# Decarbonisation Roadmap for a Sustainable and Competitive Indian Aluminium Industry

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https://doi.org/10.71659/icsoba2025-al065

## Abstract

The Indian aluminium industry is a cornerstone of the nation's industrial growth, supporting sectors like infrastructure, transportation, and energy. However, its dependence on coal-based power for smelting and refining makes it one of the highest carbon-emitting industries. As India pursues its commitment to achieving net-zero emissions by 2070, decarbonisation of the aluminium sector is crucial for balancing industrial expansion with environmental sustainability. Transitioning to renewable energy sources, such as nuclear and adopting emerging technologies like green hydrogen and carbon capture will play a pivotal role in reducing emissions. Additionally, enhancing energy efficiency through advanced smelting techniques and increasing the share of secondary aluminium production can significantly lower the industry's carbon footprint. Promoting a circular economy through increased recycling, policy-driven incentives, and stricter emission norms will further accelerate the transition.

Collaborative efforts between the government, industry stakeholders, and research institutions will be essential to create a sustainable and competitive aluminium sector that aligns with India's broader climate action goals. A structured roadmap integrating technological advancements, policy support, and investment in green alternatives will ensure that the Indian aluminium industry remains a global leader while meeting its decarbonisation targets.

**Keywords:** Aluminium, Carbon, Decarbonisation, Sustainability.

## 1. Introduction

Aluminium is among the most widely used metals worldwide and is the fastest-growing segment within the non-ferrous metals sector. Due to its lightweight, strength, and recyclability, aluminium plays a vital role in modern industrial applications and ranks second only to steel in terms of global consumption volumes. However, India's per capita aluminium consumption is still relatively low 2.6 kg compared to the global average of 11 kg – indicating significant potential for future growth [1].

### 1.1 Role in Economic Growth and Industrial Development

The Indian aluminium industry is a strategic contributor to the nation's economic development, supporting critical sectors such as infrastructure, power transmission, transportation, packaging, and renewable energy. Aluminium's high strength-to-weight ratio makes it a preferred material for electric vehicles, aerospace, solar panel frames, and wind turbine components. In particular, the power sector remains the largest domestic consumer, with aluminium widely used in conductors and cables for electricity transmission and distribution. As India advances its industrialisation and clean energy transition goals, aluminium will continue to be integral to achieving sustainable growth.

## 1.2 Current Production and Energy Consumption

Despite its advantages in end-use applications, aluminium production is highly energy-intensive and contributes significantly to industrial greenhouse gas (GHG) emissions. In 2019–2020, the Indian aluminium industry emitted approximately 77 million tonnes of $CO_2$, accounting for nearly 9 % of the country's total industrial emissions [2]. The major emission hotspot lies in the smelting stage, which is predominantly powered by captive coal-based electricity, responsible for nearly 85–90 % of total emissions from the aluminium value chain. alumina refining also contributes significantly to the carbon footprint due to high thermal energy requirements.

India has an installed aluminium production capacity of 4.1 million tonnes per annum and actual production during financial year (FY) 2023-2024 is shown in Figure 1 [3-5]. In FY 2023–2024, India accounted for 6 % of global aluminium production, with the remaining 94 % contributed by the rest of the world, underscoring India's growing presence in the global aluminium industry while highlighting the need for sustainable growth strategies [6]. The production facilities are largely concentrated in eastern India, particularly Odisha due to the availability of bauxite and coal. Secondary aluminium production constitutes nearly 31–35 % of the total aluminium produced in India. The sector is highly fragmented and largely unorganized, and heavily dependent on imported aluminium scrap. Notably, about 56 % of India's aluminium imports are in the form of scrap. The secondary aluminium sector's contribution is expected to grow, with recycled aluminium projected to see a compound annual growth rate (CAGR) of around 8 % in the near term.

