Aluminium - the strategic metal; Emerging technologies & its importance to India

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Importance of Aluminium

Aluminium is the 3rd most abundant element in the earth's crust accounting for 8% of its mass. It is also the most abundant metal which is followed by iron. Aluminium has grown 9.45 times since 1960 becoming the largest growing metal followed by copper, steel, lead, tin etc. It is the 2nd most widely used metal after steel and the most widely used non-ferrous metal. Aluminium is widely accepted as the metal of the future, strategic metal and green metal. It is the metal of the future as it is replacing many metals in various applications with its lightweight, good conductivity, corrosion resistance etc. Because of its importance in sectors like defence, aerospace, electrical, renewable energy, infrastructure, transportation, military, etc., it is also called a strategic metal. Though most of the metals are recyclable, aluminium garners special importance as green metal as its recycling requires a fraction of energy used for primary metal production.

Aluminium production

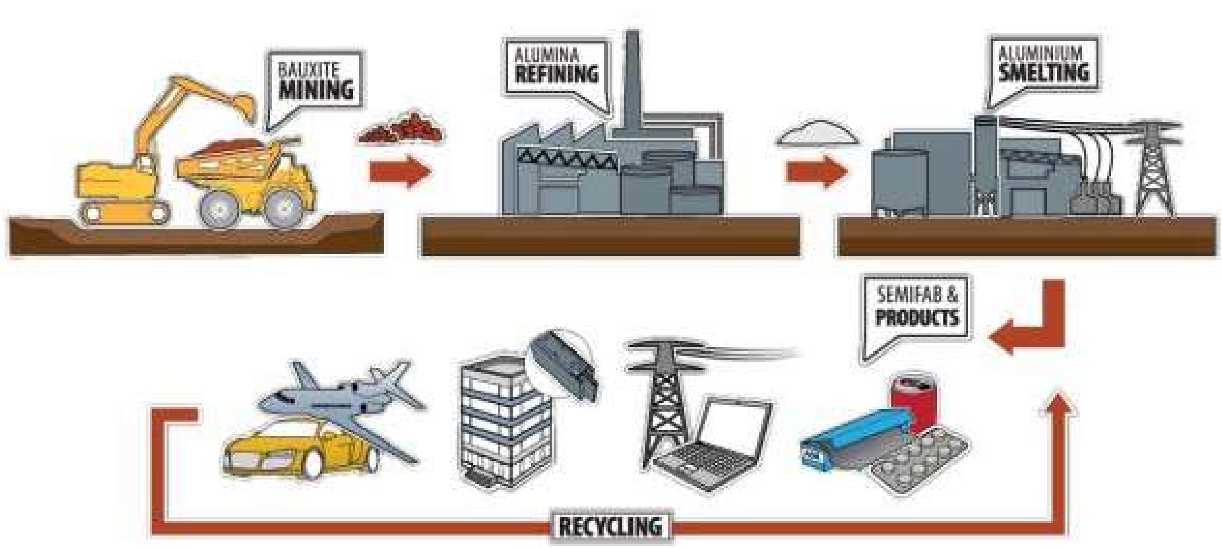

Figure 1 Aluminium production flow chart

Primary aluminium production (Figure 1) starts with the mining of its ore, bauxite, followed by refining of bauxite, where impurities in the bauxite were removed and pure alumina is obtained. Bayer's process is widely used for refining bauxite and 4 kgs of bauxite when refined, produces approximately 2 kgs of alumina and 2 kgs of red mud which contains impurities like SiO_2, TiO_2, Fe_2O_3 etc. which were present in the ore. Pure alumina obtained from the refining process is subjected to electrolysis, called the Hall-Heroult process. Electrolysis requires approximately 2 kgs of aluminium oxide, 400 grams of carbon, 20 grams of aluminium fluoride, 2 grams of cryolite and most importantly 13-14 kWh of electrical energy to produce 1 kg of aluminium. Aluminium produced will be further subjected to various downstream processes viz. rolling, extrusion, forging, drawing, etc. for making it suitable for its applications in various sectors like auto, electrical, construction & building, consumer durables, and others. At the end of life, products containing aluminium will be collected, segregated, and recycled. Apart from end-of-life products, waste generated during the machining and forming operations were also recycled.

