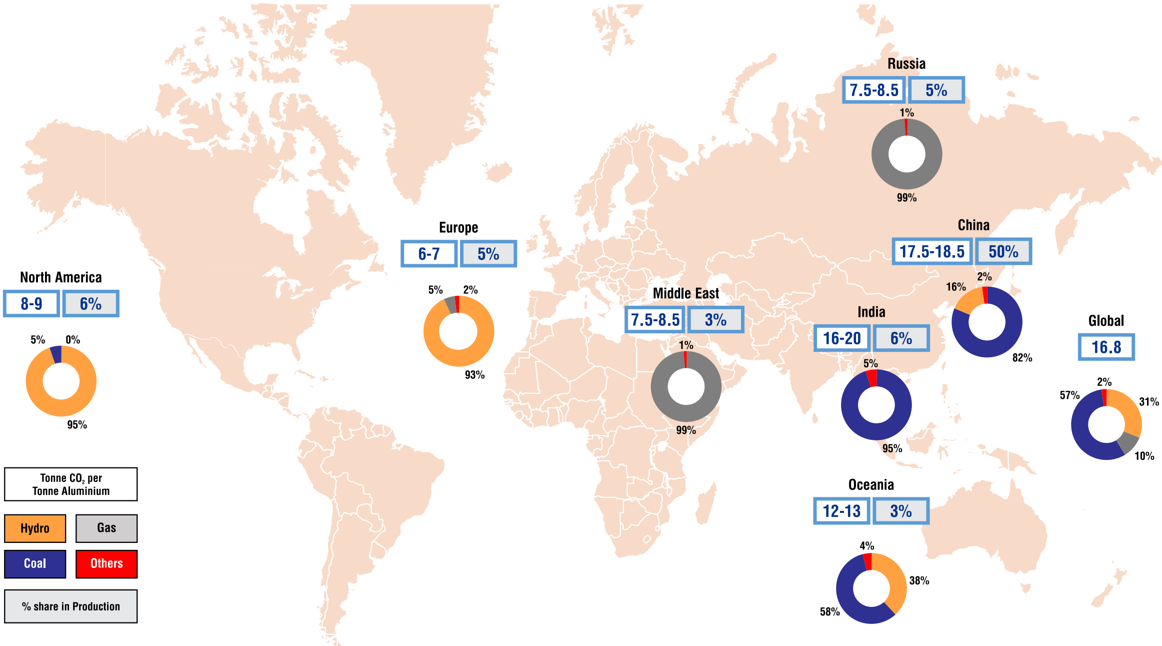
Figure 2: Leading ten aluminium producing companies globally in 2022.



Source: Primary aluminium global company production ranking | Statista

Emission intensity across geographies is not consistent with the production of primary aluminium primarily due to difference in energy sources and technological advancements. Primary aluminium producers which predominantly rely on hydropower (in Europe and North America) and gas (in Middle East) for fuel supply have an emission intensity of 6-9 tCO_2e/Mt as compared to an average emission intensity of ~19 tCO_2e/Mt for producers in Asian countries (such as India) which are more reliant on coal based thermal power plants.

Figure 3: Overview of global aluminium GHG emission intensity and energy mix in FY 2022-23



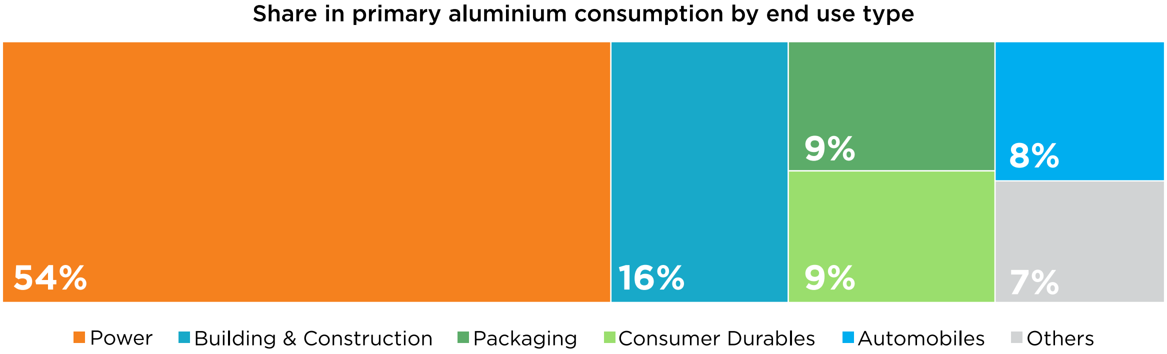
Source: Australia aluminium Association, CRISIL MI&A Research

2.2 Aluminium sector in India

India is the second largest producer of aluminium in the world and primary production accounts for about 70% of the total production of aluminium in the country[23]. However, there is scope to maximise the secondary (recycled and reused) aluminium production to reduce the carbon footprint. The market size of Indian aluminium industry was about ~INR 940 billion (GBP ~9 billion) in 2023 and is expected to grow ~1.75 times to INR 1,650 billion (GBP ~15.7 billion) by 2030 at a CAGR of ~8-10%[24]. India's per capita consumption of aluminium in FY 2023 was ~3.1 kilograms (kg) as compared to the world average of ~12 kg and China's at ~31.7 kg[25]. However, the demand for aluminium in India is expected to reach ~8 MMT by 2032, on account of estimated GDP growth of the country, coupled with various government programmes and initiatives such as the 'Make in India' scheme, smart city development programmes, rural electrification, and EV adoption. Sectors such as building and construction, transportation, packaging, electrical, and fast-emerging sunrise sectors like renewable energy, defence, and aerospace are also expected to propel the growth in demand.[26]

23 Excludes alloying additives and forms of recycled aluminium
24 India Aluminium Market Report Forecast Till 2030 (alcircle.com)
25 Aluminium sector surging in India, but hampered by labour shortages, Hindalco executive says | Reuters
26 Metal-Asia-Cover-Story-June-2022.pdf (vedantaaluminium.com)

Figure 4: Sector wise consumption of primary aluminium in India (2021)



Source : Travaux 52 paper (icsoba.org)

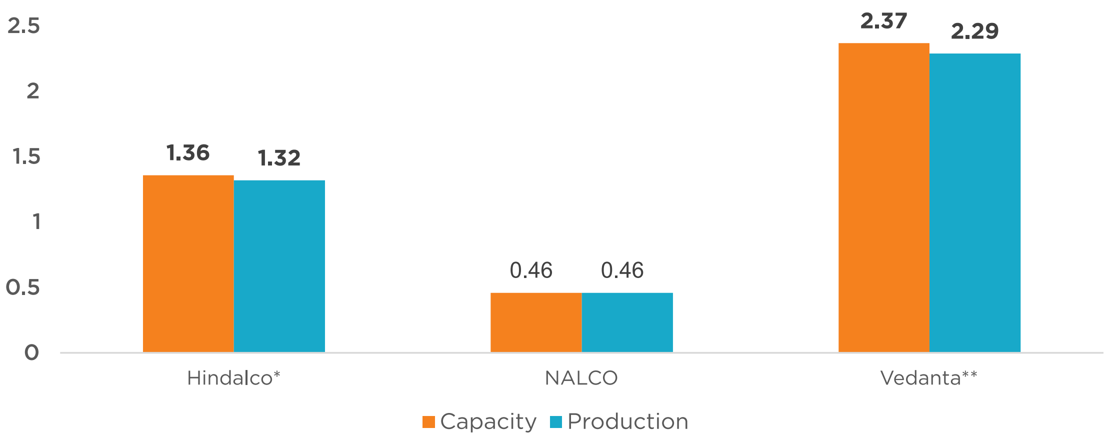
The current market size of the aluminium industry in India underscores its significant presence in global trade dynamics. With a consistent increase in demand, the industry has been a substantial contributor to India's economic growth.

Aluminium contributes to nearly 2% of manufacturing GDP[27] and with projected consumption growth, this share (% of manufacturing GDP) may go higher, reflecting its role as a key driver of economic activity, with its applications spanning over various sectors. Figure 4 depicts the approximate consumption of primary aluminium by sector in India. To further delve into the Indian aluminium industry, it is important to understand that there are three major primary aluminium producers in India i.e., Vedanta, Hindalco, and National Aluminium Company Limited (NALCO). Together these 3 players contribute to almost all the country's production capacity of ~4.07 million tonnes (FY 2022-23) of primary aluminium[28].

As evident from Figure 5 below, Vedanta is the country's largest producer of aluminium with a capacity of 2.4 MTPA, with ~48% share in the overall energy consumption. The aluminium smelting unit at Jharsuguda is the world's largest single-location smelter, with an installed capacity of 1.75 MTPA, backed by two smelters – 0.5 MTPA and 1.25 MTPA. Hindalco is the second largest producer of primary aluminium in India with a total capacity of around 1.34 MTPA with ~39% contribution in the overall energy consumption followed by NALCO operating at a capacity of 0.46 MTPA with ~13% contribution in the overall energy consumption of India.

27 Nalco_SR_2021_V3_2mar_5.07pmWithLinks.cdr (nalcoindia.com)
28 Ministry of Mines, Government of India, Home

Figure 5: Plant capacity and production during FY 2022-23 (million metric tonnes)



Source: India: production volume of aluminium by producer 2023 | Statista , Monthly Summary on Minerals and Non-Ferrous Metals for the Month of April 2023

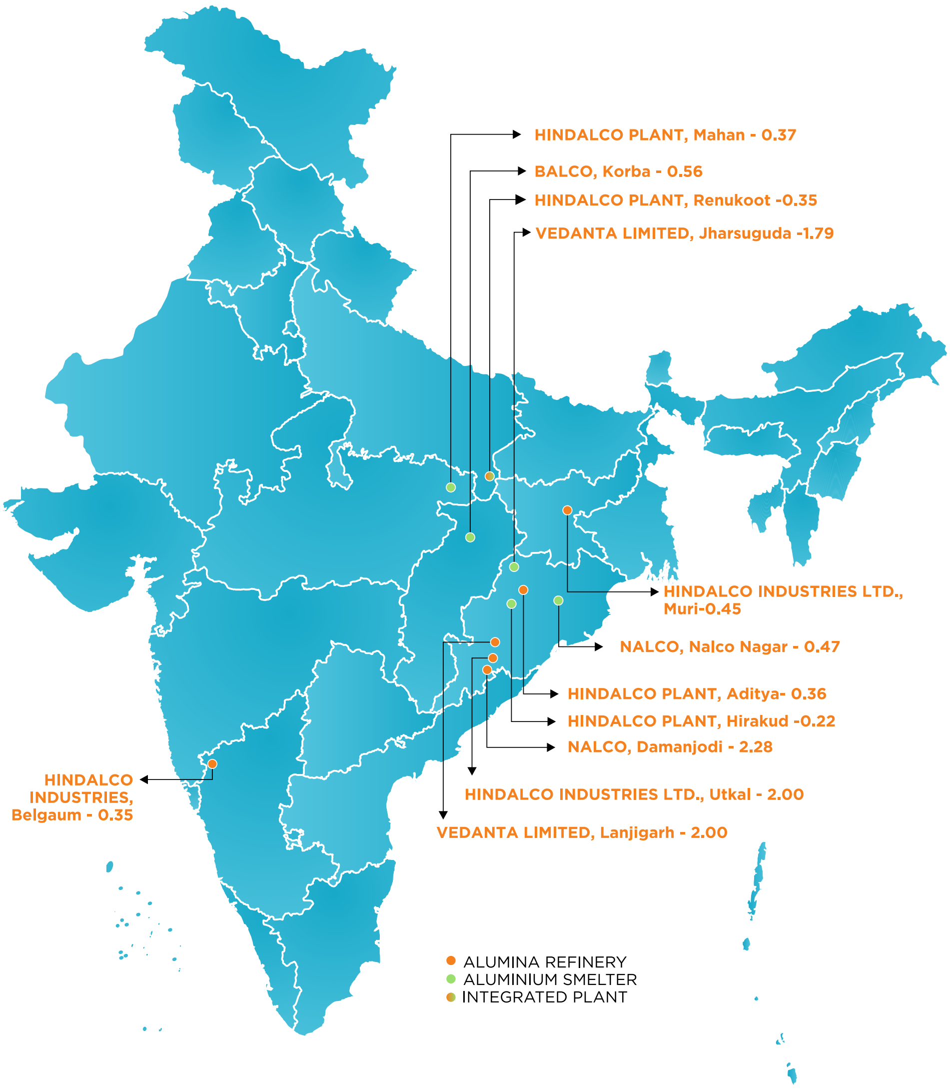
Note: Production figures pertaining to primary aluminium producers are based on available market data.

** Data pertaining to Hindalco is considering the combined figures for Renukoot, Hirakud, Mahan and Aditya units.*

*** Data pertaining to Vedanta is considering the combined figures for Jharsuguda smelter I, II and BALCO units.*

Due to better economic and management prospects, it is preferable for Indian aluminium industry units to be set up in proximity with the mining centres in states such as Jharkhand, Orissa, Chhattisgarh, and Madhya Pradesh. The production facilities, capacity of refineries, smelters, and integrated plants of different players in the aluminium sector in India along with their locations are mapped in Figure 6.

Figure 6: Locations of Indian aluminium units along with production capacity in MTPA in FY 2022 - 23



Despite having a competitive and reasonable direct current (DC) energy consumption, the Indian aluminium industry has high emission intensity of ~18 MT CO_2 per MT of aluminium[29], because of higher dependency on captive thermal power plants. In other countries such as the UK, Norway, and Canada, hydropower is the most established source of energy among all RE sources of generation. In such countries, aluminium plants (aluminium smelting and refining units) are located near the hydropower plants.

On the other hand, most of the hydropower sites and potential hydro sites in India are in northern, south-western, and eastern India while aluminium production units are mainly located in south-western region for close proximity to bauxite mines.

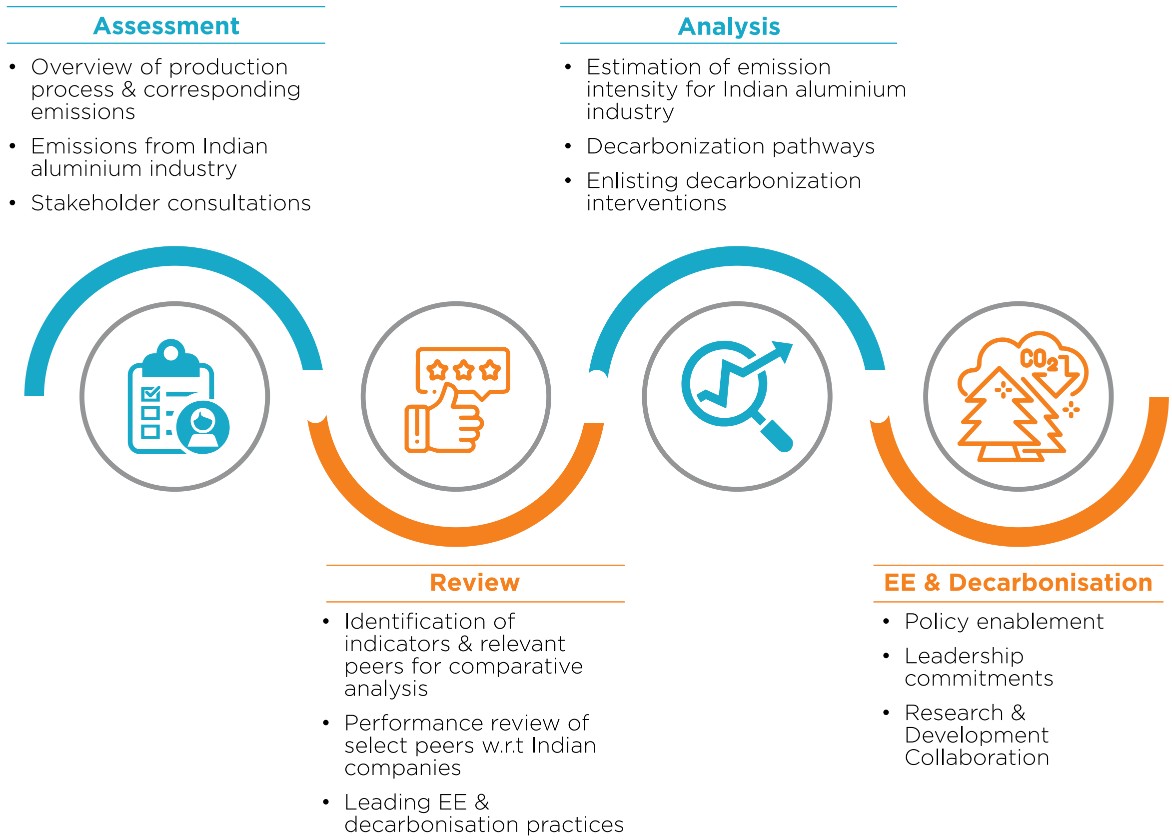
29 Analysis based on sustainability reports of primary aluminium producers in India

03

Pathways for Energy Efficiency (EE) and Decarbonisation

This section details an approach that could be adopted to develop an EE and decarbonisation strategy. Figure 7 highlights key steps for developing the strategy including three major activities i.e., i) Assessment, ii) Review iii) and Analysis.

Figure 7: Framework for development of EE and decarbonisation strategy



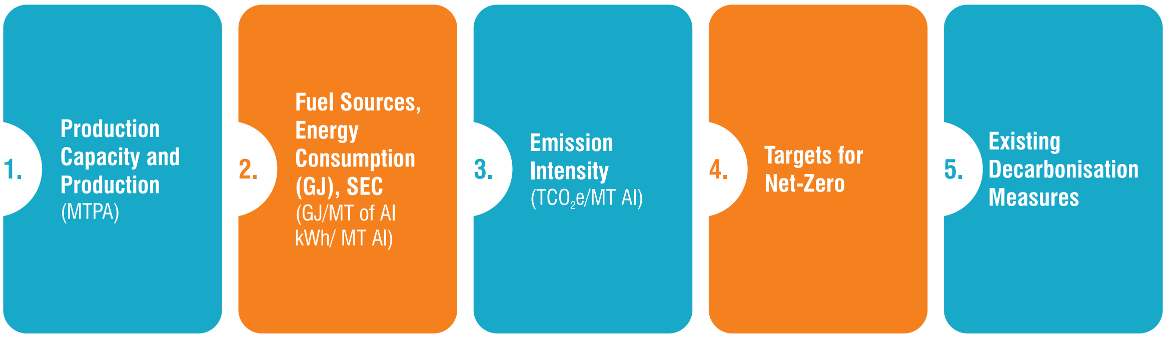
Details on each of the activities are provided below:

1. **Assessment:** From EE and decarbonisation perspective, it is important to broadly understand various steps in aluminium manufacturing process and corresponding emissions for each process. The information was collected from various secondary sources such as sustainability reports and annual reports, global reports on industry decarbonisation practices and research papers. However, there is a lack of uniformity in data reporting framework and standards across companies. Therefore, the focused consultations with various stakeholders like active industry players from alumina refining, smelting and integrated plants, leading research institutes, and low-carbon technology providers were also carried out[30]. This would set the foundation for the next step, which is assessing the performance of Indian aluminium industries with global peers.

2. **Review:** This step provides brief comparison of Indian aluminium industry with global peers on select performance indictors to identify leading global decarbonisation practices. The indicators were identified considering their criticality for evaluating the performance of aluminium companies from the perspective of adoption of decarbonisation and EE initiatives. The indicators were selected based on consultations with key stakeholders. Figure 8 below presents the Key Performance Indicators (KPIs) considered for the assessment.

30 The key points of discussion are annexed for reference

Figure 8: Key parameters for performance assessment



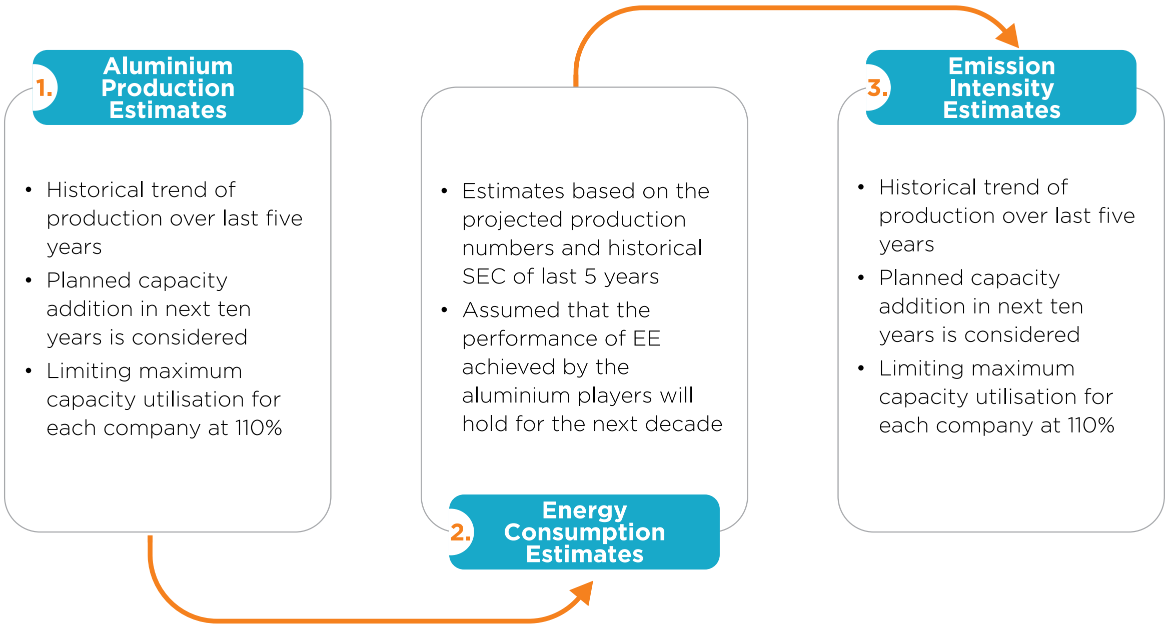
To ensure that data for all comparators are available on the common and recent timeline, the year for review has been selected as FY 2021-22 which is a reference year for which the sustainability reports and literature have been referred. For comparative assessment, leading global players such as Rio Tinto (UK), Emirates Global Aluminium (UAE), Alcoa Corporation (USA), Norsk Hydro ASA (Norway), and Alba (Bahrain) have been considered. The rationale for selection of these global peers is covered below:

- These companies together account for about a fifth of the global aluminium production.
- They are global leaders in sustainability practices and in adoption of low carbon technologies.
- They are leaders in research and development of low carbon technologies such as inert anode and HalZero.
- They are increasingly investing in diversifying energy sources and adopting clean energy.
- They have enlisted their aluminium products under the brand of green aluminium.