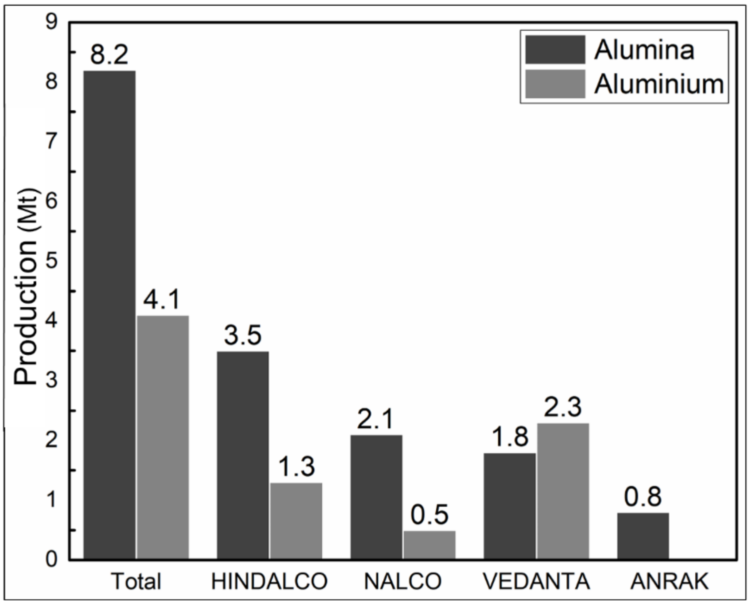

**Figure 1. Primary aluminium and alumina production in India during FY 2023-2024.**

In India, bauxite refining consumes approximately 5 600 kWh/t Al, significantly higher than the global best practice of 4 400 kWh/t Al. In the smelting phase, India's electricity consumption ranges from 13 700 to 15 300 kWh/t Al, which is on par with the global average of 14 091 kWh/t Al (see Figure 2) [3, 5, 7]. These figures highlight the urgent need to decarbonise the sector, particularly by adopting cleaner technologies.

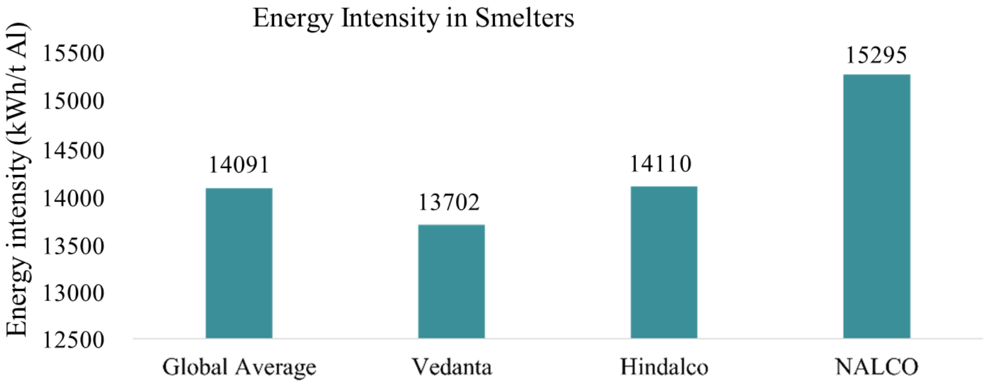

**Figure 2. Comparison of energy intensity in aluminium smelters.**

## 2. Current Emissions and Need for Transitioning to Renewable Energy Sources

The Indian aluminium industry currently exhibits a high carbon footprint, emitting approximately 17.5 tonnes of $CO_2$ per tonne of aluminium produced [2]. These emissions include direct fuel-related emissions, electricity-associated emissions, and process-related emissions.

With the introduction of dedicated climate policies and the impending implementation of the Carbon Border Adjustment Mechanism (CBAM), Indian aluminium producers are accelerating their decarbonisation strategies, particularly in light of substantial exports to the European Union (EU). Of the 4 million tonnes of aluminium produced annually, approximately 2.3 million tonnes are exported, with 29 % of this volume destined for European markets (see Figure 3).

