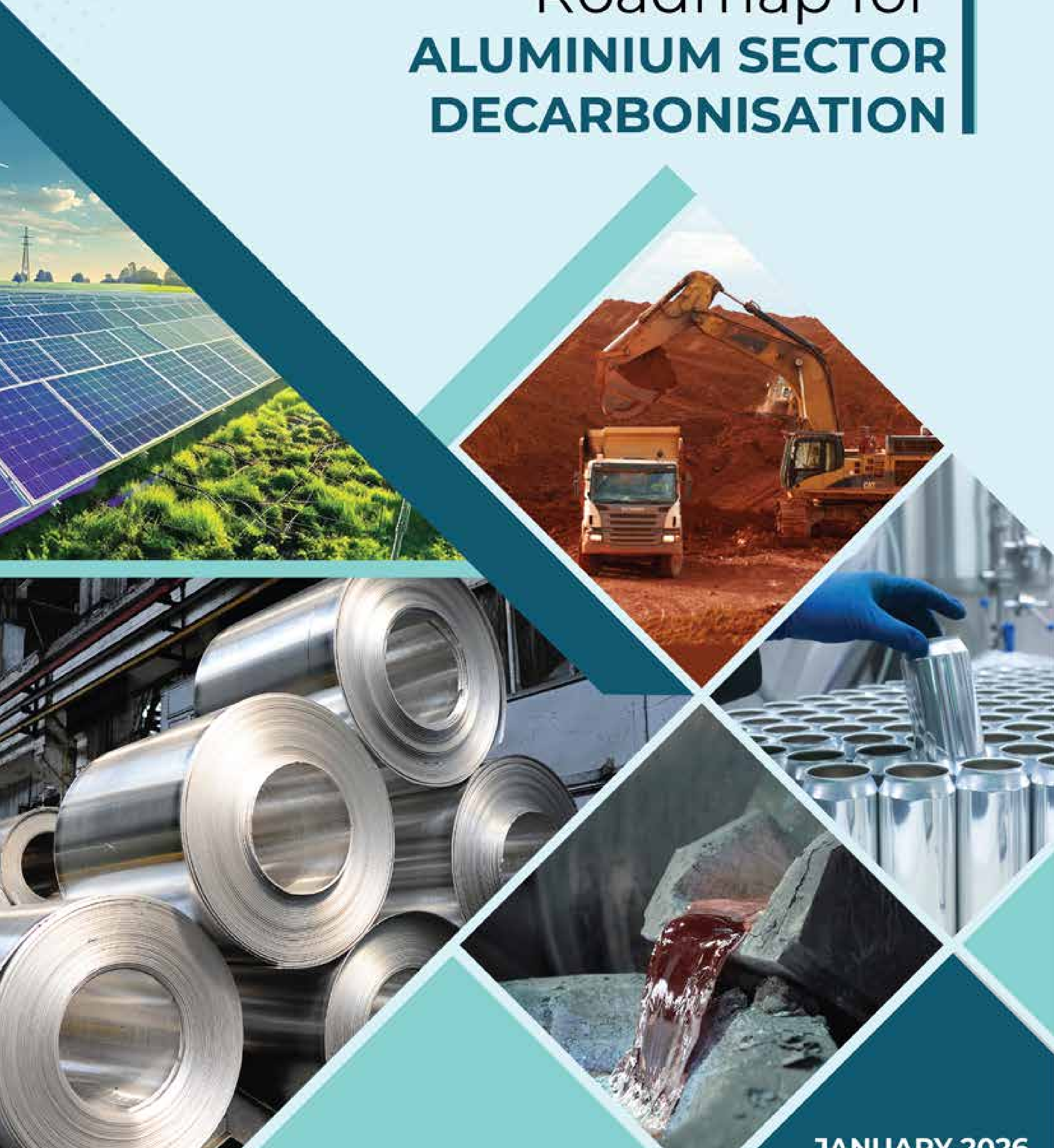
NITI Aayog

Roadmap for
ALUMINIUM SECTOR DECARBONISATION



JANUARY 2026

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सत्यमेव जयते

NITI Aayog

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Authors and Contributions

Leadership

The team is grateful for the kind mentorship of:
Shri Ishtiyaque Ahmed, Programme Director (Industry & MSME), NITI Aayog
Dr. Anshu Bharadwaj, Programme Director (Green Transition & Climate), NITI Aayog
Shri Rajnath Ram, Adviser (Energy), NITI Aayog
Shri Jawahar Lal, General Manager (Energy), NITI Aayog

Research and Writing Team

Shri Ravi Kumar, Consultant, NITI Aayog
Ms. Anupama Kumari, Consultant, NITI Aayog (Deputation from Vasudha Foundation)
Shri Chandrabhal Chakraborty, Young Professional, NITI Aayog
Shri Vishal Kumar, Young Professional, NITI Aayog
Ms. Jyoti Sharma, Senior Program Associate, WRI India
Shri NGR Kartheek, Senior Program Manager, WRI India
Shri Abhishek Bhardwaj, Senior Program Associate, WRI India
Shri Ankit Pandey (former), Senior Program Associate, WRI India

Peer reviewers

Shri Manoj Kumar Upadhyay, Deputy Adviser, NITI Aayog
Shri R Saravanabhavan, Deputy Adviser, NITI Aayog
Shri Deepak Krishnan, Deputy Director, WRI India
Ms. Shivani Shah, Senior Program Communications Manager, WRI India
Shri Ashim Roy, Lead - Energy Finance, WRI India
Ms. Gowthami T S, Program Manager, WRI India
Ms. Ankita Gangotra (former), Senior Manager, WRI US
Shri Shravan Kr. Pushkar, Consultant, NITI Aayog
Shri Saksham Agarwal, YP, NITI Aayog
Shri Anurag Pandey, YP, NITI Aayog

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Shri Ghanshyam Prasad, Chairperson, Central Electricity Authority
Dr. Anupam Agnihotri, Director, JNARDDC - Nagpur
Shri R.K. Mittal, Director, Central Electricity Authority
Shri Sachin Khasabha Bhise, Director, Central Electricity Authority
Shri Vivek Kumar Sharma, Director, Ministry of Mines
Shri Goutam Ghosh, Chief Engineer, Central Electricity Authority
Shri Vijay Meghani, Chief Engineer, Central Electricity Authority
Shri Manoj Kumar, Dy. Director, Central Electricity Authority
Shri Anshuman Swain, Dy. Director, Central Electricity Authority
Shri Sunil Kisan Khandare, Director, Bureau of Energy Efficiency
Shri Ravi Prajapati, Joint Director, Bureau of Energy Efficiency
Shri Jagadeesan V, Sector Expert, Bureau of Energy Efficiency
Shri Shrinath Chauhan, Under Secretary, Ministry of Mines
Dr. R. N. Chouhan, Senior Principal Scientist, JNARDDC - Nagpur
Shri Biju K, GM, NALCO
Shri Subrata Mohanty, GM, NALCO
Shri Anuj Kumar Panda, GM, NALCO
Shri Abhishek Kumar, Manager, Aditya Birla Group
Shri Anil Mathew, President, HINDALCO
Shri Debasish Ghosh, Vice-President, HINDALCO
Shri Rahul K, Assistant Manager, HINDALCO
Ms. Sumita Singh, Corporate & Policy Affairs, HINDALCO
Ms. Prachi Priya, AVP, Policy & ESG, HINDALCO
Shri Naveen Pant, Branch Head (GM), Jindal Aluminium
Dr. Amit Kumar Tyagi, Head & AVP, Vedanta
Shri Mitesh Pandya, Head, Vedanta

Preface

India's pursuit of sustainable and inclusive growth demands a delicate balance between economic advancement and environmental responsibility. Among the key sectors driving this progress, the aluminium industry is a vital enabler of the nation's economic development and energy transition. India is a major primary aluminium producer, accounting for 6% of the global aluminium production. Production is expected to rise from 4 MT in 2023 to 37 MT in 2070. However, this expansion will face several challenges, as the sector is projected to increase GHG emissions from 83 million tonnes of CO_2 equivalent ($MTCO_2e$) to 376 $MTCO_2e$ annually in 2070, under the Business-As-Usual scenario.

This challenge of meeting apparently contradictory goals of growing demand while addressing environmental concerns underscores the need for a strategy that aligns industrial growth with climate action. Recognising this imperative, the report, 'Road Map for Aluminium Sector Decarbonisation', provides a thorough roadmap to guide the sector toward a sustainable future. It outlines an incremental, long-term approach to significantly reduce emissions while ensuring the sector's continued contribution to India's economic progress.

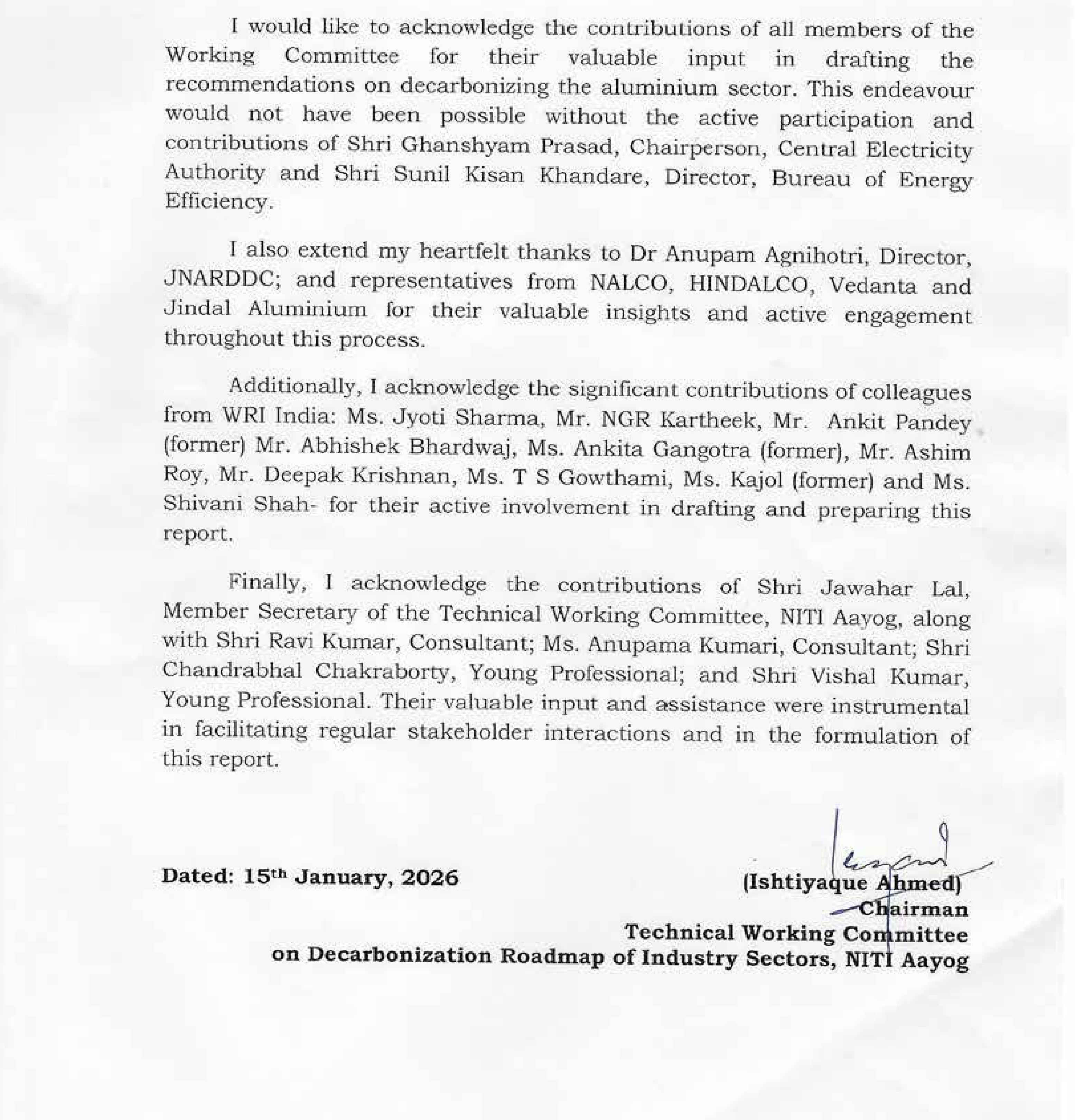
At the heart of this roadmap is the decarbonisation of power supply to the aluminium sector, as it accounts for most of the emissions in the sector. To decarbonise the associated emissions, three transformative solutions have been prioritised: expansion of renewable energy, direct supply of nuclear energy, and carbon capture, utilisation, & storage (CCUS) technologies for captive coal plants. This combination of technological developments, market-driven schemes, and policy interventions offers a practical, ambitious, and cost-effective pathway to decarbonisation.

By 2030, the proposed measures have the potential to deliver a measurable short-term impact, including significant emission reductions of about 10%, expansion of renewable power capacity, creation of green jobs, and attracting investments. These outcomes make it clear that decarbonisation is not merely an environmental necessity but also a transformative economic opportunity, enabling the emission-intensive aluminium sector to thrive in a low-carbon economy.

The roadmap is not just a strategy for emissions abatement; it is a vision for a thriving and sustainable aluminium industry in a low-carbon economy. It equips the sector to harbour innovation, lower costs, and enhance its global competitiveness in an increasingly sustainability-conscious market. This report marks the first step in positioning India's aluminium industry as a model for sustainable industrial development.

This report will guide and inform policymakers, industry leaders, and stakeholders, encouraging collaborative efforts to build a resilient and sustainable economy for the nation.

Foreword & Acknowledgement



I would like to acknowledge the contributions of all members of the Working Committee for their valuable input in drafting the recommendations on decarbonizing the aluminium sector. This endeavour would not have been possible without the active participation and contributions of Shri Ghanshyam Prasad, Chairperson, Central Electricity Authority and Shri Sunil Kisan Khandare, Director, Bureau of Energy Efficiency.

I also extend my heartfelt thanks to Dr Anupam Agnihotri, Director, JNARDDC; and representatives from NALCO, HINDALCO, Vedanta and Jindal Aluminium for their valuable insights and active engagement throughout this process.

Additionally, I acknowledge the significant contributions of colleagues from WRI India: Ms. Jyoti Sharma, Mr. NGR Kartheek, Mr. Ankit Pandey (former) Mr. Abhishek Bhardwaj, Ms. Ankita Gangotra (former), Mr. Ashim Roy, Mr. Deepak Krishnan, Ms. T S Gowthami, Ms. Kajol (former) and Ms. Shivani Shah- for their active involvement in drafting and preparing this report.

Finally, I acknowledge the contributions of Shri Jawahar Lal, Member Secretary of the Technical Working Committee, NITI Aayog, along with Shri Ravi Kumar, Consultant; Ms. Anupama Kumari, Consultant; Shri Chandrabhal Chakraborty, Young Professional; and Shri Vishal Kumar, Young Professional. Their valuable input and assistance were instrumental in facilitating regular stakeholder interactions and in the formulation of this report.

Dated: 15th January, 2026

(Ishtiyaque Ahmed)
Chairman
Technical Working Committee
on Decarbonization Roadmap of Industry Sectors, NITI Aayog

सुमन के. बेरी
उपाध्यक्ष
SUMAN K. BERY
VICE CHAIRMAN

Phones : 23096677, 23096688
Fax : 23096699
E-mail : vch-niti@gov.in

सत्यमेव जयते

भारत सरकार
नीति आयोग, संसद मार्ग
नई दिल्ली - 110 001
Government of India
NATIONAL INSTITUTION FOR TRANSFORMING INDIA
NITI Aayog, Parliament Street,
New Delhi - 110 001

Message

The aluminium industry stands as a cornerstone of the modern economy. Owing to its lightness, strength and recyclability, aluminium is indispensable to strategic sectors such as aerospace, construction, power transmission, renewable energy equipment and electric mobility sectors that lie at the heart of global efforts to address climate change. At the same time, aluminium production remains among the most energy- and emissions-intensive industrial processes, rendering its decarbonisation both urgent and complex.

At present, the emissions intensity of India's aluminium industry is estimated at around 20–21 tCO_2 per tonne of aluminium, significantly higher than the global average of approximately 15 tCO_2 per tonne. This is largely attributable to the fact that over 75 per cent of process emissions arise from electricity consumption, which continues to be predominantly coal-based.

Notwithstanding this challenge, India has emerged as one of the world's leading aluminium producers, accounting for nearly six per cent of global primary aluminium output. Moreover, domestic demand for aluminium is expected to grow at a pace considerably faster than the global average, underscoring both the scale of opportunity and the responsibility before us.

In this context, NITI Aayog constituted a Technical Working Committee to develop a comprehensive Decarbonisation Roadmap for the aluminium sector. This report, **"Roadmap for Aluminium Sector Decarbonisation"**, is the outcome of extensive consultations with industry, academia and other key stakeholders. It sets out a clear pathway towards achieving net-zero emissions, while offering practical recommendations for addressing the challenges inherent in hard-to-abate sectors. The report also identifies the policy reforms, institutional frameworks and critical enablers required to align industrial competitiveness with the imperatives of a climate-neutral economy.

I am confident that this document will serve as a credible and actionable guide for India's transition towards 'green' aluminium, supporting the sector in contributing meaningfully to our national commitment of achieving net-zero emissions by 2070.

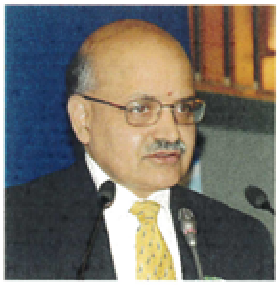
(Suman K Bery)

Place- New Delhi
Dated- 20/01/2026

बी. वी. आर. सुब्रह्मण्यम
B.V.R. Subrahmanyam
मुख्य कार्यकारी अधिकारी
Chief Executive Officer

सत्यमेव जयते

भारत सरकार
नीति आयोग, संसद मार्ग
नई दिल्ली - 110 001
Government of India
National Institution for Transforming India
NITI Aayog, Parliament Street,
New Delhi - 110 001
Tel. : 23096576, 23096574
E-mail : ceo-niti@gov.in



MESSAGE

India's aluminium sector is one of the pillars of our nation's economic and industrial development. Currently, India produces about 4 MT of primary aluminium, ranking it as the world's second-largest aluminium producer. Aluminium is used in various end-use sectors, including packaging, utensils, transportation, building & construction, electrical components, machinery & equipment, consumer durables, battery storage systems, and others.

As India targets $ 30 trillion economy by 2047, the aluminium output is expected to increase from 4 MT in 2023 to 14 MT 2047. Further it is expected to increase to 37 MT by 2070. Therefore, the aluminium industry will play a pivotal role in achieving the Viksit Bharat goals.

However, aluminium is also a greenhouse gas (GHG) emitting sector. Considering our national commitment to achieving Net Zero by 2070, we need a strategy to progressively decarbonise aluminium production. Therefore, NITI Aayog has worked to formulate a decarbonization roadmap for the aluminium sector in line with the country's Net Zero pledge.

This report, **Roadmap for Aluminium Sector Decarbonisation,** involved extensive research, consultations, and detailed analysis of the aluminium industry. More than 75% of GHG emissions from aluminium manufacturing come from electricity consumption. To address this, the roadmap adopts a phased transition strategy. It prioritizes Renewable Energy-Round the Clock power in the short term. Nuclear energy, in particular, SMRs are an important option for medium to long term decarbonisation of aluminium production. Further Carbon Capture Utilization and Storage CCUS may be necessary to tackle residual emissions from the sector in the long run. The report also discusses options to reduce emissions from non-electricity sources.

I commend the collaborative efforts of research institutions, industry stakeholders, government bodies and the NITI Team in shaping this forward-thinking framework. I thank Shri Ishtiyaque Ahmed, Programme Director (Industry), who chaired the working group, and appreciate the support provided by the Green Transition Energy & Climate Change division under Dr. Anshu Bharadwaj, Programme Director, and all working group members. I also thank our knowledge partners, World Resources Institution (WRI) for their excellent efforts.

15/1

Dated: 15th January, 2026

[B.V.R. Subrahmanyam]

WRI INDIA

1st Floor, Godrej & Boyce Premises, Gasworks Lane, Lalbaug, Parel, Mumbai 400012, India. (PH) +91 22 24713591

Message, CEO, WRI India

India’s net-zero by 2070 is a climate imperative and an opportunity for India to lead in low-carbon industrial growth. Aluminium, one of the most energy-intensive and economically relevant industries, holds great significance in this transition. In 2023, production of aluminium accounted for about 2.8 % of India's total GHG emissions. A majority of these emissions are from coal-based captive power consumed in the smelting stage. With evolving markets and increasing demand for greener materials, the urgency from aluminium manufacturers is greater, as their customer base moves toward demanding low-carbon alternatives across the automotive, packaging, and construction sectors.

India's domestic demand for aluminium is projected to increase sharply from 4 million tonnes in 2023 to over 37 million tonnes by 2070, almost three times the projected global growth rate. The surge will be driven by rapid urbanisation, rising per capita consumption, and the growth of clean energy and electric vehicle applications. A consequence is that not only will India play a critical role in shaping domestic consumption but also impact global supply chains and decarbonisation strategies in the aluminium industry. If India's aluminium industry is to remain competitive, it needs to switch decisively to cleaner energy inputs while continuing to grow and meet the rising domestic demand.

This roadmap presents a clear and technically sound strategy for decarbonising the aluminium sector. It identifies three high-impact solutions that together offer a phased, feasible decarbonisation strategy: (1) immediate adoption of RE-RTC, (2) captive nuclear power in the medium term, and (3) CCUS for coal-based power in the long term. These three solutions have emerged from detailed cost and impact assessments and represent a consensus among stakeholders on what is feasible in the Indian context. Implementation entails significant investment and regulatory support. The benefits are quite substantial. Decarbonisation of the aluminium sector can drive energy cost savings over time, unlock access to global green markets, and future-proof the sector against climate-related trade and geopolitical risks.

This roadmap presents a clear strategy for strengthening India's position in the aluminium industry. It draws from deep analysis, stakeholder consensus, and strong alignment with national priorities. With rising demand, expanding global relevance, and a clear roadmap in place, the decarbonisation of India's aluminium sector will be defined by the actions we take today. This roadmap is a call to action for industry, government, and partners to begin that journey now.