3. **Analysis:** This step deliberates on the medium and long-term scenarios of Indian aluminium industry, projecting trends of production, energy consumption, and emissions over the next 5 and 10 years, with base year as FY 2022-23. These forward-looking scenarios offer valuable insights into the Indian aluminium industry's

trajectory, considering commitments to decarbonisation and sustainability. The emissions have been estimated by exponential smoothing method. High-level steps followed for medium- and long-term estimates are presented in the figure 9.

Figure 9: High-level steps followed for medium- and long-term estimates.



Step #1 - Aluminium production estimates

- Estimation of production trends is based on the historical trend over last five years and declaration of capacity additions by leading individual companies.
- Over the past decade from FY 2012-13, production increased from 1.72 MMT to 4.07 MMT in FY 2022-23, demonstrating a CAGR of 8.7%. However, not much capacity has been added during last five-year period, which implies increase in capacity utilisation rates.
- The last five years' production trend of individual companies was assumed to follow the historical trajectory and for capacity addition, it was assumed in line with the declarations made by respective companies, resulting in the total production capacity of Indian smelters cumulating to 5.87 MTPA. While estimating the production, maximum - capacity utilisation for each company was limited at 110%, thus facilitating a thorough examination of production growth potential.[31]

Step #2 - Energy consumption estimates

- Based on the estimated production figures from step #1 and historical Specific Energy Consumption (SEC) of last 5 years, the minimum values of the last five years' SEC for each individual company have been considered for estimation of energy consumption. This scenario assumes that the performance in terms of EE achieved by the aluminium companies will continue for the next decade.

31 Stakeholder Consultation and historical trends of last five years

Step #3 – Total emissions and emission intensity estimates

- All major aluminium producers (Vedanta, Hindalco, and NALCO) have already declared their RE capacity addition of up to 1,500 MW by FY 2026-27 (cumulatively)[32] and all these companies have identified RE as a major and preferred s lever in their net-zero journey. Further, emissions are estimated under two different scenarios i.e., BAU and optimistic scenarios (with increased adoption of RE and EE measures). The latter one considers incremental improvement in EE along with RE penetration.
- **Business as Usual (BAU) scenario**: In the last 5 years (FY 2019-2023), while production of primary aluminium increased by ~12%, Indian aluminium industries have strived to maintain energy intensity in the range of 188-208 MGJ/MT (weighted average) and emission intensity of 19.7-21.7 $MTCO_2e$/MT (weighted average). Considering the same, in the BAU scenario it is assumed that until FY 2032-33, Indian aluminium industries will continue to operate at the lowest energy intensity[33] of 168 MGJ/MT and lowest emission intensity[34] of 18.31 $MTCO_2$/MT that was achieved in the last five years. The total emissions until FY 2032-33 have been estimated based on the estimated productions until FY 2032-33 (as mentioned in step-1 above) and the lowest energy and emission intensities of individual companies.
- **Optimistic scenario**: Integration of RE with the aluminium manufacturing processes is challenging due to the intermittent and variable nature of RE and high cost of balancing sources. Therefore, in this scenario, it is anticipated that the aluminium industry will adopt RE as major decarbonisation lever aligning to their net-zero road map. Further, in terms of EE, the emission intensity of Indian aluminium industries has been in the range of ~19.7 - 21.7 $MTCO_2e$/MT in the last 5 years (2019-2023), despite ~12% increase in production. Thus, it is assumed that along with enhanced RE adoption (from ~30% in FY 2024-25 to ~50% in FY 2032-33), Indian aluminium industries would implement various EE measures resulting in ~1% improvement in EE every year starting from FY 2023-24 until FY 2032-33[35]. In view of the above, the total emissions from the sector between FY 2023-24 and FY 2032-33 under this scenario have been estimated considering 1% improvement over the lowest energy intensity achieved by individual companies in the last 5 years along with RE penetration up to 50% by FY 2032-33. The production estimates until FY 2032-33 remain in line with the BAU scenario.

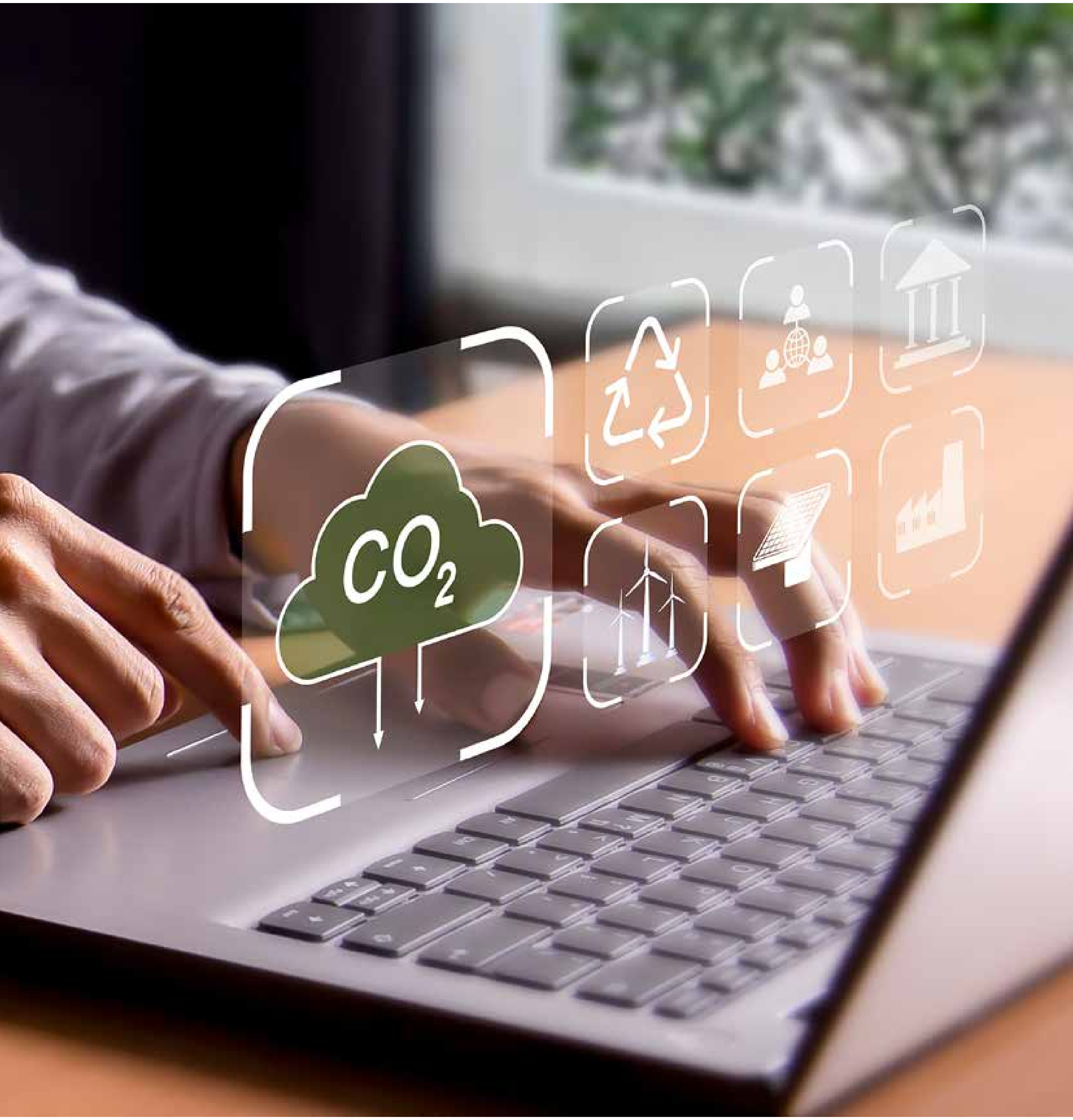
Low-carbon technologies such as inert anodes, CCS and Hal-Zero are expected to play an important role in the decarbonisation journey of aluminium sector. However, considering the declarations made by global aluminium companies and based on consultations with key stakeholders, most of these new-age technologies are expected to be commercially available and viable only after 2030. Since this report includes assessment of emissions until FY 2032-33, plausible emission reductions on account of these technologies have not been considered. For e.g., commercial rollout of inert anode is not expected until 2030 as it is still under research and development[36]. Similarly, limitations in large-scale deployment of CCS in aluminium sector include expected commercial viability beyond 2030[37] and operational challenges such as preparation of flue gases to feed into the technology.

32 Sustainability reports of respective companies
33 Lowest energy intensity considered for estimations is the weighted average lowest energy intensity of individual companies i.e., Vedanta, Hindalco, and NALCO between FY2019 to FY2023.
34 Lowest emission intensity considered for estimations is the weighted average lowest emission intensity of individual companies i.e., Vedanta, Hindalco, and NALCO between FY2019 to FY2023.
35 1% improvement considered based on consultations with stakeholders from aluminium industries and research organisations in India
36 Several companies, including Rio Tinto, Alcoa, RUSAL and Arctus Aluminium are actively developing inert anode technology. RUSAL has conducted an industrial pilot, but a larger-scale roll-out is not anticipated until 2030. Additionally, Arctus Aluminium expects a commercial-sized cell in operation in 2025 and will sell its technology, starting in 2030
37 Leading global aluminium company, Norsk Hydro, has developed a roadmap for testing and piloting the most promising CCS technologies and aims to have an industrial-scale pilot by 2030

Note:

The scope boundaries of the report are as follows:

- The report is limited to alumina refining, aluminium smelting and integrated (refining and smelting) units.
- Only Scope 1 and Scope 2 emissions are considered.
- Scope 1 emissions include direct emissions from processes such as furnaces, captive electricity generation and smelting pots while scope 2 emissions are indirect emissions such as emissions due to utilisation of electricity from the grid.
- The horizon considered for the study is up to the year FY 2032 – 33.
- Every company differs in terms of institutional structure, data reporting norms, technological advancements, spatial location, and availability of resources.


CO_2

04

Emissions from the Indian Aluminium Industry

The production of primary aluminium involves multiple stages and is energy intensive as pure aluminium does not occur naturally. More than 60% of the emissions associated with aluminium production are indirect emissions (scope 2) attributed to electricity consumption[38]. This electricity requirement accounts for about 4% of global power consumption, with up to 70% sourced from fossil fuels (predominantly coal) and the remaining 30% from renewables, primarily hydropower.[39]

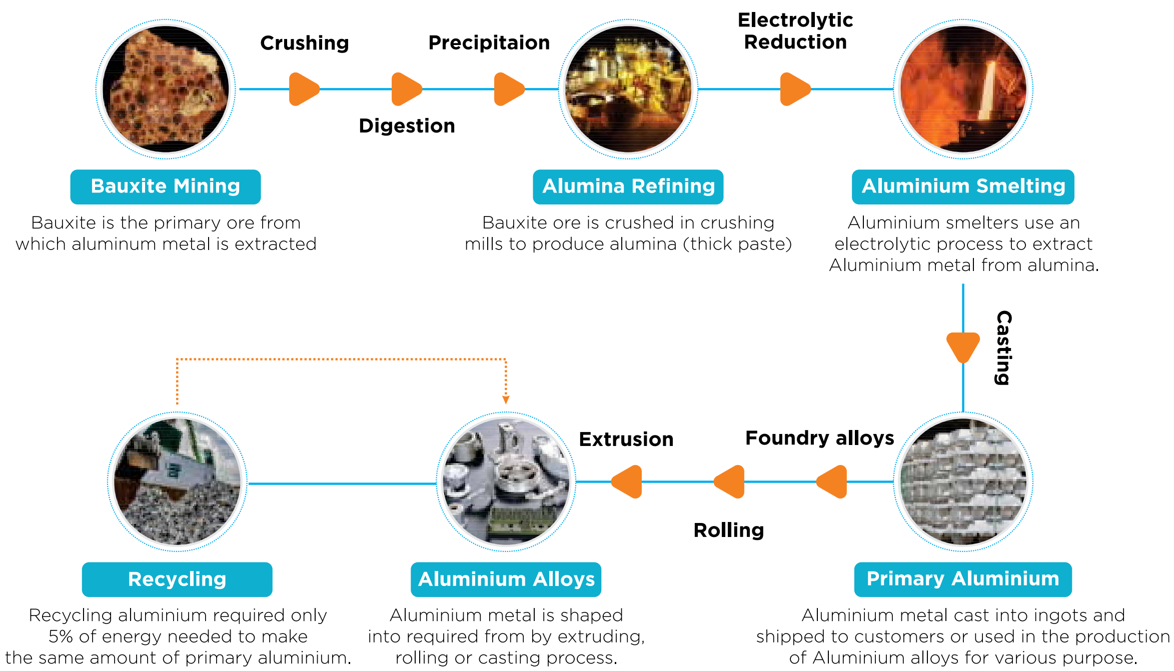
4.1 Overview of processes and associated emissions

The aluminium production process (refer to figure 10 below) begins with the mining of bauxite ore, an aluminium-rich mineral in the form of aluminium hydroxide. Approximately 90% of global bauxite is found in tropical areas. In India, bauxite is mined mainly in Odisha, Chhattisgarh, Jharkhand, Maharashtra, Gujarat, Goa, Karnataka, Madhya Pradesh, and Tamil Nadu.[40] Bauxite mining contributes insignificantly in terms of scope 1 and scope 2 emissions. Major emissions from mining are due to the thermal energy required in the process.

38 WEF_AFC_Unlocking_Technological_Scale_up_2021.pdf (weforum.org)
39 Aluminium industry net-zero tracker - Net-Zero Industry Tracker 2023 | World Economic Forum (weforum.org)
40 Bauxite mining in Jharkhand is impacting soil fertility, people's health (mongabay.com)

After mining, bauxite is crushed, dried, and ground in special mills where it is mixed with a small amount of water to produce a thick paste. This paste is collected in special containers and heated with steam to remove silicon present in the bauxite. The ore is then loaded into autoclaves and treated with lime-caustic soda.

Figure 10: Process flow for production of aluminium



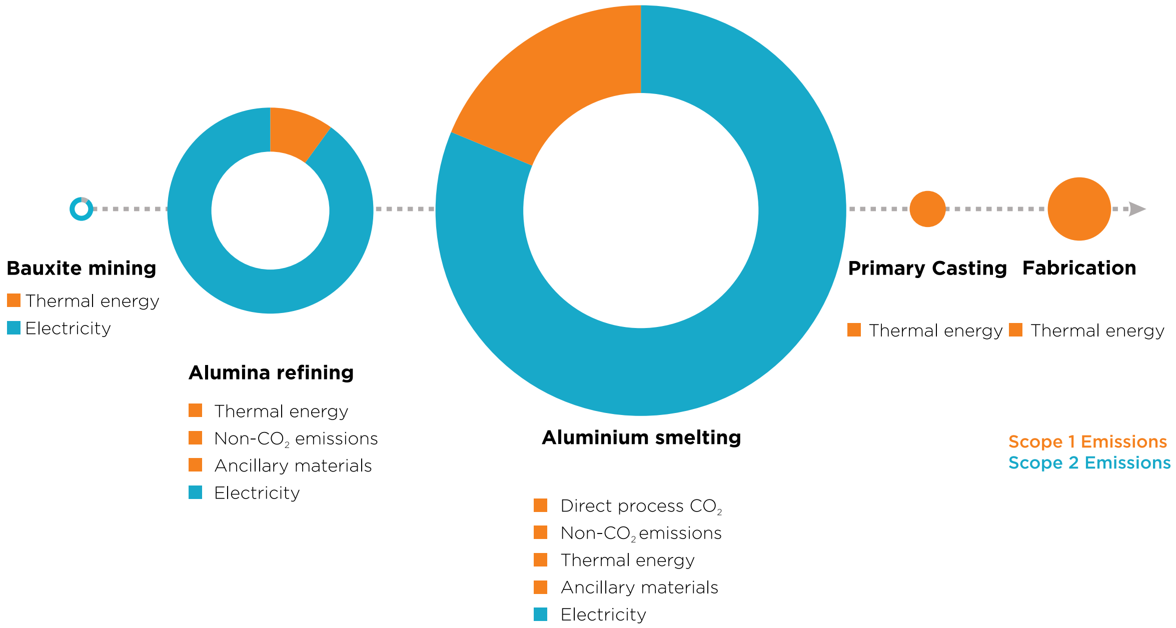
Source : https://aluminium.org.au/how-aluminium-is-made/ and https://aluminiumleader.com/production/aluminum_production/

Aluminium oxide appears in the resulting slurry while all the admixtures settle at the bottom as red mud. The sodium aluminate solution is stirred in precipitators for several days, and eventually, pure alumina (Al_2O_3) settles at the bottom. Most of the emissions released during refining are direct and non-CO_2 emissions due to the use of thermal energy required in the process. Thereafter, at an aluminium smelter, alumina is poured into special reduction cells known as smelting pots with molten cryolite at very high temperatures (950°C)[41] where aluminium oxide is reduced through electrolytic reduction to extract primary aluminium. The extracted primary aluminium can then be used to manufacture a wide range of products, from aircraft parts, vehicles for transportation, and electrical wires, to transmission lines and cans.

41 Aluminium production process (aluminiumleader.com)

Aluminium smelting consumes most of the electricity (more than 70%)[42] required in the entire aluminium production process (from bauxite mining to the fabrication of aluminium). The smelting process is the most emission-intensive process in the aluminium sector, with over three-quarters of the total CO_2e emissions, of which electricity consumption accounts for more than half (and approximately 64% of sector-wide emissions)[43] (refer figure 11). While primary aluminium accounts for less than 70% of global supply[43], its production is responsible for about 90% of the industry's total emissions.

Figure 11: CO_2-e emissions in primary aluminium production



Source: World Economic Forum[43]

42 Bureau of Energy Efficiency
43 WEF_Aluminium_for_Climate_2020.pdf (weforum.org)

In entirety, the production of one kilogram of aluminium requires 36 kWh of electricity in the value chain (from mining to smelting), of which approximately 40% (i.e., 15 kWh/kg) is consumed during aluminium smelting[44]. Due to this high dependency on electricity, decarbonisation of the sector is largely contingent on the source of electricity. The average CO_2 emissions intensity of Indian aluminium producers is approximately 48% higher than the global average since a significant proportion of power requirements are dependent on coal-based captive power generation[45]. Some of the key sources of emissions in refining, smelting and integrated units include:

1. Electricity used in refining for generation of industrial heat and steam.
2. Energy consumed for production of ancillary materials (e.g., anode baking).
3. Use of electricity for electro-chemical reduction of aluminium from alumina. The emissions are higher if fossil fuel-based electricity is used to power the electrolytic cells during the smelting process.
4. Direct CO_2 emissions from consumption of carbon anodes during electrolysis, when carbon in anode reacts with oxygen present in alumina (aluminium oxide) to produce aluminium.
5. Use of thermal energy during casting and fabrication of aluminium.
6. Transportation of finished products to other sites for manufacturing or retail and for waste processing and disposal.

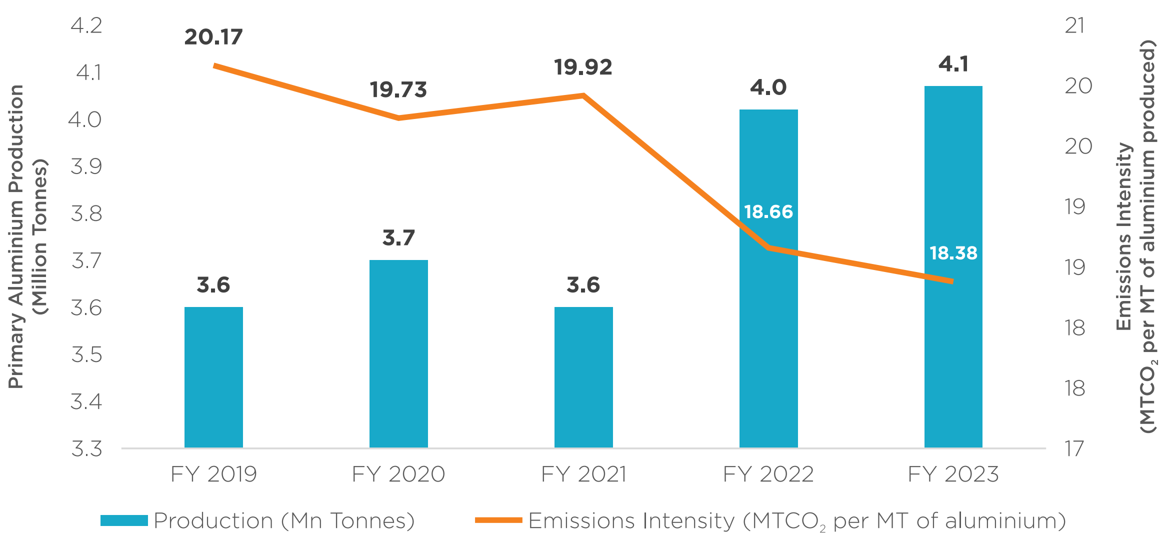
Aluminium is often referred to as an 'infinite metal' since it is 100% recyclable and can be recovered/renewed after being put to use. Furthermore, it experiences no loss of properties or quality during the recycling process. The recycling of aluminium presents both high economic and environmental prospects as it requires only 5% of the energy used[43] to produce aluminium and emits only 5% of the greenhouse gases[46]. In the long term, recycled aluminium (secondary aluminium) is expected to play an important role in meeting the growing global aluminium demand. In India, primary production accounts for about 70% of the total aluminium production, depicting the need to develop a strong industrial base for recycling aluminium scrap and promoting secondary aluminium producers, to meet the growing aluminium demand and subsequently reduce the carbon footprint[47]

44 Energy Data Management Report _pdf.pdf (beeindia.gov.in)
45 India's complex carbon emissions problem - Aluminium emissions | CRU Emissions Analysis (crugroup.com)
46 Aluminium industry net-zero tracker - Net-Zero Industry Tracker 2023 | World Economic Forum (weforum.org)
47 India Needs to Develop A Strong Industrial Base For Recycling Aluminium (businessworld.in)

4.2 Emissions trend – Indian aluminium industry

In the last five years (2019-2023), the production of primary aluminium in India increased by over 11%, despite a marginal capacity addition of 0.65 MT during the same period, implying effective utilisation of existing capacities by Indian producers. Interestingly, while annual production increased, emission intensity declined by over 7.3% during the same period, reflecting improvements in energy efficiency due to various measures adopted by industries. The trend of annual production and emission intensity of primary aluminium producers in India over the last five years (2019-2023) is depicted in Figure 12, highlighting the improvements made by the Indian aluminium industry by incorporating energy efficiency measures and improving capacity utilisation.