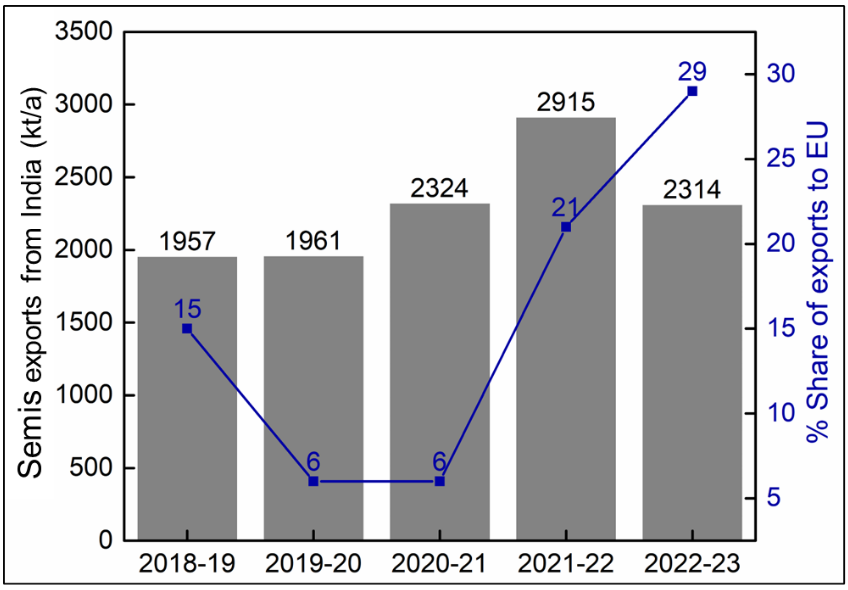

**Figure 3. Exports of semi-finished aluminium goods and EU’s share.**

In aluminium production, the share of electricity in total energy consumption varies significantly between the refinery and smelter stages. Electricity accounts for only 25 % of the total energy consumption in the refining stage, where thermal energy (primarily from fossil fuels) is dominant due to the high-temperature digestion and calcination processes involved in converting bauxite to alumina. In contrast, the smelting stage is heavily electricity-intensive, with around 98 % of the total energy consumption derived from electricity (Figure 4). This high share is primarily due to the electrolysis process used in the Hall-Héroult cell, which requires a substantial and continuous electric current to reduce alumina into aluminium metal. This contrast highlights the critical role of electricity in smelting and underlines the importance of decarbonizing the power supply to reduce overall emissions from aluminium production.

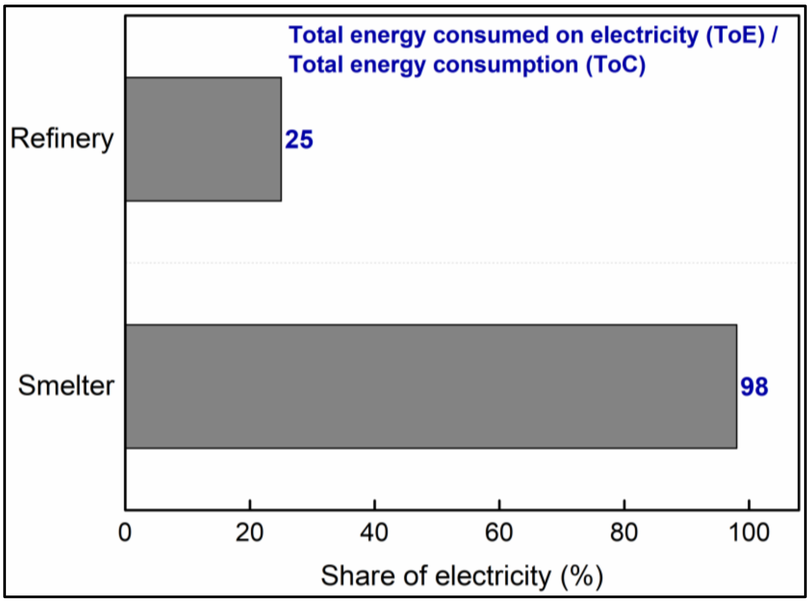

**Figure 4. Share of electricity in total energy consumption.**

The drive to lower carbon emissions is now essential not only for compliance with evolving international regulations but also to meet the rising expectations of global consumers and investors regarding environmental responsibility. To maintain export competitiveness and secure continued market access, especially in the EU, Indian aluminium producers are increasingly investing in technological upgrades and operational improvements to minimise environmental impact.