(Madhav Pai)
CEO, WRI India

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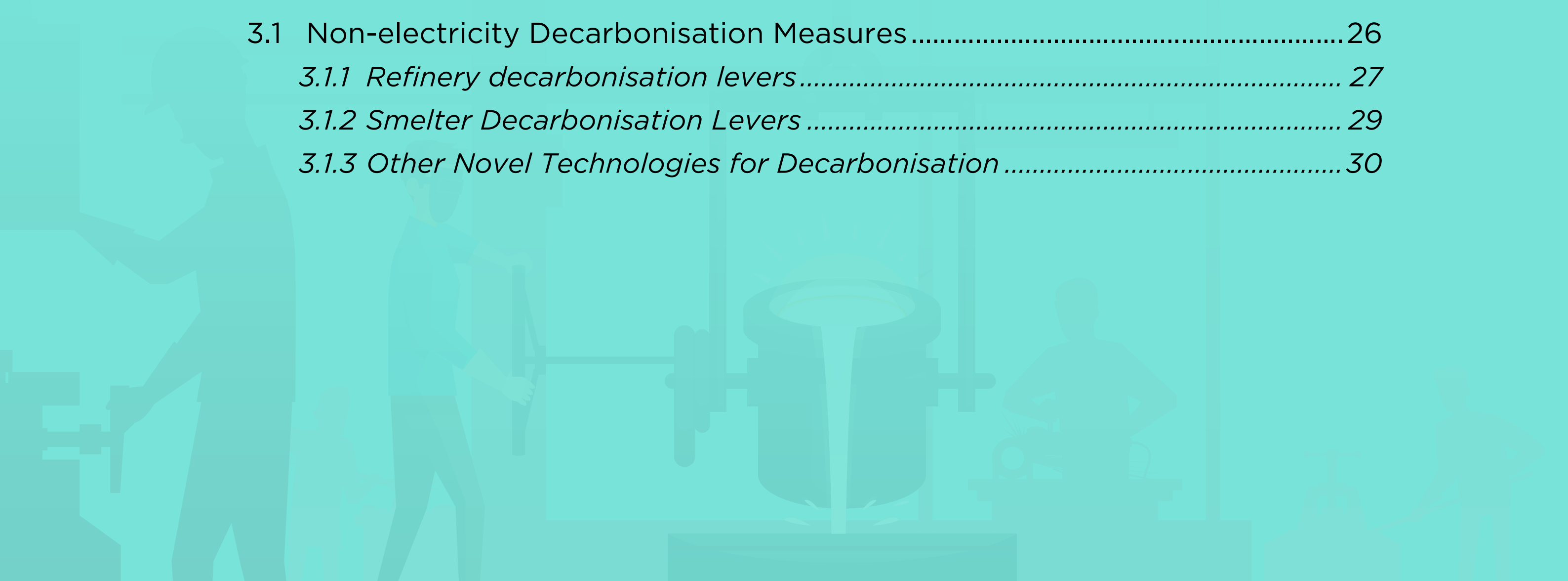

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List of Abbreviations

BAT	Best Available Technology
BEE	Bureau of Energy Efficiency
BESS	Battery Energy Storage Systems
BECCUS	Biomass Energy with CCUS
BSR	Bharat Small Reactor
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CEA	Central Electricity Authority
CEEW	Council on Energy, Environment and Water
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CII	Confederation of Indian Industry
CILMS	Composite Islanding and Load Management System
CIS	Commonwealth of Independent States
CPP	Captive Power Plant
CCTS	Carbon Credit Trading Scheme
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
CTU	Central Transmission Utility
CUF	Capacity Utilisation Factor
GDP	Gross Domestic Product
DAE	Department of Atomic Energy
DISCOMs	Distribution Companies
EE	Energy Efficiency
EPC	Engineering, Procurement and Construction
EPR	Extended Producer Responsibility
ESPs	Electrostatic Precipitators

EVs	Electric Vehicles
GH2	Green Hydrogen
GHG	Greenhouse Gases
GJ	Giga Joule
$GTCO_2e$	Giga tonnes CO_2 equivalent
HH	Hall-Héroult
HINDALCO	Hindustan Aluminium Corporation
IAI	International Aluminium Institute
IPCC	Inter-governmental Panel on Climate Change
IPP	Independent Power Producer
ISTS	Inter-state Transmission System
JNARDDC	Jawaharlal Nehru Aluminium Research Development Centre
kWh	Kilo Watt Hour
LNG	Liquefied Natural Gas
LCOE	Levelised Cost of Electricity
MACC	Marginal Abatement Cost Curve
MNRE	Ministry of New and Renewable Energy
MoP	Ministry of Power
MSW	Municipal Solid Waste
MVR	Mechanical Vapor Recompression
MT	Million Tonnes
MTPA	Million Tonnes Per Annum
Mtoe	Million Tonnes of Oil Equivalent
$MTCO_2e$	Million Tonnes CO_2 Equivalent
MWh	Megawatt Hour
NALCO	National Aluminium Company
NDCs	Nationally Determined Contributions
NPCIL	Nuclear Power Corporation of India Limited
NG	Natural Gas
OPEX	Operational Expenditure
PAT	Perform, Achieve and Trade
PFCs	Perfluorocarbons
PHS	Pumped Hydro Storage

PLF	Plant Load Factor
PLIs	Production-Linked Incentives
PPA	Power Purchase Agreement
PV	Photovoltaic
RE	Renewable Energy
RPO	Renewable Purchase Obligation
RTC	Round-the-Clock
SECI	Solar Energy Corporation of India Limited
SHANTI	Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India Act, 2025
SMRs	Small Modular Reactors
STU	State Transmission Utility
VGF	Viability Gap Funding
WACC	Weighted Average Cost of Capital
WEF	World Economic Forum

Executive Summary

The aluminium industry stands at a pivotal crossroads in its decarbonisation journey. As a key contributor to India's economy and industrial growth, the sector needs to adapt emerging global sustainability trends and ambitious emissions reduction targets. Aluminium production accounted for approximately 2.8% of India's GHG emissions or 83 $MTCO_2e$ in 2023, and without intervention, emissions could rise to 376 $MTCO_2e$ by 2070. With a national average emission intensity of 20 - 21 tCO_2/t of aluminium, significantly higher than the global average of 15 tCO_2/t, the sector clearly needs transformation.

The aluminium sector is hard-to-abate, owing to its high electricity consumption, met by coal-based electricity. Hence, reducing its carbon footprint is vital, not only to support India's net-zero goals but also mitigate export risks from emerging trade regulations, i.e. the EU's CBAM. As other nations develop low-carbon technologies & create trade measures based on embedded emissions, India's aluminium industry is presented with an opportunity to lower its emission intensity to be a global leader in sustainable metal manufacturing. This will also drive India's clean energy transition in longer run.

The global trends clearly indicate the increasing demand for low-carbon aluminium, induced by regulations and consumer choices across the automobile, packaging, and construction sectors. However, aluminium faces competition from other materials like steel and plastics, currently with a better carbon footprint. Thus, merely if the Indian aluminium industry wants to be on par with global market requirements, the shift has to be toward cleaner production routes while keeping costs under check.

Accordingly, the Working Group constituted by NITI Aayog on decarbonisation of aluminium assessed 30 proposed solutions under the decarbonisation roadmap. Low-impact options were de-prioritised, while the high-impact solutions were categorised into three main approaches. All three of these approaches focus on reducing emissions from electricity, which remains the largest source of emissions in this sector. In-depth technical and economic analysis was performed for each of the selected solutions, including detailed cost estimates, as well as additional support measures that would enable successful implementation. This assessment encapsulates the findings of many stakeholder discussions and represents practical implementation.

A value chain analysis carried out on aluminium production-from the mining of its raw materials to the production of finished metal-revealed that most of the emissions take place at the smelting stage, where alumina is being turned into metallic aluminium. Moreover, most of the emissions are related to the energy required for this process. Hence, most of the potential for decarbonisation and resulting solutions are related to a reduction of emissions linked with power generation. This is critical since the sector maintains a fleet of captive coal-power generators to ensure a continuous power supply.

The three prioritised solutions include:

(i) Short-term (till 2030): Transition to Renewable Energy-Round the Clock (RE-RTC) power and Grid connection.

(ii) Medium-term (2030 - 40): Adoption of nuclear power.

(iii) Long-term (2040 and beyond): Integration of Carbon Capture Utilisation and Storage (CCUS) with captive coal-based generation.

While RE-RTC presents a viable short-term solution, it poses operational challenges for aluminium smelters, which require continuous and uninterrupted power supply, placing high demands on the reliability of RTC mechanisms. Nuclear power provides a stable and low-emission source for the medium term but at a high upfront capital cost and with challenging regulatory, permitting, and public perception issues. CCUS is critical to long-term decarbonisation but faces high costs, infrastructure, and uncertainty regarding carbon transport and storage.

Chapter 1:

Introduction

Chapter 1: Introduction

1.1 Background

The IPCC reports working group III -Climate Change: Mitigation of Climate Change 2022 highlights that net GHG emissions have risen across all major sectors since 2010, with the industrial sector contributing 24% of the total global GHG emissions in 2019, equating to 14 GTCO$_2$e globally on account of heavy reliance on fossil fuels and energy-intensive process. As part of the industrial sector, the global aluminium industry is responsible for approximately 2% of total global GHG emissions, releasing over 1.1 GTCO$_2$e of emissions each year.

Over the past decade, direct emissions from the global aluminium industry have been on the rise due to increased production, a trend expected to continue with population and economic growth. In the road transport sector, aluminium is increasingly used in vehicle construction to lower the energy consumption of EVs due to its high strength-to-weight ratio, and in manufacturing battery pack enclosures because of its thermal conductivity and durability. Because of such properties, it also serves as an important material in components for the generation of clean energy, such as wind turbines and solar panels.

Aluminium is the key metal for clean energy, mobility, and infrastructure in India. Further, as per Aluminium Vision Document, there is a need to ensure raw material security for bauxite supply, simplify regulatory procedures to streamline processes, and deploy clean technologies across the value chain. It further calls for enhanced institutional collaboration, close industry-government partnership, and policy support to enable the integration of renewable energy, efficient recycling, and low-carbon production methodologies. These will be needed in order to build a flexible and climate-friendly Indian aluminium industry.

In this context, it is crucial to clearly identify viable options for reducing carbon emissions in aluminium production and recycling, following the best emission-reduction pathways based on the latest scientific advancements. With global demand for aluminium expected to rise, particularly low-carbon demand driven by sectors that mitigate climate change, a detailed analysis of available technologies and decarbonisation options across the value chain is essential, not only to reduce GHG emissions but also to maintain cost competitiveness and secure access to low-carbon markets.

The pathway of achieving net-zero emissions has attracted considerable attention with respect to finding technological solutions and a transition strategy for the aluminium industry. For example, major international industry associations such as the International Aluminium Institute (IAI) have worked on outlining a global vision of the low-carbon future of industry. Yet, region-specific emission and technology pathways consistent with the 1.5°C target, reflecting local conditions of the industries, remain absent. The aluminium industry is a key player both in terms of economic output and employment generation in India's industrial economy. Although it still lags the steel sector, which has maintained a consumption level of 12%, and the cement sector at 9%,

aluminium still constitutes about 2% of the manufacturing GDP, thus supporting and provides 80,000 jobs directly and indirectly (NITI Aayog, 2017). With the manufacturing sector in India growing, the contribution by aluminium will further increase. That said, it is a huge climate challenge. The sector accounts for about 2.8% of India's total GHG emissions, largely due to its dependence on coal-based electricity and other energy-intensive processes (CEEW, 2024).

While there is indeed progress over the years, especially in primary production, semi fabrication, and recycling, this transition needs to be accelerated further. NITI Aayog has mapped emission sources in the entire value chain of aluminium production and identified feasible strategies for decarbonising the sector. This covers major technologies already deployed, emerging low-carbon options, and prioritising action in line with India's climate obligations under global 1.5°C goals.

1.2 Working Group and Terms of Reference

India has committed to transitioning towards an environmentally sustainable economy. At the Conference of the Parties (COP) 26 in 2021, India announced its ambition to achieve net-zero emissions by 2070. This commitment was subsequently reaffirmed and detailed in official government communication (PIB, 2023). Decarbonisation of the industrial sector will be critical to realise India's international commitments on climate change. The industrial sector is diverse and therefore it is felt that sectoral roadmaps, especially hard-to-abate sectors, will be the way forward towards green transition.

In view of the above, the objective is to take a comprehensive approach and formulate a sectoral decarbonisation roadmap for selected hard-to-abate sectors, i.e. aluminium, cement, and the MSME sector. NITI Aayog constituted three working groups focusing on each of these sectors. The details of the sectoral technical working committee on aluminium are available in Annexure 1.

1.3 Methodology

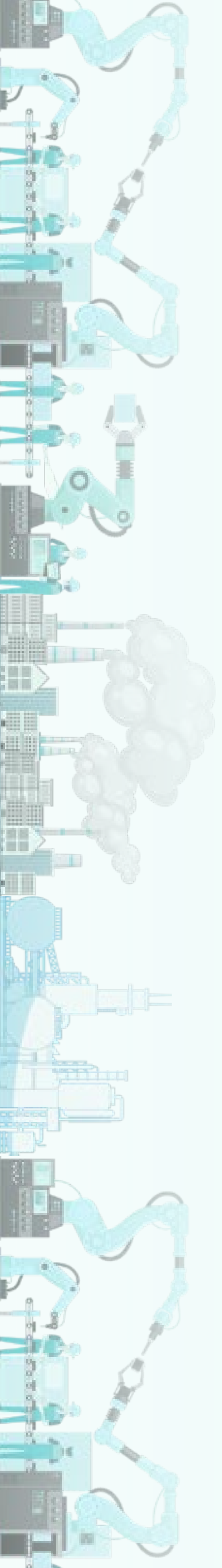
1.3.1 Scope and Approach of the Study

The scope of this study focuses primarily on the aluminium industry's upstream processes (Scope 1 and 2 emissions), which includes bauxite mining, alumina refining, and primary aluminium smelting. However, Figure 1 illustrates the comprehensive flow of both upstream and downstream processes.

Figure 1: Flow of both upstream and downstream processes

	Bauxite mining	Alumina refining	Primary Aluminium smelting	Secondary Aluminium	Casting
Scope 1	Diesel consumption	Emissions from steam production Emissions from calcination	Emissions from anode Emissions from self generated electricity Perfluorocarbon emissions from anode effects	Emissions from gas burning	Emissions from gas burning
Scope 2[i]	Energy consumption (washing plant, crushing, …)	Electricity consumption in plant	Emissions from purchased electricity	Emissions from purchased electricity	Emissions from purchased electricity
Scope 3	Diesel transport to plant Transport of consumables to plant Consumables at the mine (tires, …)	Scope 1+2 from Bauxite production Transport of bauxite to plant Lime production + transport Caustic soda production +transport	Scope 1+2+3 from alumina production Transport of Alumina and other raw materials Emission from Aluminium fluoride production Emissions of cathode Emissions of other raw materials (pet coke)	Emission from transport scrap Emission from scrap sorting (and processing)	Scope 1/2/3 Emission from Aluminium ingot (secondary or primary) Emission from transport of input material Emission from alloys

i. When energy production is not done on site
Source: (International Aluminium institute, 2023)



1.3.2 Research Methodology

The Indian aluminium industry's potential for reducing carbon emissions was examined using a mixed-method approach. This involved a literature review, stakeholder consultations, comparative analysis, and quantitative data analysis.

Literature review: For the literature review and comparative analysis, the researchers began by conducting a detailed global and Indian source review of decarbonisation strategies, technologies, and policies. They undertook a study of relevant peer-reviewed journals, industry reports, and case studies. This helped them see the prevailing trends and challenges facing the aluminium sector. A comparative analysis evaluated the Indian aluminium industry against global best practices concerning energy efficiency, emissions intensity, and technological use to indicate areas where improvement is required or could be potentially led.

Stakeholder consultation: The stakeholder consultations entailed more than 20 discussions with the government, including BEE industry experts, and technology providers. One multi-stakeholder workshop was organised at the end of Phase 1 of the study. These engagements pointed out reduction measures that were feasible and probed realistic means of pursuing those options. In Phase 2, there were four working group meetings with NITI Aayog, McKinsey, and industry participants to discuss emission reduction measures and detail implementation pathways.

Quantitative analysis: This was performed by the researchers through industry data, sustainability reports, and proprietary models for assessing the levels of emissions, the economic feasibility of interventions, and policy measures. Over 20 secondary sources, such as Council on Energy, Environment and Water (CEEW), Confederation of Indian Industry (CII), International Aluminium Institute (IAI), and World Economic Forum (WEF), were referenced to ensure the results are relevant locally while maintaining a global outlook. The report also integrated the results from McKinsey's Minespans to firm up the analytical base.

Chapter 2:

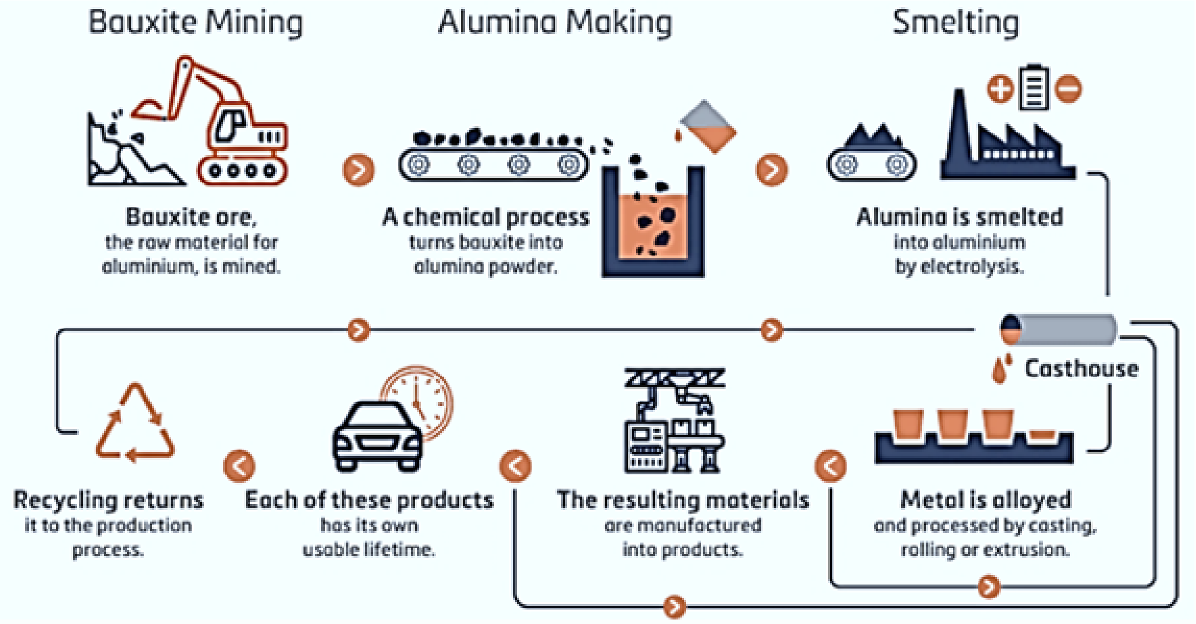
Overview of the Aluminium Industry

Chapter 2: Overview of Aluminium Industry

The formulation of a robust decarbonisation roadmap requires a comprehensive understanding of its production routes, associated emissions, and evolving global benchmarks, given the central role of aluminium in India's clean energy ambitions. Aluminium does not occur in metallic form in nature and is produced through a multi-step industrial value chain (Figure 2 and Figure 3). The production of aluminium has been broadly classified into two streams:

- Primary aluminium production is a process of metal extraction from raw materials.
- Secondary aluminium production relies on pre- and post-consumer scrap recycling.

Figure 2: Step-by-step process of making Aluminium

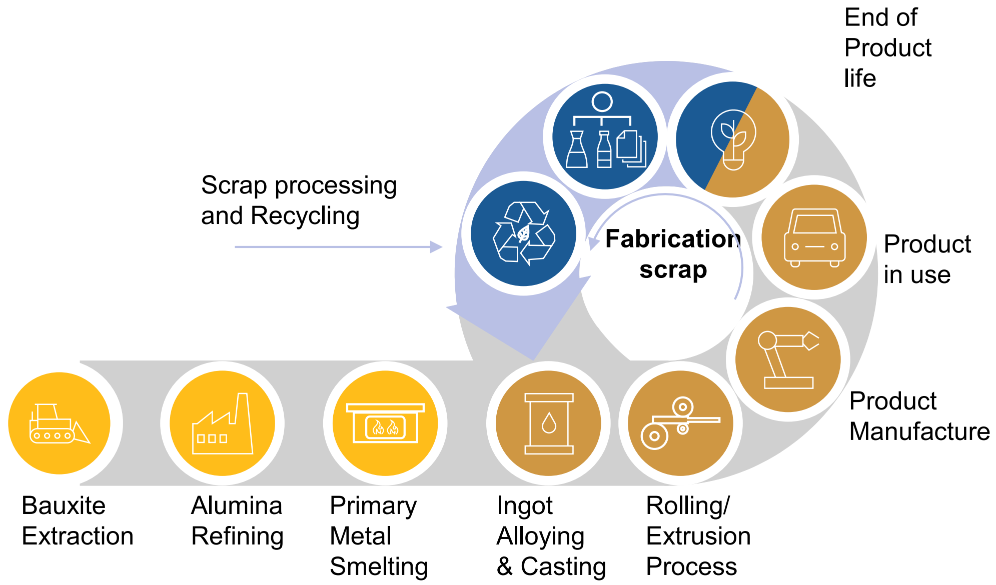


Source: (Ministry of Mines)

In the conventional method, ore containing between 40 and 60 percent aluminium oxide is extracted through bauxite mining. This is usually followed by alumina refining, which is a chemical process designed to purify bauxite into 99% pure alumina in white powder form (Histalu 2024). In turn, the resulting alumina is reduced to metallic aluminium by electrolysis, usually performed in carbon-intensive facilities as a result of reliance on fossil-fuel-based electricity.

This metal, after alloying and casting, is rolled or extruded to produce various forms of semi-finished products for different industries. These eventually become finished goods, which after their useful life are returned to the production cycle via scrap sorting, processing, and recycling.