Figure 12: Primary aluminium production capacity, annual production, and emissions intensity of Indian producers (FY 2019 – 2023)[48]



Source: Analysis based on sustainability reports of primary aluminium producers in India.

48 Analysis based on companies sustainability reports of respective organisations and presentations from CII National Award for Excellence in Energy Management

05

Comparative assessment of Indian aluminium industries with global peers

In this section, a comparative assessment of the performance of Indian aluminium industries with global peers on key qualitative and quantitative metrics is presented. The following parameters have been considered for the comparative assessment (identified in consultation with stakeholders including active industry players from alumina refining, smelting, and integrated plants, leading research institutes, and low-carbon technology providers):

- **Production and capacity utilisation**: Helps to understand the scale of production and operational efficiency.
- **Energy consumption, fuel sources and SEC:** Provides a comparative assessment of energy efficiency among different players. Higher Specific Energy Consumption (SEC) signifies lower energy efficiency.[49] [50]
- **Emission intensity:** Emission intensity is the level of GHG emissions per unit of economic activity, usually measured at the national level. Higher emission intensity indicates a greater need for decarbonisation.[51]

49 Every company differs in terms of institutional structure, data reporting norms, technological advancements, spatial location, availability of resources etc.
50 Emission data for Hindalco and NALCO includes combined emissions from smelters, refineries and downstream production.
51 Emission intensity comparison becomes intricate when considering the diverse technical parameters among smelter units utilising different technologies such as GAMI, AP etc.

- **Commitment to net-zero targets:** Depicts the proactiveness of various industry players towards sustainable and responsible manufacturing.
- **Existing EE / decarbonisation measures:** Helps in identifying leading decarbonisation and energy efficiency practices followed worldwide.

In this comparative assessment, five leading global aluminium companies from various geographies have been selected. These global aluminium companies are also leaders in the adoption of sustainability measures in their business practices:

Table 1: Indian and global peers for comparative assessment.

Company	Company size	Capacity (MTPA)*	Headquarters
Vedanta Limited*	INR 1,437 billion[52] 13.51 billion GBP	2.29	India
Hindalco*	INR 2,160 billion[53] 20.31 billion GBP	1.32	India
NALCO*	INR 131 billion[54] 1.24 billion GBP	0.46	India
Rio Tinto	INR 4,502 billion (GBP 43 billion)[55]	3.2	UK
Emirates Global Aluminium (EGA)	INR 668 billion (GBP 6.38 billion)[56]	2.5	UAE
Alcoa Corporation	INR 225 billion (GBP 2.15 billion)[57]	2.2	USA
Norsk Hydro ASA	INR 1,570 billion (GBP 15 billion)[58]	2.3	Norway
Alba	INR 342.40 billion (GBP 3.27 billion)[59]	1.62	Bahrain

* The company size for Indian companies represents their sales for 2024

Note: *The capacity is as per 2021-22 data.

52 Vedanta Ltd share price | About Vedanta | Key Insights - Screener
53 Hindalco Industries Ltd share price | About Hindalco Inds. | Key Insights - Screener
54 National Aluminium Company Ltd share price | About Natl. Aluminium | Key Insights - Screener
55 Rio Tinto Company Profile - Office Locations, Competitors, Revenue, Financials, Employees, Key People, Subsidiaries | Craft.co
56 EGA reports competitive financial results for 2023, with highest-ever production from mining to metal
57 Alcoa Corporation Reports Fourth Quarter and Full Year 2022 Results | Alcoa Corporation
58 Norsk Hydro Revenue 2010-2023 | NHYDY | MacroTrends
59 Facts & Figures - Aluminium Bahrain (Alba) (albasmelter.com)

Summary of the comparative assessment of Indian aluminium companies with global peers is provided in Table 2 below.

Table 2: Highlights of the comparative assessment of Indian aluminium sector with global peers[60]

#	Parameters	Indian aluminium sector	Global peers

1	**Production and Capacity Utilisation**	• Production capacity of primary aluminium in India: 4.02 MMT in FY2021-22 (~5% of global production)
		• Capacity utilisation[61]:
		  • Hindalco ~102% (maximum)
		  • NALCO ~99%
		  o Vedanta ~97%
			• These 5 global peers (refer Table 2) have a cumulative capacity of ~11.82 MTPA.
			• Capacity utilisation[62]:
			  o EGA has highest utilisation of ~109% followed by Alba (~100%).
			  o Other global peers have utilisation of less than 100%

2	**Energy Consumption**[63]	• Leading performer: ~53 GJ/Mt of primary aluminium	• Leading performer: ~50 GJ/Mt of primary aluminium[64, 65]
	DC Electricity Consumption[66]	• Leading performer: 12,973 kilowatt-hours per metric tonne (kWh/Mt) • Average: ~13,320 kWh/Mt	• Leading performer: 12,500 kWh/Mt • Average: ~13,745 kWh/Mt
	RE Usage[67]	• 0.8% of the total energy consumption is RE based	• Companies in European, North American, and South American regions derive more than 90% of power from hydro generation
3	**Emission Intensity**	• Leading performer: ~16.2 $tCO_{2-}e$/Mt • Average: ~ 18 $MtCO_{2-}e$/Mt	• Leading performer: ~1.6 $tCO_{2-}e$/Mt • Average: ~ 11.2 $tCO_{2-}e$/Mt
4	**Net-Zero Targets**[68]	• Hindalco and Vedanta: by 2050 • NALCO: by 2060	• Rio Tinto, Norsk Hydro, EGA, Alcoa: by 2050 • Alba: by 2060
5	**Existing EE/ decarbonisation measures**	• Equipment modifications and process improvement • Energy management solutions • Recycling and circular economy	• RE adoption • Technological advancements • Recycling and circular economy

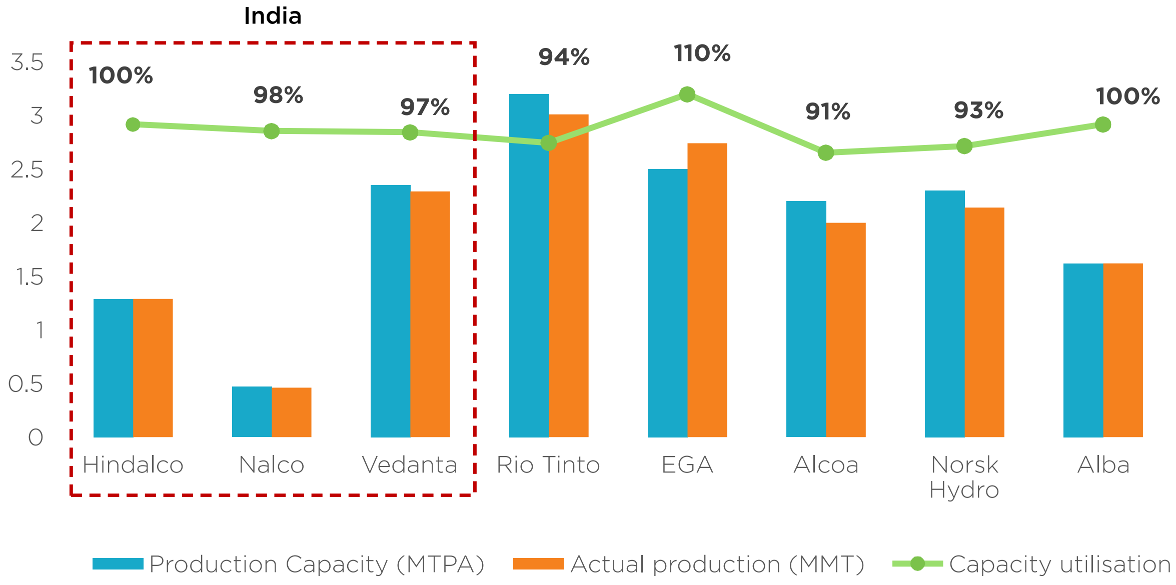
The comparative analysis indicates that while Indian aluminium industries demonstrate an edge over their global peers in terms of efficiency and capacity utilisation, there are potential areas for improvement, particularly in terms of reducing emissions, increasing renewable energy adoption, and aligning with global sustainability goals. A strategic focus on these aspects is critical to enhance the industry's environmental performance and long-term sustainability.

60 Sustainability development reports, respective companies' annual reports and websites
61 Sustainability reports of respective companies
62 Sustainability reports of respective companies
63 Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations.
64 Sustainability reporting (riotinto.com)
65 Alcoa Foundation 2022 Sustainability Report
66 Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations.
67 Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations.
68 Delivering a Net-Zero Future for Aluminium - RMI

5.1 Production capacity

The cumulative annual primary aluminium production in India reached 4.02 MMT in FY 2021-22, a noteworthy achievement against the total installed capacity of 4.11 MTPA. Vedanta emerged as a leading contributor, accounting for 56% of the total annual production, followed by Hindalco at 32%, and NALCO at 12%. In 2021-22, Indian smelter units operated at an average of approximately 99% capacity utilisation, with Hindalco leading the pack at a capacity utilisation of approximately 102%. The remarkable capacity utilisation of Indian aluminium companies is one of their key strengths as they continue to compete with international companies in the global marketplace. Details on the total smelter capacity, aluminium production, and capacity utilisation of Indian and five key global companies for 2021-22 are provided in the Figure 13.

Figure 13: Smelter capacity, aluminium production and capacity utilisation, FY 2021–22



Source: Sustainability reports of respective companies

5.2 Energy consumption, fuel sources and SEC

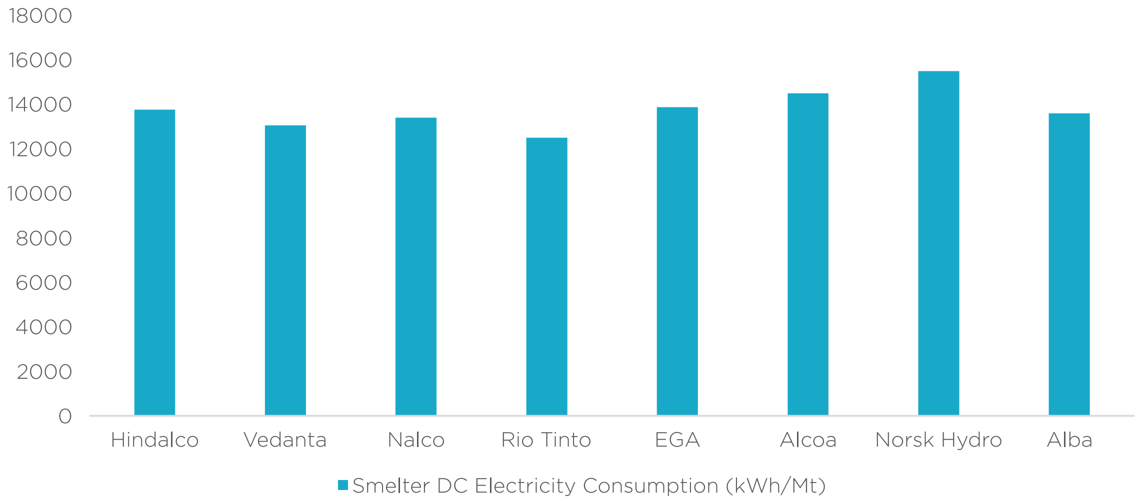
The energy landscape of smelters in India is characterised by electricity usage sourced largely from captive power plants supplemented by grid supply. In terms of energy sources, a predominant reliance on coal is evident, constituting more than 98% of the energy mix, with the remaining sourced from other fossil fuels like natural gas and fuel oil, and a minor share from renewable energy (~0.8%). This composition reflects the current energy mix, indicating potential for diversification and increased adoption of renewable sources to enhance sustainability.

Globally, the power source scenario is different: approximately 99% of the power in Alba (Bahrain) and EGA (UAE) smelters is based on natural gas; hydropower accounts for around 95% of Norsk Hydro smelter's power needs; approximately 86% of Alcoa's total consumption is from renewable energy such as hydropower, wind, or solar PV; and Rio Tinto majorly depends on renewable energy, accounting for about 72% of their total energy consumption.[69]

69 Sustainability reporting (riotinto.com)

Another key indicator for energy efficiency (EE) and decarbonisation is Specific Energy Consumption (SEC). Indian smelters operate at an average SEC of approximately 52 to 71 GJ of energy per million tonne (Mt) of aluminium produced, based on reporting. This is in line with leading global standards of approximately 50 to 74 GJ/Mt for smelters such as Norsk Hydro, Alba, and Alcoa. However, the SEC for EGA and Rio Tinto are reported to be around 118 GJ/Mt and 132 GJ/Mt, respectively.

Figure 14: Specific DC electricity consumption of Indian and 5 key global smelters, FY 2022-23



Specific DC electricity consumption of India and global (kWh/Mt)

	INDIA	GLOBAL
Lowest	12,973	12,500
Average	13,322	13,745

Source: Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations.

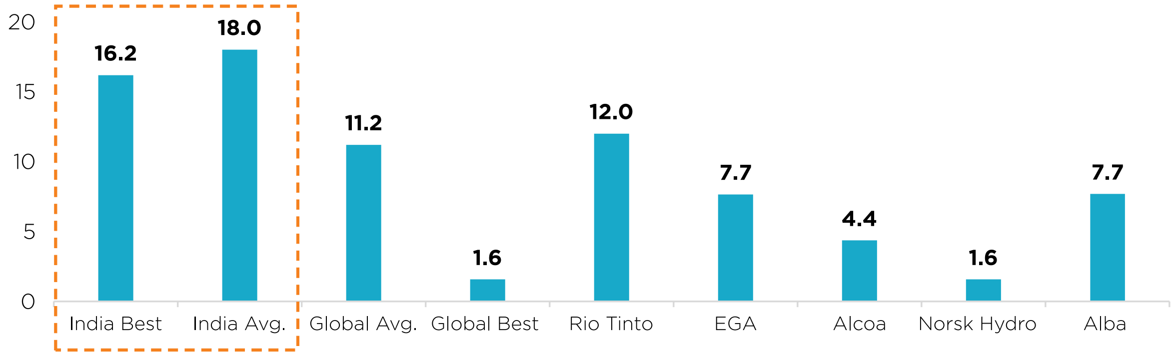
The comparative analysis of DC power consumption depicted in Figure 14 above indicates that the range of lowest to average DC SEC of Indian smelters (12,900 to 14,500 kWh/Mt) is in line with that of their global counterparts (12,500 to 15,500 kWh/Mt). This underscores the standardised energy requirements within the aluminium smelting process, prompting further exploration into the factors contributing to this equilibrium and potential avenues for optimisation in this critical facet of the industry's operational landscape. However, because every smelting unit may utilise different technologies, it is difficult to compare the smelting units directly.

5.3 Emission intensity

Emission intensity refers to the total emissions (tCO_2e) towards the production of one tonne of aluminium. Figure 15 below showcases the emission intensity of various Indian and global aluminium smelters, including the energy-related emissions across alumina refining and smelting processes. While Norsk Hydro (Norway) emerges as the global leader in terms of best (lowest) emission intensity with near-zero emissions of approximately 1.6 tCO_2e per tonne of aluminium, primarily due to the use of hydropower, smelters in India have demonstrated the highest emission intensities globally.

India's best smelter operates at an emission intensity of approximately 16.2 tonnes of CO_2 equivalent per tonne (tCO_2e/t), compared to the national average of approximately 18 tCO_2e/t. However, they still lag behind the global average of approximately 11.2 tCO_2e/t. Other smelters across the globe, such as Alcoa (USA), use a mix of low-emission grid electricity and captive hydropower plants, and Rio Tinto (Australia) uses high-emission grid electricity.

Figure 15: Emission intensity (tCO_2e/t)



Source: Analysis based on companies Sustainability reports and CII National award for Excellence in Energy Management presentations

Note:

1. The emission data for Indian players combines figures for both alumina and aluminium production (downstream production)).
2. Emission intensity for Hindalco, NALCO and Vedanta is calculated based on the data available in their respective sustainability reports.

Emission intensity of India and global in tCO_2-e/t

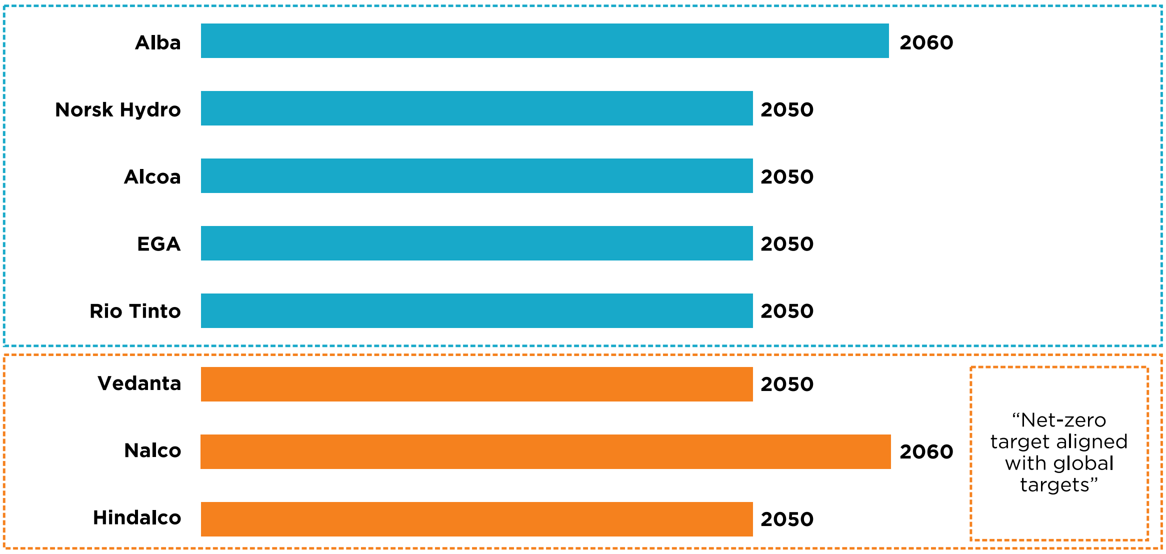
	INDIA	GLOBAL
Lowest	~16.2	~1.6
Average	~18	~11.2

5.4 Net-zero targets

Aluminium has been at the forefront of many industrial and engineering innovations of the 20th century and continues to power a sustainable future. While global demand for aluminium is projected to increase by approximately 80% by 2050, aluminium companies are facing pressure from corporations and governments to reduce their carbon footprints. In response, aluminium companies have committed to achieving their respective net-zero emission targets soon.

The majority of the leading aluminium companies in the world have committed to achieving net-zero emissions by 2050, including Vedanta and Hindalco, which account for approximately 90% of India's total primary aluminium production capacity (refer to Figure 16).

Figure 16: Net-zero targets by year of national and international companies in the aluminium ecosystem



Source: Analysis based on sustainability reports of respective companies and CII National award for Excellence in Energy Management presentations

Note: *NALCO aims to be net-zero by 2060 or earlier.

Additionally, there have been specific global initiatives such as the 'Mission Possible Partnership (MPP)', wherein leading companies have endorsed a new strategy for action to decarbonise the sector in this decade and help make the global goal of net-zero by 2050 viable. The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries, including aluminium, in the next 10 years. The present signatories of the initiative include Alcoa, Emirates Global Aluminium (EGA), and Rio Tinto[70].

70 International Aluminium Institute (international-aluminium.org)

The emission reduction targets of various global aluminium companies have been summarised in the table below:

Table 3: Company wise GHG emission reduction targets

Aluminium Company	Targets
Hindalco[71]	• 25% specific GHG emission reduction by 2025 • Net-zero emissions by 2050
Vedanta [72]	• GHG emission reduction by 25% till FY 2024-25 against FY 2011-12 level (25.5 $tCO_{2\text{-}}e$/Mt of aluminium) • Net-zero emissions by 2050
NALCO[73]	• Increase in non-fossil power sources to 40% by 2030. • Net-zero emissions by 2060
Alcoa[74]	• Reduce GHG emission intensity (Scope 1 and 2) by 30% by 2025 and by 50% by 2030 considering 2015 as baseline. • Net-Zero emissions by 2050
Alouette, Canada[75]	• 30% carbon emission reduction below current level of 1.83 $tCO_{2\text{-}}e$/ Mt of aluminium (Scope1) • Net-zero emissions by 2050
GFG Alliance/ Alvance [76]	• Achieve carbon neutrality by 2030
Norsk Hydro[77]	• Reduction GHG emissions by 30% by 2030 • Net-zero emissions by 2050
Alba[78]	• Reduction carbon emission by 50% in 2024 • Net-zero emissions by 2060
Rio Tinto[79]	• Reduce carbon intensity by 30% and absolute emissions by 15% by 2030. • Net-zero emissions by 2050

71 tcfd-summary-report-fy-2021-22-report.pdf (hindalco.com)
72 Vedanta Sustainability Report 2021-22 (vedantalimited.com)
73 Annual Reports | NALCO (National Aluminium Company Limited) | A Govt. of India Enterprise (nalcoindia.com)
74 Alcoa States Its Ambition to Reach Net-Zero Greenhouse Gas Emissions by 2050 | Alcoa Corporation
75 Microsoft Word - ASI Summary Audit Report Aluminerie Alouette Certificate No 85 (PS).docx (aluminium-stewardship.org)
76 Delivering CN30 | ALVANCE British Aluminium
77 annual-report-2022-eng.pdf (hydro.com)
78 Think Sustainability and Make a Change
79 Sustainability and Annual Reports

5.5 Existing EE/ decarbonisation measures

With the aim of achieving net-zero targets, Indian and international aluminium industries are consistently making efforts towards decarbonising their operations and have also declared their respective action plans. In the case of India, switching to low-carbon fuels, recycling and circular economy practices, and technological advancements such as Carbon Capture, Utilisation, and Storage (CCUS) and inert anodes are touted as the key levers for decarbonisation in the next decade. Indian aluminium industries have plans to increase the share of renewable energy in their energy mix by adding approximately 1,500 MW of renewable energy by the year 2026-27 in a phased manner.