## 3. Decarbonisation and Marginal Abatement Cost Curves (MACC)

With rising pressure, aluminium industry needs to reduce carbon intensity, there is a critical need to adopt cleaner technologies, improve energy efficiency, and shift toward renewable energy sources. However, these interventions vary widely in terms of cost and impact. This is where Marginal Abatement Cost (MAC) analysis becomes a powerful decision-making tool. By quantifying the cost per tonne of $CO_2$ reduced for each decarbonisation measure, MAC analysis helps prioritize technologies that offer the most cost-effective emissions reductions. It enables policymakers, plant operators, and investors to identify low-hanging fruits such as energy efficiency improvements and renewable energy integration, while also planning for higher-cost measures like carbon capture and emerging technologies in the long term. In this way, MAC serves as both a strategic and economic compass, guiding the aluminium industry along a phased and financially viable path to net-zero emissions.

### 3.1 Methodology for MACC

To identify the Marginal Abatement Cost (MAC) of decarbonisation measures in the aluminium industry, a systematic methodology was followed (Figure 5). First, available technologies with a Technology Readiness Level (TRL) above 7 were shortlisted to ensure commercial viability. These technologies were then vetted for relevance and feasibility within the context of aluminium production. Following this, each technology's emission reduction potential was assessed along with its impact on the cost of aluminium production, considering capital investment, operating costs, and savings from improved efficiency. This approach allows for a comparative evaluation of abatement measures and helps build a MAC curve that informs cost-effective decarbonisation pathways. This paper considers interventions up to FY 2030, focusing exclusively on technologies with TRL above 7, reflecting a practical and implementation-ready decarbonisation pathway.

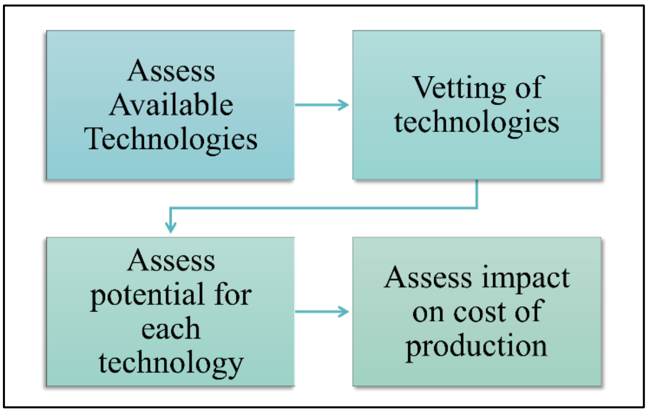

**Figure 5. Methodology for estimating marginal abatement cost curves.**

### 3.2 Marginal Abatement Cost Curves for Aluminium Smelter

In the context of aluminium smelters, the key decarbonization technologies assessed in this paper are:

a) **100 % graphitised cathode implementation:** Utilizes fully graphitized carbon cathode blocks in aluminium electrolysis cells to lower electrical resistivity, reduce energy losses, and extend cell life.
b) **Copper insert collector bar installation in potline:** Embeds high-conductivity copper inserts to decrease cathode voltage drop, improve current distribution, and enhance energy efficiency in aluminium smelter pots.
c) **Smart pot controller implementation:** Deploys advanced digital control systems to continuously monitor and optimize potline operations, improving process stability, energy efficiency, and reducing carbon foot print.
d) **Capital solar power installation:** Involves installing large-scale solar photovoltaic (PV) plants to supply renewable electricity, reducing the carbon footprint of aluminium production.
e) **Heat rate improvement in the CPP through operational improvement:** Implements process optimizations and maintenance best practices in captive power plants (CPPs) to increase thermal efficiency and lower coal consumption per unit of electricity generated.
f) **Magnetic compensation loop in the smelter:** Installs magnetic compensation loops around potlines to counteract magnetic field disturbances, stabilizing metal pad movement and improving current efficiency.
g) **Biomass co-firing in boiler:** Partially replaces coal with biomass in power plant boilers to reduce fossil fuel use and lower greenhouse gas emissions.
h) **Natural gas co-firing in CPP boiler:** Blends natural gas with coal in captive power plant boilers to decrease carbon emissions and improve combustion efficiency.
i) **RE-RTC integration in the smelter through PPA:** Integrates round-the-clock (RTC) renewable energy (RE) supply into smelter operations via power purchase agreements (PPAs), ensuring a reliable, low-carbon electricity mix.
j) **Anode baking furnace fuel conversion to NG:** Converts anode baking furnace fuel from coal or oil to natural gas (NG), reducing emissions and improving combustion efficiency in anode production.