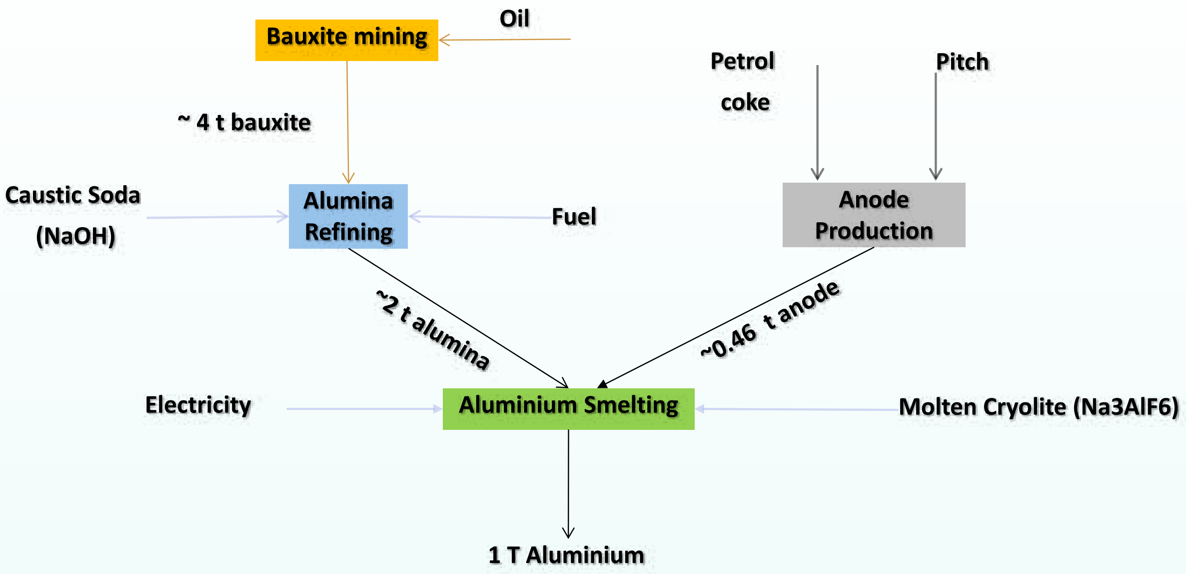
Figure 3: Life cycle of aluminium



Secondary aluminium is ~95% less emission-intensive than primary aluminium production because recycling saves ~95% of the energy (~13-14 kWh of electrical energy /kg on average consumed in primary production)
Very low scope for further decarbonisation of secondary aluminium – growth of metals recycling industry not covered under scope of the committee
Source: (Hulamin, International Aluminium Institute 2020, Ministry of Mines, India)

As shown in Figure 4, out of each four tonnes of bauxite ore, approximately two tonnes of alumina are produced. Further, the smelting of alumina produces approximately 1 tonne of aluminium. The production of aluminium is a capital and energy-intensive process. In sum, the cost of alumina, power and labour account for about 75-80% of the total production cost of aluminium (NITI Aayog 2017).

Figure 4: Process diagram of primary aluminium production



Source: (Author's compilation)

The recycling stage gives rise to secondary aluminium, one of the important avenues for circularity and emission reduction. The emission intensity of aluminium production also depends vastly on the type of feedstock used and the source of energy powering the process. Similarly, both primary and secondary production can be divided into five distinct categories, each representing a different profile of emissions.

Primary: Conventional primary aluminium with the highest emissions, reliant on fossil fuels and less efficient technologies.

Primary (Low CO_2): Primary aluminium with reduced emissions achieved by using cleaner sources and improving energy efficiency in the production process but higher emissions than ultra-low

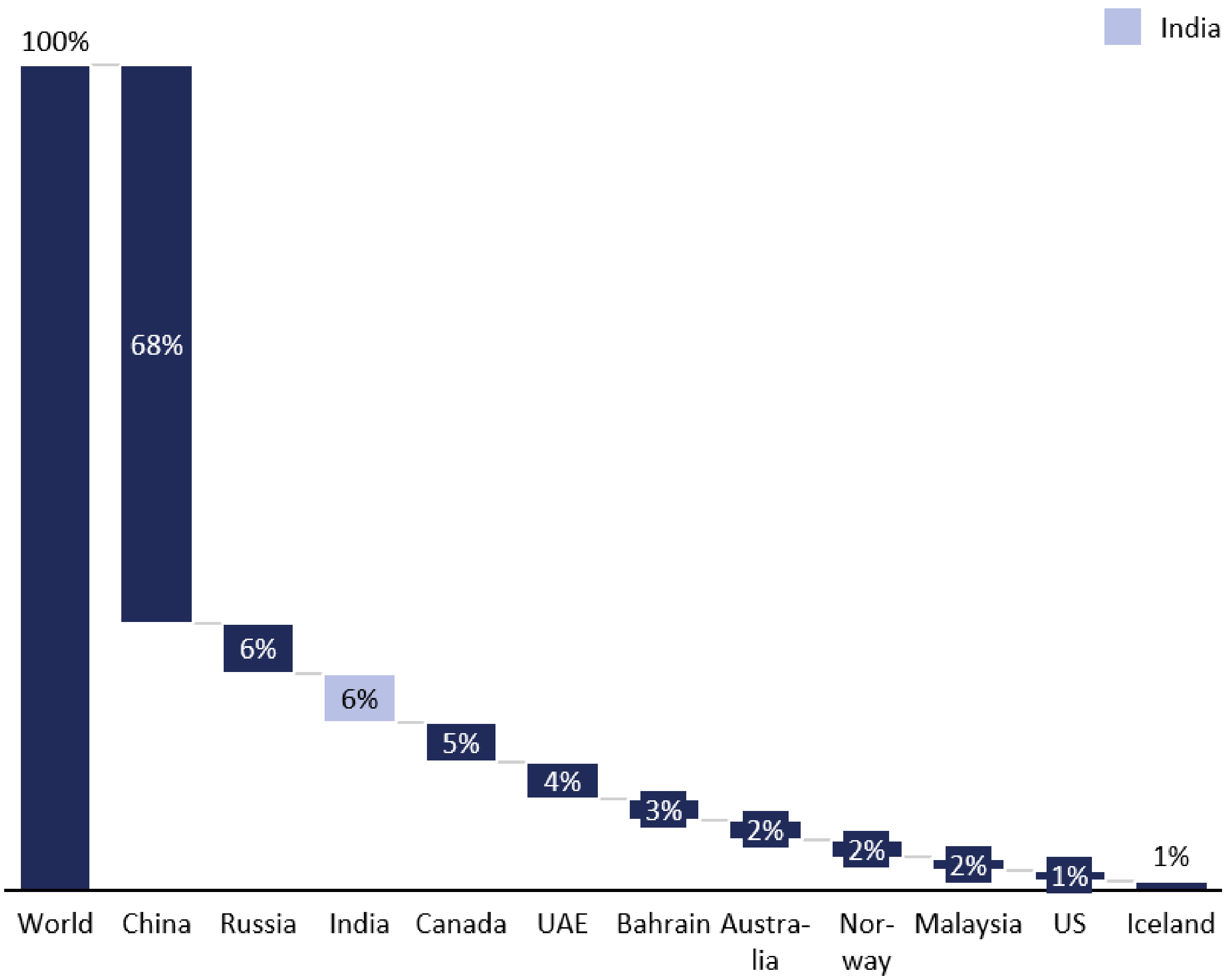
Primary (Ultra-low CO_2): Primary aluminium produced with emissions <2 tCO_2/tAl (IAI 2024) achieved through advanced technologies and RE integration.

Secondary (Grey): aluminium originating from pre-consumer scrap may have higher emissions attributed to the energy-intensive nature of recycling processes and the quality of scrap used.

Secondary (Green): This route utilises aluminium from post-consumer scrap and green energy sources.

About 70% of global aluminium production still comes from the primary route, i.e., smelting, with a significant share still based on emission-intensive processes, such as grey primary production. The rest consists of secondary aluminium, both green and grey, which depends on the scrap supply and energy mix during recycling. Global primary aluminium production is highly concentrated in a few nations. As depicted in Figure 5, China has 68%, the dominant share of the global primary aluminium, while Russia and India each contribute 6%. This positions India among the top three producers and makes it a strategic country for low-carbon transition of the sector. Hence, India's decarbonisation of its aluminium industry, especially the primary sub-sector, will be crucial not just for India's national climate goals, but also for global industrial emissions abatement.

Figure 5: Global primary aluminium production share by regions



Source: (International Aluminium Organisation, CRISIL, Indian Mineral Yearbook)

2.1 Global Aluminium Outlook

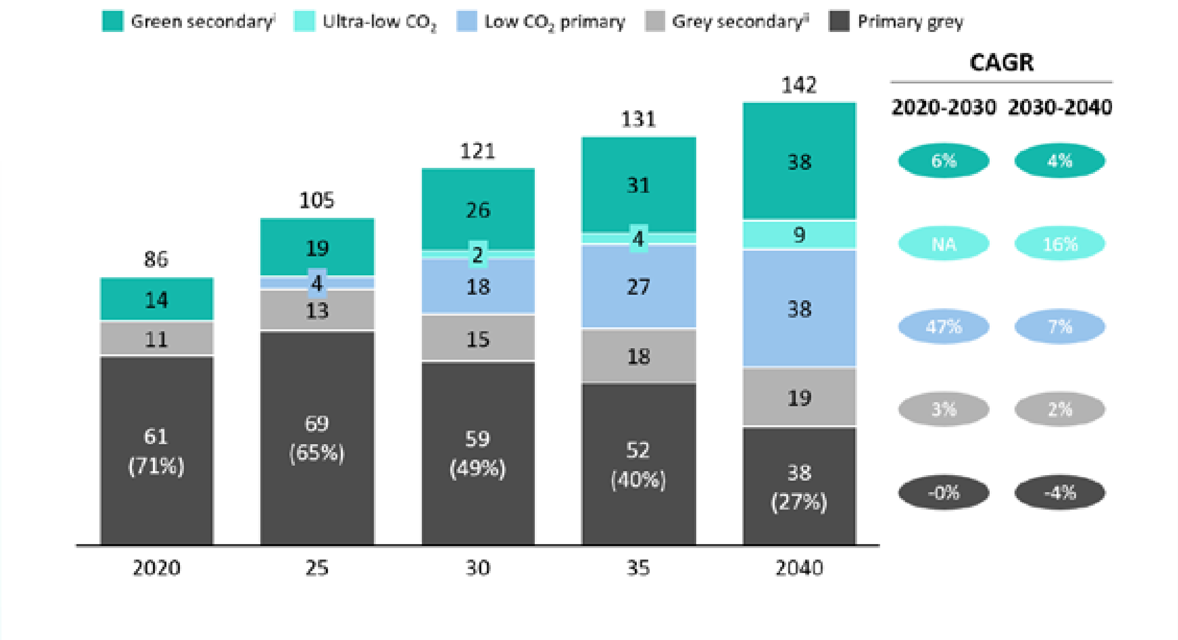
At a period when the aluminium industry is witnessing a transformation driven by global decarbonisation demands, regulatory actions, and evolving consumer preferences, the demand for clean aluminium is gaining traction globally.

2.1.1 Global Demand Outlook

Global aluminium demand is undergoing a remarkable shift towards low-emission products, with end-use sectors taking concrete steps to reduce embedded carbon in their products. Figure 6 shows the expanding global demand for aluminium, from 86 MT in 2020 to 142 MT by 2040. This growth is accompanied by changing composition of aluminium demand, by source. In 2020, grey primary aluminium accounted for 71% of total demand. Howeverby 2040, this would have been reduced to 27%, a reflection of the shift to low-emission alternatives. Green secondary aluminium demand exhibits momentum, from 14 MT in 2020 to 38 MT by 2040 with an effective CAGR of around 5%. Ultra-low CO_2 primary aluminium is expected to start from 2 MT in 2030 and gradually expand, reaching 9 MT by 2040.

These numbers illustrate the unstoppable transition across global supply chains toward cleaner aluminium production.

Figure 6: Global aluminium demand



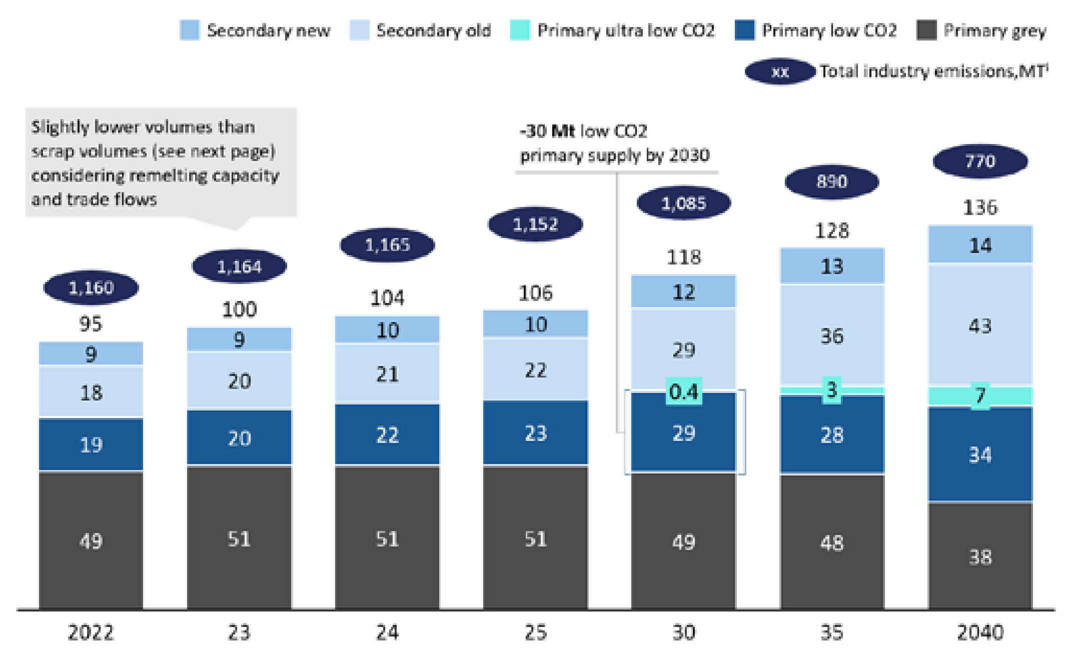
i Post-consumer scrap, and scrap from green primary sources on a regional level
ii Pre-consumer scrap from primary sources > 4 tC02/tAl
Source: (MineSpans, McKinsey Aluminium decarbonisation pathway model Q2 2024)

The decarbonisation trend is strongly driven by demand from the automotive and packaging sectors, particularly in Europe and North America. These regions are acting toward ambitious climate goals and regulatory mechanisms, such as the EU's CBAM, which creates incentives to use low-carbon materials. Consequently, procurement decisions are increasingly shaped by the carbon intensity of aluminium, encouraging the industry to adopt cleaner production technologies and increase recycling of green scrap.

2.1.2 Global Supply Trends

The supply scenario for the aluminium industry is changing gradually, not only in terms of overall output but also in its shift towards low-emission processes of production. The total global aluminium supply is projected to rise from 95 MT in 2022 to 136 MT by 2040, as depicted in Figure 7. Not only is the overall volume on the rise, but the composition of supplies is also undergoing remarkable change. As discussed above, the share of high-emission primary grey aluminium will decline from around 71% in 2020 to just about 27% in 2040, with producers turning to greener alternatives.

Figure 7: Global Aluminium Supply (Primary and Secondary), million tonnes



i Absolute emissions across the entire aluminium value chain, from bauxite mining to semis production
Source: (McKinsey 2024)

One key driver is the rising output of primary low-CO_2 aluminium, which will reach around 29 MT by 2030, reflecting the industry's improving potential to avoid emissions thanks to better electrification and other process efficiencies. The production of primary ultra-low CO_2 aluminium through futuristic technologies-essentially comprising hydrogen-based refining, carbon-chlorination with CO regeneration, and inert anodes-will remain very low, below 0.5 MT in 2030. These technologies hold major uncertainties, in particular with regard to anode material performance, and are still at the research stage.

Looking to 2040, ultra-low CO_2 aluminium supply is expected to increase to around 7 MT as these technologies mature and scale. Meanwhile, the industry's total emissions are projected to drop drastically, from over 1,000 MT today to approximately 770 MT in 2040, marking a steady but essential transition across the value chain.

This transition is driven by four critical global trends:

I. There is increasing attention on Scope 3 emissions within public procurement and regulations like the EU's CBAM.

II. There is an increasing demand for secondary aluminium as Original Equipment Manufacturers strive for 40-80% recycled content by 2030.

III. Aluminium faces growing competition from other promising materials, such as steel and plastics, which offer a lower carbon intensity, cost and better properties.

IV. High-quality recycled aluminium inputs are becoming more widespread from the expansion of secondary processing capacity.

The primary aluminium sector focuses on aggressive decarbonisation strategies, potentially for emissions less than 4 tCO_2/tonne via indirect emissions and a close eye for emissions less than 0.5 tCO_2/tonne via advanced smelting technologies (IAI 2024). The combination of these measures displays a more extensive structural change toward a low-carbon aluminium supply chain compatible with global climate objectives.

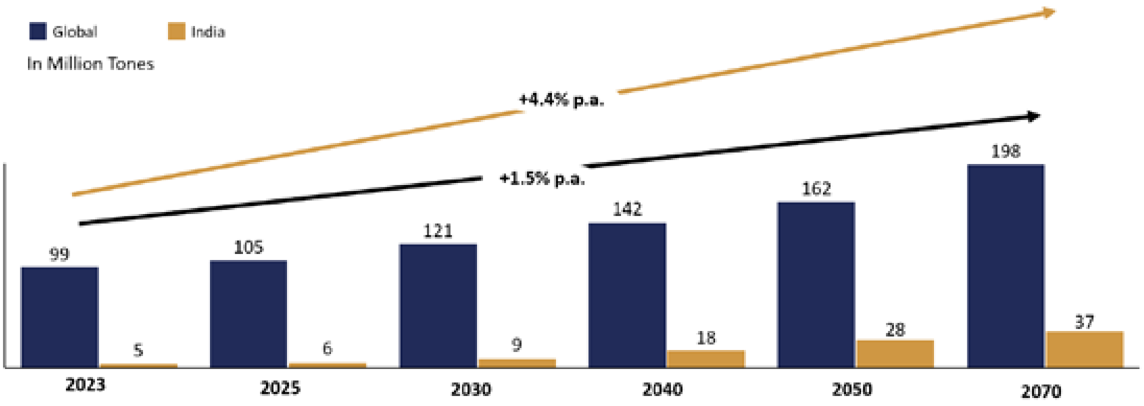
2.2 India Aluminium Outlook

The aluminium industry in India, over the next decade and in line with global trends, will evolve with new requirements powered by increasing demand, shifts in composition, and a stronger emphasis on decarbonisation will shape the aluminium industry in India over the next decade. Yet, the pace of change, sectoral drivers, and production structure in India have quite different characteristics compared to global dynamics.

2.2.1 India Demand Outlook

The growth of demand for aluminium in India is likely to outstrip the global average by a long distance. Compared with the rest of the world, which will see a rise in aluminium demand of about 1.5% per year, India's demand will increase by about 4.4% annually, rising from 4 MT in 2023 to 37 MT by 2070 as shown in Figure 8. Driving this faster growth in India are the following factors: the country's rapid population increase; its large-scale urbanisation plans-in fact, about 70% of India's urban infrastructure that the country will need by 2047 is yet to be built; and the expected increase in per capita aluminium consumption.

Figure 8: Production (Primary + Secondary) comparison of India with the world



Source: (NITI Aayog projections)

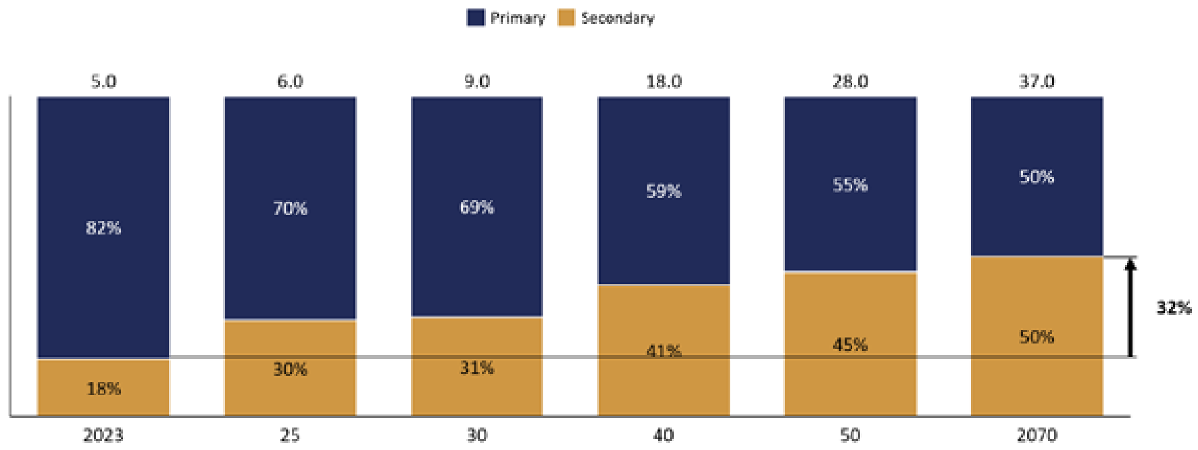
The applications related to energy transition, such as renewable sources pertaining to photovoltaic systems and grid connectivity, and the transition toward EVs, will require higher aluminium use intensity. India will lead the global demand for aluminium, with its growth potentially influencing global supply chains and decarbonisation strategies of the industry.

2.2.2 India Aluminium Supply Outlook

The aluminium supply in India will see rapid growth over the coming decades to meet the growing demand. The majority of this growth will originate from an increase in primary aluminium production, which is projected to rise from 4.1 MT in 2023 to 18.6 MT by 2070, growing at an average annual rate of about 3.3%.

In India, together with the forecasted increase in primary aluminium production, the contribution of secondary aluminium will also increase substantially over time. From the current contribution of 18%, the secondary aluminium is likely to contribute about 50% of India's total aluminium supply by 2070, as depicted by Figure 9. This trend indicates a greater emphasis on the circular economy principles and energy efficiency, as the manufacture of aluminium from scrap utilises significantly less electricity compared to its production from raw materials, since power is required only for melting. Yet, primary production will continue to be relevant and given that each tonne requires a huge quantity of electricity, its estimation at 14 MWh/tonne, the overall energy demand of this industry will keep increasing. As projected, addressing such demand may require about 40 GW installed power capacity up to 2070 in a business-as-usual scenario, and this becomes another reason why switching to cleaner sources of energy is crucial for sustainable growth.