The table below briefly presents some existing energy efficiency (EE) and decarbonisation measures adopted by Indian and leading global companies in the aluminium ecosystem.

Table 4: Company wise EE and decarbonisation measures adopted.

Aluminium company	EE and decarbonisation measures
Hindalco[80]	• Plans to increase total RE capacity to 300 MW by 2025 • EE measures include phased implementation of copper insert collector bar, installation of clamp modification, cast iron sealing, step-stub anode, pot noise and application of Digital Twin.
Vedanta [81]	• Converting a calciner from oil to natural gas firing: enabling fuel savings • Procurement of 1500 MW of RE • Assessing adoption of Natural Gas at Cast-house and bake oven. • Adoption of inert anode and wetted cathode technologies • Study to examine adoption of hydrogen for calciner at alumina refinery. • Special emphasis on recycled aluminium in collaboration with Runaya refining
NALCO[82]	• Operation with energy-efficient equipment and systems Transition to clean energy mix, NALCO generated 280 million units (MU) wind energy and 0.703 MU solar energy in year 2022. • Increased focus on aluminium recycling. NALCO has recycled ~ 8,000 MT of aluminium scrap, nearly all of it generated internally as of 2022-23.
Alcoa[83]	• Increase use of RE to 75% of total energy mix • ELYSIS zero-carbon smelting process and mechanical vapour recompression (MVR) to reduce emissions in the alumina refining process. • Adoption of inert anode technology. Alcoa invented the inert anode technology for aluminium smelting that serves as the basis for the ELYSIS joint venture. ELYSIS aims to have its technology available for installation from 2024 and the production of larger volumes of carbon-free aluminium approximately two years later.
Alouette, Canada[84]	• Use of hydroelectricity • Increased use of natural gas • Recovery and recycling of carbon and refractory materials from spent pot lining (SPL)

80 https://www.hindalco.com/sustainability/sustainability-reports 2022-23
81 https://www.vedantalimited.com/vedanta-sr3/aim-4.html
82 https://mines.gov.in/admin/storage/ckeditor/NALCO_42ndAnnualReport2023_eng_1704194658.pdf
83 https://news.alcoa.com/press-releases/press-release-details/2021/Alcoa-States-Its-Ambition-to-Reach-Net-Zero-Greenhouse-Gas-Emissions-by-2050/default.aspx
84 https://aluminium-stewardship.org/wp-content/uploads/2020/07/ASI-Summary-Audit-Report-Aluminerie-Alouette-85-PS.pdf

Aluminium company	EE and decarbonisation measures
Alvance [85]	• Around ~88% of electricity consumption is sourced from hydropower. • Alvance is framing a pilot to launch by 2024 in the hope of capturing up to 70% of emissions from the smelting process.
Norsk Hydro[86]	• Adoption of RE, ~70% energy consumed is sourced from renewable sources. Development of Hal-Zero Technology • Hydro CIRCAL – recycling technology • Norsk Hydro has recently announced that they are exploring options to use CCS for aluminium, with Norsk Hydro setting a goal of using CCS on a commercial scale by 2030
Aluminium Bahrain B.S.C.[87]	• Plans for installation of 5-7 MW solar farm. • Zero-waste Spent Pot Lining treatment plant. • Carbon sequestration. • Alba and Mitsubishi Heavy Industries have formed an alliance for adoption of carbon capture technology. • MoU with Bahrain Petroleum Company (Bapco) for feasibility analysis of hydrogen.
Rio Tinto[88]	• 4 GW of wind and solar, backed by energy firming and storage solutions. • Adoption of hydro-based smelting technology • ELYSIS and AP4X cell technology under implementation • Adoption of aluminium recycling. They have an aluminium recycling facility at Arvida Plant. Rio Tinto is also offering fully recycled aluminium products which is done via their joint venture with 'Matalco'.

The detailed comparison between the Indian aluminium industry and its global counterparts unveils a complex landscape. While India demonstrates strength in production capacity, it continues to tackle environmental challenges such as high energy consumption and emission intensity, largely stemming from a heavy reliance on fossil fuel-based power. In contrast, leading global peers exhibit a more sustainable approach by strategically leveraging renewable energy sources and innovative technologies, in line with their ambitious net-zero targets.

The findings underscore the need for the Indian aluminium sector to accelerate its transition towards cleaner energy alternatives and innovative solutions to address environmental concerns, fostering a competitive and sustainable trajectory. Implementing robust measures, such as increased adoption of renewable energy, embracing cutting-edge technologies, and aligning with global sustainability standards, will not only enhance the industry's environmental performance but also ensure its continued competitiveness in the dynamic global landscape.

However, renewable energy sources such as solar and wind are variable and intermittent in nature, requiring balancing sources such as energy storage. These balancing sources come with their own set of challenges, including limited sites for pumped hydro storage and the high cost of battery storage technologies. A collaborative and concerted effort from all stakeholders, including industry players, policymakers, and investors, is pivotal in steering the Indian aluminium sector towards a more sustainable and resilient future.

85 https://alvancebritishaluminium.com/delivering-cn30/
86 https://www.hydro.com/globalassets/06-investors/reports-and-presentations/annual-report/jenincharge22/annual-report-2022-eng.pdf
87 Think Sustainability and Make a Change.pdf
88 rt-climate-report_2022.pdf


CO2

06

Leading Decarbonisation Practices

As highlighted in the previous sections, despite having competitive specific DC electricity consumption, the emission intensity of Indian aluminium companies (~18 tCO_2e/t) is still much higher than the global average (~11.2 tCO_2e/t) due to heavy reliance on coal-based power. Thus, it is imperative for Indian aluminium companies to implement a set of decarbonisation levers tailored to the specific dynamics of the country.

This section evaluates the leading global decarbonisation practices that hold the key to transforming the Indian aluminium sector into a more environmentally responsible and sustainable sector. The adoption of energy efficiency (EE) measures, low-carbon energy sources, circular economy practices, waste management, and technological advancements are critical levers for the industry in its journey towards decarbonisation. Tackling the current reliance on coal-based energy is fundamental as we aim for a strategic and holistic approach to reducing carbon emissions.

A list of various decarbonisation measures and technologies adopted by leading players is provided in Table 6. These practices and technologies have been categorised into four major categories: i.e., (i) Low carbon energy sources: Initiatives for the adoption of alternatives to fossil fuels.; (ii) EE and monitoring interventions: Introducing process improvements, equipment upgrades, and energy management solutions.; (iii) Circular economy and waste management: Increasing the reuse and recycling of aluminium at various lifecycle stages. and (iv) Technological advancements: Adoption of low-carbon technologies to reduce emissions at the source.

Table 5: Summary of assessment of leading global decarbonisation practices and technologies across critical factors

Decarbonisation practice/ technology	Readiness level	Specific conditions where options work best	Abatement Potential	Barriers to adoption	Examples of capabilities/ expertise of UK and other international companies
Low carbon energy sources					
Adoption of RE	High (Proven)	Dedicated transmission line from the grid to receive quality and uninterrupted power	• ~70% of total emissions in sector is on account of electricity consumption during smelting[89] • RE adoption aids significant reduction in emissions arising from electricity use	• Availability of round the clock power • Reliability of the grid	• Alvance's smelting facilities are driven by hydro-electric power and a complex of on-site bio-diesel units. This combination of renewable energy sources makes the site one of the greenest metal production plants in the UK. • Hydro Aluminium's core strategy is to grow their operations in regions of the world where they can use power with zero emissions, such as hydropower, wind power, solar power, and more.[90]
Use of Green Hydrogen in Calciner	High	Favourable for new Calciners in Refineries, however, can also be retrofitted to old calciners	• Rio Tinto has partnered with ARENA to conduct a feasibility study into using clean hydrogen to replace natural gas in the calcination stage at their Yarwun alumina refinery in Gladstone • Rio Tinto has also filed patents for the hydrogen calcination process[91]	• Availability, transportation and storage infrastructure of green hydrogen • High Capital Cost	• Hydro Aluminium conducted a test at a cast house in their extrusion plant in Navarra, Spain, where green hydrogen replaced natural gas as fuel for the recycling of aluminium. The test was led by hydrogen specialists from Hydro Havrand, Hydro's dedicated green hydrogen company, in collaboration with Fives, an industrial engineering group known for its expertise in hydrogen burner technology and solutions tailored to the aluminium industry. The consortium continues building capabilities in the fuel switch to hydrogen, aiming to be the leading provider of industrial fuel switch solutions in green hydrogen.[92] • Rio Tinto, a UK company, has partnered with the Australian Renewable Energy Agency (ARENA) to research the potential for using green hydrogen to replace natural gas in the calcination process of alumina refining at Yarwun. The hydrogen calcination plant at the Yarwun Alumina Refinery is at a relatively advanced stage of development. The project consists of a 2.5 MW onsite electrolyser to supply hydrogen and a retrofit of one of the refinery's calciners to operate with a hydrogen burner.

89 Aluminium industry net-zero tracker - Net-Zero Industry Tracker 2023 | World Economic Forum (weforum.org)
90 Renewable power and aluminium (hydro.com)
* Hydro is an international company with operations in multiple countries including locations across the UK.
91 Rio Tinto and ARENA to study hydrogen calcination to reduce carbon emissions in alumina refining - Green Car Congress
92 World's first batch of recycled aluminium using hydrogen fuelled production

Decarbonisation practice/ technology	Readiness level	Specific conditions where options work best	Abatement Potential	Barriers to adoption	Examples of capabilities/ expertise of UK and other international companies
Energy monitoring and efficiency interventions					
Copper insert and onsert collector bars	Medium to High	Potential energy reduction works for low amperage cells if the thermal balance is maintained.	• Using copper insert has the potential of energy reduction in low amperage cell.	• Inappropriate designing can lead to underperformance	• A new cathode lining was developed and tested at the Aditya Aluminium smelter to reduce specific energy consumption. The copper insert in the collector bar was modified for uniform cathode current distribution and reduced resistance.[93]
Magnetic compensation loop (MCL) for reducing DC consumption	High	Gami technology-based smelters offer better prospects for deployment of MCL as compared to AP36 technology that already has a robust design with good magnetic balance	Beneficial for balancing magnetic field due to increase in current. MCL deployment offers potential savings in input electricity.	• The units with AP36 technology are not in favour to install MCL	• By incorporating established and verified AP Technology™ components, such as the magnetic compensation loop and new lining, the Aluminium Dunkerque plant identified an opportunity to enhance the potline amperage. This improvement was achieved while still operating within the plant's overall capabilities, considering optimisations in anode production and casting.[94]
Digital Twin	High		It has the potential to monitor parameters such as current intensity, bath temperature, and pot life, eventually helping in reducing energy consumption and carbon emissions.	• Lack of technical know how	• Apart from focusing on safety and health, Hydro aims to take a leading position in sustainability in the aluminium market. Hydro has implemented Automated Guided Vehicles (AGVs) and digital twin technology, streamlining their operations through digital predictive maintenance at their Sunndal plant in Norway.[95] • EGA's Al Taweelah alumina refinery uses digital twin technology. The Operator Training Simulator (OTS) functions as a digital twin, creating a virtual replica of the plant. By incorporating thermodynamic process models and mirroring the distributed control system (DCS), the OTS played a pivotal role in identifying design gaps and potential issues during commissioning and start-up, ensuring a seamless ramp-up of aluminium production.[96]

93 manufactured-capital.pdf (hindalco.com)
94 AP_newsletter_2018_v9B.pdf (ap-technology.com)
95 The Collaborative Triangle of Aluminium Innovation (hydro.com)
96 The digital twin explained | EGA

Decarbonisation practice/ technology	Readiness level	Specific conditions where options work best	Abatement Potential	Barriers to adoption	Examples of capabilities/ expertise of UK and other international companies
Circular economy and waste management					
Bauxite Residue – Holistic use	Medium	Proximity to the industries that can utilise red mud, such as cement industry	It has the potential to be used in cement industry thus contributing towards circular economy.	• High Alkalinity of the Bauxite residue • Higher Na_2O content in Bauxite residue makes it difficult to use in various applications	• Hydro Alunorte and Wave Aluminium have collaborated to build a bauxite residue processing plant in Brazil. This project aims to recover commercially valuable materials from bauxite residue. The innovative technology used in this plant, developed and patented by Wave Aluminium, can separate different minerals from bauxite residue and convert them into commercially viable materials.[97]
Spent pot lining – Use in cement etc.	High	Proximity to the industries that can utilise SPL, such as cement y industries.	It has the potential to be used in cement industry, contributing towards circular economy.	• Spent pot lining contains hazardous materials such as fluorides, cyanides, and polycyclic aromatic hydrocarbons, which pose challenges in its safe handling and disposal • Transportation costs, storage requirements, and regulatory compliance during transit	• The UK aluminium industry has made substantial investments to enhance EE in production and improve both internal and external environments. Notably, they have significantly reduced emissions of fluorides, sulphur-dioxide, and dust. The fluorides collected during "dry scrubbing" in furnace gases are now fully recovered and spent "pot-linings" are recycled instead of being sent to landfills.[98] Befesa aluminium Salt Slags Recycling Services provides 3 separate but complementary services: Salt slag, Spent Pot Lining (SPL) and refractory lining recycling services. [99]
Dross – Recycling and use	High	Both for Green Field Projects and retrofitting in existing Smelter units	It has potential applications in sectors like auto, construction, electrical etc., thus contributing to circular economy.	• Dross recycling for use in Green Field Projects or retrofitting existing smelters requires high-quality material with consistent composition • Establishing recycling facilities or modifying existing smelters to accommodate dross recycling demands substantial investment in infrastructure and technology • Meeting environmental regulations and health standards	• Altek is a technology company with expertise and experience in the design, manufacture, and installation of aluminium dross and scrap processing systems. Dross can amount to 5% of a facility's total production, so preserving metal units is vital. Partnering with Altek ensures maximum revenue from your dross. Altek reduces dross levels before it leaves the furnace and ensures that metal unit recovery is maximised at each stage of the recycling process.[100] • Tandom is a UK metal recycling company that does dross processing. They tailor their process to maximise value of the dross for the supplier by processing lower grade and higher-grade dross to ensure maximum metal yield.

97 Hydro and Wave Aluminium to recover minerals from bauxite residue
98 3-aluminium-and-sustainability.pdf (alfed.org.uk)
99 Befesa
100 Aluminium Dross Processing | Recycling and Recovery | ALTEK (altek-al.com)

Decarbonisation practice/ technology	Readiness level	Specific conditions where options work best	Abatement Potential	Barriers to adoption	Examples of capabilities/ expertise of UK and other international companies
Technological advancements					
Inert anodes	Medium	More suitable for new smelting pots but can be retrofitted to existing smelting pots	• Inert Anodes have potential to reduce emissions from smelting. • In comparison to full-scope industry average emissions, metal produced with inert anodes has an 85% lower carbon footprint[101].	• Increased energy demand resulting in higher GHG emissions specifically when energy is derived from fossil fuels • Ambiguity in terms of commercialisation	• ELYSIS is developing inert anode technology, which eliminates all direct greenhouse gases (GHGs) from the traditional smelting process and instead produces oxygen. The prototype cells of ELYSIS' inert anode technology are located at Rio Tinto's Alma smelter in Saguenay-Lac-Saint-Jean, Quebec.[102]
Carbon Capture Utilisation and Storage (CCUS)	Medium	Captive Thermal Power Plants and Smelter Process (Mostly applicable for Thermal Power Plants) or in the processes where concentration of CO_2 emissions is high	Reduction in GHG emissions from the flue gases. Alvance is framing a pilot to launch by 2024 in the hope of capturing up to 70% of emissions from the smelting process[103].	• High initial cost • Absence of Carbon Utilising Industries in nearby vicinity • Lack of Infrastructure for storage • The flue gases in aluminium smelters have a relatively low concentration of CO_2, at ~1%. Most of the existing carbon capture technologies capture flue from fossil power production and industries with higher concentrations of CO_2, typically above 4%[104] • Additionally, flue gases from aluminium smelting contain pollutants that challenge compatibility with existing capture technologies	• Alvance is working in a consortium alongside Trimet, LRF (Rio Tinto's research centre), and the Fives Group to evaluate the most economical way to capture carbon in aluminium smelters. The initiative is examining amine technology to determine the feasibility of capturing flue gases directly versus the need to concentrate the CO_2 for better capture. Alvance is planning a pilot project to launch by 2024 with the aim of capturing up to 70% of emissions from the smelting process.[105] • Hydro is developing Carbon Capture and Storage (CCS) solutions that can be retrofitted into aluminium plants already in operation. Hydro has assessed over 50 CCS technologies and developed plans to test and pilot the most promising ones at an industrial scale. Their goal is to establish an industrial-scale pilot by 2030. Studies indicate that off-gas capture could effectively capture most of the CO_2 emissions from aluminium smelters, even if it leads to increased dimensioning, power requirements, and operational costs. Additionally, Hydro is exploring direct air capture (DAC) units as a supplementary option. These DAC units can recover process heat, thereby reducing power demand and operational expenses.

101 Inert Anode Technology (enplusgroup.com)
102 ELYSIS selects Alma smelter for commercial size 450 kA inert anode prototype cells (riotinto.com)
103 WEF_AFC_Unlocking_Technological_Scale_up_2021.pdf (weforum.org)
104 Developing carbon capture and storage technology for aluminium smelters (hydro.com)
105 (PDF) LCA Analysis Decarbonisation Potential of Aluminium Primary Production by Applying Hydrogen and CCUS Technologies | Sotiris Kottaridis - Academia.edu

Decarbonisation practice/ technology	Readiness level	Specific conditions where options work best	Abatement Potential	Barriers to adoption	Examples of capabilities/ expertise of UK and other international companies
Hal Zero Technology	Low to Medium	Smelter Process	Reduction process GHG emission. This technology can result in releasing only oxygen during smelting process	• The technology is still in developmental stage	• Hydro's HalZero represents a significant advancement in the quest for zero-emission aluminium production. This innovative proprietary technology aims to completely decarbonise the smelting process, thereby eliminating emissions from both electrolysis and anode baking. Instead of releasing CO_2 into the atmosphere during the production of aluminium,[106] HalZero converts alumina to aluminium chloride prior to electrolysis. The chlorine and carbon are kept in a closed loop, resulting in the emission of oxygen rather than CO_2. The successful testing and modelling of the HalZero process at Hydro's research and development laboratory in Porsgrunn, Norway, have paved the way for further verification at a test scale. The ambitious goal is to produce the first emission-free aluminium by 2025 and eventually achieve industrial-scale pilot volumes by 2030.[107]
Mechanical Vapour Recompression (MVR) for Alumina Refinery	High	Green Field Projects and retrofitting in existing alumina refinery – applicability depends on configuration.	Early estimates predict that MVR powered by RE could reduce carbon emissions from alumina refineries by ~70%[108]	• High capital cost and applicability based on configuration of existing plant • Availability of round the clock renewable power	• Alcoa's pioneering efforts in deploying Mechanical Vapour Recompression (MVR) technology for alumina refining showcase the industry's commitment to sustainability and emissions reduction. The project seeks to electrify steam production by using renewable power to drive mechanical vapour recompressors, thereby displacing fossil-fuelled boiler steam.[109]

Based on the assessment, switching to low-carbon energy sources and adopting energy efficiency (EE) measures emerge as important levers for the decarbonisation of the aluminium sector over the next ten years, considering their high readiness level and abatement potential. Additionally, it is important for aluminium companies to consistently evaluate and adopt new technologies such as inert anodes, Mechanical Vapour Recompression (MVR), and HalZero to further reduce greenhouse gas (GHG) emissions.

At the same time, investing in a circular economy is crucial due to the numerous advantages associated with aluminium recycling, such as significant energy savings of up to 95%, reduced waste disposal and landfill needs, and reduced capital costs—only 10% compared to primary smelting. These leading decarbonisation practices are discussed in detail in the following sections.

106 Hydro's steps towards decarbonised aluminium production | International Aluminium Journal (aluminium-journal.com)
107 HalZero – zero-emission electrolysis from Hydro
108 WEF_AFC_Unlocking_Technological_Scale_up_2021.pdf (weforum.org)
109 Mechanical Vapour Recompression for Low Carbon Alumina Refining - Australian Renewable Energy Agency (ARENA)

6.1 Low carbon energy sources

a. Adoption of renewable energy (RE)

Approximately 64% of the emissions associated with aluminium production are indirect emissions (scope 2) attributed to electricity consumption.[110] Thus, reducing emissions from electricity alone can contribute significantly to overall emissions reduction. Table 6 provides a region-wise share of various sources of energy used for the production of aluminium.