The technology diffusion analysis presented in Figure 6 reveals distinct adoption patterns across various decarbonization technologies in the aluminium smelting sector. The data shows that some technologies, such as smart pot controller implementation (74 %) and 100 % graphitised cathode implementation (80 %), have seen relatively high uptake. In contrast, measures like anode baking furnace fuel conversion to natural gas, RE-RTC integration, and capital solar power installation have seen no adoption (0 %). Other technologies, such as magnetic compensation loop (46 %), CPP heat rate improvement (20 %), and copper insert collector bar installation (7 %), show varying degrees of implementation. This pattern highlights where the industry is focusing its efforts and where barriers to adoption may exist. These technologies benefit from existing infrastructure compatibility and require minimal operational disruptions, facilitating faster implementation across the industry. Renewable energy integration shows moderate diffusion rates, constrained primarily by grid infrastructure limitations and regional energy market dynamics.

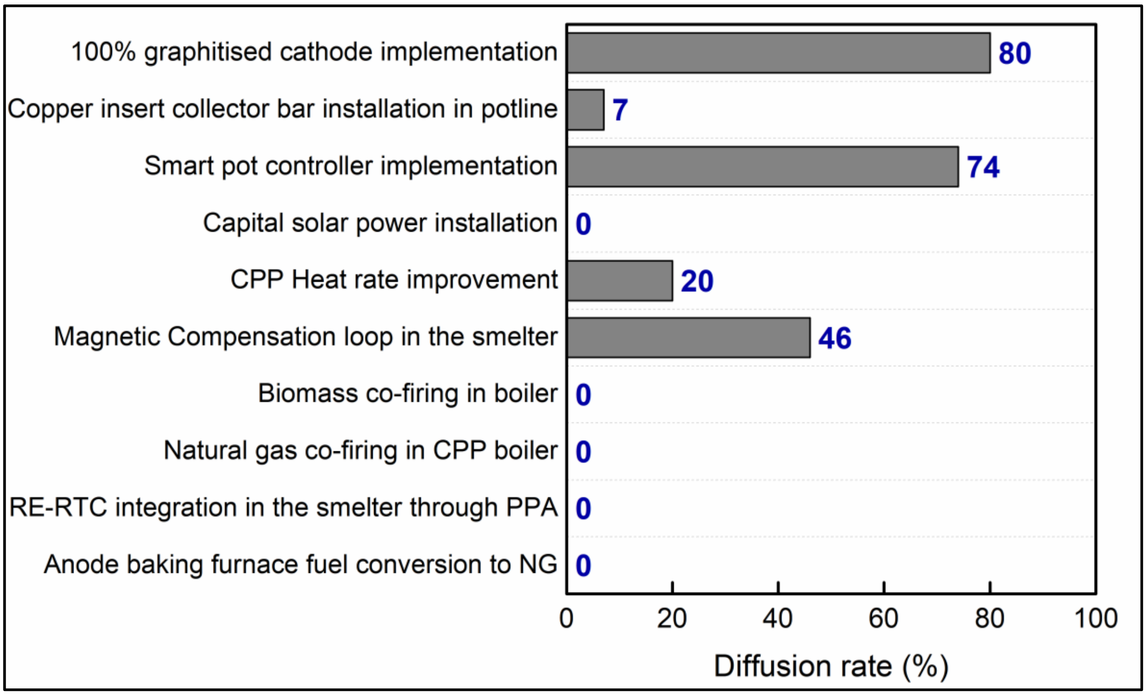

**Figure 6. Diffusion rates for various technologies.**

Figure 7 presents the marginal abatement cost curve (MACC) for different decarbonization measures, illustrating the cost-effectiveness hierarchy of various emission reduction strategies. The MACC framework compares the expense required to reduce one additional tonne of $CO_2$ emissions, incorporating implementation costs while accounting for future financial savings from emission reductions. Technologies with negative marginal abatement costs (right side of the curve) actually save money while reducing emissions – examples include implementation of 100 % graphitised cathodes, copper insert collector bars, smart