Figure 9: Forecast primary and secondary aluminium supply share in India (in MT)



Source: (NITI Aayog projections)

2.3 Overview of Aluminium Sector Related Emissions in India

Along with this growth in domestic aluminium production, there is a corresponding need to manage the sector's growing carbon emissions. India's aluminium industry-from mining to smelting-is largely powered by captive coal-based electricity and remains one of the most carbon-intensive in the world. This section presents an overview of the existing emissions profile of primary aluminium production in India. It highlights key sources of emissions along the value chain and points out stages offering the largest opportunity for decarbonisation. Understanding the emissions profile is essential for designing targeted interventions for a low-carbon transition.

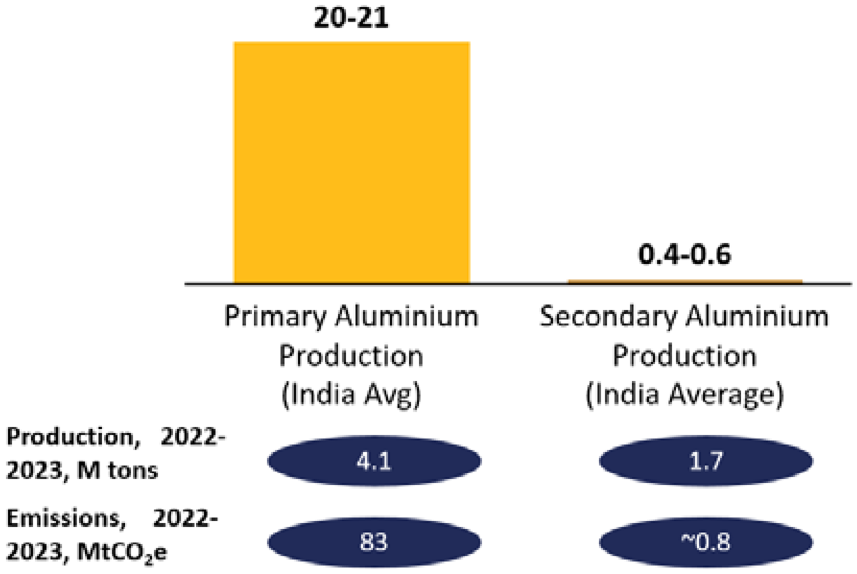
The following are the sources of carbon emission from aluminium production:

- The main direct process emissions include aluminium electrolysis, the combustion of fuels used onsite - mainly for process heat in alumina refining - and the oxidation of carbon anode. Indirect emissions from the consumption of electricity used for smelting. Aluminium production also generates PFCs, a potent GHG, anode effects occur i.e., the alumina ore content in the electrolytic cells falls below critical levels. The quantity of PFCs they generate depends on the frequency and duration of these occurrences (Gibbs 2000).

- The emission intensity in India is quite different for the primary and secondary -recycled routes of aluminium production. The average Indian primary production is roughly around 20-21 tCO_2/t, as depicted by Figure 10, much above the average global level of approximately 15 tCO_2/t. This is due to the high share of coal-based electricity used in smelting, which represents over 75% of the total emissions in Figure 11 at 14.8 tCO_2/t.

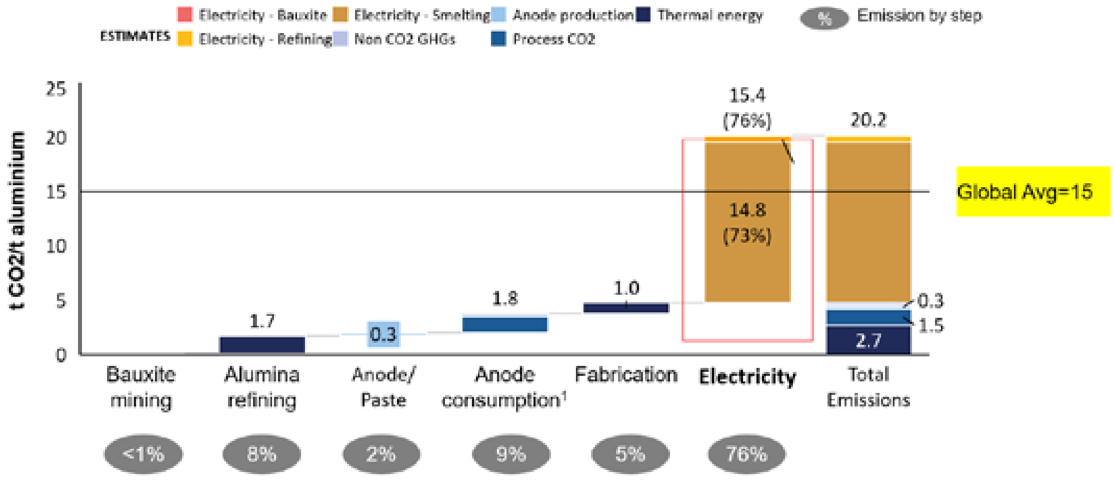
By contrast, secondary aluminium production from scrap is almost 95 per cent less carbon-intensive, emitting only 0.4-0.6 tCO_2/t. In FY 2022-23, India produced 4.1 MT of primary aluminium, contributing 83 $MTCO_2e$ emissions. In comparison, secondary aluminium production was 1.7 MT (including non-regulated share), emitting much smaller 0.8 MTCO$_2$e. The numbers indicate a clear opportunity-increasing the share of recycled aluminium in India's supply mix can play a major role in reducing emissions in the sector.

Figure 10: CO$_2$e emissions intensity for Indian aluminium industry in 2023 (in tCO$_2$e/t Al)



Source: (Ministry of Mines 2023)

Figure 11: CO$_2$e emissions by unit process in each process step for Indian aluminium industry in 2023.



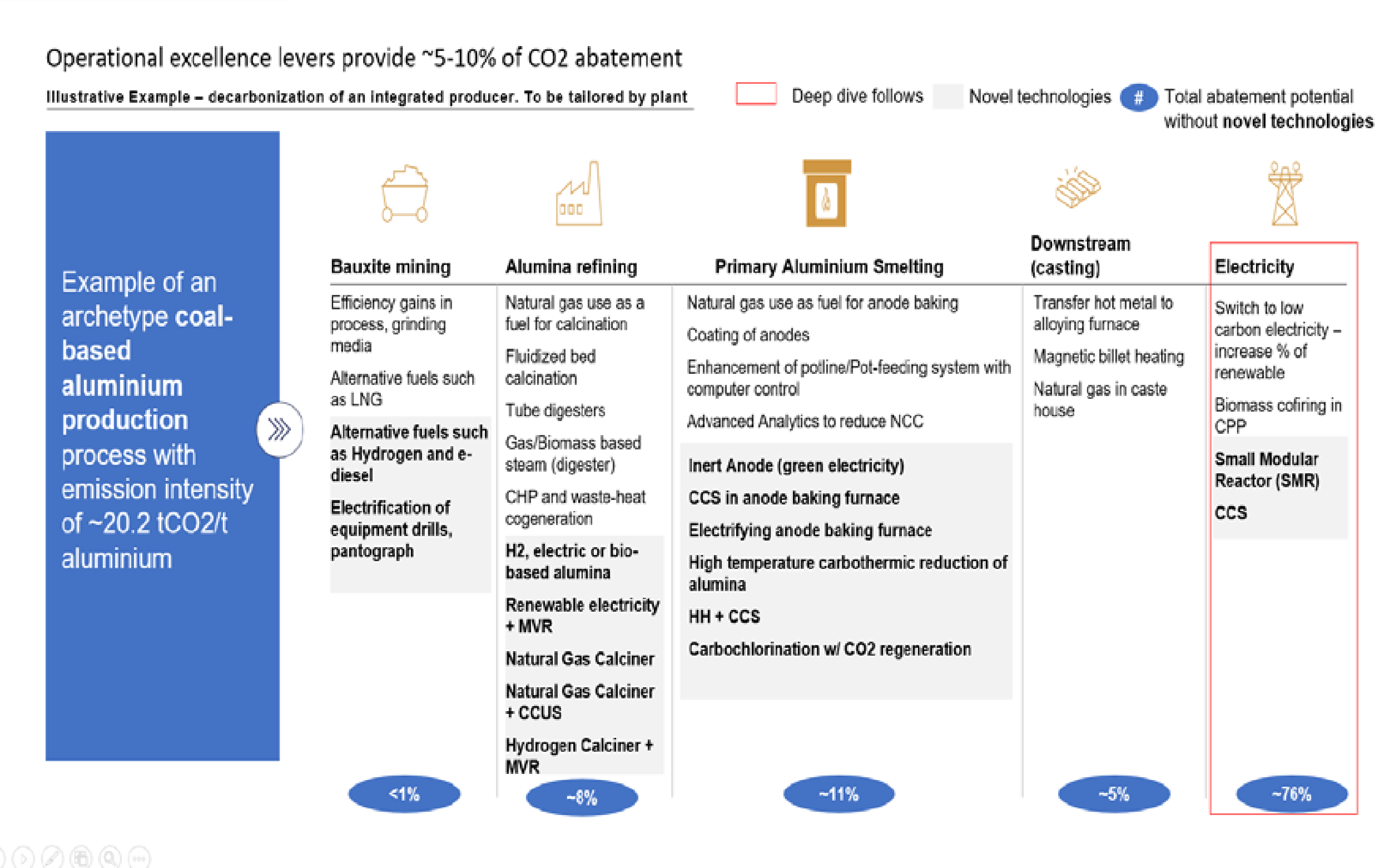
**For FY 2022-23, Scope 1 + Scope 2 emissions from all processes from mining to casting. All major players in India are integrated players from mining to casting with captive power production and own coal mines.*
Source: (Vedanta 2024; HINDALCO 2023; NALCO 2023; Ministry of Mines 2023).

These findings highlight the urgent need to move towards renewable energy, enhance energy efficiency, and introduce low-carbon technologies along the entire value chain of aluminium in India. So far, this section has focused on emissions from primary aluminium production, which remains a major source of carbon emissions in the Indian aluminium industry. However, it is equally important to examine the potential for secondary aluminium production. Due to its much lower emission intensity, secondary aluminium production presents a sustainable low-carbon pathway towards catering to future aluminium demand. The next section summarises key areas where further decarbonisation of primary and secondary aluminium production can be pursued.

2.4 Primary aluminium potential areas for decarbonisation

Decarbonisation of the Indian aluminium industry is a complex process, with coal-based production routes offering the greatest challenges and opportunities. The net-zero pathway will require strategic technology deployment - both proven and emerging - throughout the five identified stages in the production lifecycle: bauxite mining, alumina refining, primary aluminium smelting, downstream casting - as provided in Figure 12.

Figure 12: Process-wise potential areas for decarbonisation of Indian aluminium industry.



Operational excellence levers provide ~5-10% of CO2 abatement

Illustrative Example – decarbonization of an integrated producer. To be tailored by plant

🟥 Deep dive follows ▨ Novel technologies # Total abatement potential without **novel technologies**

Example of an archetype **coal-based aluminium production** process with emission intensity of ~20.2 tCO2/t aluminium

Bauxite mining	Alumina refining	Primary Aluminium Smelting	Downstream (casting)	Electricity
Efficiency gains in process, grinding media Alternative fuels such as LNG **Alternative fuels such as Hydrogen and e-diesel** **Electrification of equipment drills, pantograph**	Natural gas use as a fuel for calcination Fluidized bed calcination Tube digesters Gas/Biomass based steam (digester) CHP and waste-heat cogeneration **H2, electric or bio-based alumina** **Renewable electricity + MVR** **Natural Gas Calciner** **Natural Gas Calciner + CCUS** **Hydrogen Calciner + MVR**	Natural gas use as fuel for anode baking Coating of anodes Enhancement of potline/Pot-feeding system with computer control Advanced Analytics to reduce NCC **Inert Anode (green electricity)** **CCS in anode baking furnace** **Electrifying anode baking furnace** **High temperature carbothermic reduction of alumina** **HH + CCS** **Carbochlorination w/ CO2 regeneration**	Transfer hot metal to alloying furnace Magnetic billet heating Natural gas in caste house	Switch to low carbon electricity – increase % of renewable Biomass cofiring in CPP **Small Modular Reactor (SMR)** **CCS**
<1%	~8%	~11%	~5%	~76%

Source: (Vedanta 2024; NALCO 2023; HINDALCO 2023; Ministry of Mines 2023)

Each step in the process has a different potential for reduction of emissions. Based on the analysis and expert interviews conducted for this study, the following abatement potentials without novel technologies are identified for the Indian aluminium industry:

- **Bauxite mining: Minimal contribution by bauxite mining to total emissions (about <1%).** Decarbonisation at this stage lays the foundation for sustainable aluminium production. Improvements at this stage should focus on energy use reductions and the adoption of cleaner technologies. The efficiency gains in grinding and crushing equipment also reduce energy consumption. Electrification of mining machinery, i.e., drills and shovels, further reduces dependence on fossil fuels while allowing avenues to RE integration. Transitioning to alternative fuels like hydrogen and e-diesel also helps decrease emissions.

- **Alumina refining: The abatement potential at this stage of alumina refining is around 8%** and depends on improvements in process efficiency and the integration of clean energy sources. Among these, the shift from coal to natural gas during calcination is one of the critical pathways since calcination with natural gas greatly reduces the levels of emissions in industries while offering equivalent effectiveness in operations. Other developing alternatives are fluidised bed calcination and hydrogen-based alumina refining. Next comes RE integration, particularly via Mechanical Vapor Recompression (MVR), and biomass-fueled steam systems, which also can further improve sustainability. Nevertheless, these require considerable investments and changes to infrastructure, hindering its widespread adoption.

- **Aluminium smelting: Primary aluminium smelting is one of the carbon-intensive stages of processing, with about 11% potential for abatement.** The transition to natural gas for anode baking is a reasonable near-term solution. Advanced analytics can optimise potline performance, reduce waste, energy consumption, and costs of non-conformities. Another possibly game-changing technology in the smelting process is that of inert anodes, which would eliminate direct carbon emissions. Powering anode baking, adopting high-temperature carbothermic reduction, and implementing carbochlorination techniques with carbon regeneration represent further advances. The challenge here is the high cost and complexity of integrating into ongoing processes.

- **Casting: Downstream casting has the abatement potential of about 5% and could be optimised through energy management.** For example, hot metal transfer to alloying furnaces eliminates the need for reheat along the chain, hence reducing energy consumption. Magnetic billet heating improves EE and has lower associated emissions than conventional technologies. In addition, natural gas as the main energy source in casting house operations presents additional reduction opportunities in carbon intensity of the sector. While opportunities in this area are limited, they become important for incremental progress in overall decarbonisation.

- **Electricity consumption, therefore, is the dominant source of emissions, accounting for about 76% of the abatement potential.** Accordingly, decarbonisation of

electricity is vital. At the heart of this transition lie the RE sources, including solar and wind. On-site RE generation by aluminium producers is a direct sustainable supply option. Biomass co-firing in Captive Power Plant (CPPs) is an interim solution for coal-fired-based power supply. New and emerging technologies include Small Modular Reactors (SMRs) that can provide low-carbon, steady, and reliable supplies of electricity. Finally, CCS technologies applied to power generation further mitigate the emission issue as it captures and stores CO_2 effectively. Yet, this transition also raises challenges in terms of scalability, costs, and the need for regulatory support to drive the transition on wide scales. Since this aspect of aluminium production offers a huge potential for decarbonation, the same is covered in detail under the study.

2.5 Secondary Aluminium Production as a Lever of Emissions Abatement

- This research focuses on the decarbonisation of primary aluminium, since it represents the dominant source of emissions for the aluminium industry. At the same time, however, scrap usage to produce secondary aluminium cannot be disregarded, since this avoids the consumption of resources entailed in the extraction of metallic aluminium from bauxite.

- Recycling of aluminium scrap is intrinsically much more sustainable compared to primary production, using 95% less energy than the production of primary aluminium (IAI). In India, the share of recycled aluminium is about 30% (18% from the organised and 12% from the unorganised sector) (CRISIL 2022). India has committed to net zero by 2070, which requires planning for resource efficiency and a circular economy that encompasses the aluminium sector.

- The growth in China, India, and Japan is driving the Asia-Pacific region to have the highest share of the global secondary aluminium market. A significant driver is the automotive sector, seeing an increasing use of aluminium. According to the Japan Aluminium Association, secondary aluminium production was 669.8 thousand metric tonnes in 2023, up from 664.8 thousand tonnes in 2022. The IAI reports that North American production has a scrap content of 57%, the highest recycling input rate anywhere in the world. Major players such as Novelis Inc. and Alcoa invest heavily in the circularity of aluminium. Notably, Novelis has announced a USD 2.5 billion new smelter and mill in Alabama, to produce 600 kilo tonnes annually, marking the first fully integrated aluminium mill in the US.

- Because demand for aluminium keeps growing, this low-emission production route needs further cleaning to give a comprehensive decarbonisation strategy. In this process, the emissions are very minimal because the scrap melts, mainly during furnace operations, the energy applied in sorting and cleaning, and the addition of additives such as fluxes that remove impurities and hence improve metal recovery.

To translate these opportunities into tangible emission reductions, a combination of technical, operational and energy-system interventions is as follows:

a. **Energy Efficiency Improvements:** The application of energy-efficient measures such as regenerative burners, induction furnaces, and tilting rotary furnaces could result in a considerable reduction in specific energy consumption. These technologies allow waste heat recovery, effective use of fuel, and better process control.

b. **Fuel Switching:** Transitioning from conventional fossil fuels to cleaner fuels such as natural gas, hydrogen, or RE-based electricity can provide substantial emissions reductions. In particular, electric furnaces powered by RE will eliminate direct emissions.

c. **RE Integration:** Integration of RE for powering sorting, melting, and casting operations increases the sustainability of the process. Solar power procurement via open access or captive generation can be done, subject to scaling of RE capacity.

d. **Improved Scrap Quality and Circularity:** Improving segregation of scrap and pre-processing treatment may lead to improved efficiency during melting.

While these measures offer significant emission reduction potential, their effectiveness is contingent on addressing some bottlenecks that are:

(i) Lack of standardised channels to collect post-consumer scrap **-** especially from the key sectors of end-of-life automobiles and consumer products. Most scrap collection is through informal channels, and this results in inconsistent metal quality with poor alloy segregation.

(ii) High levels of impurities in scrap metals due to mixing with plastics and other alloys, i.e., iron, copper, zinc, etc. can cause deterioration in the properties of the resulting aluminium, for instance, mechanical strength, corrosion resistance, and castability of the molten aluminium.

(iii) There is limited automation and digitisation in operations, which restricts efficiency and productivity. This is common in small units and will limit the ability to meet upcoming demands, both legally enforced and market based.

(iv) Absence of a dedicated policy for processing scrap aluminium. There are guidelines, such as the Non-Ferrous Metal Scrap recycling framework by the Ministry of Mines. There is, however, no central policy guiding aluminium recycling, along the lines of the Steel Scrap Recycling Policy, 2019, notified by the Ministry of Steel.

Addressing these challenges will be crucial to scale up clean secondary production of aluminium. The following measures will drive circular economy in aluminium:

a. **A National aluminium recycling policy**, which lays out the roadmap and targets of circular metal usage. This can accelerate recycled metal usage.

b. **Promote domestic scrap utilisation** and expand the formal sector to improve the quality and segregation of scrap.

c. **Legally mandating EPR** targeting aluminium-intensive sectors, i.e. automobiles, appliances, etc.

d. **Create a scrap exchange portal** or empower a previously existing one for real-time trading, leading to formalisation and efficiency.

e. **Mandate a quota for low-emission aluminium** in public projects, which will boost demand for recycled aluminium, alongside green primary production.

In summary, recycling aluminium scrap is a key strategy to decarbonise the emission-intensive sector. By improving the supply of scrap metal, process improvements, proper policies and investments, the sub-sector can become the route of choice to produce net-zero aluminium in the near future.

Chapter 3:

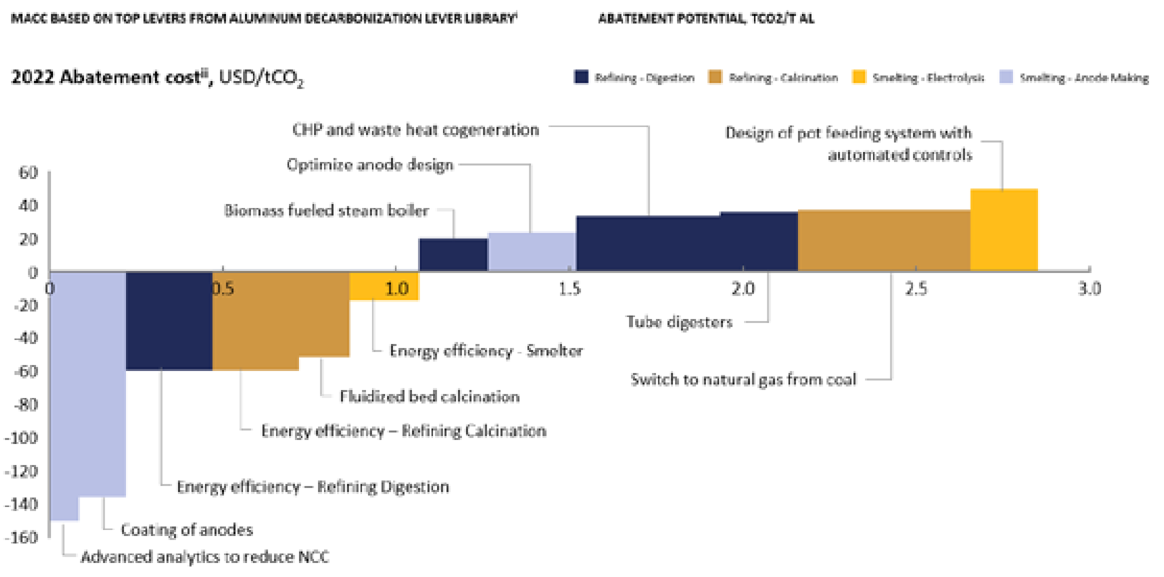
Key Levers for Decarbonising India's Aluminium Sector

Chapter 3: Key levers for decarbonising India’s aluminium sector

This chapter sets the stage for understanding where India’s aluminium sector currently stands in its decarbonisation journey and the path ahead. In the following sections, we explore key electricity and non-electricity measures across the aluminium value chain, along with the associated challenges. In addition, this section also presents the progress made under initiatives such as the Perform, Achieve, and Trade (PAT) scheme, pinpointing the achievements and gaps. This chapter concludes by identifying prioritised high-impact solutions that can accelerate the transition towards a low-emission sector.