110 WEF_AFC_Unlocking_Technological_Scale_up_2021.pdf (weforum.org)

Table 6: Region wise aluminium production and share of different electricity sources utilised in primary aluminium smelters, 2021[111]

Region	Aluminium production (Million tonnes)	Renewables (solar, wind, geothermal)	Hydropower	Natural Gas	Nuclear	Coal
Europe (Including Iceland, Norway, Ukraine, and the U.K.)	7.5	1.8%	92.7%	1.2%	3.4%	1.1%
Gulf Region (Oman, Qatar, Saudi Arabia, UAE)	5.9	0.7%	0%	99.3%	0%	0%
Asia (Excluding China but including Bahrain, India, Indonesia, Kazakhstan, Malaysia)	4.5	0.5%	5.5%	0%	0%	94%
North America (Canada, USA)	3.9	0%	95.3%	0.01%	0.1%	4.6%
Oceania (Australia, New Zealand)	1.9	1.8%	37.7%	0.7%	0%	57.8%
Africa (Cameroon, Egypt, Ghana, Mozambique, Nigeria, South Africa)	1.6	0%	41.2%	0%	0%	58.8%
South America (Argentina, Brazil)	1.2	2.3%	81.8%	15.9%	0%	0%

111 The Shift Toward Renewable Power in Aluminium Smelting - Light Metal Age Magazine

Hydropower is one of the cleanest, most widely used, and most established source of power for aluminium production in many countries. Alvance British Aluminium in the UK sources approximately 88% of its energy from hydropower. Similarly, Norsk Hydro in Norway is heavily dependent on hydropower for aluminium production. Norsk Hydro ASA operates 40 hydropower plants in Norway, with a combined production of 13.7 TWh in a normal year. The purpose of Norsk Hydro's hydropower assets is to secure a stable power supply for its primary aluminium plants located in Norway; hydropower is mainly generated and used for internal consumption.[112]

Challenges

A pivotal shift in energy supply options is underway as the aluminium industry transitions towards cleaner energy sources. For the aluminium industry, options for renewable energy (RE) supply are limited due to the intermittent and variable nature of solar and wind power. However, variability and intermittency can be balanced with the help of energy storage systems (ESS) such as pumped storage and battery storage. Nonetheless, the adoption of such systems at scale in the aluminium industry faces limitations due to high upfront investments. To summarise, the adoption of RE sources for aluminium production faces several challenges:

- Ensuring a stable and uninterrupted power supply can be difficult with intermittent renewable sources without suitable energy storage solutions.
- The industry's reliance on the grid for power supply can be a barrier, as grid stability and reliability issues may affect production processes.
- Achieving round-the-clock RE provision requires substantial prerequisites, and realising such continuous renewable power generation faces obstacles, notably the limited storage capacity. This limitation represents a significant challenge in ensuring an uninterrupted supply of RE.
- In India, aluminium load centres are located close to mining areas and not hydro generating sites, making bilateral purchase of hydropower expensive.

Aluminium producers can also explore options for entering into power purchase agreements (PPAs) with RE developers for reliable round-the-clock (RTC) power. Other emerging options include captive solar power. Emirates Global Aluminium (EGA) in the UAE was the first to use solar power to produce aluminium commercially, marketed under the brand name "CelestiAL." Solar power is supplied by Dubai Electricity and Water Authority (DEWA), which operates the Mohammed bin Rashid Al Maktoum Solar Park in the desert outside Dubai, and by Emirates Electricity and Water Company (EWEC) from Noor Abu Dhabi at Sweihan. Solar power is transmitted to EGA via the electricity grid and is tracked and traced using the International Renewable Energy Certification system, ensuring that the energy used to produce EGA's CelestiAL solar aluminium has been sourced from the sun. BMW Group was the first customer for CelestiAL solar aluminium, and EGA has also announced supply deals with Tier 1 suppliers of Mercedes-Benz and Nissan. Emirates Global Aluminium is in the process of completely shifting to solar and nuclear energy for aluminium production in the near future.[113]

In the Indian aluminium landscape, Hindalco's RE portfolio includes solar, wind, hydroelectric, and biomass-based projects, with a capacity of 108 MW as of FY2022-23. Additionally, they are in the process of adding another 71 MW of RE to the mix.[114] Their Hirakud unit is planning to install a 1,000 MW floating solar plant in the catchment area of the Hirakud dam.[115] At the same time, India has a massive hydroelectric potential of 145,320 MW, but only 29% has been harnessed so far[116].

112 Integrated Annual Report 2023_ENG.pdf (hydro.com)
113 EGA plans shift to nuclear and solar for aluminium production as demand soars (thenationalnews.com)
114 Hindalco's Annual report 2022-23
115 Hindalco aims to lead in EV Market through Battery Foil Manufacturing - India Whispers
116 India has only developed 29% of its hydroelectric potential (hydroreview.com)

Policy scenario and way forward

The Government of India has implemented several policy measures to promote renewable energy (RE) in the aluminium sector. This includes the waiver of interstate transmission system (ISTS) charges for hydroelectric plants and the release of guidelines for pumped storage plants (PSPs) to simplify clearance processes. Indian aluminium companies have started entering medium- to long-term agreements for procuring round-the-clock (RTC) renewable power to reduce GHG emissions as part of their net-zero strategy.

The adoption of RE sources can be accelerated through various interventions such as:

- Introducing incentives to encourage the adoption of renewable sources of energy to reduce the cost of RE electricity generation.
- Promoting PPAs for the aluminium industry to source RE, such as hydro, solar, and wind power.
- Utilising energy storage systems (ESS) such as pumped storage and battery storage, which can be incentivised to boost adoption due to the high investment costs.

As the aluminium industry continues to prioritise decarbonisation and sustainability, several renewable sources like hydro, solar, and nuclear offer numerous benefits for aluminium smelting, including environmental sustainability, cost competitiveness, reliability, and long-term energy security. These renewable sources are expected to play an increasingly important role in meeting the energy needs and thereby aiding in the reduction of emissions from energy consumption. Achieving reductions in GHG emissions to meet net-zero targets will require aluminium producers to utilise 100% clean power sources for the smelting process. These sources can either be renewable, such as solar, wind, hydro, and nuclear, or through captive power plants retrofitted with Carbon Capture, Utilisation, and Storage (CCUS) technologies.

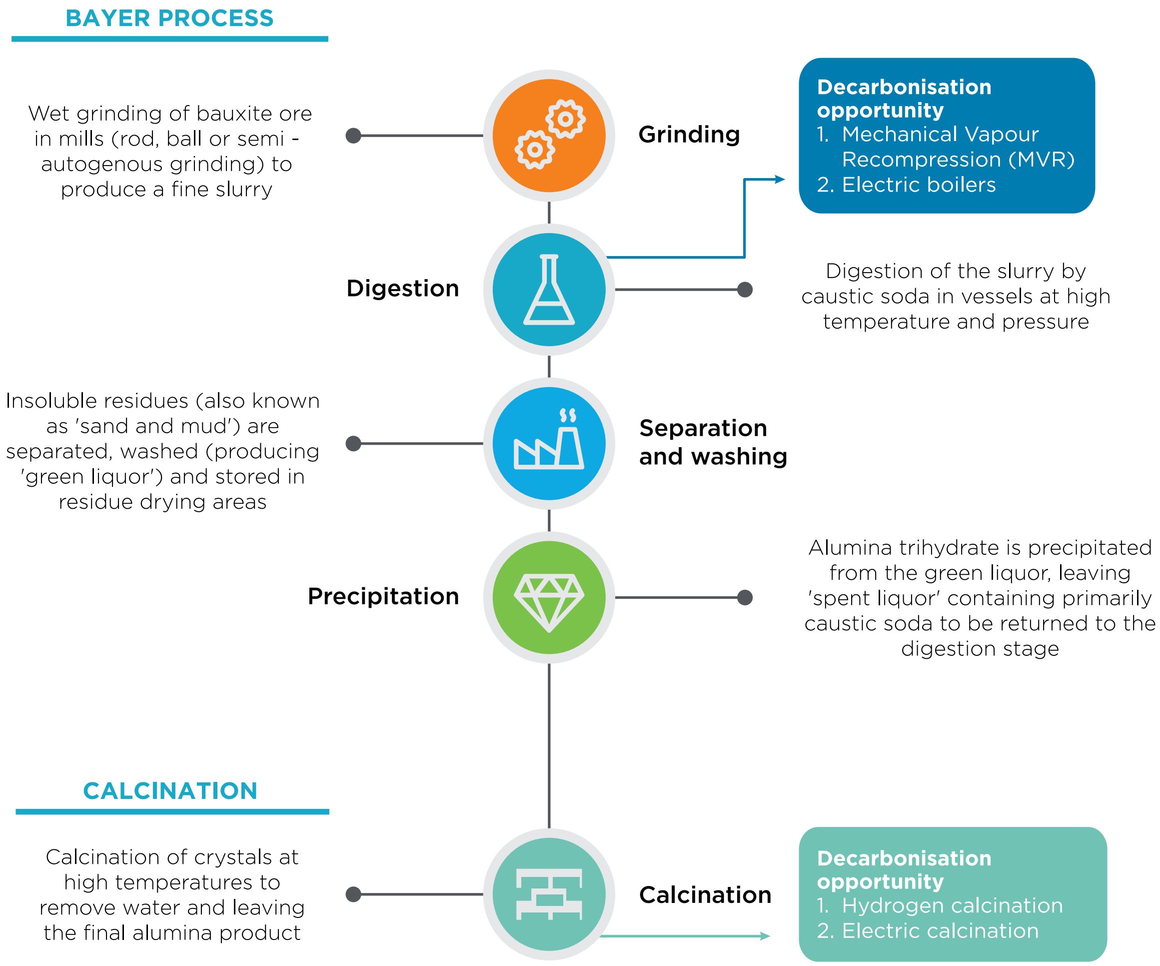
b. Green hydrogen in calcination

Calcination is the last step in the alumina refining process, requiring temperatures exceeding 900°C to remove chemically bound water from the alumina trihydrate crystal that is associated with alumina. This process occurs in alumina calciners that traditionally operate on natural gas and account for approximately 30% of the total GHG emissions from alumina refineries. The energy intensity of alumina production from bauxite is about 7 – 13 GJ per tonne of alumina.

In contrast to bauxite mining and aluminium smelting, the path to reducing emissions in alumina refining is complex. Alumina refining relies on fossil fuel combustion for process heat, lacking readily available low-emission alternatives that are both technically proven and economically viable. Addressing this issue requires focused intervention and substantial transformation within the alumina refining sector to achieve effective emission reductions.

Substituting fossil fuels with green hydrogen during the calcination stage in alumina refining offers tremendous potential for significant emission reduction in this energy-intensive and emission-intensive stage. Furthermore, capturing and compressing steam from the calciner can displace the need for fossil fuels for steam generation in the refinery process. Embracing these innovative clean energy solutions marks a vital stride towards achieving environmentally sustainable aluminium production. Adopting green hydrogen for calcination represents a promising avenue for decarbonising the alumina sector.

Figure 17: Overview of alumina refining process



Source: Arena.gov.au

Challenges

Electrolysers, which are used to produce hydrogen, are considered mature, established technology with a high technology readiness level. However, the use of electrolysers for high-temperature processes in industrial applications, such as in alumina refining, is yet to be commercialised. The barriers to large-scale adoption of hydrogen in the calcination process are as follows:

- Producing green hydrogen requires extensive access to large-scale renewable energy (RE) sources. It also requires significant external infrastructure to store and transport hydrogen.
- Despite its potential, green hydrogen currently faces challenges in terms of cost competitiveness, conversion efficiency, and availability in large volumes.
- Green hydrogen, produced via electrolysis, uses RE sources such as solar or wind power. However, the intermittent nature of renewables poses challenges for the consistent electricity supply required for large-scale production. The limited availability and reliability of RE hinder green hydrogen production, complicating its scalability.

Policy scenario and way forward

India's commitment to building a hydrogen economy is evident from the National Green Hydrogen Mission with an allocation of INR 19,700 Crore in the 2023 budget. At the same time, various state-level initiatives have been taken to support green hydrogen projects in India, such as the Maharashtra Green Hydrogen Policy 2023 and Karnataka's establishment of India's first green hydrogen cluster.

Increasing collaborative efforts between governments and industries is imperative to overcome these barriers, to ensure the scalability and economic viability of green hydrogen. This would ultimately contribute to the larger goal of achieving environmentally sustainable aluminium production.

Case study showcasing use of green hydrogen in calcination by Rio Tinto, UK

Rio Tinto, a UK-based company, has partnered with the Australian Renewable Energy Agency (ARENA) to research the potential for using green hydrogen to replace natural gas in the calcination process of alumina refining at Yarwun. The hydrogen calcination plant at the Yarwun Alumina Refinery is at a relatively advanced stage of development. The project consists of a 2.5 MW onsite electrolyser to supply hydrogen and a retrofit of one of the refinery's calciners to operate with a hydrogen burner. Sumitomo Corporation will own and operate the electrolyser at Rio Tinto's Yarwun site and supply the hydrogen directly to Rio Tinto. The electrolyser will have a production capacity of more than 250 tonnes of hydrogen annually. This approach offers lower capital costs and on-site implementation under a retrofit scenario (excluding hydrogen production). While the benefits of adopting green hydrogen in calcination are evident, overcoming the associated challenges will be essential to unlocking the full potential of hydrogen in advancing sustainable aluminium production.

Case study on Conversion of existing HFO based Firing system to Natural gas-based firing system in Anode Baking Furnace

Aditya Alumina's (Hindalco Unit) conversion of its ABF-1 (Anode Baking Furnace 1) from heavy fuel oil (HFO) to natural gas marks a significant advancement in sustainable industrial practices. As the first aluminium smelter in India to implement this change, Hindalco aims to reduce greenhouse gas emissions from the anode baking process by approximately 30% and completely eliminate harmful sulphur oxides (SOx) emissions. This transition to a cleaner, more efficient fuel source not only enhances operational efficiency but also aligns with global efforts to reduce carbon footprints and improve air quality.

The Smelter Units in Odisha have the opportunity to consider the utilisation of natural gas (blending) in captive power plant boilers to substitute the fossil fuel in the boiler. The presence of a natural gas pipeline passing near these smelter units means that natural gas availability will be improved.

6.2 Energy monitoring and efficiency interventions

Several options are available for monitoring energy consumption and enhancing efficiency. Some of these measures are being implemented by Indian aluminium producers, while others are still in pilot/ testing phases.

a. Copper insert and onsert collector bars

Copper insert technology in collector bars is an effective and economically beneficial option for energy reduction in aluminium smelters. The use of copper inserts in the collector bars significantly reduces horizontal currents, thus improving cell stability and potentially reducing energy consumption. However, using copper inserts increases heat loss through the collector bars, eventually impacting the thermal balance of low amperage cells, which are designed to be heat conservative. Therefore, the use of copper inserts in low amperage cells requires careful evaluation of thermal balance.[117]

Increased research and development to study the effectiveness of the technology and accelerate the adoption of copper inserts and onserts, along with knowledge sharing between peers, is imperative for achieving

117 (PDF) Impact of copper insert on low amperage aluminium reduction cell (researchgate.net)

energy efficiency (EE) via this technology. Several companies are working towards testing and implementing this technology. For example, Aditya Aluminium (part of Hindalco Industries Ltd.) has developed and tested a new design of copper-inserted collector bar (CuCB) along with cell lining in one pot, and it is expected that the Specific Energy Consumption (SEC) of the pot will reduce by approximately 70 kWh/MT of aluminium produced[118].

b. Magnetic compensation loop (MCL) for reducing DC consumption.

Magnetic Compensation Loop (MCL) is used in smelting to allow for stable operation of pots at higher amperage. It helps manage the magnetic fields that can affect the efficiency of the smelting process. The installation of an MCL, along with a booster rectifier and circuit, has been shown to enable operation at even higher amperages, which can lead to reduced DC consumption.

MCL is beneficial for balancing the magnetic field due to the increase in current. This is expected to stabilise the operation of the pots by stabilising the metal movement within the pot. Additionally, MCL would provide extra margin to reduce the voltage, offering potential savings in input electricity. Gami technology-based smelters offer better prospects for the deployment of MCL compared to AP36 technology, which has a robust design with good magnetic balance. MCL deployment offers potential savings in input electricity, and a few Indian companies are also planning to deploy MCL by 2024.

c. Digital Twin

A digital twin in the aluminium industry is a digital representation of an industrial unit like a smelter, which facilitates optimising performance, predicting outcomes, and improving quality by monitoring parameters such as current intensity, bath temperature, pot life, and pot failure prediction. It is utilised for predictive maintenance using artificial intelligence and machine learning. The digital twin of the smelter predicts the current efficiency of individual pots, and predictive maintenance helps improve process performance and reduce the carbon footprint.

Several Indian companies are increasingly implementing this technology. For example, at Hindalco's smelter, a digital twin was developed with the Aditya Birla Science and Technology Company (ABSTC) team for predicting the current efficiency of individual pots. The prediction model was tested and deployed at Mahan to improve process performance and reduce carbon footprint. Additionally, a digital twin with the AWS cloud platform was implemented at the Aditya smelter for real-time monitoring of various process parameters.

Case study showcasing digital twin technology by Hydro Aluminium

Hydro Aluminium, an international company with operations in multiple countries including various locations across the UK, has implemented automated guided vehicles (AGVs) and digital twin technology in the aluminium sector. They are streamlining their operations through digital predictive maintenance at their Sunndal plant in Norway. Apart from focusing on safety and health, Hydro aims to take a leading position in sustainability in the aluminium market.

118 Hindalco annual report 2022-23

Challenges

The Indian aluminium industry faces several challenges in adopting energy-efficient technologies, including a lack of efficient knowledge-sharing platforms, limited awareness, and insufficient incentives for decision-makers in the aluminium industry to implement energy efficiency measures and adopt new technologies. Additionally, the need for significant capital investment (CAPEX) in the case of brownfield projects is another limiting factor in the adoption of such technologies.

Policy scenario and way forward

With the advent of global decarbonisation measures such as the Carbon Border Adjustment Mechanism (CBAM), it is imperative for the Indian government to introduce incentives to encourage the adoption of energy efficiency and decarbonisation technologies, specifically for export-oriented industries such as aluminium. Investment to promote such technologies will ultimately reflect in the expansion and growth of the Indian economy.

6.3 Circular economy and waste management

Aluminium is often referred to as an 'infinite metal' because it is 100% recyclable. Furthermore, it experiences no loss of inherent properties or quality during the recycling process. Aluminium recycling presents both high economic and environmental prospects, as it requires approximately 95% less energy than what is required to produce primary metal and consequently prevents corresponding greenhouse emissions. In the long term, recycled aluminium is expected to play a critical role in meeting aluminium demand.[119 120]

In addition to the recycling of finished products, the aluminium industry offers immense opportunities in circular economy and waste management. The holistic use of major wastes and by-products, such as bauxite residue from the refinery process, spent pot lining material, and dross from the smelter, is vital to achieving a circular economy (excluding fly ash/coal ash as it is not considered in the objective of decarbonisation).

For example, Vedanta Aluminium produces more than half of India's aluminium at 1.97 million metric tonnes, at its smelters in Jharsuguda (Odisha) and BALCO (Chhattisgarh). Approximately 1.5% of the total quantity is lost in the form of aluminium dross, a by-product that contains recoverable aluminium, aluminium nitrides and oxides, spinel, dimagnesium silicate, gupeiite, and sodium titanate. Runaya Refining[121], through a technological tie-up with TAHA International S.A., is not only able to improve aluminium recovery to nearly 90%, but also creates value-added products for other industries. After recovering aluminium, Runaya processes the non-metallic portions of the residual dross to produce briquettes, which are used as slag conditioners in the steel industry. At Vedanta's facility in Jharsuguda, using Runaya's dross technology has not only ensured a significantly higher metal recovery rate but also created energy savings of up to 800,000 GJ and reduced CO_2 emissions by over 260,000 tonnes annually[122].

119 Recycling - The Aluminium Story
120 Copper Insert Collector Bar for Energy Reduction in 360 KA Smelter | Request PDF (researchgate.net)
121 New age resources technology company with focus on sustainability, technology, and resources
122 Vedanta Aluminium awarded for waste to wealth technology

Case study showcasing circular economy & waste management in UK companies

Real Alloy UK Ltd.: Formerly known as Aleris Recycling (Swansea) Ltd. until 2015, Real Alloy UK serves as the UK division of Real Alloy, a worldwide aluminium recycler and re-processor. Real Alloy UK's facilities cater to various industries, including automotive, construction, and packaging. Their Swansea-based headquarters oversee a wrought alloy recycling plant dedicated to converting scrap metal.

Tandom, a UK-based metal recycler, has an initiative for recycled aluminium to help manufacturers reach sustainability targets. Tandom introduced LOCAL – Low Carbon Aluminium, an initiative where the LOCAL logo is stamped on aluminium to show that it has been sourced and recycled in the UK.

Source: Real Alloy - The Real Standard for Recycled aluminium ; aluminium processing - Tandom

a. Bauxite Residue (BR)

Bauxite residue, also known as 'red mud,' is produced during the extraction of alumina from bauxite in the Bayer Process. For every tonne of alumina produced, approximately 1.2 tonnes of bauxite residue is generated.[123]

Due to its high alkalinity, the residue is not allowed to be discharged into the environment and is stored in specially designed containment areas. Recent developments have proven its utilisation in the cement industry. Research is underway in different parts of the world for the holistic use of bauxite residue in the extraction of valuable metals such as iron, alumina, and rare earth elements (REE) for use in iron and other allied industries.

In India, HINDALCO uses 100% of its bauxite residue in the cement industry. As cement production requires other raw materials, logistics play an important role in the viable use of bauxite residue at all locations.

Case study showcasing use of BR in aluminium processing

Hydro Alunorte and Wave Aluminium have collaborated to build a bauxite residue processing plant in Brazil. This project aims to recover commercially valuable materials from bauxite residue. The innovative technology used in this plant, developed and patented by Wave Aluminium, can separate different minerals from bauxite residue and convert them into commercially viable materials.