pot controller systems, etc. Technologies with positive costs (left side) require net investment for each tonne of $CO_2$-e abated, such as anode baking furnace fuel conversion to NG, RE-RTC integration in the smelter through PPA, Natural gas co-firing in CPP boiler, etc. The positioning reflects the current cost dynamics of renewable energy deployment, including grid integration expenses and infrastructure modifications required for industrial-scale renewable energy utilization. This analysis enables decision-makers to prioritize "no-regret" options first and plan for higher-cost interventions as policy or market conditions evolve.

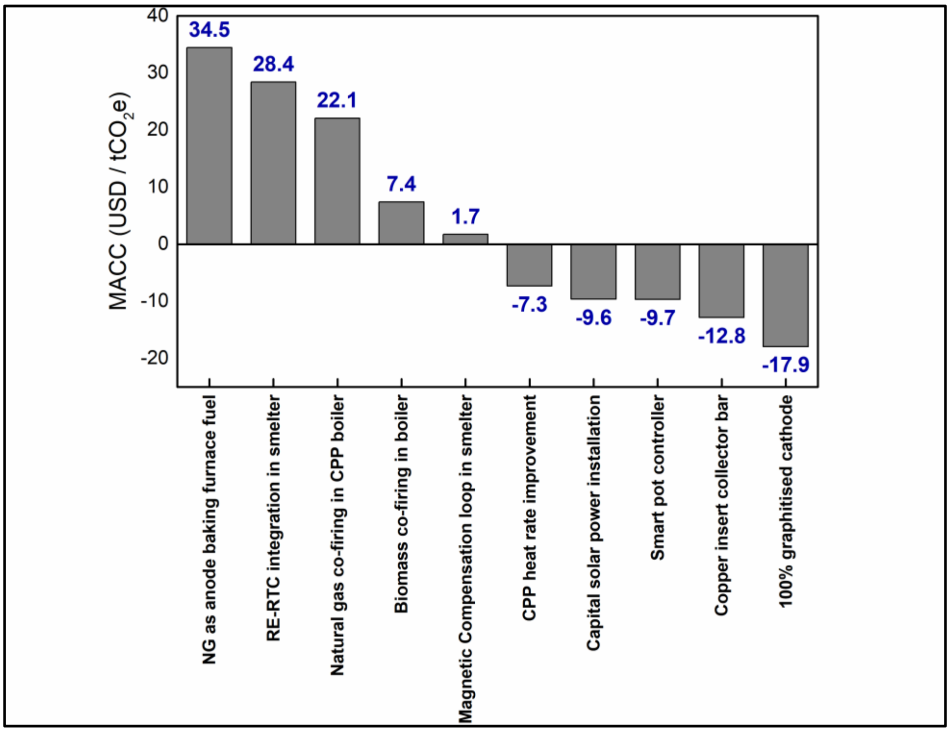

**Figure 7. MACC for different potential decarbonisation measures.**

The GHG abatement potential analysis in Figure 8 quantifies the emission reduction capacity of various decarbonization measures across the aluminium smelting value chain. Renewable energy adoption presents the largest abatement potential, capable of addressing the substantial indirect emissions from electricity consumption in the electrolysis process. It is essential for understanding the scale of emission reductions achievable and for setting realistic targets in line with regulatory or voluntary climate commitments. It demonstrates that while some measures offer modest abatement, others are essential for achieving sector-wide targets. Energy efficiency improvements, while individually modest in abatement potential, collectively represent substantial emission reductions when implemented across the industry. Figure 8 also shows suggests that combining multiple technologies can deliver synergistic benefits, achieving greater reductions than any single measure alone. This holistic view supports the development of comprehensive decarbonization roadmaps for the aluminium sector.