3.1 Non-electricity Decarbonisation Measures

Figure 13: Marginal Abatement Cost Curve (MACC) of a coal-based aluminium plant (non - electricity decarbonisation measures)



i MACC would need to be adapted to organisation-specific parameters & setup (e.g. gas-based power). Overlap between levers has been removed e.g. natural gas use as a fuel & steam boiler electrification are mutually exclusive levers in a refinery.
ii Abatement cost using amortised capex over 25 years.

Source: McKinsey’s analysis and CEEW 2024

Figure 13 shows the marginal abatement cost curve of a coal-based aluminium plant with a focus on non-electricity emissions. This curve includes various stages of production and different levers have been evaluated at each stage. It is estimated that 70 to 80% of the non-electricity emission reduction can be achieved without any increase in the cost. However, all the technologies must be implemented, both energy efficiency (with low or negative abatement costs) and those with positive abatement costs such as fuel switching, highlighting the importance of integrating both the technologies. Therefore, a combination of improvement in operations, innovation in technology, and careful selection of energy costs is required for deep decarbonisation.

Key insights

- **There is a substantial potential for EE improvement in refining and smelting processes**. Measures in refining, digestion and calcination show negative abatement costs, i.e., these interventions save cost while simultaneously reducing emissions. For instance, EE in refining digestion has the highest negative abatement cost, around -60 USD/tCO_2, illustrating that not only do these steps reduce emissions, but they also save operational costs. Similarly, EE in refining calcination and the coating of anodes provide significant emissions reductions at no additional cost, contributing to early-stage abatement.

- **Levers such as optimisation of anode design, biomass-fuelled steam boilers, and waste-heat cogeneration show positive abatement costs** ranging between 0 to 20 USD/tCO_2. This indicates that while these measures require investment, the overall costs remain manageable for the sector.

- **Fuel switching (coal to natural gas) has a high positive abatement cost** of around 30 USD/tCO_2, indicating that it is not only capital intensive but also higher operational costs. The delivered cost of natural gas is 11.3 USD/GJ due to import and distribution costs. On the other hand, biomass has a landed cost of 4.7 USD/GJ making it a cheaper alternative, and coal is even further cheaper.

Different measures provided in the MACC have been segregated according to the process and have been detailed in the following subsections.

3.1.1 Refinery Decarbonisation Levers

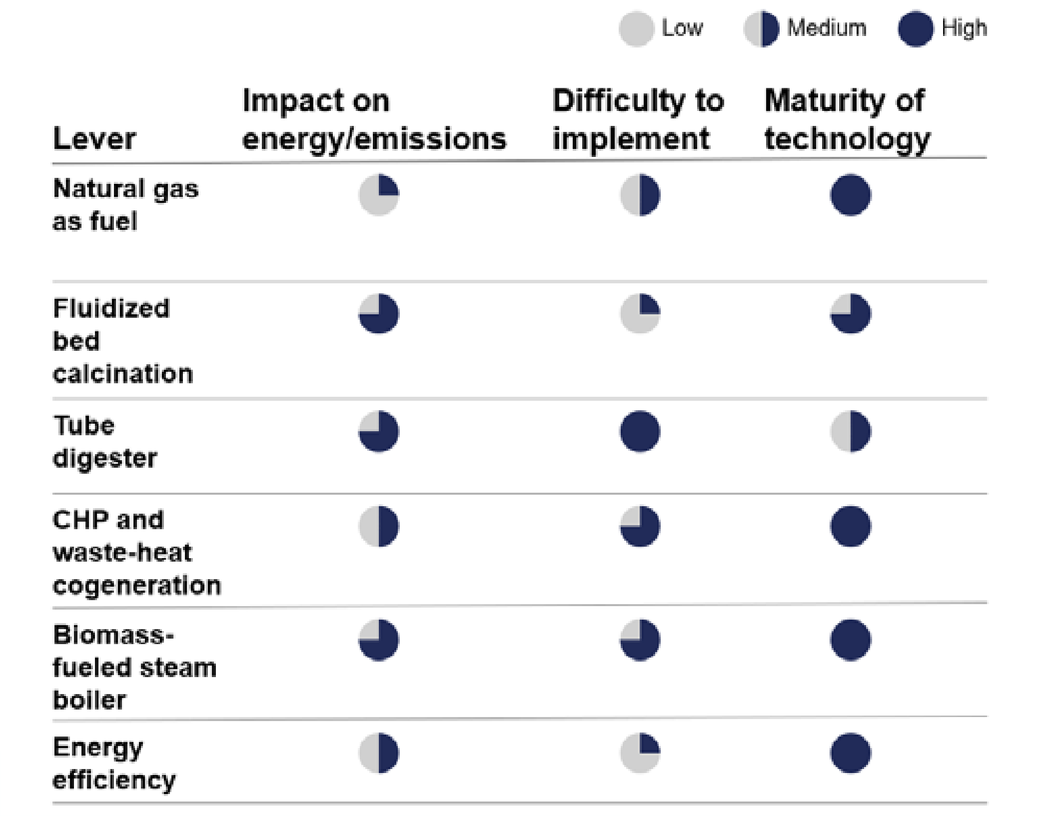
The major levers in refinery decarbonisation are energy efficiency, fuel switching to clean fuels, and tube digesters. These levers have their own unique implementation challenges and opportunities. For example, compared to fossil fuels used in aluminium refineries such as coal and oil, natural gas has lower specific emissions (EIA 2024). Burning natural gas produces approximately 50 to 60% less CO_2 per unit of energy compared to coal and 25% compared to oil (EIA 2022). However, the cost of natural gas is higher than the fuel currently used.

Moving from oil-fired boilers to gas-powered steam generators is a high TRL lever that reduces emission in the low to moderate range. Similarly, in relation to rotary kilns, Circulating Fluidised Beds also represent an energy-efficient alternative, with better heat recovery capabilities. Indeed, fluidised bed systems can realise up to 50% higher energy savings when integrated waste heat recovery is applied; they can also allow for considerable NOx and CO_2 reductions depending on the process and type of material treated. According to (DoE US 2017). These technologies present one of the many immediate opportunities for emission reductions because of their relatively simple implementation and established maturity.

On the other hand, innovations such as tube digestion, CHP, and waste-heat cogeneration are even more advanced but with a more complex solution. Tube

digestion, for example, allows operations below 10 GJ per tonne of energy input, but its implementation is challenging as this requires substantial redesign and has space considerations, especially for existing plants (EMEP 2023). Meanwhile, CHP systems, which co-generate heat and power, present a well-established method of integrating EE with emissions reduction, though they demand a high level of coordination and complexity in operation.

Figure 14: Levers for refinery decarbonisation



○ Low ◑ Medium ● High

Lever	Impact on energy/emissions	Difficulty to implement	Maturity of technology
Natural gas as fuel	◔	◑	●
Fluidized bed calcination	◕	◔	◕
Tube digester	◕	●	◑
CHP and waste-heat cogeneration	◑	◕	●
Biomass-fueled steam boiler	◕	◕	●
Energy efficiency	◑	◔	●

Source: Expert interviews with (HINDALCO, NALCO, and VEDANTA 2024)

Biomass-based steam boilers also offer a transition route from coal. This will not only cut CO_2 emissions but also lead to negative CO_2 emissions if implemented together with CCS technology. The emission reduction will be moderate to high, with some implementation challenges, according to (Liu 2023). Finally, efforts toward enhancing EE, even though they are incremental in benefit, would contribute to reducing both thermal and electrical energy consumption. Together, these levers represent a balanced approach to decarbonising refineries, with a mix of mature, easily deployable technologies and more innovative high-impact solutions critical for long-term sustainability in the aluminium sector.

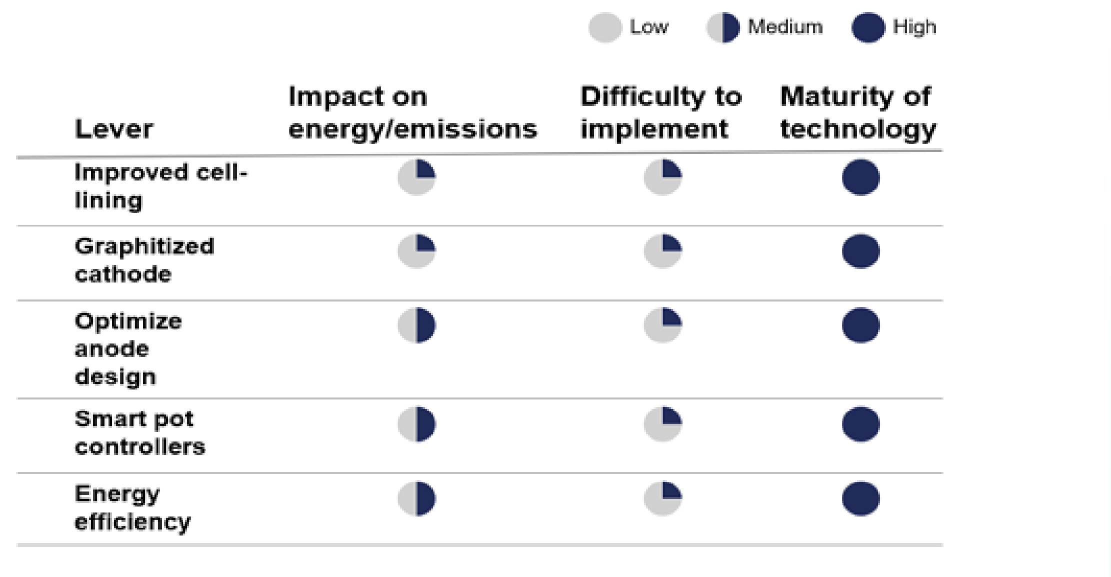
3.1.2 Smelter Decarbonisation Levers

Like refinery decarbonisation, in smelter decarbonisation also, increasing EE and improving cell design are major levers. For instance, the cathode lower components comprise a rectangular steel box reinforced on the inside with carbon, refractory bricks, and insulating materials. With aluminium plants continuing to ramp up potline amperage to increase production, there is a need to hasten the rate of heat transfer from the sidewalls of the cathode to maintain the frozen cryolite ledge to protect the sidewall lining material. Key measures include high thermal conductivity silicon carbide sidewall blocks, steel fins, and air cooling to maintain the cryolite ledge and protect cathode linings with rising potline(Tabereaux and Peterson 2014).

Advanced materials like copper clads, aluminium/steel welds, and graphitised cathodes reduce electrical resistivity and energy use while improving pot life (Rivoaland 2016). Although the technologies are mature, they are moderately difficult to implement as well as offer a low-to-moderate emissions reduction impact.

Another key lever is optimised anode design. With sloped and perforated anodes, smelters can facilitate improved gas circulation through the molten cryolite bath to enhance throughput and further reduce energy consumption. Like other levers, this is mature, providing important energy and emission benefits but with medium difficulty in implementation. Smart pot controllers are technologically advanced solutions that employ predictive analytics in optimising energy use and anode effects. But they are considered a bit challenging to deploy. These, along with energy buffering systems, help in managing fluctuations in power.

Figure 15: Levers for smelter decarbonisation



○ Low ◑ Medium ● High

Lever	Impact on energy/emissions	Difficulty to implement	Maturity of technology
Improved cell-lining	◔	◔	●
Graphitized cathode	◔	◔	●
Optimize anode design	◑	◔	●
Smart pot controllers	◑	◔	●
Energy efficiency	◑	◔	●

Source: Expert interviews with (HINDALCO et al., "Expert from Indian Industries," 2024)

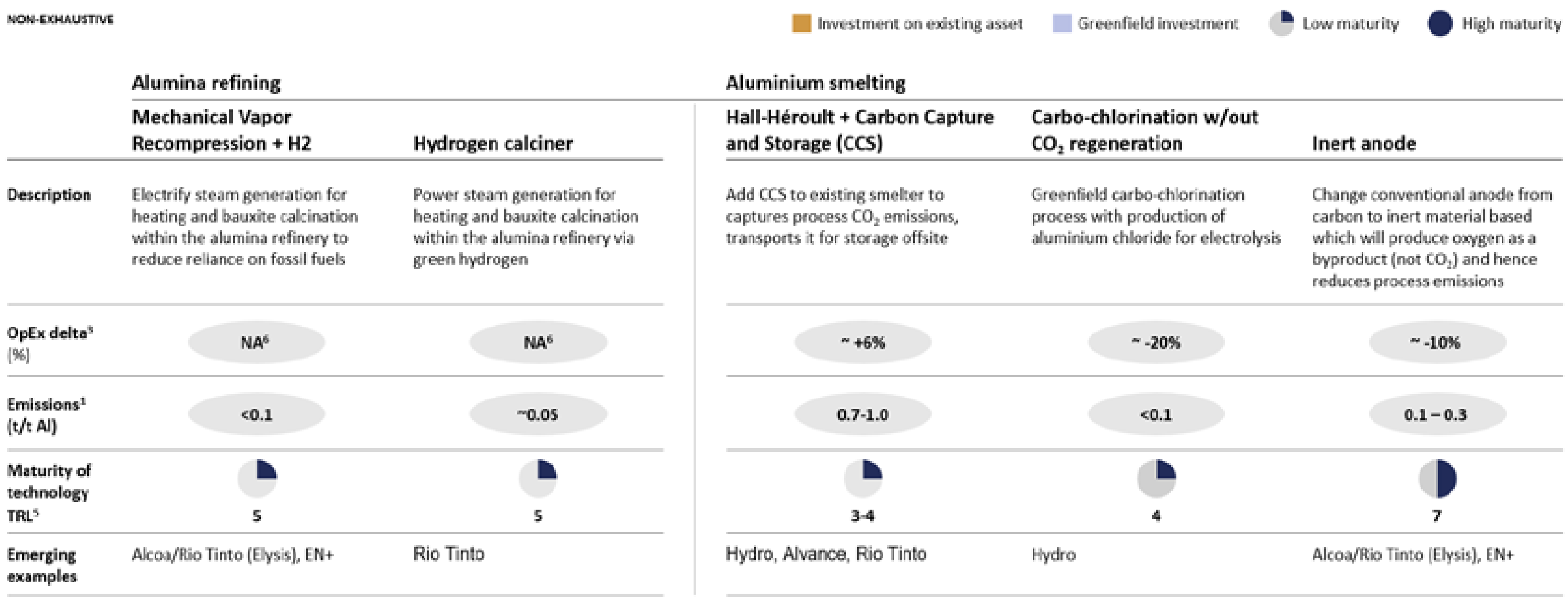
Adopting the technologies listed above will enable intermittent RE to be used exclusively for aluminium smelting and accelerate progress toward sustainable practices. This will involve significant investments and changes in production sites over the coming twenty years. EE measures-both operational and technology-related-continue to provide the backbone for decarbonisation for now, offering moderate but urgent overall cuts in energy use by smelters. These levers together represent a holistic approach toward low-carbon aluminium smelting, balancing technology maturity and significant emissions reduction.

3.1.3 Other Novel Technologies for Decarbonisation

This section analytically looks at “moonshot” technologies-advanced, high-impact innovations with potential to reduce CO_2 emissions in aluminium smelting and alumina refining to near-zero levels. Many technologies listed here focus on areas where conventional processes are carbon-intensive and propose transformative changes rather than incremental improvements. Each option varies significantly in technical maturity, investment type, and operational impact, reflecting the complex challenges and trade-offs involved in achieving deep decarbonisation.

Selected technologies have been represented in Figure 16, that could lead to a breakthrough in the reduction of emissions from alumina refining as well as aluminium smelting processes. Figure 17 provides the Capex expected for the adoption of these technologies, which is based on McKinsey’s modelling on internal aluminium supply projections and expert interviews.

Figure 16: Non-electricity moonshot technologies for mid-to-long-term decarbonisation.



NON-EXHAUSTIVE

🟧 Investment on existing asset 🟪 Greenfield investment ◔ Low maturity ● High maturity

	Alumina refining		Aluminium smelting		
	Mechanical Vapor Recompression + H2	Hydrogen calciner	Hall-Héroult + Carbon Capture and Storage (CCS)	Carbo-chlorination w/out CO_2 regeneration	Inert anode
Description	Electrify steam generation for heating and bauxite calcination within the alumina refinery to reduce reliance on fossil fuels	Power steam generation for heating and bauxite calcination within the alumina refinery via green hydrogen	Add CCS to existing smelter to captures process CO_2 emissions, transports it for storage offsite	Greenfield carbo-chlorination process with production of aluminium chloride for electrolysis	Change conventional anode from carbon to inert material based which will produce oxygen as a byproduct (not CO_2) and hence reduces process emissions
OpEx delta[3] (%)	NA[6]	NA[6]	~ +6%	~ -20%	~ -10%
Emissions[1] (t/t Al)	<0.1	~0.05	0.7-1.0	<0.1	0.1 – 0.3
Maturity of technology TRL[5]	◔ 5	◔ 5	◔ 3-4	◔ 4	◑ 7
Emerging examples	Alcoa/Rio Tinto (Elysis), EN+	Rio Tinto	Hydro, Alvance, Rio Tinto	Hydro	Alcoa/Rio Tinto (Elysis), EN+

i. Across Scope 1 and 2.

ii. Retrofit on existing assets except for carbo-chlorination, which is a Greenfield smelter investment.

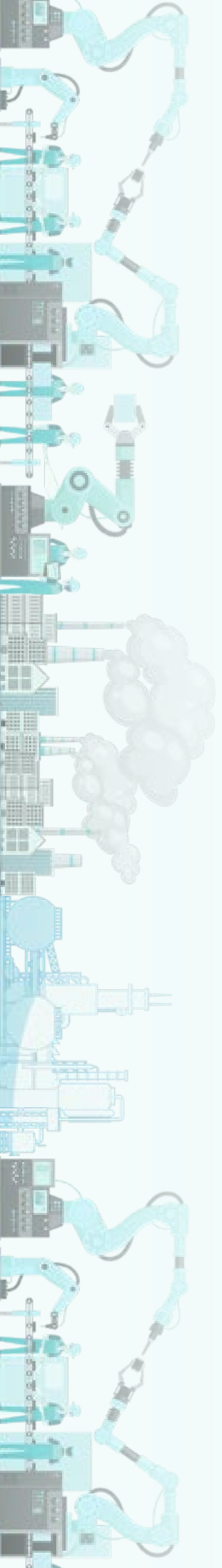
iii. Change in Opex (Opex delta) compared to conventional Bayer process in case of alumina refining and conventional HH in case of aluminium smelting; Net lower cost for Inert anode as higher electricity consumption is more than offset by lower anode spend.

iv. Based on USD to INR conversion of 83.5.

vi. TRL for aluminium industry.

vii. Negligible at current NG prices of ~11.3 USD/GJ.

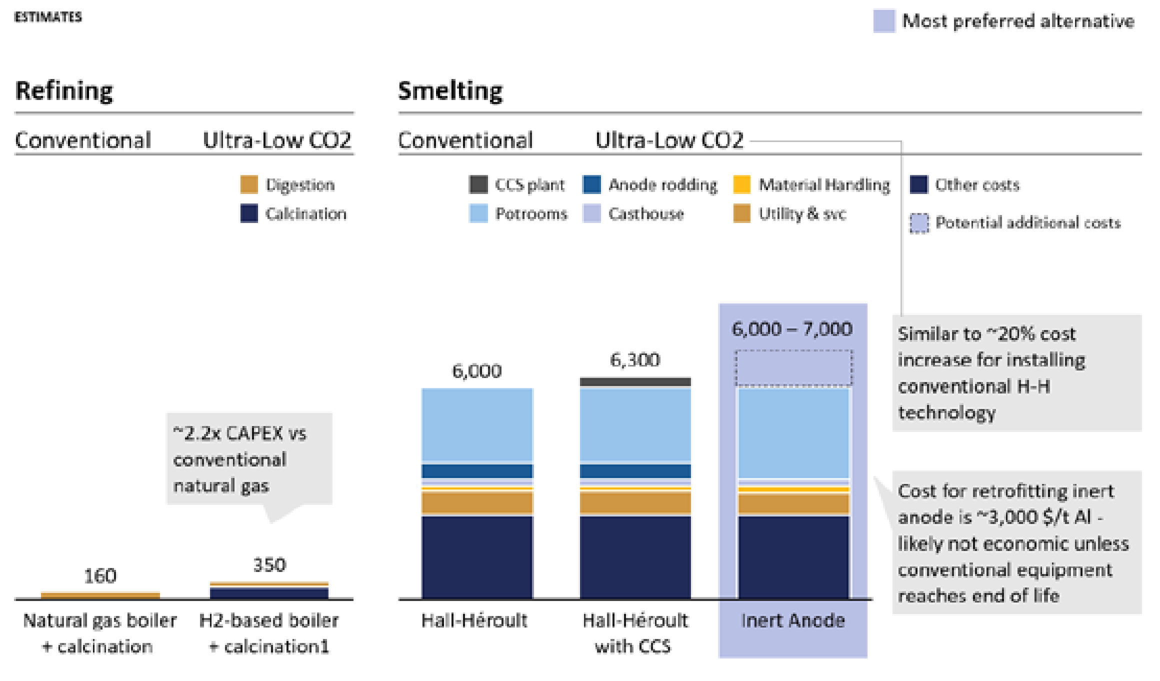
Source: (Mission Possible Partnership 2021; HINDALCO, NALCO, and VEDANTA 2024; McKinsey 2024)



MVR with hydrogen and hydrogen calciner represent breakthrough approaches in alumina refining. Both technologies aim to electrify or shift to GH2 for steam and heat generation, traditionally achieved through fossil fuel combustion. These technologies, by leveraging GH2, address the high carbon emissions from heating and calcination processes. They even show a close-to-negligible emission footprint of less than 0.1 t/Al, thus proving that carbon-free heating is possible. However, they are still at pilot-stage technology readiness level at TRL 5, with limited industrial deployment and applications. This indicates that it still needs industry-wide validation since scaling hydrogen-based solutions require massive infrastructure and energy input, with very important questions about the availability of GH2 and also the economic viability for wide-scale adoption in India. Current development is being supported by Alcoa/Rio Tinto, EN+, etc.