123 Sustainable Bauxite Residue Management Guidance - International Aluminium Institute (international-aluminium.org)

b. Spent Pot Lining (SPL)

Spent Pot Lining (SPL) is a solid waste generated during the smelting process of primary aluminium. Almost half (40-50%) of the SPL generated is recycled and used in other industrial processes, such as the production of cement, steel, and mineral wool. It can also be treated and deposited in specially designed and closely monitored landfills. The industry is researching ways to identify opportunities to recycle SPL and reduce landfill use.[124]

However, since SPL is a by-product of an industrial process, it has several safety requirements and recommendations for handling, as it contains hazardous materials such as fluorides, cyanides, and polycyclic aromatic hydrocarbons. These pose challenges in its safe handling and disposal, thus increasing transportation costs, storage requirements, and regulatory compliance during transit.

Investing in technology to process SPL to remove cyanide and use it in the cement and refractory industries as a potential material, due to its high carbon and refractory material contents, is crucial to reducing landfill waste. The carbon and refractory parts are separated for use in different industries. Since 2010, Emirates Global Aluminium (EGA), in collaboration with cement companies in the UAE, has been exploring the potential use of SPL in the cement manufacturing process. They also embarked on a study to assess the environmental benefits of adding SPL to the cement manufacturing process.[125]

c. Aluminium recovery from dross and scrap

Similar to SPL, dross is generated by aluminium smelters in equivalent quantities. Additionally, a significant amount of aluminium scrap is generated from both smelters and other secondary industries using aluminium. While white dross contains around 40%-80% aluminium metal, black dross contains approximately 5%-25% aluminium metal[126], The scraps are a potential source of aluminium, with about 99% aluminium content.

Dross is a source of metal (through the remelting process) and refractory material. Scraps are a potential source of secondary aluminium production for various applications in the automotive, construction, and electrical sectors. These are produced by processing scrap with unit operations to match the desired characteristics.

However, dross recycling for use in greenfield projects or retrofitting existing smelters requires high-quality material with consistent composition. Meeting environmental regulations and health standards is also vital. Increased investment in infrastructure and technology is crucial for establishing recycling facilities or modifying existing smelters to accommodate dross recycling.

In India, a centralised dross treatment facility is planned to be set up, aimed at revolutionising waste management practices and bolstering sustainable resource utilisation.

124 Spent pot lining Overview V8 (international-aluminium.org)
125 Spent pot lining Overview V8 (international-aluminium.org)
126 1689940634.69551_Aluminium-Dross-Processing-A-Global-Review-Sample-Copy.pdf (alcircle.com)

Case study showcasing aluminium recovery from dross and scrap by Tandom, a UK metal recycling company

Tandom is a UK metal recycling company that specialises in dross processing. They tailor their process to maximise the value of the dross for the supplier, processing both lower-grade and higher-grade dross in the following ways:

- Lower Grade Dross: Processed through a bespoke dross mill to separate residual aluminium from aluminium oxides. This enhances aluminium recovery in tilt furnaces, allowing all dross grades to be transformed into various end products.
- Higher Grade Dross: Directly processed in a tilt rotary furnace (TRF), which maximises energy efficiency and recovery. TRFs come in different sizes; at Tandom, they employ 13-tonne and 6-tonne capacity TRFs fired with advanced oxygen-gas burners. The TRF's advantage over fixed axle furnaces lies in its lower salt usage, resulting in reduced slag volumes and higher metal yields.

Challenges

At the system level, India lacks an efficient ecosystem for scrap collection, segregation, and processing facilities (such as scrap yards). This is evident from the high share of imported scrap. Furthermore, there is a lack of proper disposal practices and opportunities for better management of the major wastes generated throughout the lifecycle of aluminium.

Policy scenario and way forward

The pursuit of a circular economy within the aluminium industry through enhanced recovery and utilisation of waste and by-products demonstrates a significant step towards sustainability and decarbonisation. The innovative approaches to repurpose bauxite residue (BR) in cement production, coupled with ongoing global research exploring its potential for extracting valuable metals, exemplify a commitment to holistic resource utilisation. Similarly, the processing of spent pot lining (SPL) to remove cyanide and its subsequent application in cement and refractory industries showcase advancements with high readiness levels.

Furthermore, the strategic recovery of aluminium from dross and scrap aligns with circular principles, addressing environmental concerns and fostering secondary aluminium production for diverse applications. The government is framing waste management policies like zero landfill, extended producer responsibility (EPR) schemes, and the public provision of separated aluminium scrap recycling collection systems, which can induce and encourage transfers to the aluminium secondary sector, albeit without any direct financial outlay for governments.[127] EPR, a crucial tool in achieving a circular economy, is a policy approach that shifts responsibility for managing the environmental impact of products throughout their lifecycle from consumers to producers.[128] Such initiatives not only contribute to waste reduction but also create symbiotic relationships with other industries, such as iron, steel, and cement, fostering a more sustainable and interconnected industrial ecosystem in the aluminium sector.

127 Travaux 52 paper (icsoba.org)
128 The Role of EPR in India's Circular Economy Journey (corpzo.com)

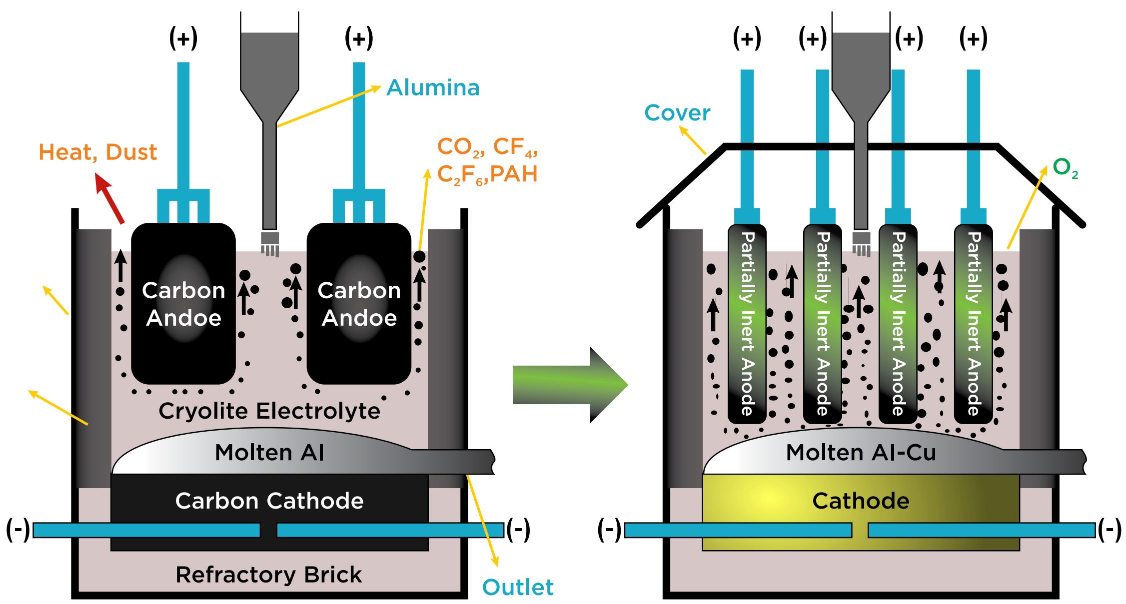
6.4 Emerging technological advancements

Low carbon intensive metal will drive a massive wave of aluminium that's about to hit global markets, as the industry comes under more pressure to decarbonise. This would culminate in the adoption of decarbonisation technologies that have the potential to either curb or capture emissions. This section lists key low carbon emerging technologies in the aluminium industry.

a. Inert Anodes

The smelting process uses carbon anodes that are consumed during electrolysis, which is the most carbon-intensive step in aluminium production. The carbon present in the carbon anode reacts with oxygen, breaking the existing bonds of aluminium and oxygen to form pure aluminium and CO_2 as the byproduct. This process is known as chemical reduction. It is estimated that for producing 1 tonne of aluminium, more than 400 kg of carbon anode is consumed. Figure 18 below illustrates the smelting process of aluminium.

Figure 18: Illustrative of aluminium smelting process[129]



Source: lotusarise.com

Inert anodes are made of materials such as ceramics, metal alloys, and cermet that are non-reactive. These anodes break the bonds of aluminium and oxygen through electrolytic reduction, which results in an additional power requirement and no consumption of inert anodes. Thus, inert anodes exhibit higher theoretical levels of energy consumption than carbon anodes (~9.2 kWh/kg Al). This section assesses inert anode technology for decarbonising the aluminium industry. Inert anodes exhibit physical stability at operational temperatures, resistance to molten electrolytes, and resilience to thermal shock at 960°C. Their electrochemical stability, electronic conductivity, and mechanical robustness make them suitable for deployment, including electrical connections to the bus, start-up procedures, and power interruptions.

129 lotusarise.com

On the direct emissions reduction front, inert anodes have the potential to completely offset direct CO_2 emissions from electrolytic and anode production processes. Inert anodes reduce direct emissions associated with carbon anode consumption by approximately 10–15% of sectoral emissions, assuming the use of renewable energy (RE). In addition to reducing direct CO_2 emissions, inert anodes provide the following advantages:

- Environmental Advantage: Conventional aluminium smelting methods rely on carbon anodes, which are consumed in the Hall-Héroult process, releasing large amounts of carbon dioxide. The continuous manufacturing and frequent changing of carbon anodes disrupt the stability, productivity, and energy efficiency (EE) of the cell. Additionally, undesirable reactions, dissolution, or corrosion with the bath occur at a slow rate, contaminating the produced aluminium.
- Control of Anode Current Density (ACD): Inert anodes enable greater control of the critical ACD, representing the largest voltage drop in the cell. The release of oxygen instead of carbon dioxide provides a significant environmental advantage. The technology has the potential for retrofitting into existing cells with limited modifications, utilising the current alumina and aluminium handling infrastructures.

Incorporating inert anodes into aluminium production processes presents a potential cost-saving opportunity, even though initial capex is expected to be high. Eliminating carbon anodes reduces capital along with operational costs, with estimates suggesting a 25% to 30% decrease for new pot lines adopting inert anode cell technology. Despite proprietary nature and unknown current costs, projections indicate a significant economic impact, with a potential 3% reduction in operating costs and a 2% improvement in return on investment for greenfield installations.[130].

Challenges to Adoption of Inert Anode Technology:

- Supply Chain Constraints: While no identified geographical or regional factors hinder the use of inert anodes, challenges may arise in terms of supply chain constraints, particularly concerning the availability of materials and initial technology-related costs.
- Carbon Neutrality Feasibility: The feasibility of achieving true carbon neutrality also depends on regional accessibility to cost-effective renewable power. The adoption of inert anodes may face challenges related to increased electricity demand and potential indirect emissions if the energy source relies on fossil fuels.
- End-of-Life Requirements: Despite being non-consumable during electrolysis, inert anodes necessitate proper infrastructure for disposal or recycling at the end of their life cycle.

As the Indian aluminium sector strives for a balance between economic viability and environmental responsibility, the incorporation of inert anodes emerges as a transformative catalyst, positioning the industry as a more sustainable and globally competitive player in aluminium production. The integration of inert anode technology is a crucial step for the Indian aluminium industry's journey towards sustainability and environmental responsibility. Aligned with the industry's goals of reducing its carbon footprint, this innovation has the potential to entirely offset direct CO_2 (scope 1) emissions. However, challenges related to material supply chains and initial technology costs persist.

Collaborative efforts and knowledge sharing among industry stakeholders, researchers, and policymakers are essential for overcoming challenges and ensuring a smooth and strategic adoption of inert anode technology. Additionally, the increased adoption of renewable energy sources will also be vital for the adoption of inert anode technology, considering the increased energy demand.

130 Inert anode technology for aluminium smelters | Climate Technology Centre & Network | Tue, 11/08/2016 (ctc-n.org)

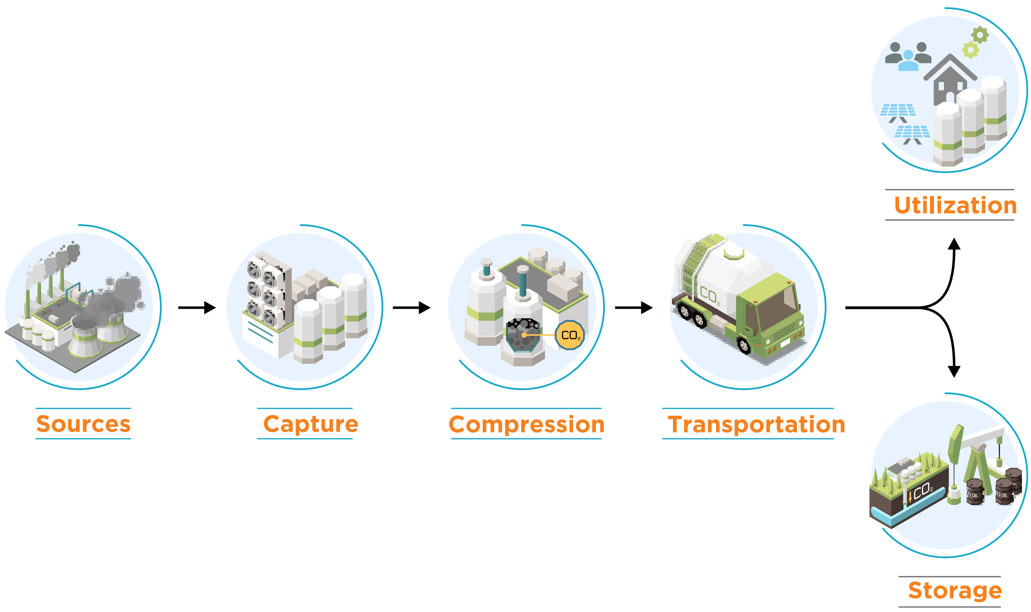
Carbon Capture Utilisation and Storage (CCUS)

CCUS is aimed at reducing CO_2 emissions from industrial processes (such as refining and smelting) and power generation by capturing CO_2, followed by transportation, utilisation as a raw material in other industries, or permanent underground storage (refer to Figure 19). These technologies separate CO_2 from the gaseous stream and produce a CO_2-rich (>90% CO_2) stream that can be readily compressed and transported to the storage or utilisation site.

Traditionally, the technology is known for its applications in the oil and gas sector, especially for enhanced oil recovery (EOR). However, ongoing advancements in CCUS technology are touted to address emissions and securely store carbon, focusing on the decarbonisation of hard-to-abate industries. Once the carbon emissions are captured, they can be repurposed as valuable inputs for creating products in other industries, including cement and tyres, fostering a circular economy approach. This not only mitigates the environmental impact but also enhances resource efficiency, contributing to the sustainable development of the Indian aluminium sector.

The technology is well established for industries with higher concentrations of CO_2 in flue gases, such as thermal power plants and the oil and gas industry. However, the technology is yet to find its niche for aluminium industrial processes such as refining and smelting.

Figure 19: Illustrative of steps under Carbon Capture Utilisation and Storage



Some of the barriers to large-scale adoption of CCUS in the aluminium industry include:

- High Initial Costs: The establishment of CCUS infrastructure involves high initial capital costs and additional operational costs to remove impurities from the flue gases that cannot be fed into the CCUS system.
- Energy Intensity Balancing: The energy-intensive nature of aluminium production requires a careful balance between emissions reduction and maintaining energy efficiency.
- Infrastructure Development: The lack of a well-established infrastructure for carbon capture, transportation, and storage in India necessitates substantial investment and planning.

Adoption of Carbon Capture, Utilisation, and Storage technologies presents a promising avenue for the Indian aluminium industry to address carbon emissions, align with global sustainability goals, and contribute to the development of a more environmentally friendly and resource-efficient sector until the point where the Indian aluminium industry shifts to renewable energy (RE) power in an economic and efficient manner.

The barriers to CCUS can be overcome by incentivising CCUS technology, thereby reducing upfront costs. Furthermore, the formation of industrial clusters with other industries and nearby industrial sites is also vital, enabling resource sharing and creating opportunities for additional revenue streams such as the monetisation of byproducts like carbon stored from CCUS.

The Indian aluminium sector is increasingly recognising the importance of implementing CCUS technologies to address environmental concerns and contribute to sustainable practices. With recent developments and the availability of round-the-clock (RTC) renewable power, industries are increasingly planning to replace coal-based electricity with renewable energy (RE). Since the aluminium industry is very sensitive to power reliability and quality of RTC low-carbon electricity, in the short term, Indian industries are expected to depend on captive thermal power for supplying quality and reliable power. Moreover, there are a limited number of RTC power and hydropower projects in India. Until such circumstances change, CCUS can be a prominent lever to reduce the carbon emissions due to captive thermal power generation.

Case study showcasing adoption of CCUS by a UK aluminium company

Alvance is working in a consortium alongside Trimet, LRF (Rio Tinto's research centre), and the Fives Group to evaluate the most economical way to capture carbon in aluminium smelters. The initiative is examining amine technology to determine the feasibility of capturing flue gases directly versus the need to concentrate the CO_2 for better capture. Alvance is planning to launch a pilot by 2024 with the goal of capturing up to 70% of emissions from the smelting process.

Implementing CCUS can result in a notable reduction in the sector's overall carbon emissions, aligning with global climate goals and positioning the Indian aluminium sector as a responsible player in the transition to a low-carbon economy.

b. Hal-Zero

HalZero is a proprietary technology of Norsk Hydro based on converting alumina to aluminium chloride prior to electrolysis. Chlorine and carbon are kept in a closed loop, thus eliminating emissions of CO_2 and emitting oxygen instead.

The advantages of producing aluminium by electrolysis from its chloride are as follows:[131]

- Approximately 30% lower specific electric power consumption (700°C vs 950-960°C).
- No requirement of high-quality carbon materials (uses graphite non consumable electrodes).
- Reduction in capital investments, operating expenses, product costs, and emissions; utilises less scarce and aggressive chlorides over fluorides.
- The technology aims to decarbonise aluminium smelting, eliminating emissions from both electrolysis and anode baking, resulting in emissions-free aluminium production.

131 HalZero – zero-emission electrolysis from Hydro

At Hydro's research and development laboratory in Porsgrunn, Norway, technologists have successfully tested and modelled the HalZero process. Following these developments, they are currently in the process of validating the technology on a test scale. The company has set the target to produce the first aluminium batch using HalZero by 2025, with the goal of achieving industrial-scale pilot volumes by 2030.

While substantial research is still needed to mature the HalZero process for industrialisation, initial studies and lab tests indicate that an industrial-scale HalZero plant would have power consumption and operating expenditures comparable to current electrolysis technology. The capital expenditure for a full-scale HalZero smelter is anticipated to be in line with the cost of establishing new conventional smelter capacity. HalZero is applicable for both greenfield aluminium plants and brownfield replacements of obsolete potlines, allowing for the re-use of existing smelter infrastructure.

The technology is still in the developmental phase, necessitating increased research, feasibility studies, followed by demonstration projects by aluminium companies and research institutes.

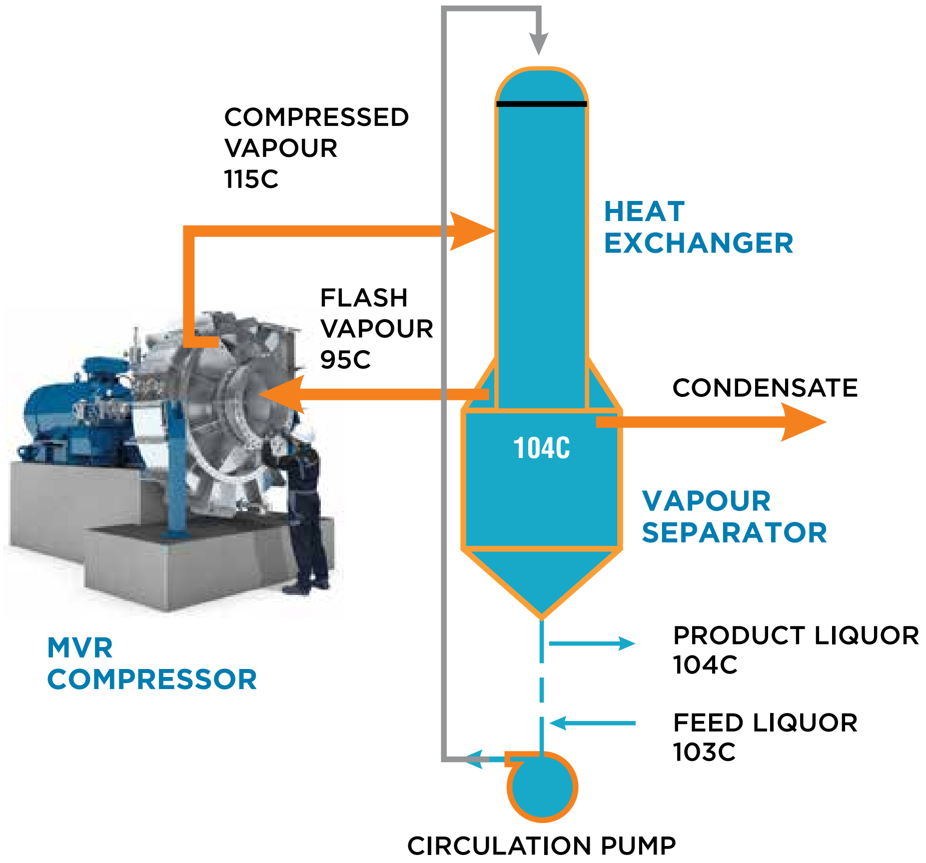
For the Indian aluminium industry, adoption of HalZero technology in aluminium smelting represents a significant opportunity, especially in greenfield projects. By eliminating emissions from both electrolysis and anode baking processes, HalZero offers a pathway towards achieving emission-free smelting technology.

c. Mechanical vapour recompression (MVR) for low carbon alumina refining

Alumina refining serves as an intermediary stage in aluminium production. Bauxite undergoes processing in alumina refineries to yield aluminium oxide, referred to as alumina. Subsequently, alumina is subjected to smelting through the Hall-Héroult process, employing electrolysis to eliminate oxygen and generate pure elemental aluminium. The alumina refining sector presently stands as a notable consumer of fossil fuel energy and, consequently, a significant GHG emitter. Around 70% of GHG emissions from the refineries arise from the utilisation of energy for process heating in the Bayer refining circuit.