Figure 9 presents a detailed investment analysis across various decarbonization measures, highlighting the substantial capital required for industry transformation. Renewable energy infrastructure emerges as the most investment-intensive, reflecting the extensive grid modifications and generation capacity needed to support the aluminium smelting sector. The chart contrasts low-cost measures—such as process optimization and minor upgrades, with high-cost options like renewable integration and (carbon capture, utilisation an storage (CCUS) deployment. By outlining the upfront costs, impact, and cost-effectiveness of each option, the figure supports informed financial planning, helping companies and policymakers allocate resources strategically and navigate the financial challenges of deep decarbonization.

This comprehensive analysis reveals that aluminium industry decarbonization requires a coordinated approach combining immediate efficiency improvements with long-term technological transformation. The analysis demonstrates that while some technologies offer immediate economic benefits through negative abatement costs, breakthrough technologies require substantial upfront investments with longer payback periods. The technology diffusion patterns indicate that energy efficiency measures will achieve rapid implementation due to their proven commercial viability and immediate cost benefits.

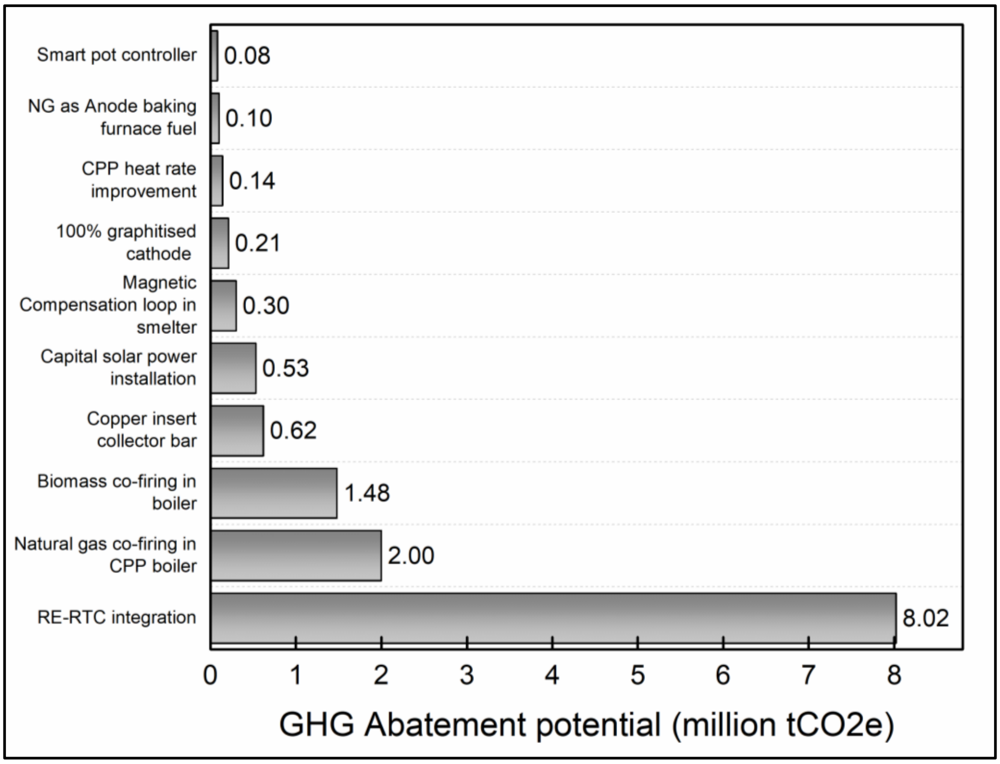

Figure 8. GHG abatement potential of various measures.