According to Figure 17, refining with hydrogen-based boilers and calcination-an ultra-low CO_2 technology-entails Capex of around USD 350 per tonne of aluminium, more than twice the Capex of conventional NG-based digestion and calcination at USD 160 per tonne. This two-fold increase reflects the high infrastructure costs associated with integrating hydrogen into the refining process. Despite this increase, refining remains relatively less capital-intensive compared to smelting.

Figure 17: Greenfield capex in EU and North America of refining & smelting, USD/t Al



Source: McKinsey modelling based on internal aluminium supply projections, (HINDALCO et al., "Expert from Indian Industries," 2024).

In the aluminium smelting, Hall-Héroult with CCS is a retrofit option that captures carbon emissions from existing smelting processes for transport and storage

elsewhere. Retrofitting CCS onto existing infrastructure may present a functional near-term emissions reduction path (this at a 6% operational expense increase). Its moderate maturity (TRL 3-4) would show that carbon capture in smelting is feasible but could be expensive and operationally complex, since it needs infrastructure for storage, besides regulatory frameworks for safe and long-term sequestration.

These developments have been adopted by a few of the global aluminium suppliers, including Hydro, Alvance, and Rio Tinto. In contrast, Carbo-chlorination and Inert anode technologies represent more transformative approaches. Carbo-chlorination aims to completely eliminate the CO_2-forming reaction by producing aluminium chloride for electrolysis, resulting in dramatically fewer emissions (<0.1 t/Al) and a potential 20% reduction in operating costs. However, this is greenfield technology (TRL 4), entirely new facilities, which needs capital investment and technical adaptation. It fits the long-term decarbonisation target but with considerable risk and resource need. Meanwhile, Inert anode technology replaces carbon-based anodes with inert materials at the source of CO_2 formation consequently yielding oxygen in its place. With a TRL of 7, it is one of the most mature options, already being implemented by major industry players such as Alcoa and Rio Tinto under the Elysis initiative. It balances feasibility and impact well, offering significant reductions in emissions with just a moderate increase in operational costs, hence one of the more immediately scalable solutions.

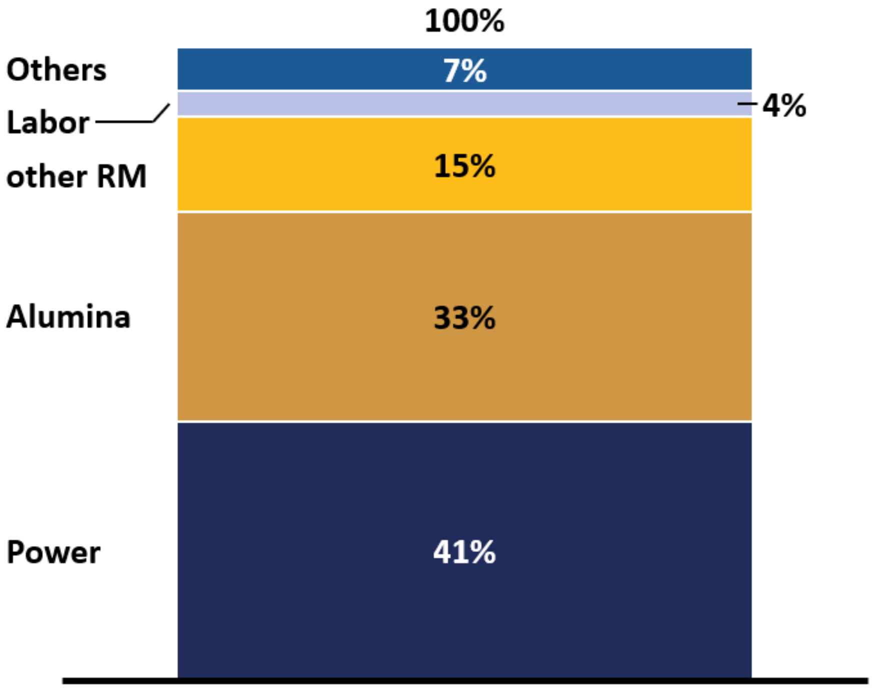
For smelting, the capital cost of deploying Hall-Héroult with CCS or inert anode technology is similar, which underlines that each of these ultra-low carbon emissions technologies requires a serious upgrade of the existing smelting infrastructure. Inert anode retrofits may be challenge since the costs are comparatively very high. In many instances, such retrofits will be economical only when the existing equipment is near the end of its operational life. The retrofit makes commercial sense in those cases; otherwise, it becomes impossible because the widespread changes that would be required for pot rooms and other essential elements make the retrofitting impractical. This chart also illustrates the relative increase in investment associated with transitioning from traditional HH technology to low-carbon alternatives in smelting. Both HH + CCS and inert anode installation cost about 20% more. This is important considering the investment in an industrial-scale smelting operation. This suggests that the actual feasibility of inert anode technology, being retrofittable or not, depends on how much longer the existing equipment can effectively be used.

Substantial investments and collaboration across industries by technology suppliers and users are required for these technologies to move from pilot projects to commercial deployment. In India, these options are viable to a great extent based on the availability of GH2, regulatory support for CCS, and capital for mature technologies like inert anodes. These futuristic technologies indicate that long-term planning and innovation are necessary to achieve decarbonisation goals in the aluminium sector.

3.2 Electricity Decarbonisation Measures

Manufacturing of aluminium is an electricity-intensive industry. This is manifested in the cost structure, which is majorly utilised for paying electricity bills. Figure 18 depicts that power alone constitutes about 41% of the total cost structure in India's aluminium industry, which is higher than all other inputs, including the raw material input (alumina), which contributes about 33%. For smelters like Vedanta Korba, at one plant producing 0.58 MT per year, approximately 14000 kWh of electricity is consumed to produce one tonne of aluminium[1], which implies huge energy requirements of 1,740 MW to achieve full utilisation. Besides, the dependence on CPPs, which are largely coal-based, increases carbon emissions from the sector. Presently, 9.4 GW of CPP capacity is operational for about 4.1 MT of installed aluminium capacity in India (Industrial Punch 2021), thereby leading to both surging emissions and a surge in operational risk, since smelter cells degrade at a very rapid rate if power supply is disrupted for even short durations (ICPA 2021). These elements make power decarbonisation in aluminium a complex yet important challenge, particularly amid a growing need by the industry to contribute to global carbon reduction targets.

Figure 18: Typical aluminium production cost breakup, India, percent



Source: Industry provided data.

To further understand how changing the source of electricity in smelting is the primary lever to decarbonise primary aluminium production, Figure 19 illustrates the emissions intensity of primary aluminium production across different energy sources. Hydro-based production emits the least, at approximately 4 to 5 tCO_2/t because of the use of renewable hydropower, which avoids fossil fuel emissions (Norsk Hydro

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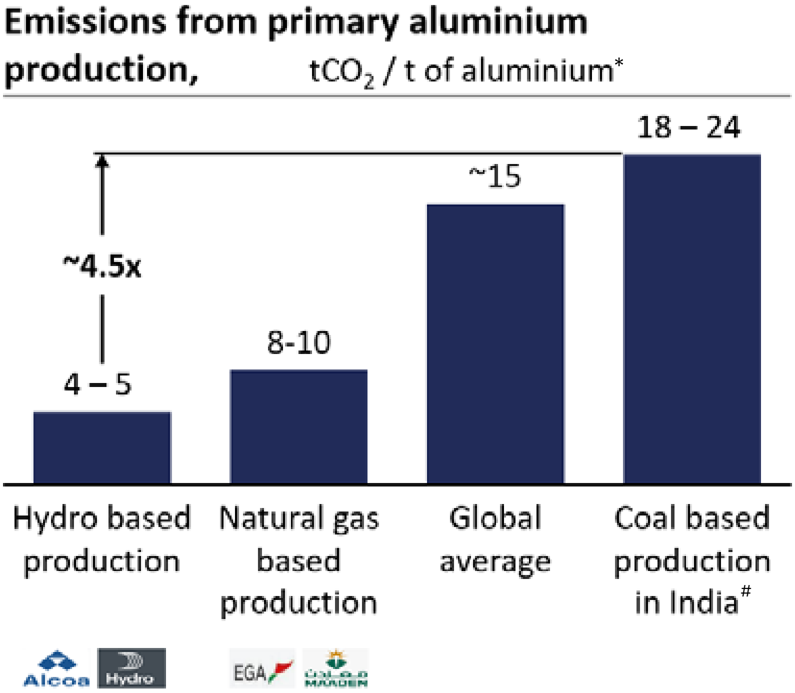
[1] 95% used for smelter operation and 5% used during alumina refining

ASA).[2] In contrast, natural gas-based production has higher emissions at around 8 to 10 tCO_2/t, as the combustion of natural gas, though much cleaner than coal, still emits considerable GHGs. Globally, the average intensity of aluminium production is around 15 tCO_2/t, reflecting the wide difference in energy mixes in different regions. However, coal-based production in India is very high, with emissions ranging from 18 to 24 tCO_2/t.[3]

Figure 19: Primary aluminium production emissions based on energy source



*Scope 1 + Scope 2 emissions from all processes from mining to casting. All major players in India are integrated players from mining to casting with captive power production and own coal mines.
Industry average of 19.2 tCO_2/tonne
Source: (EU Commission 2019)

The selection of electricity sources represents the most important factor determining carbon intensity in primary aluminium production. Figure 20 gives an overview of the energy mix in global aluminium production, to which India is an outlier due to its extremely high dependence on coal.

Coal makes up a full 99% of India's energy mix for producing aluminium, far above the global average of 56%. The near-total dependence on coal as the primary source of energy for aluminium smelting raises the carbon footprint of the Indian aluminium industry. In contrast, countries like South America and the CIS, where hydro sources provide 81% and 94%, respectively, of power, illustrate the potential of cleaner sources of electricity to bring down the carbon footprint of production substantially.

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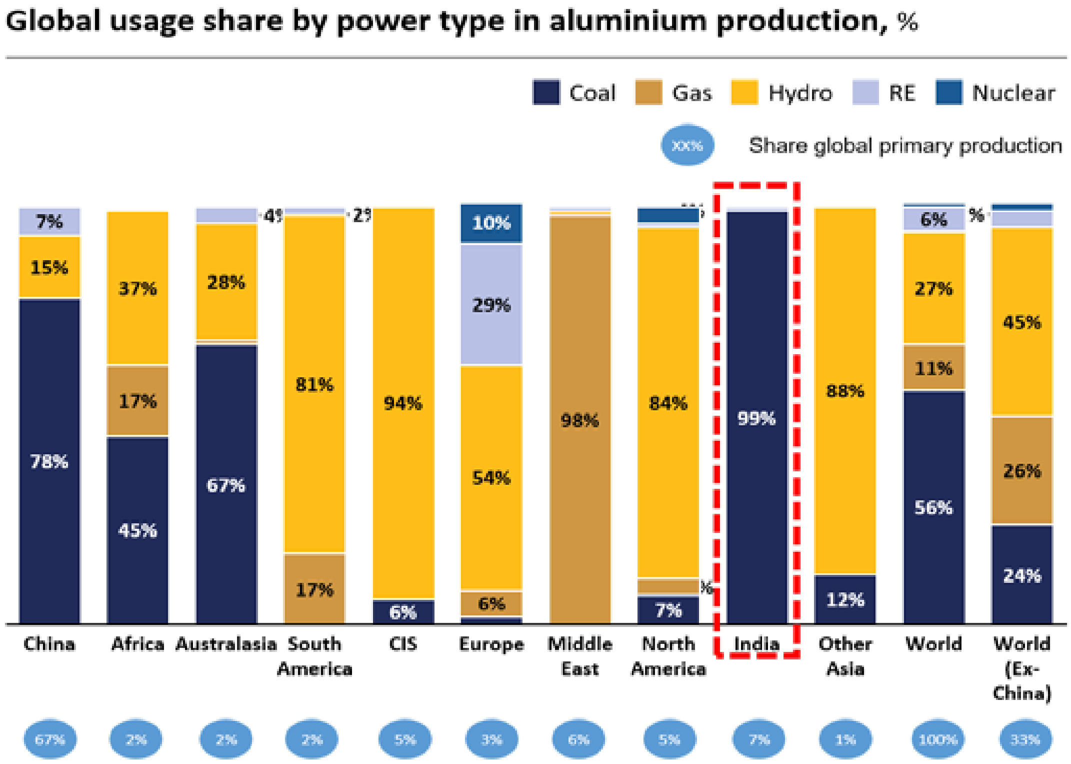
[2] Smelters in regions with 100% hydropower have emissions intensity less than 4-5 CO_2e t/t (Scope 1 and Scope 2).

[3] For coal-based smelters, electricity emissions factor is ~ 1 $kgCO_2/kWh$ for CPP, 0.7 $kgCO_2/kWh$ from grid.

Figure 20: Global usage share by power type in aluminium production



#Industry average of 19.2 tCO_2/tonne
Source: (EU 2020)

The analysis makes it clear that shifting the energy source in smelting processes offers the most immediate and significant lever for the decarbonisation of India's primary aluminium production. Regions like Europe and North America, with a diversified energy mix including hydro, nuclear and renewable energy, present viable pathways for reducing coal dependence while ensuring stable energy supplies. In this regard, addressing India's strong coal dominance through greater RE adoption and exploring the role of energy-efficient technologies in smelting is critical to emissions reduction and aligning the sector with national and global decarbonisation goals.

3.2.1 Role of Clean Energy in Smelting

Figure 21 gives a preliminary, non-exhaustive analysis of potential sources of electricity for decarbonisation of smelter operations in India. The viability of each energy source is assessed based on capacity, expected generation, and applicability to meet the high base load demand required for smelting processes. The options are categorised by their commercial readiness: Commercialised (C), Pilots (P), and Demonstration (D) stages.

Figure 21: Smelter electricity decarbonisation potential archetypes

Preliminary Non-exhaustive

▌ Applicable in combination with PPA and/or grid

C Commercialized P Pilots D Demonstration

		Typical capacity,MW	Capacity factor,%	Expected generation,MW	% of smelter load	Notes
Hydro	C	1,875	40%	750	100%	May be limited by available capacity. High applicability, long lead time and possibly limited availability nearby.
SMR	P	833	90%	750	100%	Scalable but under development. High applicability, but technology not proven.
Nuclear reactor	C	833	90%	750	100%	Scalable but long construction duration. High applicability, long lead time and possibly limited availability in near-term
NG+CCUS	D	938	80%	750	100%	Limited by NG price and CCUS capacity. High applicability, but implementation feasibility not proven and infrastructure not available.
Coal+CCUS	P	1,071	70%	750	100%	Limited by CCUS capacity. High applicability, but implementation feasibility not proven and infrastructure not available.
BECCUS	P	938	80%	750	100%	Both CCUS and biomass availability can be limiting. High applicability, but technology not proven and possible raw material issues
On-shore wind	C	100-300	30-35%	30-105	5-14%	Intermittent archetype not scalable without storage or alternate power back-up. Hence, low potential for applicability
Off-shore wind	C	250-600	35-55%	88-330	12-44%	
Solar PV	C	200-800	15-20%	30-160	4-21%	
Solar CSP	C	100	20%	20	3%	
RE RTC	C	100-400	70%	70-280	10-30%	Intermittent archetype not scalable without storage or alternate power back-up. Hence, limited potential for applicability for short-term
RE RTC + Pumped hydro	C	100-700	80-85%	80-600	10-70%	High applicability, but not enough scale available currently and landed cost is very high compared to captive production cost
RE RTC + Battery storage	C	100-700	80-85%	80-600	10-70%	

US department of energy, Solar Energy Industry Associations
BECCUS: Bioenergy Carbon Capture Storage, CCGT: Combined Cycle Gas Turbine, CSP: Concentrated Solar Power, PV: Photo-Voltaic, SMR: Small Modular Reactor, CCUS: Carbon Capture Utilisation and Storage, RES: Renewable Energy Sources.
**Not many examples present in India as of now, hence potential typical data used.*
Source: (EIA 2022; Mignacca and Locatelli 2019; Donnison 2020; The Goldman Sachs Group, Inc. 2020; Wind Europe 2021)

The following observations have been derived from information in Figure 21:

- **Hydropower is a commercially proven solution**, delivering firm power when integrated with the grid. Despite its scalability, hydropower is geographically constrained by the availability of suitable water bodies. It remains a highly applicable option for smelters due to its capability to meet 100% of the load. In many instances, it is very applicable for smelters since it can meet 100% of the load. However, seasonal variability and long project lead times may mitigate against the application of hydropower. PPAs can offer price stability over the long term and procurement certainty but cannot resolve issues of low generation due to seasonality.

- **SMRs are a promising pilot-stage technology**. With a capacity factor of 90%, they meet all the energy requirements for smelters when functional. These reactors can be scaled up, are much safer than traditional nuclear technologies, and are suitable for decentralised applications. However, operational pilots are lacking in India at present, and deployment will require support from the policy level, followed by necessary regulatory approvals and integration with PPAs or grids to ensure reliability during their downtime. Based on studies, conventional nuclear power is a mature option and thus highly applicable to smelters. Its high-capacity factor is suited to address energy requirements uninterruptedly. As the capital cost is high, PPAs with nuclear plants would take care of the economics. Along with this, integration with the grid will help in peak load management. The major challenges are long construction periods, high capital costs, and public safety concerns.

- **Coal + CCUS offers a route for coal-based power to be decarbonised**. Pilots are running worldwide, but there is a lack of demonstrated projects in India. At a 70% capacity factor, coal with CCUS can be relied upon to meet smelter loads, where there is the need for investment into capture technologies and storage infrastructure. PPAs may economically stabilise the operations, while integration into the grid provides for conformance with emissions standards through offset mechanisms. NG + CCUS, though in their demonstration phase, also offer a plausible transition pathway based on the leveraging of existing NG infrastructure. Operating at an 80% capacity factor, they will be able to meet smelter demand with a considerable lowering in emissions. But scalability, infrastructure requirements, and carbon capture cost continue to be challenging for CCUS. Supply risks could be handled through PPAs with gas suppliers, while grid integration ensures backup in case of any operational hiccup.

- **Bio Energy with CCUS (BE-CCUS) makes use of renewable biomass energy in concert with CCUS**. While maintaining the potential for carbon negativity, limited biomass availability and the maturity of CCUS technologies hinder its applicability. Smelters may use PPAs with biomass suppliers for their needs or grid-based energy as supplementary sources during shortages.

- **Among the renewables, onshore and offshore wind and PV are known to be intermittent**; hence, they cannot act as an exclusive feeding source for smelting. They would need a grid or extra storage/backup to ensure reliability of supply. CSPs, because of their inherent storage potential, are better placed to serve the smelters, but their costs and applicability in India are not very encouraging due to low smelter load compared to PV systems.

- **RE-RTC solutions integrated with backup solutions, such as PHS and BESS, ensure a continuous supply of power**. These can reach capacity factors of 85-100%. These combinations may thus theoretically fulfil the requirements for continuous smelter operations. These technologies still face some challenges, though: limited scale availability and high costs compared to captive power production (CEA 2024). Battery storage provides a certain amount of flexibility but has deep implications for cost due to the battery replacement cycle and other parameters. For instance, developers will need to build more than the stated capacity to achieve the monthly Capacity Utilisation Factor (CUF) of 70% and annual CUF of 80% of RTC projects. Optimal costs and reliable electricity could be possible through grid integration and PPAs. Table 1, gives the comparative picture of these two storage options on different criteria:

Table 1: Comparative analysis - Pumped Hydro Storage (PHS) vs Battery Energy Storage System (BESS)

Criteria	PHS	BESS
Hard Cost	INR 7.8 Crore/MW (two reservoirs), INR 6.1 Crore/MW (one reservoir)	INR 2.90 Crore/MWh (including GST)
Life	35-40 years; additional 35-40 years after modernisation	8-10 years (battery replacement cycle-dependent)
Yield	75%-80%	68% (Vanadium Redox Flow), 79% (Lead-acid), >85% (Li-ion)
Levelised Cost of Storage	Lower than BESS	Higher than PHS
Gestation Period	60-84 months (site-dependent)	Less than 24 months
O&M Cost	Higher	Lower
Auxiliary Power Consumption	Lower	Higher
Disposal Concern	None	High (battery disposal challenges)
Environmental Impact	Low	High
Reliance on Import	No	Yes (grid-scale systems need imports)

Source: (World Energy Council India 2022)

This analysis shows that while renewable sources alone are not yet capable of providing consistent, high-load power for smelting, integrating them with storage or fossil-based solutions is a promising pathway for decarbonising

electricity in the aluminium sector. The selection of a power source will be based on availability, cost, and technological readiness; therefore, a mix of advanced renewables combined with backup systems emerges as the most viable pathway for smelter decarbonisation.

3.2.2 Challenges in Power Decarbonisation for Smelting

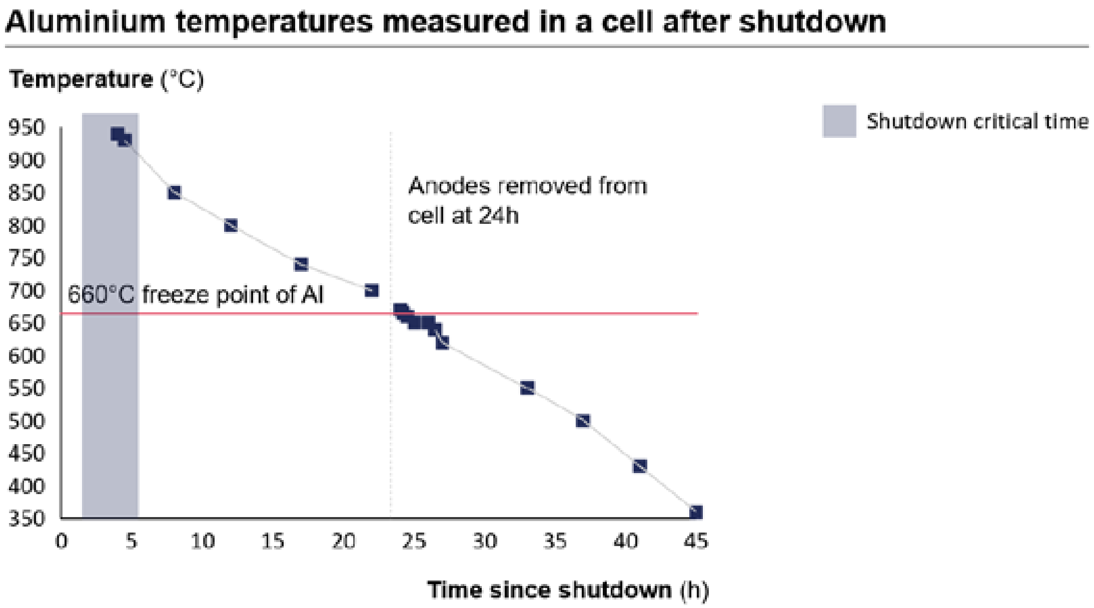
Several challenges constrain the process of aluminium smelting, mainly due to its very high energy requirements and the need for constant, uninterrupted power. Adding renewable sources of energy can further create issues with intermittent power and stability of operation. Key challenges in decarbonising the electrical power sources for aluminium smelting pinpoint specific technical and operational barriers that must be overcome.