Challenges for the industry

Globally challenges for the aluminium industry for its growth and development are E^3 viz. (i) economy (reducing the cost of production), (ii) energy (reducing the energy consumption) and (iii) environment (reducing the carbon footprint). But at the national level, apart from these E^3 challenges, Education or awareness about aluminium among the public is an additional challenge for increasing its per capita consumption in the country. Hence challenges for the domestic aluminium industry are symbolically E^4.

Wastes generated by the aluminium industry

Major wastes generated by the industry are red mud, dross, spent pot lining (SPL), fly ash and carbon dioxide. Red mud is produced during the refining of bauxite. Whereas SPL, fly ash, dross and CO_2 are produced from electrolysis. CO_2 emissions are from direct and indirect sources, where consumption of carbon anodes during the electrolysis contributes to the direct emission of CO_2. While aluminium electrolysis is an energy-intensive process and most of the electricity produced is from thermal power plants in the country, electricity consumption contributes to indirect emissions. Globally and nationally several efforts and research are being carried out for bulk utilization of wastes generated, reduction of emissions and energy consumption.

Aluminium demand and impact on various sectors

In India, aluminium and its alloys have a high impact on sectors viz. automotive, aviation, construction, defence manufacturing, electrical and electronics, food processing, oil & gas, ports, space and thermal. It has low to medium impact in sectors viz. tourism, textiles & garments, renewable energy, railways, pharmaceuticals, leather, IT, chemicals and biotechnology.

Abundant availability of coal & good quality bauxite and infrastructure operatives played a crucial role in the country to become 2nd largest producer of aluminium in the world. The current per-capita consumption of aluminium in India is very low at just 2.5 kgs compared to the global average of 11 kgs, country has robust growth prospects for aluminium in the future. If India's per-capita consumption reaches half the world average, it would imply that aluminium consumption will become more than 5 mT per annum. Economic growth acts as a fundamental driver of aluminium consumption in the country. The weight of aluminium utilized in automobiles is very less in the country when compared to the global average and it is increasing steadily for light-weighting and reducing carbon footprint.

History of Indian Aluminium Industry

After the discovery of the Hall-Heroult process for bulk production of aluminium, domestic aluminium production started with establishing the Indian Aluminium Company in 1943 with an installed capacity of 2500 tons per annum (TPA). Later HINDALCO in 1962, MALCO and BALCO in 1965 were started in the country and BALCO is now owned by Vedanta. A public sector unit, NALCO was established in 1987 with an installed capacity of 2,18,000 tpa. Today installed capacity for aluminium production in the country is 4.1 mt and India stood as 2nd highest aluminium producer in 2020 globally, with a production of 3.75 mt. India's aluminium production during the 1950s is a few thousand tons per annum and increased many folds to its current level of a few million tons per annum.

India's position

Indian bauxite deposits are the 5th largest in the world and account for 5.1% of the world's deposits. India has a reserve of 3.8 billion tons of good quality bauxite deposits. India has 6 refineries that produced approximately 6.4 mT of alumina from bauxite in 2018 making it the 4th largest alumina producer in the world. During 2018, India was the 2nd largest producer of aluminium in the world with 7 smelters contributing to a production of 3.7 mT which accounted for around 5% of the world's aluminium production. Since aluminium production is energy-intensive and most of the electricity produced in the country is through thermal power plants, being the 3rd largest coal producer in the world, helped the country and the aluminium industry to achieve several milestones.