In the present Bayer circuit, bauxite is treated with caustic soda at around 140°C to 170°C to extract alumina, referred to as low-temperature digestion. If the temperature requirement is around 250°C, it is referred to as high-temperature digestion. In both processes, Bayer liquor, a recirculating solution of caustic soda, dissolved aluminium, and water, is heated to the required temperature using steam. The hot Bayer liquor extracts the alumina-bearing components from bauxite (digestion), residual solids are removed (through residue separation and washing), and the liquor is then cooled to precipitate alumina tri-hydrate crystals (precipitation). These crystals are collected and calcined to form alumina. The remaining 'spent' liquor is then reheated, and some water is removed by evaporation to increase the caustic concentration again before it is recirculated back to digestion (evaporation).

Figure 20: Illustrative of Mechanical Vapour Recompression (MVR)



Source: MVR Evaporation Feasibility Study by Alcoa

Alumina refineries use evaporation technologies designed around fossil fuels, typically employing a multistage flash evaporation train, which results in high GHG emissions. On the other hand, Mechanical Vapour Recompression (MVR) provides the motive force to drive evaporation, similar to how boiler steam drives conventional evaporation. MVR is best suited to a single-stage evaporator configuration. The design features a single heat exchanger, an integrated vapour separator, no external steam supply, and no cooling water circuit.

In the MVR process, vapour from the vapour separator is compressed by the MVR compressor, causing the vapour's condensing temperature to increase by about 20°C. This provides sufficient thermal driving force to heat the liquor falling through the heat exchanger tubes, causing the liquor to evaporate and create more vapour to be compressed. Condensed vapour from the heat exchanger is removed from the system as condensate, and concentrated product liquor leaves the vapour separator[132].

Figure 20 illustrates the single-stage evaporator configuration of MVR. The technology offers a pathway to significantly decrease GHG emissions from alumina refining by utilising renewable energy (RE) power to drive MVR, displacing energy and steam derived from fossil fuels.

RE-powered MVR is considered the most feasible method for providing low-emission

132 MVR Evaporation Feasibility Study by Alcoa

Bayer process heating due to the following reasons:

- Reduction in overall electricity consumption by 66% compared with conventional evaporator.[133]
- When powered using RE, MVR emits no carbon emissions.
- The technology eliminates the need for boiler feed water and recovers waste vapour, thus reducing water use.

Although MVR is a mature and well-established technology used in distillation plants, dairy processing facilities, and various other sectors, its utilisation in the aluminium industry is still in the initial phases of demonstration. Numerous uncertainties persist, including the expenses associated with retrofitting existing facilities, the cost of establishing new facilities, and the timeline required to attain commercial viability. The technology is expected to be commercialised after 2027. Integration of MVR would result in a substantial increase in electricity needs, necessitating access to affordable round-the-clock renewable electricity. The adoption of MVR technology in aluminium refining units may depend on specific plant configurations and economic considerations.

The adoption of MVR technology presents a promising avenue for the Indian alumina industry to mitigate its greenhouse gas emissions and enhance sustainability. Although MVR is a well-established technology in various sectors, its integration into alumina refineries is in the early stages of development. The technology's significant potential to reduce electricity consumption positions it as a feasible solution for both brownfield and greenfield operations. However, challenges associated with its adoption include:

- Substantial Electricity Requirements: MVR technology requires a significant amount of electricity.
- Uncertainties Around Retrofitting Costs and Commercial Viability: The costs of retrofitting existing facilities and establishing new ones remain uncertain.
- Timeline for Commercial Viability: The technology is expected to become commercially viable after 2027.
- Successful implementation in the alumina industry hinges on overcoming these barriers by adopting RE sources and additional energy efficiency measures. This offers a tangible pathway for India's alumina sector to thrive sustainably in a carbon-constrained world.

133 MVR Evaporation Feasibility Study by Alcoa

6.5 Success stories from the UK:

Alvance British Aluminium

Alvance British Aluminium is a member of the GFG Alliance, a worldwide organisation specialising in heavy industrial processes. They produce aluminium with a comparatively low carbon footprint by utilising hydropower and leveraging the strength of Highland potential, with sustainability as their core value. They have achieved remarkably low carbon intensity compared to their global peers. Furthermore, approximately 88% of their electricity consumed is sourced from hydro energy resources. Their sustainable operations, combined with plans for setting up an aluminium recycling facility, indicate their consistent efforts to achieve their carbon neutral target by 2030 and become leaders in sustainable aluminium production. Some of their noteworthy achievements as of 2022 are:[134] [135]

Headquartered in Lochaber, Scotland

Operates the only smelter unit in the UK

Capacity: 48,000 tonnes per annum

Aim to be carbon neutral by 2030

Around 88% of electricity is sourced from the Lochaber Power & Hydro scheme, pivotal in achieving exceptionally low carbon intensity.

Carbon footprint: **62,422 tCO_2-e**

Energy intensity: **14.2MWh/t aluminium**

Carbon intensity: **1.99 tCO_2-e/t aluminium**

Leader in aluminium recycling

About 86% of all waste produced in 2022 was recycled/ reused.

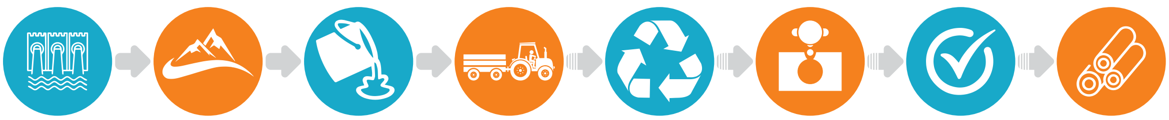
Aluminium Recycling and Billet Casting Facility construction is planned adjacent to the smelter.

Further, increasing capacity from 48KTPA-100KTPA also reducing carbon footprint.

Green energy & molten aluminium from existing smelter will be used in the facility alongside the recycled scrap metal to produce aluminium as depicted below.

About 16% of employees were female

Over 20% decrease in PFC and PM Emission intensity since 2021



134 Home | ALVANCE British Aluminium
135 Annual Sustainability Report 2022 (alvancebritishaluminium.com)

Novelis UK Ltd

Novelis UK Ltd is a subsidiary of Hindalco Industries, the world's largest recycler of aluminium and part of the broader Aditya Birla Group. Established in 1993, Novelis UK Ltd has its headquarters in Warrington, Cheshire, and specialises in recycling aluminium and producing ingots and aluminium sheets.

Sustainability: Novelis uses the GHG Protocol to calculate their Scope 1, Scope 2, and Scope 3 emissions. They have seen a 14% decrease in their absolute emissions since FY16. Novelis has changed how they calculate their carbon footprint to follow the equity share approach outlined in the GHG Protocol.

Novelis' plant in Latchford, UK[136]:

- Novelis Latchford, located in Warrington, UK, is one of Europe's largest aluminium used beverage can recycling plants. Additionally, it holds the distinction of being Europe's largest closed-loop recycling operation for automotive aluminium rolled products, with an annual recycling capacity of up to 195,000 tonnes.
- Novelis has taken a significant step toward sustainability by collaborating with JLR. Together, they established the first closed-loop system in Europe, which includes a dedicated railway service for efficient aluminium delivery between Novelis and JLR's production site in the UK. This innovative approach not only reduces waste but also contributes to a circular economy.
- Novelis benefits from its strategic positioning due to economic integration and geographical proximity between the EU, UK, and Switzerland. Operating across borders, Novelis leverages well-established and efficient supply chains. This interconnectedness allows the company to achieve economies of scale, benefiting value chains throughout Europe.

Mechatherm International[137]

Mechatherm International Ltd. is a leading provider of bespoke cast house equipment to the aluminium industry, specialising in solutions tailored to industry-specific requirements. The major services of Mechatherm International Ltd. are in areas of casting, heat treatment, recycling, and automation. Their solutions help aluminium manufacturers improve production speed, implement process automation, and enhance energy efficiency (EE) and waste energy recovery.

Mechatherm is working with Aston University (UK) to gather information on thermal management processes to create and commercialise a variety of cost-effective solutions that enhance EE through waste heat use. Mechatherm has experience in supplying heat treatment and re-heat furnaces for the aluminium industry internationally, including India.

136 Novelis to Trial Use of Hydrogen in Recycling Furnaces
137 https://www.mechatherm.com/

Key actions of Government of India for decarbonisation of the aluminium industry

The Government of India is in the process of developing the Indian Carbon Market (ICM), where a national framework will be established with the objective of decarbonising the Indian economy by pricing Greenhouse Gas (GHG) emissions through the trading of Carbon Credit Certificates. The Bureau of Energy Efficiency, Ministry of Power, along with the Ministry of Environment, Forest & Climate Change, are developing the Carbon Credit Trading Scheme for this purpose. The ICM is expected to enable the creation of a competitive market that can provide incentives to climate actors to adopt low-cost options by attracting technology and finance towards sustainable projects that generate carbon credits. It can be a vehicle for mobilising a significant portion of the investments required by the Indian economy to transition toward low-carbon pathways.

The ICM will develop methodologies for the estimation of carbon emissions reductions and removals from various registered projects and stipulate the required validation, registration, verification, and issuance processes to operationalise the scheme. The aluminium industry is also one of the prospective participants of the ICM.

6.6 Gender Equality and Social Inclusion (GESI)

As global aluminium companies continue to enhance production and efficiency to meet the growing demand while navigating the energy transition to achieve climate goals, it is essential for companies to address key areas such as Gender Equality and Social Inclusion (GESI) to promote an inclusive society. GESI is an approach intended to eliminate existing barriers in order to increase access, enable decision-making, and enhance participation of marginalised populations. Energy-intensive industrial sectors can draw from this approach to ensure that marginalised populations are both equitably represented in the sector and benefit from the value added by the sector.

Incorporating GESI initiatives has benefits such as value creation, and contributions to innovation and profitability for companies and the sector. A case study on GESI in the global aluminium industry is presented below.

Case study on GESI in the global aluminium industry

Gender equality is a fundamental condition to achieve a just and efficient transition to a low-carbon economy. Successful inclusion of women in the sector means achieving greater diversity and complementarity, as well as expanding the pool of talent to better address the demand for skills.[138]

The aluminium industry has historically had a predominantly male workforce, with disparities in gender representation.[139] In industries such as manufacturing, mining, and power, it has been rare for women to rise to leadership roles. However, companies are now increasingly taking initiatives towards expanding opportunities for women in senior leadership and technical roles and fostering a culture of inclusivity. Ensuring equal rights, respect, and opportunities for women and gender-diverse people is both an ethical imperative and a strategic priority for sustainable development. Globally, several key players in the aluminium industry have focused on increasing female representation, setting remarkable examples for their peers to adopt.

In India, the representation of women in the metal and mining sector has been dismally low historically, with women representing just 7.0% of all workers in the sector between 2010 and 2015 [140]. Further, women comprise a paltry share of top executives at global metals and mining companies, holding just 11.1% of C-suite positions[141] Companies are consistently working towards encouraging women's participation in these sectors. Major aluminium-producing companies in India are also contributing towards women's empowerment by implementing several initiatives for promoting gender diversity and equality in the workforce. Details on the initiatives and outcomes adopted by international as well as Indian companies are provided in the table below:

International companies		
Company	**Initiatives**	**Outcomes & targets**
Rio Tinto	Focusing on representation of women across all levels in their business through initiatives such as recruitment campaigns targeting women and offering fair and equal pay to employees irrespective of gender. [142]	In 2023, company witnessed increase in: • overall women representation from 22.9% to 24.3% • percentage of women in senior leadership roles to 30.1% from 28.3% • percentage of women in operations and general support roles to 17.7% from 16.2%.[143]
Norsk Hydro	Their primary commitment in the diversity strategy has been to promote the sustainable and increasing inclusion of women in operations.	Hydro is committed to promote inclusion of women in the workforce: • As of 2023, females represent 20% of their workforce, and they are consistently working on improving increasing this by means of several initiatives under their Diversity, Inclusion and Belonging strategy. [144] • The global goal of increasing women representation in its teams to 25% by 2025 and, in Brazil, it is working on different fronts to achieve this goal.

138 The Role of Women in the Decarbonization Path – GWNET (globalwomennet.org)
139 Driving Gender Equity in the Aluminium Sector: ASI's Approach | Newsfeed | Aluminium Stewardship Initiative (aluminium-stewardship.org)
140 Women Forge New Paths In The Metals & Mining Industry (themachinemaker.com)
141 Few women at the top in global metals, mining sector | S&P Global Market Intelligence (spglobal.com)
142 Rio Tinto female recruitment drives attract more than 3000 applicants
143 Rio Tinto statement - WGEA Gender pay gap
144 Hydro increases female representation in its work board

International companies		
Company	**Initiatives**	**Outcomes & targets**
Novelis (Subsidiary of Hindalco)	Novelis has announced that their path to a sustainable and circular future goes beyond environmental commitments by setting new targets to reshape a more diverse and inclusive workforce.	Novelis is committed to increasing greater gender representation: • They aim to achieve approximately 30% representation of women in senior leadership positions. • They aim to achieve 15% representation of women in senior technical roles by 2024.[145] Currently, 14.88% of their total employees are women, who also account for 30.51% of employees in management positions (including top, middle, and junior management).[146]
Indian companies		
Company	**Initiatives**	**Outcomes & targets**
Vedanta	• Actively support the female workforce through progressive policies such as spouse hiring programs, year-long childcare leave, and flexible work arrangements. • Implement various initiatives in recent years to cultivate women leaders. Programs like V-Lead and the Diversity Growth Workshop identify high-potential women in middle management and upskill them. • Their "Shree Shakti" initiative in Odisha allows women to participate in night shifts. Additionally, they offer world-class townships with amenities such as schools, healthcare facilities, daycare centres, and recreational facilities, creating a supportive environment for families.	Vedanta, a leading aluminium producer in India, is also at the forefront of implementing GESI: • Currently, women comprise approximately 22% of their workforce, which is remarkable considering the global metals and mining industry, with an average representation of around 12% as of 2022.[147] • The company is on track to achieve 30% female representation in the workforce by the end of FY 2025, five years ahead of its initial target of 2030..

145 Novelis to increase women representation to 30% in senior leadership positions by 2024, ETHRWorld (indiatimes.com)
146 Hindalco: Integrated annual report 2022-23
147 Women in metals, mining make modest gains in leadership roles | S&P Global Commodity Insights (spglobal.com)

Indian companies		
Company	**Initiatives**	**Outcomes & targets**
Hindalco	• Working towards increasing women's representation in the workforce, Hindalco has undertaken various measures to promote inclusivity, including in the hiring process. • Several initiatives, such as introducing a Dual Career Policy, providing daycare facilities, offering flexible working options, empathy building, and the WAH (Women at Hindalco) conclave, are also noteworthy.	Currently, 8.37% of their total employees are women, who also account for 8.62% of employees in management positions (including top, middle, and junior management).[148]
NALCO	• They provide equal opportunities to all employees. • To empower women and increase gender diversity in the workforce, they are actively working to promote female employment by offering equal opportunities in all areas, including pay and benefits, professional advancement, and social security benefits.[149]	In FY 2022-23, female representation in executive and non-executive categories was 5.21% and 6.4%, respectively.

148 Hindalco: Integrated annual report 2022-23
149 NALCO: Sustainable development report 2022


ESG

07

Decarbonisation Pathways for Indian Aluminium Sector

This section summarises the outcomes of the analysis on expected emissions corresponding to the production and energy consumption of Indian aluminium sector in the medium and long term.

These estimates provide the necessary insights and data to inform decision-making, set realistic targets, optimise resource allocation and investments, formulate targeted policies, engage stakeholders, and achieve both economic and environmental benefits through sustainable and efficient sector decarbonisation, contribute to significant reductions in greenhouse gas emissions, helping to mitigate climate change and achieve environmental sustainability.

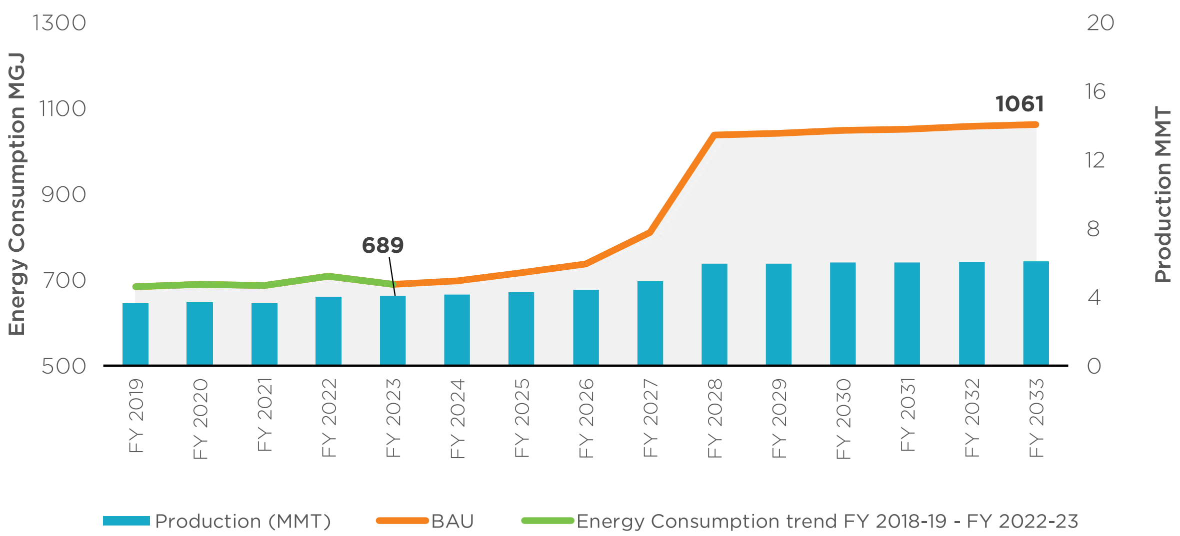
7.1 Emission estimates

Based on the emission estimates in this section, realistic and achievable targets for reducing energy consumption and emissions can be set, helping to guide policy and investment decisions. Estimates can facilitate the development of targeted policies and regulations aimed at promoting energy efficiency, RE adoption, and emission reductions in the sector.

a. Production estimates for the sector in medium (5 years) and long term (10 years)

The total aluminium production capacity of the country in the year 2033 is expected to reach ~6 MMT, considering capacity additions similar to the historical trends of individual companies and limiting the capacity utilisation to 110%. (Refer Figure 21). Capacity expansion for primary aluminium production involves a lengthy process of legal and compliance procedures such as getting consent from respective pollution control boards, submitting details of solid waste management and pollution control measures, hence, the growing demand of aluminium is expected to be met by a combination of primary and secondary (recycled) aluminium in the future. According to sustainability reports, Vedanta has announced a smelter capacity addition of 0.5 MMT by FY 2026-27, While NALCO has plans to set up 0.5 MMT additional smelting capacity which is likely to come up by end of FY 2028-29. Additional ~0.5 - 0.8 MMT is expected to come from other means.

Figure 21: Total Production and Energy Consumption (MGJ) estimates



Note:

1. Energy consumption for BAU is calculated considering the minimum SEC for individual company for the period of 2018-2019 to 2022-2023w

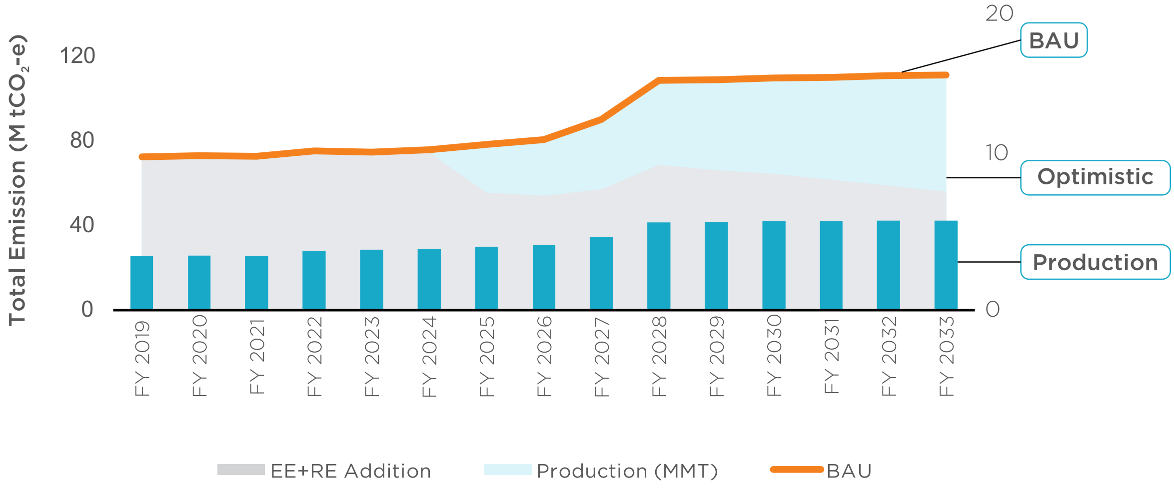
b. Sector energy consumption estimates in medium term and long term

By the year 2032-33, the total energy consumption for aluminium production is expected to increase by over 1.5 times to ~1,060 MGJ, corresponding to the increase in production capacity to ~6 MMT, under the BAU scenario by 2032-33. As illustrated in Figure 21, the projected energy consumption for primary aluminium in the medium to long term indicates that the total energy consumption in 2033 will be 1.5 times higher than that in 2023 under the BAU scenario. This underscores the need for significant additions to power generation capacity for the Indian aluminium industry. Going forward, RE-based power plants should be the preferred choice for power sourcing over conventional captive generation.

c. Sector emission estimates in medium term and long term

When assessing emission estimates, it reveals that while BAU scenarios indicate an upward emission trend (refer figure 22), the integration of EE measures and aggressive adoption of RE (from ~30% in FY 2024-25 to ~50% in FY 2032-33) together significantly contribute to the reduction of emissions. The total emissions reduce to an extent of ~50% of the total emissions in comparison to BAU scenario, reinforcing the role of sustainable practices and regulatory frameworks in achieving the emission reduction trajectory. The total projected emission under different scenarios is presented in the Figure 22.