Power fluctuations: A given challenge in aluminium production, where the smelting pots need very high temperatures, at about 950°C, maintained with a stable DC current of 0.35 milliamps and voltage of 4.2 to 4.5V. Even slight power fluctuations disturb the alumina solubility, decreasing the volume of production and purity of aluminium, which varies between 99.5 and 99.8 per cent. Impurities such as iron reduce conductivity, tensile strength, and ductility. Other than that, fluctuations in power change the density of the molten metal, increase explosion risks, and cause thermal shocks that can lead to early failures of the pots and hazardous waste. Also, unstable power causes interference in thermal cycles, enhances power consumption, emissions, and loss in production, which, in turn, affects efficiency and quality.

Power Outage: Aluminium smelters rely on a constant and reliable supply of power, since even very short network outages lead to significant operational and economic implications. The Composite Islanding and Load Management System (CILMS) supports power fluctuation management; however, the variability in renewable energy supplies can lead to load shedding. Outages of less than 30 minutes reduce production efficiency from 94% to 90%. Outages longer than 60 minutes lower the temperature below 940° C, leading to partial pot stoppages and quality degradation. If the power outage persists for more than 90 minutes, then the efficiency could collapse to 50% due to partial solidification of the metal. Prolonged outages of 120 to 240 minutes totally solidify the pots and take 15 days for its restart with devastating impacts on production. It also generates hazardous wastes. Figure 22 presents critical risk in power failure on aluminium smelters' operations: fast temperature loss within the smelter cells. As soon as a power failure occurs, the temperature of aluminium inside the cells drops sharply. From the graph, it is observed that within five hours of shutdown, the temperature of aluminium has dropped dramatically, close to the freezing point of 660° C. Within 5 hours of power failure, the commencement of solidification of the electrolyte occurs, making operational issues very severe with a possibility of permanent damage to the pots. After 24 hours, the anodes must be removed, further complicating the restart process with possible impacts on cell life. The electrochemical reaction caused by these

unforeseen shutdowns leads to irreversible damage to the pots and reduced lifetime. The quick restoration of power is crucial to maintaining the productivity and lifetime of operation in smelters.

Figure 22: Graph showing aluminium temperature profile after shutdown in a cell.



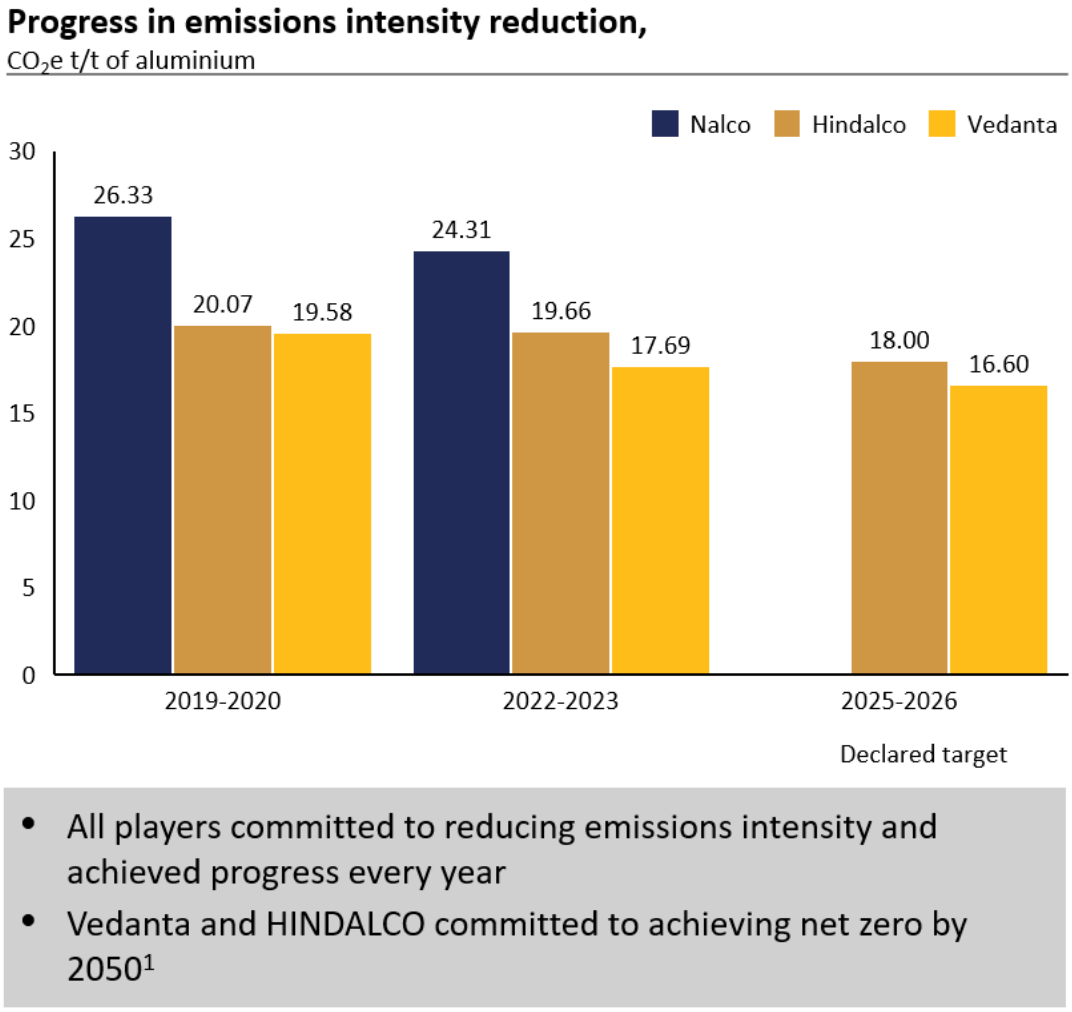
Source: (Øye 2011)

Intermittency of RE: The intermittency of RE creates some problems in producing aluminium, as it requires a continuous supply of power. The schedules of RE change during the day due to which backup from CPPs is necessary. CPPs have to modify their PLF according to the availability schedules of RE. Variations in PLF are difficult technically because of ramp–up and ramp–down limits, frequent changes, and delays in restarting coal mills. Partial loading increases costs and reduces efficiency and plant life. Moreover, partial loading enhances environmental and safety hazards like increase in emission and boiler explosions. Stable power alone can ensure efficient smelting. Therefore, partial load operation of CPPs is not feasible.

3.3 Progress in Decarbonisation of the Indian Aluminium Industry

This section shows how the industry has been proactive in terms of emission reductions. From 2019-2020 to 2022-2023, each of the key players showed significant progress in terms of reduction in emissions intensity. This will develop further as Vedanta and Hindalco are leading from the front with declarations of commitments to achieve net-zero by 2050. These kinds of initiatives are crucial to make the aluminium sector, while reducing its own environmental footprint, contribute to India's journey toward a sustainable and low-carbon future.

Figure 23: Indian aluminium industries' progress in emissions intensity.



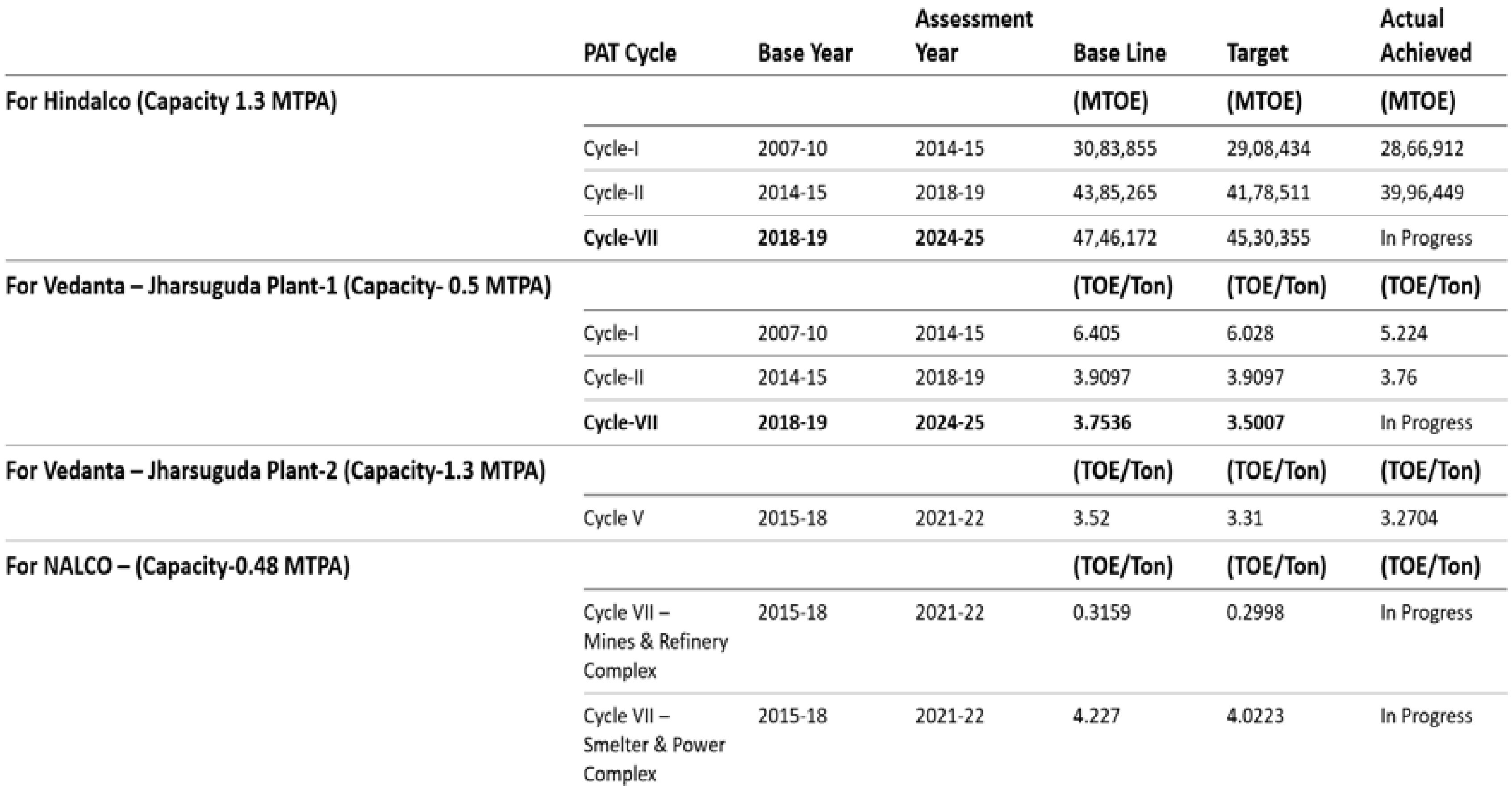
- All players committed to reducing emissions intensity and achieved progress every year
- Vedanta and HINDALCO committed to achieving net zero by 2050[1]

Source: (HINDALCO 2023; NALCO 2023; Vedanta 2024)

3.3.1 Role of the Perform, Achieve, and Trade (PAT) Scheme

It is very well reflected from the various PAT cycles' data that the PAT scheme has driven notable improvement in EE within the Indian aluminium industry. Major players that have been tracked across the various cycles include Hindalco, Vedanta Jharsuguda Plant-1 and Plant-2, and NALCO, among others, with significant energy reductions observed over time.

Figure 24: Energy Efficiency gains achieved by industry through PAT cycles.



	PAT Cycle	Base Year	Assessment Year	Base Line	Target	Actual Achieved
For Hindalco (Capacity 1.3 MTPA)				**(MTOE)**	**(MTOE)**	**(MTOE)**
	Cycle-I	2007-10	2014-15	30,83,855	29,08,434	28,66,912
	Cycle-II	2014-15	2018-19	43,85,265	41,78,511	39,96,449
	Cycle-VII	**2018-19**	**2024-25**	47,46,172	45,30,355	In Progress
For Vedanta – Jharsuguda Plant-1 (Capacity- 0.5 MTPA)				**(TOE/Ton)**	**(TOE/Ton)**	**(TOE/Ton)**
	Cycle-I	2007-10	2014-15	6.405	6.028	5.224
	Cycle-II	2014-15	2018-19	3.9097	3.9097	3.76
	Cycle-VII	**2018-19**	**2024-25**	**3.7536**	**3.5007**	In Progress
For Vedanta – Jharsuguda Plant-2 (Capacity-1.3 MTPA)				**(TOE/Ton)**	**(TOE/Ton)**	**(TOE/Ton)**
	Cycle V	2015-18	2021-22	3.52	3.31	3.2704
For NALCO – (Capacity-0.48 MTPA)				**(TOE/Ton)**	**(TOE/Ton)**	**(TOE/Ton)**
	Cycle VII – Mines & Refinery Complex	2015-18	2021-22	0.3159	0.2998	In Progress
	Cycle VII – Smelter & Power Complex	2015-18	2021-22	4.227	4.0223	In Progress

Source: (BEE 2023, Company reported data.)

- For Hindalco's 1.3 MTPA plant, the PAT cycles have demonstrated steady energy savings. Starting from a baseline of 30.83 Mtoe in Cycle-I (2007-10), the target was set at 29.08 Mtoe for the plant, with an actual achievement of 28.66 Mtoe in the year 2014-15. This progress continues in Cycle II, where Baseline rose to 43.85 Mtoe, with a target of 41.78 Mtoe, and an achieved value of 39.96 Mtoe by2018. Currently, the plant participates in the ongoing Cycle VII (2018-25) with a targeted decreased to 45.30 Mtoe.

- Vedanta's Jharsuguda Plant-1 (0.5 MTPA) has shown improvement in EE from Cycle I through Cycle VII. During Cycle I, the baseline of 6.40 Mtoe/t was set, with a target of 6.02 toe/t, and an achievement of 5.22 toe/t by 2014-15. In Cycle II (2014-18), the plant did better than its target of 3.90 toe/t, achieving 3.76 toe/t. The plant has further targeted a reduction in energy intensity to 3.50 toe/t from a baseline of 3.75 toe/t in the ongoing Cycle VII. Vedanta's Jharsuguda Plant-2, with 1.3 MTPA capacity, participated in Cycle V during 2015-22, during which its energy intensity was reduced from a baseline of 3.52 toe/t to an achieved level of 3.27 toe/t, against a target of 3.31 toe/t.

- NALCO has a smaller capacity of 0.48 MTPA, which again showed improvement through PAT Cycle-VII across two complexes: the mines and refinery complex, and the smelter and power complex. The mines and refinery complex set a baseline of 0.31 toe/t, aiming for 0.29 toe/t, while the smelter and power complex aimed to reduce from 4.22 toe/t to 4.02 toe/t.

- Overall, these PAT cycles indicate an organised approach by the aluminium industry toward achieving measurable energy reductions. While aluminium manufacturing is a highly energy-intensive industry, such focused reductions demonstrate the commitment of the sector toward improving EE and reducing carbon footprint over time.

3.3.2 Other Steps Being Taken by the Industry Towards Decarbonisation

The Indian aluminium industry has undertaken various initiatives aimed at achieving decarbonisation[4].

- Hindalco has introduced **Copper-Insert Collector Bar (CuCB) technology**, improved cell lining, and enhanced current magnetic compensation for better EE. It is also using predictive analytics for pot control and increasing anode length for reduced energy consumption.

- Hindalco's Belagavi refinery uses a **biomass boiler to supply a third of its steam and power**, along with improvements in liquor productivity, steam economy, and statistical modelling to reduce evaporator steam consumption. It also employs Computational Fluid Dynamics (CFD) modelling to reduce

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[4] Source: Indian aluminium industry reported data.

calciner oil consumption and solar power with battery storage at Bagru and GP Mines.

- Hindalco has **co-fired 100,000 tonnes of biomass in FY23- 24**. and has reduced auxiliary power consumption. It has an installed renewable capacity of 173 MW and aims for 200 MW by FY25, with a target of adding storage by FY27.
- Hindalco is also developing a **renewable hybrid system with storage for RTC power**, planning 100 MW by FY26 and 100 MW by FY27.
- Vedanta has fully **graphitised cathodes, developed a smart pot controller, and optimised carbon anode consumption** to reduce emissions. It is also upgrading anode lining and reducing auxiliary power use.
- Vedanta focuses on **onsite captive solar installations** and circulating fluid bed technology in calciners.
- Vedanta is upgrading **air preheaters and economisers, implementing biomass co-firing**, and targeting 30% RE consumption by 2030, with over 1330 MW in PPAs signed for RE.
- NALCO is shifting to 40% non-fossil power by 2030, improving **anode baking efficiency, and enhancing pot graphitisation for lower voltage operation**. It is also adopting energy-efficient compressors and high-efficiency dryers to optimise power use.
- NALCO has adopted **Heavy Fuel Oil additives in calciners to reduce consumption, modified green liquor headers to save coal, and optimised power savings with auto start/stop control logic for turbid pumps**. Additionally, Electrostatic Precipitators (ESPs) are used in charge ratio mode for improved boiler efficiency.
- NALCO has modernised **air preheaters, optimised condensate extraction pumps, and replaced high-pressure heaters** to improve efficiency and reduce coal consumption.

3.4 Identification of Prioritised Solutions

3.4.1 Initial Sub-categorisation

A systematic evaluation process was undertaken to identify high-impact solutions for decarbonisation within the aluminium sector. This was done through secondary research, consultation with the stakeholders and working group members, and expert interviews with representatives from the industries and the government. Out of the 30 decarbonisation initiatives identified for the aluminium industry (see Annexure 2 for a complete list), a structured filtering approach was applied to prioritise actionable solutions, and have hence been summarised into eight

subcategories, with each of the subcategories promising a significant reduction in emissions:

- **Subcategory 1: Exclusive Green Power Grid for Aluminium Production-** Create green power corridors or captive renewable grids that only aluminium smelters and refineries can use. This will provide low-carbon power around the clock that is separate from the coal-dominated state grid and will lead to significant, verifiable reductions in emissions.

- **Subcategory 2: Offer technical and regulatory support to the existing CPPs for RE-RTC to guarantee integrity in operations-** A 15–20% reduction in emissions/tonnes of aluminium is possible with 30% RE blending, while with 70% RE blending, a 45-60% reduction is realised. The time for impact on this is estimated at 3-7 years and will involve the development of feasibility studies and industry-DISCOM-CEA collaborations in depth. This requires proactive state DISCOMs and CEA support to further decarbonisation through hybrid RE and coal power operations.

- **Subcategory 3: Biomass Co-firing Mandates in CPPs-** A 5% biomass cofiring mandate in CPPs can reduce the cost of aluminium production by 2-3% per tonne within three years, subject to the availability and suitability of biomass. There is no need for funding from the government, but a regulatory review must be conducted in order to assure biomass supply and stable pricing considering growing industrial demand.

- **Subcategory 4: Provide Nuclear Power for Existing and New Smelting Capacity-** Nuclear power will potentially decrease the number of emissions from aluminium smelting by 70-75% per tonne. However, the infrastructure and policy development necessary will take longer than ten years. No direct funding from the government is required, but planning is essential for aligning this ‘power supply’ with the needs of industry, as well as establishing a structure that serves to efficiently direct nuclear energy to smelting

- **Subcategory 5: Allocate Hydro Power for Current and New Smelting Capacity-** Smelting using only hydro-electric power can achieve a decrease in emissions of 70-75% per tonne of aluminium; the achievement will take three to seven years since it depends on long–term planning. Government financial support is not called for, but challenges that may arise include limited hydro capacity and need for prioritising industrial use over PHS.

- **Subcategory 6: Economic Incentivisation for Biomass/ Municipal Solid Waste (MSW) Use for Steam and LNG use in calciners-** A 2–3% reduction in emissions per tonne of aluminium may be achieved by using biomass/ MSW for steam and LNG use in calciners. This could be achieved in three years or less, depending on biomass and natural gas supply. There is a need for financial incentive to economically compensate for the high Capex and Opex costs, estimated at about USD 50-60 per tonne of CO_2 reduced. Pilot

demonstration for technology assessment and Capex support for firms using biomass and MSW as fuel are required.

- **Subcategory 7: Mandate Incremental Adoption of EE Measures in Smelters and Refineries-** 5-10% reduction per tonne of aluminium can be achieved within three years with no government funding. The BEE can lead this initiative using the Carbon Credit Trading Scheme (CCTS).

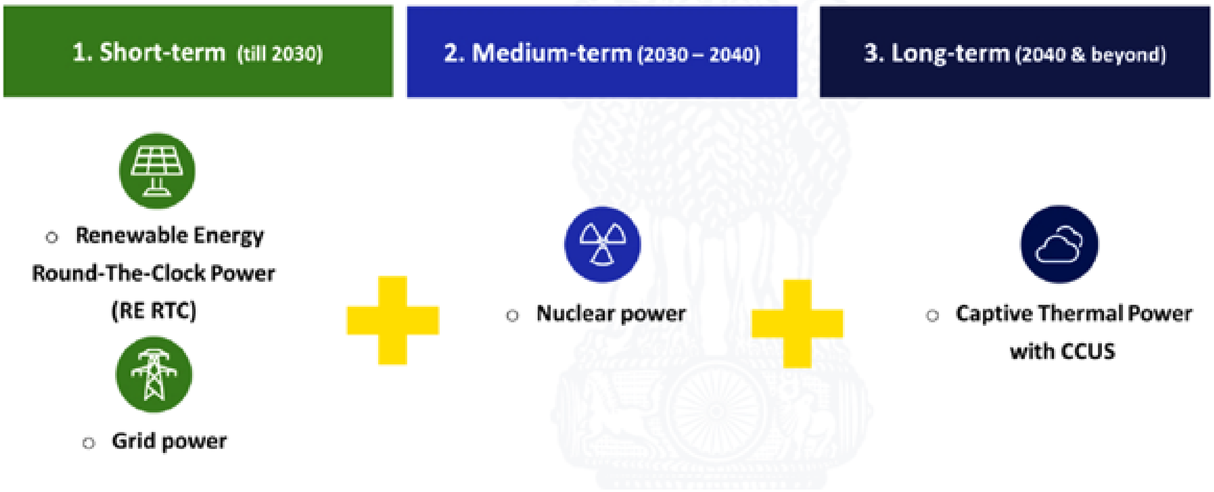
- **Subcategory 8: Enable Local Commercialisation of Key Moonshot Technologies for Decarbonisation-** Emission reductions of 2-4% can be achieved using technologies like inert anodes, CCU, MVR, GH2 calciners, and carbochlorination. Transitioning from coal-based CPPs to SMR could reduce emissions by up to 75%. These benefits are anticipated in 7 to 10 years, government financial support is crucial for research, pilot projects, and scaling due to high initial costs. Challenges include the need for advanced technology maturity and the absence of established market frameworks for new decarbonisation methods.