Production & Consumption of aluminium in India

Vedanta, HINDALCO and NALCO are the primary aluminium producers in the country with a total installed capacity of 4.1 mT. Production of aluminium in the country has seen a 3-fold increase since 2007 during which aluminium production was around 1.2 mT. Sectors in India are characterized by companies ranging from fully integrated to product specialists. The downstream segment comprises more than 150 large and mid-sized companies and a much larger base of smaller and unorganized players in the country.

Bauxite resources in the country

Most bauxite ores are situated in the states Of Odisha, Andhra Pradesh, Gujarat, Jharkhand, Madhya Pradesh, Chhattisgarh and Maharashtra. Odisha accounts for more than 50% of the bauxite ores followed by Andhra Pradesh with 16% and Gujarat with 8%. The distribution of bauxite resources amongst central India, eastern & western ghats is shown in Figure 2 (a) and locations of bauxite ores is shown in Figure 2 (b).

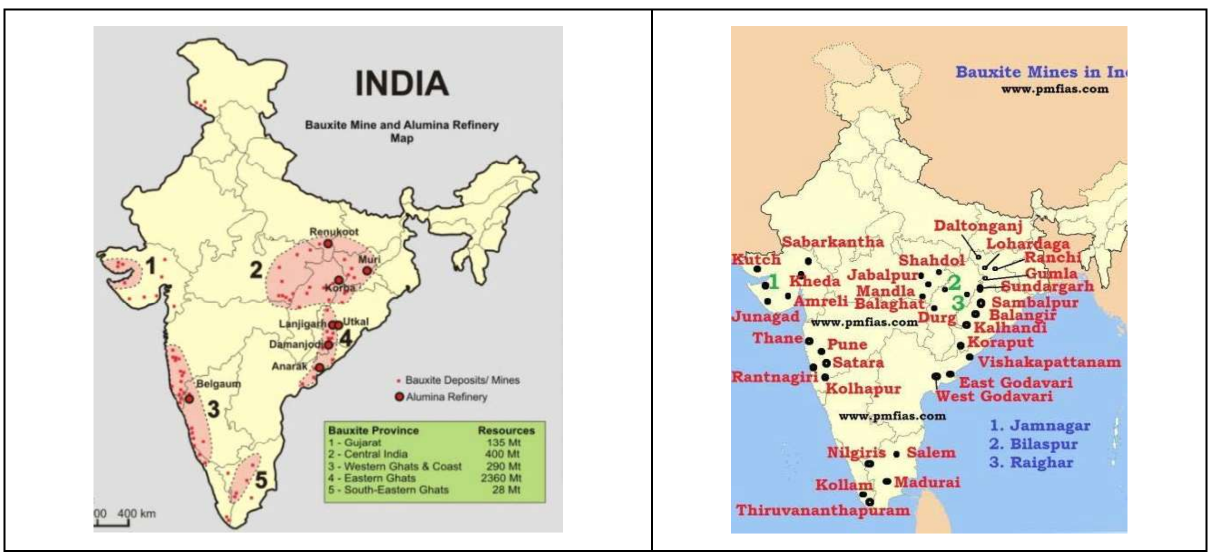

Figure 2 (a) Bauxite mines and alumina refinery map; (b) bauxite ore locations

A shift in aluminium production base:

The aluminium production base is shifting from West to East due to rising power, labour, environmental costs, logistics and aluminium prices in the West. The abundant availability of alumina in India, gas in the middle east and cheap sources of energy in south-east Asia result in huge opportunities for the creation of joint ventures among the countries in the East.

Aluminium consumption by applications in the country

The government's thrust on the power sector is the dominant consumer of aluminium in India, which augurs well for the aluminium industry. The electric sector accounts for 45% of the aluminium consumption in the country followed by transport (18%), construction (15%), machinery (9%), consumer durables (8%) and packaging (5%). The consumption pattern for aluminium in the country is different from the world's consumption where construction and auto are leading consumers of aluminium. This is also one of the reasons for lower per-capita aluminium consumption in the country which is currently at 2.5 kgs. Aluminium is a key metal that will be needed during the further industrialization phase of India and hence its demand is expected to become 8 mT by 2025 which will be boosted by urbanization, rising PCI, government schemes like Make-in-India & Smart Cities.