Figure 22: Total emission ($MtCO_2e$) estimates



Note:

1. Emission for BAU is calculated considering the minimum emission Intensity for individual company for the period of 2018-2019 to 2022-2023.
2. The RPO contribution is factored into the Combined Power Plant (CPP) as per the notification. For coal-based power plants, 1 MWh is considered equivalent to reducing ~0.97 tCO_2-e for calculating emission reductions.
3. Additionally, based on stakeholder discussions, the impact of EE measures is estimated to result in a 1% reduction in energy consumption and emissions over a 10-year period.[150]

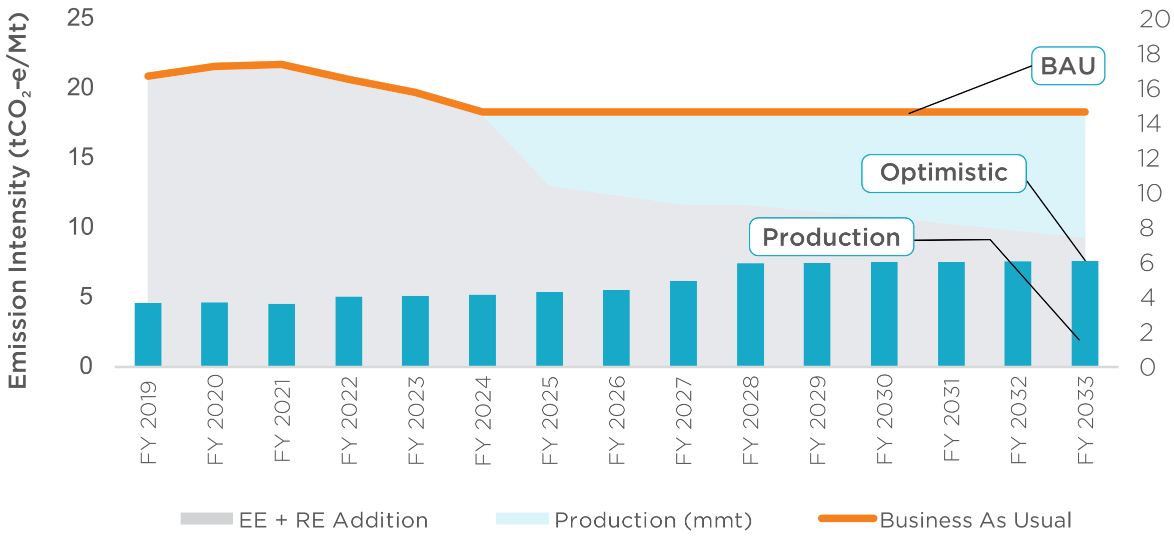
d. Emission intensity in medium term and long term

Emission intensity of Indian aluminium sector in FY 2022-23 was ~18 tCO_2-e /Mt. In the BAU scenario, a consistent emission intensity has been considered across the presented timeline.

The transformative potential emerges with the integration of RE and EE measures, ushering in a noteworthy reduction. Anticipated to reach ~ 9 to 10 tCO_2-e/Mt of aluminium by FY 2032-33, this substantial decrease is attributed to a synergistic blend of embracing RE-based electricity to constitute more than half of the total consumption and implementing overarching EE improvements.

150 Amt für Umweltschutz (cea.nic.in)

Figure 23: Total emission intensity (tCO_2-e/Mt) estimates



It becomes evident that the Indian aluminium sector can reduce its carbon footprint by FY 2032-33 mainly through adoption of RE as energy supply option and leveraging scope of EE improvements by adopting EE measures.

The scenario, particularly under the influence of RE and EE initiatives, reveal a significant reduction in emissions and intensity. These underscore the need for continued efforts from the key stakeholders to align with global environmental goals, showcasing a transformative journey towards an eco-friendlier and resilient future.

The Indian aluminium industry has taken up a target of net-zero by 2050 (NALCO before 2060). As per the current estimate, the sector will be achieving the interim target by reaching the emission intensity to 50% in 10 years' duration. With aggressive RE penetration, adoption of the innovative EE measures, technology intervention and CCUS, the sector is likely to achieve its target.

7.2 Interventions for decarbonisation of Indian aluminium sector

In response to the formidable challenge of decarbonising the aluminium sector, global initiatives have emerged, adopting innovative practices and cutting-edge technologies. These efforts are delineated across three distinct categories, each contributing to the overarching goal of achieving near-zero emissions by 2050. Indian aluminium industry can also draw learnings from these global initiatives to accelerate its progression towards decarbonisation.

Electricity decarbonisation:

Electricity decarbonisation can be a critical pathway for Indian sluminium sector for mitigating emissions involves the decarbonisation of electricity generation, given its substantial contribution to overall emissions. Notably, Germany is strategically utilising RE to address intermittency challenges, employing smelters as virtual batteries. Norway is harnessing wind energy to power its electricity generation, and the UAE is expanding solar projects seamlessly integrated with smelters to enhance overall sustainability.

Direct emissions reduction:

This involves addressing emissions from fuel combustion through electrification, the adoption of green hydrogen, and the utilisation of advance technologies such as inert anodes and CCUS. For instance, Canada is currently testing innovative technologies such as inert anodes, which have the potential to significantly reduce process emissions. In Brazil, there is an exploration of transitioning from heavy fuel oil to liquefied natural gas as a strategy to achieve substantial emissions reductions. Meanwhile, in Europe and Australia, there is a concentrated effort on harnessing hydrogen as a cleaner alternative to traditional fuels.

Recycling and resource efficiency:

Resource efficiency and recycling not only play a pivotal role in reducing the demand for primary aluminium but also have the potential to significantly reduce the emissions in India. Adopting closed-loop recycling systems, the USA, Europe, and Japan aim to collect and reuse manufacturing scrap. Germany is investing in advanced sorting technologies, and Europe's aluminium producers strive for a fully circular economy within a decade, significantly curbing annual emissions.

The role of circular economy and carbon trading to promote energy efficiency and ensure supply chain security in near future is indispensable for Indian aluminium industry. Recycled aluminium is essential to meet future demand of aluminium, and alignment of sustainability goals. While carbon trading scheme is a powerful tool for driving decarbonisation of Indian carbon intensive industries by leveraging market dynamics to incentivise emission reductions, fostering innovation, ensuring transparency, and aligning with the global climate goals. The Government has already initiated the development of the unified carbon market mechanism 'Indian Carbon Market' (ICM) which will mobilise new mitigation opportunities through demand for emission reduction credits by private and public entities. This comprehensive approach, blending technological innovation with strategic initiatives, underscores the industry's commitment to navigating the path towards a sustainable and low-carbon future.

Indicative Cost Benefit Analysis (for illustrative purpose)

CCUS as well as RE adoption are the two critical levers to decarbonise the Indian aluminium sector in the next decade. The aluminium industry can either choose to adopt RE supply options, which has its own set of challenges such as intermittency and variability of generation, proximity of hydro power plants, high cost of battery storage technologies etc. or they can adopt CCUS technology for decarbonising the captive thermal generation.

CCUS

- Based on preliminary analysis the levelised cost of CCUS for each kg of CO_2 is estimated at ~ INR 5.5 (GBP 0.055).
- If aluminium industry targets to reduce existing carbon intensity of ~16-20 kg of CO_2 per kg of aluminium by ~70% i.e., to ~4.7 kg of CO_2/kg, then ~10.9 kg of CO_2 is required to be captured and stored resulting in an additional cost of ~INR 60 per kg of aluminium produced.
- Broadly it is estimated that at carbon credit certificate price at ~INR 834 (~8 GBP) per tonnes of CO_2, a low carbon premium of about INR 38-40 per kg of Al is required to cover the cost of CCUS.
- Sensitivity analysis portrayed that with increase in carbon credit certificate rice and low carbon premium, the payback period reduces significantly.
- Therefore, as emission norms become more stringent in India and carbon market matures, CCUS will emerge as an attractive and viable option.

Transitioning to RE

- It is estimated that with an increased penetration of RE, carbon intensity of a luminium can be reduced to around 9 kg of CO_2/kg by 2030, from current level of 16 - 20 kg of CO_2/kg of Al.
- Based on the power pricing assumptions, it is anticipated that cost of power consumption per kg of aluminium may increase to INR 5-6 per kg of aluminium due to high cost of RTC RE.
- However, the same can be compensated by additional revenue generated though sale of carbon credits.
- Any premium received on account of sale of low carbon aluminium will be additional income for the aluminium industry.

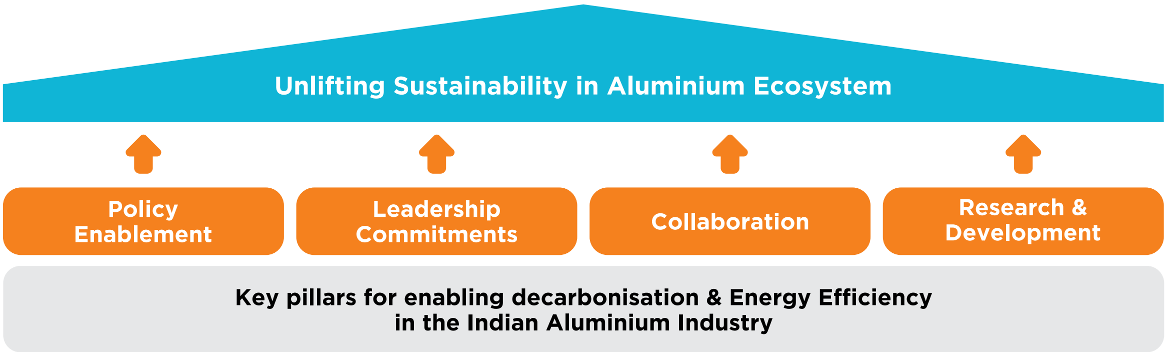

WEEK-2
WEEK-3

08

Conclusion and Way Forward

Considering the assessment provided in earlier sections and based on review of leading international best practices, it is proposed that the following key four pillars need to be strengthened to accelerate decarbonisation of the Indian aluminium sector. The key pillars include policy enablement, leadership commitment, collaboration, and research and development, which are discussed below.

Figure 24: Four key pillars for accelerating decarbonisation of the Indian aluminium sector



1. Policy enablement

Decarbonisation of the aluminium landscape is largely propelled by regulatory and policy initiatives. These initiatives can be in the form of a grant or incentives or enabling policy environment. The government may consider the following initiatives to enable accelerated decarbonisation of Indian aluminium sector:

- Introduce incentives to reduce RE cost and integration of RE sources by promoting balancing sources such as energy storage systems.
- Create PPAs with relevant RE developers to develop and provide firm and dispatchable renewable power to aluminium industry.
- Ease financing for low-carbon technologies and promotion of circularity.
- Create standard certifications for aluminium with lower carbon footprint.
- Change procurement policy to encourage low carbon aluminium in the infrastructure sectors.
- Increase focus on the circular economy and maturing disruptive technologies, to reduce aluminium's environmental footprint and enable a low-carbon product.[151]
- Enforce the Environment Protection Act and Vehicle Scrap Policy and incentivise scrap recovery and collection through principal route.
- Introduce quality standards and guidelines for imported scrap.
- Encourage knowledge sharing, increased transparency in data in form of sustainable development reports and promote standard reporting framework.
- Establishing a domestic carbon market to leverage the benefits of decarbonisation and expedite industry efforts to achieve net-zero.

2. Leadership commitments

A purposeful transformation of any industry necessitates a collective sense of commitment and conviction from the leadership, which is also effectively communicated to all stakeholders to encourage stakeholders to share the same vision, principles, and culture. Leading industries in several sectors including the aluminium sector, have committed to net-zero targets. Thus, it is essential for the leadership to develop a culture of sustainability in the organisation to enable achieving the larger objective.

151 Low-Carbon Aluminum is Supporting Carbon Neutrality and the Circular Economy | Fluor

The suggested interventions to enhance decarbonisation of the aluminium sector include:

- Engaging industry players in the processes of EE and decarbonisation target setting and upcoming planned initiatives to ensure responsible manufacturing and improved compliance.
- Ensuring continuity in collaborative research programmes such as IDEEKSHA platform for wider coverage and knowledge dissemination.
- Developing appropriate capacity building measures to expedite the evolution of low carbon technologies with industry associations and financial institutes.
- Organising periodic cross-industry workshops to discuss, evaluate technology advancements and explore areas of synergies across industry associations.
- Introducing specific career progression measures addressing the needs of women to encourage equal participation of women in the workforce, especially in the middle and upper management roles.

3. Research and development

Focused research and development, by aluminium companies, research institutes and startups as well as knowledge sharing is crucial to study and pilot new technologies for decarbonisation and energy efficiency. Institutes such as Jawaharlal Nehru Aluminium Research Development and Design Centre (JNARDDC) should work closely with BEE and active industry players to develop, demonstrate, and promote indigenous technologies and provide value addition services to both primary and secondary aluminium.

Additional suggested interventions to enhance decarbonisation of the aluminium sector through encouraging research and development may include:

- Collaborative research like Mission possible partnership (MPP) and platforms such as IDEEKSHA platform, is a joint initiative of the BEE, Government of India, and UK Government's FCDO.
- Collaboration on introducing smart technology in India's power sector.
- Leveraging the 2030 Roadmap for India-UK future relations, joint training programmes could be organised to enhance skills related to circular economy practices.
- Collaboration on the development of certifications and standards for aluminium with lower carbon footprint between the Bureau of Indian Standards (BIS) and international institutions (including from the UK) such as the Aluminium Stewardship Initiative (ASI), Standard Norge, British Standards Institution (BSI), UK's National Standards Body (NSB), etc.

4. Collaboration

Collaboration with peers in the aluminium industry as well as strategically with other industries can promote knowledge sharing and create opportunities for combined research and innovations. This will also be beneficial for adopting hub and cluster approach in partnership with industrial sites in the vicinity of the aluminium production units. It will provide all the partners with opportunities to scale, share resources and risks and aggregate and optimise demand.[152]

For example, aluminium companies may partner with other industries and nearby industrial sites to create industrial clusters for sharing of resources. The other opportunities to collaborate and to promote sustainable aluminium business are mentioned below:

- Indian research institutes to work closely with line ministries, and respective pollution control boards to implement extended producer responsibility (EPR).

152 JNARDDC (igi-global.com)

- Indian research institutes to lead and promote demonstration of advanced low carbon technologies.
- Indian research institutes to work closely with relevant agencies to facilitate the introduction of certifications for aluminium with low carbon footprint and secondary aluminium.
- Encourage research and development through collaboration of aluminium companies, industry associations across borders, start-ups, and peers to evaluate and pilot of new decarbonisation technologies and capacity building initiatives.

09

Annexures

9.1 Insights from stakeholder consultations

Table 7: Insights from stakeholder consultation

S. No.	Area of Discussion	Brief of the Discussion
1	**Sources of electricity supply**	
A	Long term PPA's for buying round the clock (RTC) green power	• Several smelting units are engaging with developers for purchasing firm green power. Further, the units have invested in the development of green power evacuation infrastructure.
B	Captive solar	• Despite the limited space availability, units are considering installing solar rooftop. Moreover, some units are assessing the feasibility to utilise their closed or abandoned mines to install floating solar plants.
2	**Energy efficiency technological interventions**	
A	Co-firing LNG in one boiler and two furnaces	• Some units have converted the boilers to use 50% liquified natural gas (LNG) for co-firing along with coal. • The units are dependent on gas transmission infrastructure which will be eventually supplying LNG for co-firing of boilers and furnaces.
B	Copper insert & onsert collector bars	• Adoption of insert and onsert collector bars in the smelting pots have been found economically beneficial. • Onsert bars are still under trial operations.
C	Magnetic compensation loop (MCL) for reducing DC consumption	• MCL is beneficial for balancing magnetic field due to increase in current. This is expected to stabilise the operation of the pots by stabilising the metal movement in the pot. MCL would also provide additional margin to reduce the voltage. • MCL deployment offers potential savings of 150 kWh/ Tonne of Al in input electricity. • Gami technology-based smelters offer better prospects for deployment of MCL as compared to AP36 technology that has a robust design with good magnetic balance.
D	Digital Twin	• Several smelter units are developing or already using 'Digital Twin software' for real time monitoring of various process parameters. The technology is utilised for predictive maintenance using artificial intelligence (AI) and machine learning (ML).
3	**Emerging technological advancements**	
A	Inert Anodes	• Installation of inert anodes will decrease scope 1 (direct) emissions but at the same time inert anodes are expected to increase the energy consumption by as much as 20%. • Renewable energy and recycling will be the crucial along with Inert anodes adoption. • Companies are following the developments in the inert anode technology, and some have plans to adopt the same after commercialisation.

S. No.	Area of Discussion	Brief of the Discussion
B	Carbon capture, utlisation, and storage (CCUS)	• Commercially available CCUS technologies in India (e.g., Carbon Clean's CCUS technology) require additional expenses towards preparation of the exhaust to feed in (SOx and NOx should not be present in the flue gases). However, it can be utilised to reduce scope 1 emissions from the captive power plants without changing the source of generation. • Units are evaluating the economic viability of the technology. • Also, no established industries are available to utilise the captured carbon from the technology. • There is support required from international players in terms of knowledge sharing and capacity building on CCUS.
4	**Challenges faced in implementing energy management and decarbonisation technologies**	
A	Challenges in technology adoption	• The smelting technology differs from unit to unit. Some units operate on new smelting technologies such as AP36 while some operate on older technologies such as Gami. Thus, the decarbonisation technology advancements or upgradations may require significant retrofitting. • Though, coal-based captive power plant supplies reliable power on the other hand renewable energy (except hydro power) supply is not tested in terms power supply reliability for smelting units. • Less scope of captive solar adoption because of the space constraints. • Lack of clear guidelines on Green and low carbon aluminium. • The aluminium production requires stable & reliable power supply. • Additionally, high cross subsidy surcharge (CSS) levied on renewables renders purchasing of RE power expensive.
5	Recycling and Waste Management	• Currently, India lacks an aluminium recycling ecosystem. • ~4-5% of aluminium is extracted from dross (a byproduct of the aluminium smelting process) and while ~ 20-30% of dross produced is sold, the rest is stored in warehouses. • Considering the hazardous nature of dross, its inter-state transfer is not feasible due to policy constraints. • Policy interventions are required to facilitate utilisation of spent pot lining (SPL) in the cement industry. • There is a need to define green aluminium, unless the green aluminium is defined at national level, customers will likely not be paying premium price.

S. No.	Area of Discussion	Brief of the Discussion
		• Companies are consistently working towards reducing their carbon emissions. For example: Vedanta is producing two categories of green aluminium: o Restora (Low Carbon aluminium) – it is produced using renewable energy sources with carbon emission intensity of less than 4 tonnes of CO_2e/tonne of aluminium produced. o Ultra Restora (Ultra-low Carbon aluminium) – it is produced using aluminium recovered from dross, a byproduct of aluminium smelting, in partnership with Runaya Refining.
6	**CBAM and Carbon Markets**	• As most of Indian aluminium industries use captive thermal power plants to power smelter units. Thus, CBAM is likely to majorly impact the economic prospects of the Indian aluminium industry. At the same time, CBAM will eventually accelerate the progress towards decarbonisation. • The process adopted for reporting carbon data in India is more stringent and extensive than the Carbon Border Adjustment Mechanism (CBAM). For e.g., Emission reporting under CBAM does not include the emissions from anode baking process and is specific to product that is exported.
7	**GESI**	Companies are taking various measures to ensure equal participation of females. For example: • Women at Hindalco (WAH) is an initiative undertaken by Hindalco for increasing the participation of women employees. Number of women employees have grown from 5% to 9%. • Initiatives like V-Lead and Dsssiversity Growth at Vedanta, aim to identify high-potential women in middle management and provide them with skills and opportunities for joining decision making bodies. Vedanta has target to achieve 30% gender diversity ratio by 2030.
8	**Policy Support**	It was highlighted that policy support in the following areas will accelerate decarbonisation and energy efficiency in the Indian aluminium industry: • Governments should support the aluminium sector with economical access to firm renewable power, aiding companies in their transition away from fossil fuels. • Policymakers should create a conducive environment for Carbon Capture, Utilisation, and Storage (CCUS) projects, addressing challenges related to the usage and storage of captured carbon emissions. • Support for developing a robust aluminium recycling ecosystem in India by developing mechanisms for aluminium recovery along with incentives to promote recycling business.

S. No.	Area of Discussion	Brief of the Discussion
		• Appropriate financial support/ incentives to encourage adoption of new and advanced technologies as retrofitting such technologies involves additional expenses. • Government can play a key role in engaging with active industry players to promote knowledge sharing. • Removing Inter-State Transmission System charges can encourage the use and transmission of renewable power across regions, facilitating the decarbonisation efforts of aluminium companies. • Support to ensure the availability and sustainable use of biomass, supporting aluminium companies in reducing emissions in their captive power plants. • Investment support in research and development initiatives at a national level to accelerate the deployment of innovative technologies that contribute to the decarbonisation of the aluminium industry. • Support in presenting the case of the Indian aluminium industry to the EU commission for an extension of the deadline for the end of free allowances from 2034 to 2040, taking into account that India announced its target to achieve net-zero by 2070 and the EU's announced its target to achieve net-zero by 2050 —15 years later than the industrial net-zero timeline proposed in CBAM. This should include recommendation to extend support to their import partners in implementing low-carbon technologies. • Recommending that the relevant ministries establish taxonomy for "Green Aluminium" and "Low Carbon Aluminium".

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This report has been prepared by under the UK-India bilateral Technical Assistance programme – "Accelerating Smart Power and Renewable Energy (ASPIRE)", which is being implemented by Foreign Commonwealth and Development Office (FCDO), Government of UK in association with the Ministry of Power and Ministry of New and Renewable Energy, Government of India. KPMG and Idam infrastructure advisory private limited are the implementing partners of ASPIRE programme.