- **Subcategory 9: Provide Economic Viability Support for RE-RTC Power Adoption via Third-party Open-access Route:** Integration of RE into aluminium production can lead to significant reductions in emissions, with a 15-20% decrease per tonne of aluminium achievable through a 30% blend of RE, and a 45-60% reduction possible with a 70% blend. However, the realisation of these benefits will take approximately three to seven years, due to the development and commissioning of RE projects. To make this transition, the incentives and tariff reductions by the government are a must to support it, and their estimated costs will range from INR 2-4 per kWh of blended RE power based on a consumption of 14,000 kWh per tonne of aluminium. Successful implementation requires the creation of a funding corpus and strong coordination with the MoP and state DISCOMs companies for facilitating third-party access.

3.4.2 Priorities for Achieving Emission Reduction

The subcategories of solutions mentioned in the section above can be prioritised for the decarbonisation of the Indian aluminium industry. However, considering immediate deliverables on the emissions reductions targets by 2030 that India has set, the study has finalised five priorities solutions that have been aggregated across short-term, medium-term and long-term depending on their applicability. Figure 25 depicts a phased approach to decarbonise electricity usage in aluminium smelters:

Figure 25: Prioritised solutions for decarbonising primary aluminium sector electricity



i RE-RTC
ii BSR (Bharat Small Reactors) are 220 MW Pressurised Heavy Water Reactors (PHWR) with an impeccable safety and excellent performance record, which are compact and tailored for captive use
iii Small modular reactor (SMR) is a nuclear reactor that is designed to be built in a factory, transported to a site, and then used to generate power. SMR is therefore much faster to build and start operation and their small size provides the flexibility needed for industrial operations

Source: McKinsey analysis

A. Short-term (till 2030): Renewable and Grid Power Transition

In the near term, aluminium producers can begin reducing their power-related emissions by utilising available renewable and grid-based options.

- **Renewable Energy Round-The-Clock (RE-RTC) Power:** Industries can procure RE through open access, long-term Power Purchase Agreements (PPAs), or develop captive renewable capacity. Round-the-clock RE ensures a stable and cleaner power supply, helping industries decouple from coal-based captive generation.

- **Grid Power:** As India's national grid increasingly integrates renewable power, grid electricity now carries a lower emission intensity. Switching some of the captive demand to grid power provides an Immediate pathway to reduce emissions while maintaining operational flexibility.

These short-term solutions can enable the aluminium sector to achieve quick emission gains while building readiness for deeper transition options. However, these short-term solutions face unique challenges such as changes in policy may create planning and investment risks for industry stakeholders. For example, Introduction of reverse bidding in the onshore wind sector, leading to uncertainty in power procurement.

B. Medium-term (2030–2040): Integration of Nuclear Power

In the medium term, nuclear energy can provide a secure, low-emission supply as baseload to aluminium smelters, complementing intermittent renewable power. Three strategic approaches will be presented:

- **Installation of Small Modular Reactors (SMRs) and Bharat Small Reactors (BSRs):** These advanced reactors can be developed near industrial clusters to supply steady and clean electricity. In addition, SMRs offer scalability, safety, and reduced transmission losses for industrial use.
- **Group Captive Nuclear Model for Large Reactors:** A few aluminium producers come together in a group captive model to jointly invest in or contract power from large-scale nuclear plants. This approach allows for sharing responsibility and cost efficiency with assured access to reliable base load power.
- **PPAs or Open Access from Upcoming Nuclear Plants**: Industries can enter into long-term PPAs or open access contracts with nuclear plants operated by the government or authorised entities. This model provides flexibility to source clean electricity without direct plant ownership.

Together, these nuclear power pathways can significantly reduce grid dependency and provide stable, low-carbon power for smelter operations during the 2030–2040 decade. Till now, participation in the nuclear energy sector was limited to the central government and its entities. However, **The Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Act, 2025**, which was enacted by the Parliament recently, has opened up the nuclear energy sector for participation by the private sector. The Act permits private sectors to build, own, operate or decommission a nuclear power plant and also participate actively in the nuclear fuel fabrication value chain. Now private players can leverage this opportunity to invest in the nuclear energy sector and set up captive nuclear power plants. The Bhabha Atomic Research Centre (BARC) has also initiated development of 200 MW(e) Bharat Small Modular Reactor (BSMR-200), which aims to repurpose thermal power plants and establish captive power plants in energy-intensive hard-to-abate industries.

C. Long-term (2040 & beyond): Captive Thermal Power with CCUS

In the long term, coal-based captive power plants can transition towards CCUS to achieve near-zero emissions.

CCUS Integration with Captive Thermal Power Plants:

- Existing captive plants can be retrofitted with CCUS technologies to capture CO_2 before it is released into the atmosphere.
- Pilot-Scale CCUS Demonstration: In the short term, a pilot-scale project can be initiated within the aluminium sector to demonstrate the technical know-how of CO_2 capture, transport, utilisation, and storage from thermal

power generation. This will help establish technical feasibility for future large-scale deployment.

Over time, these actions will enable the aluminium industry to sustain reliable power while achieving deep decarbonisation and aligning with India's Net Zero 2070 goal. However, limitations of these long-term solutions are:

- High investment costs and uncertainty around carbon market mechanisms.
- Lack of established legal and safety frameworks for CO_2 capture, transport, and long-term storage.
- Insurance, liability transfer, and risk-sharing mechanisms for leakage of stored CO_2 are not yet developed.
- Limited technical demonstration projects available to validate large-scale deployment feasibility.

Chapter 4:

Recommendations and Conclusion

Chapter 4: Recommendations and Conclusion

A phased approach will be crucial for the aluminium sector of India on it's way to a low carbon future. In this regard the recommendations are structured to reduce emissions in the near term while the whole sector is prepared for low carbon transformation in the long run.

4.1 Short-term: RE-RTC

Among these three options, RE-RTC is the low-hanging fruit. This becomes the preferred short-term pathway for decarbonisation with the scaling-up of RE capacity and increased RE blending grid power. The existing policy framework, comprising ISTS waivers, RPO, and PPA, is envisaged to provide an enabling platform for the growth of renewable energy in different sectors in the short run. This expansion, however, needs to be supplemented with the modernisation of the grid to cope with the greater share of renewables in the grid as well as the intermittent nature of RE production.

This is vital, as any interruption in power supply is detrimental to aluminium production, especially for the smelters, resulting in reduced productivity in both quality and quantity, and also reducing the operational lifespan of the smelter.

As a safeguard against this, aluminium plants keep CPPs, which mostly use coal as fuel. Measures to expand RE usage must account for captive power generation. The following measures will be helpful in this regard:

- **Permit dual Central Transmission Utility-State Transmission Utility (CTU-STU) connectivity:** Allow dual connectivity, especially for plants requiring voltage levels above 440 kV, and to support simultaneous injection and withdrawal of power from the grid.
- **Enable simultaneous grid operations:** Permit simultaneous withdrawal of RE power and injection of excess CPP power into the grid to support real-time power balancing.
- **Allow conversion of CPP to individual power producer (IPP):** Enable surplus CPP generation to be sold as IPP, with relaxed conditions, and waiving additional fees for such capacity.

4.2 Medium-term Nuclear Power

Nuclear power offers a stable, low-carbon option for the aluminium sector. To enable the application of nuclear energy in hard-to-abate industries, the government has opened up the nuclear energy sector for enabling active participation of the private sector. The **Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Act, 2025** permits private companies and their JVs to hold the

license for building, owning and operating nuclear power plants and fuel fabrication facilities. The SHANTI Act also aligns India's civil liability framework with the global best practices and resolves the long-standing issues such as supplier's liability. It acknowledges the crucial role of an empowered regulator in a market shifting from a monopoly to multiple players and empowers the Atomic Energy Regulatory Board (AERB) with statutory status. Simultaneously, the Bhabha Atomic Research Centre (BARC) has taken up the development of 200 MW Bharat Small Modular Reactor (BSMR-200) in pursuance of the budget announcement of deploying indigenous SMRs by 2033. BSMR-200 is being designed for repurposing thermal power plants and establishing captive nuclear power plants in energy-intensive industries.

Nuclear power can be made available to industry after 2030 by 3 different approaches-

- **Small Modular Reactor (SMRs):** Industry stakeholders may consider establishing Small Modular Reactors (SMRs) in proximity to their operations to meet their electricity requirements. SMRs are expected to have low gestation period and low land footprint. They may offer a feasible pathway for smaller units seeking to transition towards nuclear energy.

- **Group Captive Model:** Under the proposed group captive arrangement, a nuclear power plant may be established, either in proximity to or at a distance from aluminium smelters, to serve a consortium of aluminium industry stakeholders. The capital expenditure for establishing the facility would be shared among the participating industry players. In accordance with prevailing regulatory norms, captive consumers must have a minimum ownership of 26% in the plant and consume at least 51% of the electricity generated annually.

- **Open Access to Nuclear Power:** In an open access system, industrial consumers can procure/tender electricity from nuclear power plants situated anywhere in the country. This system allows major consumers to procure their requirement directly from any producer of their choice without having to bear the capital cost of establishing a generation facility.

The SHANTI Act, 2025 empowers the Central Government to develop norms and mechanisms for fixing the tariff of electricity from nuclear power plants. The central government needs to develop and notify special norms and mechanisms to enable deployment of nuclear power in aluminium sector through the above three approaches.

4.3 Long-term: Coal-based CPP+CCUS

Long-term use of CCUS can play a crucial role in the long-term decarbonisation of coal-based captive power plants; however, to achieve this, immediate support is required for the establishment of at least a pilot-scale CCUS project that would establish the technical know-how related to capture, transport, utilisation, and storage of CO_2 from aluminium smelter-linked power plants. The success of these pilots will depend on policy and regulatory support under the proposed National CCUS Mission in terms of a clear MRV system, plant design and equipment standards, and CO_2

storage standards. Safety and liability protocols regarding CO_2 leakage, insurance, and long-term site management need to be accorded explicit status.

Finally, financial incentives like carbon credit eligibility, viability gap funding, and green taxonomy recognition for CCUS projects would be critical to bring about active industrial participation and de-risk early investments.

While CCUS offers deep decarbonisation potential, the technology remains expensive and commercially unproven at full industrial scale, especially for aluminium. High capture costs, infrastructure requirements, and uncertainty around long-term storage make it a longer-term option requiring substantial government and policy support.

4.4 Recommendations

Decarbonising the aluminium sector is essential, with nearly 76% of emissions arising from electricity consumption. The Working Group has identified and prioritised three practical solutions short-term transition to RE-RTC power, medium-term adoption of captive nuclear energy and long-term deployment of CCUS with captive coal-based power -supported by fiscal, non-fiscal and institutional coordination.

A. Short Term: Shift to RE-RTC Power

In the short term, aluminium producers are encouraged to transition towards RE-RTC electricity through PPAs or by developing captive RE capacity. This shift includes replacing CPP with grid electricity where feasible and contracting direct hydro power. The RE-RTC pathway is expected to support a green power share of 3% by 2030 and 15% by 2035.

B. Medium Term: Shift to Captive Nuclear Power

In the medium term, nuclear energy can provide a secure, low-emission supply as baseload to aluminium smelters, complementing intermittent renewable power. The aluminium stakeholders can invest in the nuclear energy sector and set up captive nuclear power plants by adopting three strategic approaches:

- Installation of Small Modular Reactors (SMRs) and Bharat Small Reactors (BSRs)
- Group Captive Nuclear Model for Large Reactors and
- PPAs or Open Access from Upcoming Nuclear Plants

C. Long Term: CCUS with Captive Coal Power

In the long term, aluminium producers should deploy CCUS on captive coal power plants to mitigate emissions from baseload operations. While CCUS represents a critical pathway for hard-to-abate emissions, its feasibility depends on pilots and infrastructure development. Adoption may be possible post-commercial pilot completion, with significant fiscal and technical support required for its execution. To support the implementation of the prioritised solutions, the following enablers have been identified:

D. Non-Fiscal measures:

The following regulatory and operational enablers are recommended as necessary to ensure smooth technical integration of RE-RTC power in the aluminium sector:

- **Exclusive Green Power Grid for Aluminium Production:** Create dedicated green feeders or RE power corridors for aluminium smelters and refineries, so they receive reliable 24×7 clean electricity that is kept separate from the coal-based grid. This ensures genuine RE-RTC supply, prevents mixing with fossil power, and allows transparent tracking of emissions reductions.

- **Permit dual CTU-STU (Central Transmission Utility- State Transmission Utility):** Allow dual connectivity, especially for plants requiring voltage levels above 440 kV or simultaneous injection and withdrawal of power.

- **Enable concurrent grid operations:** Allow simultaneous withdrawal of RE power from the grid and injection of CPP power into the grid to facilitate real-time balancing of power.

- **Operational flexibility:** Granting of regulatory flexibility for ramp-up/ramp-down of CPP output to meet plant operational or maintenance requirements.

- **Permit conversion of CPP to IPP:** Let excess CPP capacity be sold as IPP, with relaxed conditions, and even consider waiver of additional surcharge or taxes on such converted capacity to improve viability.

The following non-fiscal measures are necessary for the development and deployment of nuclear power as a medium-term decarbonisation option in the aluminium sector:

- **Land Boundary Regulation Reform:** Amendment of the prevailing norms that require an exclusion zone and a natural growth zone of at least 1km and 5km radius, respectively, around a nuclear power plant. Reduction of exclusion zone to about 500 meters, where feasible without compromising safety, would ease land acquisition challenges especially for SMRs equipped with passive safety features and new technologies.

- **Water Resource Management Support:** Facilitate access to large volumes of water required for nuclear operations by a factor of 4x of CPPs through coordinated approvals and sustainable sourcing strategies.

- **Right-of-Way for Wastewater Discharge:** Provide regulatory support and community involvement in securing right-of-way to discharge treated wastewater and perception management with local stakeholders.

- **Smooth Approvals and Permitting:** The total time required for construction of a large nuclear power plant is about 11 to 12 years, out of which approximately half of the time is consumed in pre-project activities and approvals. There is a need to fast-track the permitting system and to develop a single-window system that will reduce delays in projects.

Non-fiscal measures that are of paramount importance for the long-term adoption of smelter operation with CPP equipped with CCU include the following:

- **Develop CO_2 transport and storage infrastructure** through a hub-and-cluster model to enable shared access and reduce costs.
- **Identify and map suitable geological storage** basins with government-backed assessments to support long-term planning.
- **Streamline environmental and regulatory approvals** for CCUS projects, including transport pipelines and injection wells.
- **Facilitate coordinated industrial cluster development** by aligning state industrial policies, infrastructure planning, and stakeholder engagement.

E. Phased Institutional Coordination Measures:

The decarbonisation process of the aluminium sector requires strong institutional coordination to be effective and timely. The strategic institutional steps are outlined as described below.

- **Establish an inter-agency coordination mechanism** involving MoP, MNRE, MoEFCC, DAE, and NITI Aayog to ensure proper alignment and smooth implementation of policy actions across RE, nuclear power, and CCUS technologies.
- This will involve **designating a central nodal agency or green transition task force** that leads decarbonisation initiatives for the aluminium sector under India's overall strategy for a net-zero transition. In essence, this would ensure coordinated efforts, monitoring of progress, and their alignment with the nation's decarbonisation goals. Representation will come from the government, industry, academia, multilaterals, and other stakeholders in the green transition of the aluminium sector.
- Enable **early interaction between industry and implementing agencies** like NPCIL, SECI, NTPC, and PGCIL, specifically with regards to planning and implementation of RE-RTC supply mechanisms and future nuclear integration pathways. Such interactions will help address constraints on technical, regulatory, and supply sides in the early stages.
- Devise a **policy framework to underpin the CCUS industry**. Key elements include project permitting, long-term rights for storage, attribution of liability, and legal clarity in preparation for CCUS technologies deployment in hard-to-abate industrial sectors such as aluminium.
- **Harmonise the state and central clearances** related to the development of green infrastructure, including grid upgrades, RE plants, and CCUS networks near the aluminium smelter clusters. This would reduce approval delays and allow for faster on-ground implementation.

- **Integrate the needs of the aluminium sector into the national energy transition platforms** like the National Green Hydrogen Mission and the emerging carbon market frameworks. This would ensure that decarbonisation priorities in the sector are suitably represented and supported by national-level policy instruments.

- **Enable public-private coordination platforms** that bring together industry stakeholders, technology providers, investors, and government agencies to align on decarbonisation investments, share knowledge, streamline financing, and establish clear regulatory timelines.

A set of coordinated fiscal, regulatory, and institutional measures should come together to form a stable ecosystem that can enable the transformation of the emission-intensive aluminium sector and support energy transition throughout its value chain.

4.5 Conclusion and Way forward

As the analysis has shown, shifting the power supply to cleaner sources would not only involve considerable investment but also require the overcoming of several technical and legal barriers. Consultation with stakeholders suggests that a near-term decarbonisation pathway-3% green power share by 2030 and 20% by 2035, which is 15% from RE-RTC (Renewable Energy- Round the Clock) and 5% from captive nuclear-is achievable. The existing framework on renewable energy will go a long way in facilitating RE-RTC in the near future either in the form of captive capacity, procurement from third parties, or increased share of renewables in green power. These necessitate modernisation and reliability of the grid, thus attracting interest at both national and state levels of the government. Support would also be needed to facilitate simultaneous grid withdrawal and injection.

In the medium term, nuclear energy can serve as a secure, low-emission baseload for aluminium smelters, complementing renewables. It can be adopted through three approaches that are deployment of Small Modular Reactors (SMRs) and Bharat Small Reactors (BSRs) near industrial clusters; group captive models, and long-term PPAs or open access contracts with upcoming nuclear plants for flexible sourcing. Collectively, these approaches can reduce grid dependency and provide stable, low-carbon power for smelters in the 2030–2040 decade. The SHANTI Act, 2025, permits private companies and their JVs to hold the license for building, owning and operating nuclear power plants and fuel fabrication facilities thereby enabling private industry to invest in captive nuclear power generation

CCUS is expected to remain a long-term solution, as its adoption may be delayed well beyond 2035, pending development of necessary infrastructure and enabling ecosystems, alongside technology adapted for the sector. This will enable the captive coal-based power plants, maintained by the Aluminium sector, to continue as a source of baseload power. To support this strategy, a pilot project in the sector is recommended, as it will demonstrate the feasibility of CCUS facilities in the sector and provide insights into necessary technical adaptations required for the sector. This will need backing in the form of financial support, legal framework, and established infrastructure for CCUS from capture at source to storage in sinks.

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Annexures

Annexure 1

Table 2: The sectoral technical working committee on Aluminium

S. No.	Composition	
1	Shri Ishtiyaque Ahmed, Sr. Advisor, NITI Aayog	Chairman
2	Shri Rajnath Ram, Advisor, NITI Aayog	Member
3	Representative from the Ministry of Mines	Member
4	Representative from BEE	Member
5	Representative from Jawaharlal Nehru Aluminium Research, Development & Design Centre	Member
6	Representatives at the level of Chief Sustainability Officer or equivalent:	Member
	• Hindalco	Member
	• Vedanta	Member
	• NALCO	Member
	• Jindal Aluminium	Member
7	Shri Jawahar Lal, General Manager, Energy, NITI Aayog	Member Secretary
8	McKinsey & Company	Knowledge Partner
9	WRI India	Knowledge Partner

Terms of Reference (ToR) for the committee were:

(i) Identifying the sources of emission along the production value chains and establishing baseline sectoral emissions.

(ii) Analysing the current strategies of the government and private sector.

(iii) Analysing the international market trends and preparing the sector outlook on competitiveness.

(iv) Identifying and prioritising the various decarbonisation levers for each sector, including circular economy and resource efficiency.

(v) Developing sector-specific abatement curves to illustrate decarbonisation levers, their potential abatement, and associated costs.

(vi) Identifying key projects and enablers required to achieve aspired decarbonisation pathways, including:

   a. Policy and Regulatory frameworks.
   b. Technology interventions, with high-level assessment on commercial viability.
   c. Sources of capital and funding.

(iv) Formulating sector-specific action plan and associated financial funding mechanism.

(v) Any other measures/activities required for achieving the objectives of the Committee.

Annexure 2

Table 3: Comprehensive list of 30 initiatives for decarbonisation

1	Advanced analytics to reduce non-carbon costs (NCC)
2	Coating of anodes
3	Fluidised bed calcination
4	Energy Efficiency - Refining
5	Energy Efficiency – Smelter
6	Improved cell-lining
7	Graphitised cathode
8	CHP and waste-heat cogeneration
9	Optimise anode design
10	Smart pot controllers
11	Tube digester
12	Biomass/MSW use for steam and LNG use in calciners
13	MVR+H2
14	Carbo-chlorination w/out CO_2 regeneration
15	Hall-Héroult + Carbon Capture and Storage (CCS)
16	Inert anode
17	Hydrogen Calciner
18	Hydro
19	SMR
20	Nuclear Reactor
21	NG+CCUS
22	Coal + CCUS
23	BE+CCUS
24	On-shore wind
25	Off-shore wind
26	Solar PV
27	Solar CSP
28	RE RTC (Third Party Open Access)
29	RE RTC + Pumped hydro
30	RE RTC + battery

NOTES

सत्यमेव जयते

NITI Aayog