The growth rate of aluminium in the country

The per cent growth rate of aluminium production, consumption, exports and scrap imports is shown in Figure 3. Though India is the 2nd largest producer of aluminium, it is a net importer of aluminium. India exports primary ingots and imports alloys and finished goods of aluminium which calls for indigenous technology development for alloy production and value addition of aluminium semis.

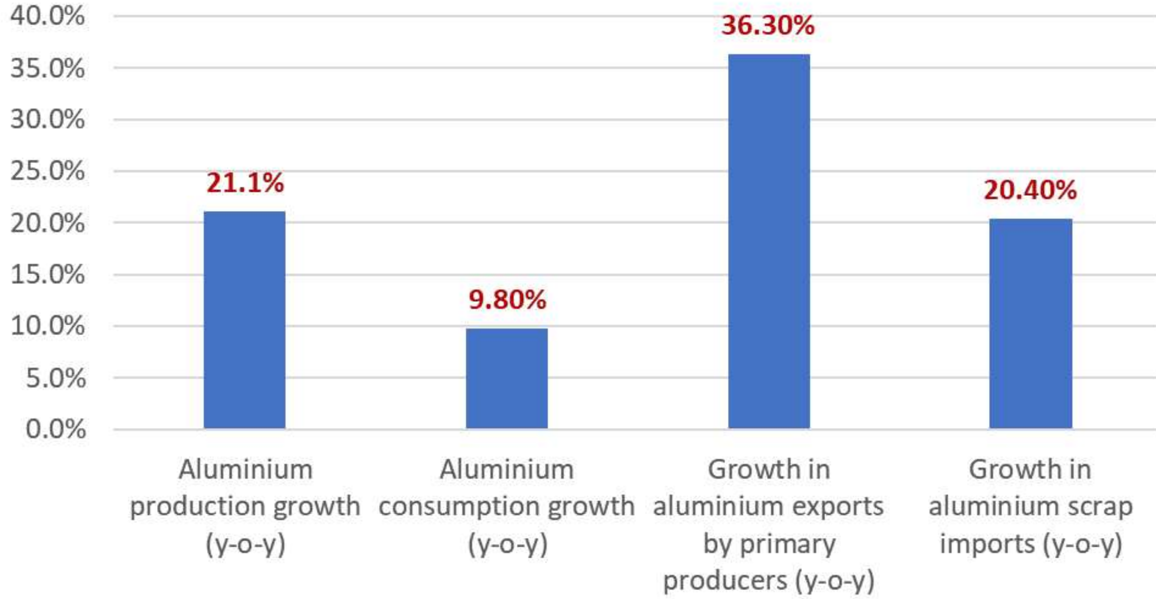

Figure 3 Percent growth rate of aluminium in India during FY18

More than 60% of the aluminium is likely to be produced and consumed in China, but growing markets in Brazil and India, increasing accessibility of resources, including energy in Russia, Africa and South-East Asia could change the pattern of aluminium production and consumption once more, this time southwards, as well as eastwards.

Contribution of recycling to the growth of aluminium

Apart from primary metals, India has witnessed strong growth from the recycling industry. The growing emphasis on environment conservation and sustainable development has increased the focus on metals recycling. With time, the share of recycling in the total metal production has increased significantly and is almost in part with the global level. In India, recycled aluminium production is around 30% of the total aluminium produced which is on par with the global share of recycled aluminium production.

The secondary production of metals through recycling significantly lower resources as compared to the requirement for primary production and contributes significantly to meeting the total demand for non-ferrous metals in India. Out of all metals, aluminium recycling requires the lowest energy when compared to the energy that was required to produce primary aluminium. Percentage of primary metal energy saved by recycling for various metals viz. aluminium, nickel, copper, zinc, lead and steel are 95%, 90%, 85%, 75%, 65% and 60% respectively.