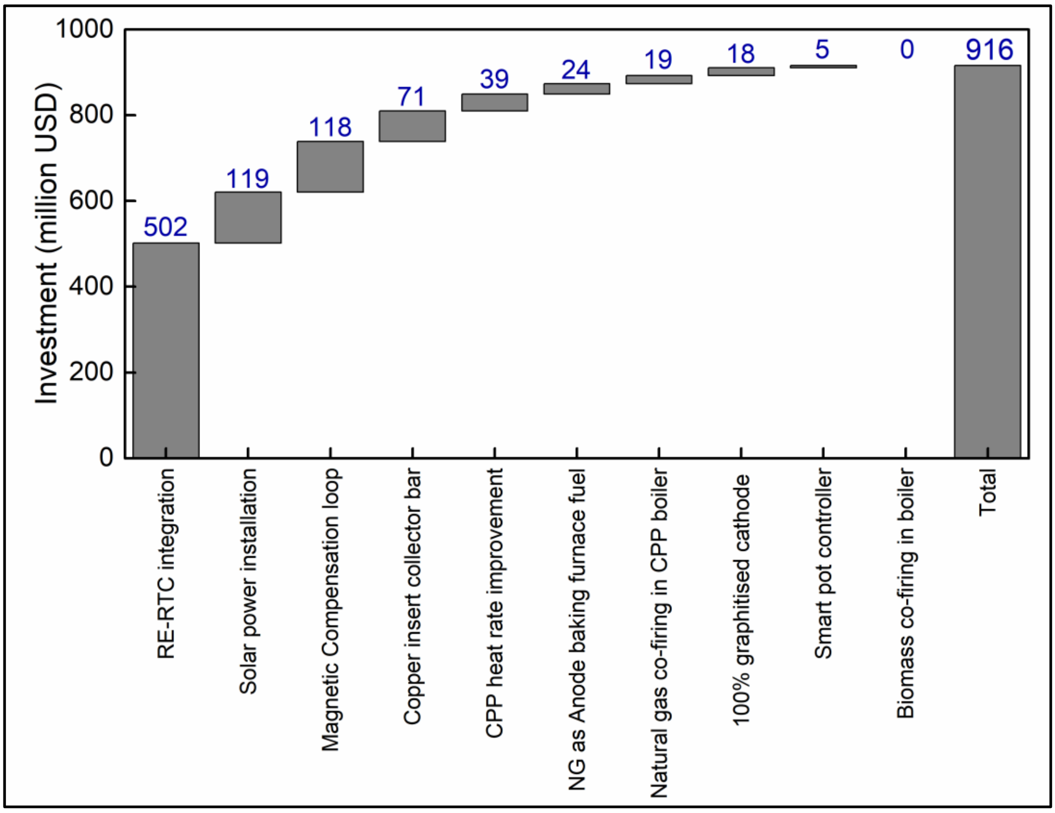

Figure 9. Sum of investments by measures in million USD.

## 4. Conclusions

Achieving meaningful emissions reductions in the aluminium sector requires a portfolio approach – combining readily available, cost-effective technologies with strategic investments in high-impact, capital-intensive solutions. Policymakers and industry leaders must overcome financial, technical, and operational barriers to accelerate the adoption of underutilised measures. A coordinated, phased implementation – guided by robust data and continuous innovation – is essential to align the sector with global climate goals.

The analysis underscores the contrast between widely adopted, low-cost solutions and high-impact measures that remain underutilised due to significant investment or operational hurdles. A balanced, holistic strategy that integrates both incremental improvements and transformative technologies will be key to advancing decarbonisation.

- Adoption vs. Impact: Technologies with high diffusion rates (e.g., smart pot controllers, graphitised cathodes) often correspond to those with negative or low marginal abatement costs, indicating that cost-effective solutions are more readily adopted.
- Cost vs. Potential: Some high-impact measures (e.g., RE-RTC integration) have both significant abatement potential and high investment requirements, posing financial and operational challenges for widespread adoption.
- Strategic Prioritisation: The analysis highlights the need to balance immediate, cost-saving interventions with longer-term, capital-intensive strategies to achieve deep decarbonisation.

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