Aluminium as a strategic metal

The notion of 'strategic minerals' or 'critical minerals' is relatively new to policymakers in India as compared to other major economies of the world. As per Council on Energy, Environment and Water's (CEEW) report on non-fuel minerals, 2016, aluminium was classified under Zone III with low economic importance & low supply risk (least critical). In the 1950s itself, India has recognized aluminium as the most vital metal in war.

As per the US, The National Strategic and Critical Minerals Production Act of 2013, the term strategic and critical minerals mean necessary minerals

- For national defence and national security requirements;
- for the Nation's energy infrastructure, including pipelines, refining capacity, electrical power transmission and generation, and renewable energy production;
- to support domestic manufacturing, agriculture, housing, telecommunications, healthcare, and transportation infrastructure;
- for the Nation's economic security and balance of trade

Futuristic & Innovative technologies

Currently, sensors are being used for determining the real-time measurement of alumina content, superheat, temperature and bath ratio of the electrolysis bath during the Hall-Heroult process.

Figure 4 shows various areas of research identified in various processes, applications and recycling of aluminium viz. utilization of red mud produced during refining, spent pot lining produced during smelting, light-weighting of transport, collection & sorting of EoL products, recycling of packaging, contamination in recycling etc.

But there is scope for mature and small improvements in cell designs, feeding systems, bath composition and control systems in the Hall-Heroult process. A reduction in energy consumption by 0.2 – 0.5% per year, improvement of current efficiency to over 95% to reduce overvoltage are such small improvements envisaged in the aluminium electrolysis process. Technological and engineering improvements in the electrolysis process includes point feeder improvements with the incorporation of accurate cell controllers and advanced process controllers to reduce the frequency of AE & control operational variables.

Technologies that are still in the concept and research stage are wetted, drained cathode technology, alternate cell concepts which combine wetted & drained cathodes with inert anodes, commercial-scale carbothermic reduction, etc.

As per International Aluminium Institute's Mission 2020, the following were the targets for the aluminium industry:

- 5% reduction in the energy intensity
- Reduction of electrical energy consumption to 11 kWh/kg of aluminium produced during smelting
- 25% reduction in the cost of metal production
- 25% reduction in energy usage for melting
- Increase of current efficiency to 97% at a low energy input
- Reduction of electrical energy consumption to 13 kWh/kg of aluminium for retrofitted smelters

This shows that the aluminium industry is continuously striving to overcome the 3E challenges.

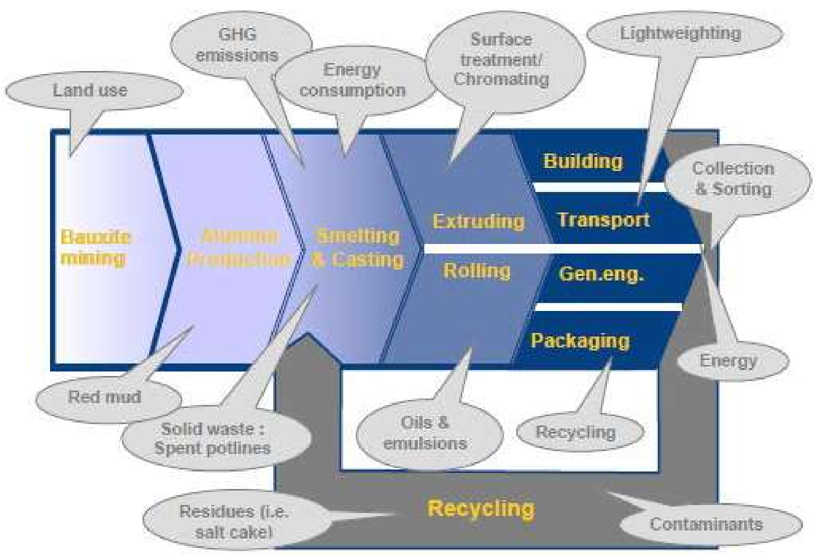

Figure 4 Research areas related to aluminium production, usage and recycling

Net Energy Advantage

Aluminium products generate a net energy advantage (NEA) over their life cycle. NEA is possible when aluminium products save more energy during their useful life than was required to produce those products.

Internationally, there are several projects worth over 100 million dollars related to aluminium production are being carried out in cost-shared funding. Some of the projects are selective adsorption, intelligent pot room operations, revolutionary cell technologies, isothermal melting process, reduction of oxidative melt loss, prevention of molten aluminium-water explosions, texture in aluminium alloys, etc.

Some of the current challenges of the Indian aluminium industry are reducing ACD, current density to achieve maximum energy savings, reduction of power consumption from around 16 kWh/kg to 12 kWh/kg to achieve 11 kWh/kg, reduction of voltage from 4.1 volts to 3.8 – 3.4 volts and reducing heat losses. The following cell technologies help the Indian aluminium industry reduce energy consumption, cost and carbon footprint:

- Inert sidewall
- Increasing conductivity of anodes
- Decreasing corrosion rates
- Decreasing ACD from 1 inch to 0.5 inch
- Optimization of electrolyte chemistry
- Operating temperature
- Elimination of electrode penetrations
- Eliminate anode carbon, CO/CO_2 emissions, perfluorocarbons (PFCs)
- Production of oxygen as a by-product which is possible with inert anodes

Incorporating inert anode with the wetted cathode in aluminium electrolysis cell leads to a 10% reduction in operating costs, 5% increase in cell productivity and 41% reduction in greenhouse gas (GHG) emissions. But drawbacks of the same include the higher cost of inert anode material, contamination of metal and higher anode wear rate.

The best non-Chinese technology, the DX+ has the following advantages

- Highest productivity per unit cell area of all smelters

- Anode current density – 0.9 A/cm^2
- Lowest energy of high-amperage cell – 13 kWh/kg of aluminium
- 96.2% current efficiency
- Lowest PFC emissions
- Uses capabilities of modern control instrumentation and knowledge
- Uses modified work practices through applying knowledge from advanced process sensing.

Chinese aluminium producer, Chinalco made a significant breakthrough in Electrolytic Aluminium Technology by installing 600 kA super-large cells which were developed by SAMI in seven years. These cells were designed to solve technical difficulties like magnetic fluid stability as well as operational stability. After being tested for 1.5 years the energy consumption of these cells was as low as 12.14 kWh/kg of Al.

Future trends

Amperage increase has been the trend for many years now. This has implied lower cell voltage to maintain a proper heat balance in the cell. It may seem to create an opportunity now for gains in cell voltage, which probably will be below 4.0V in the future. Lower energy consumption will be required, as the aluminium industry will be expected to save energy in the years to come.

Aluminium may become an even greener metal than today. For the aluminium industry to be a winner, it must be among the very best in technology and operations. Technically, the aluminium production process can be most energy-efficient, close to zero GHG emissions and lowest carbon footprint. But on the way to achieving zero GHG emissions, the aluminium industry may face the following challenges:

- Focus more on lower specific energy consumption & eliminate AE
- Recovery of energy from main heat loss sources, like cathode linings and gas exhaust systems
- Collecting and cleaning CO_2 from the electrolysis process itself may be a technically possible future scenario

The status of emerging technologies in the aluminium sector is given in Table1.

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Table 1 Status of various emerging technologies in the aluminium sector

Area	Technology	Status
Electrode technology	Inert Anode	Demonstration
	Wetted cathode	Demonstration
	Multipolar cells	Demonstration
	The novel physical design of anodes	Commercial with low adoption
Reduction technology	Carbothermic reduction	Pilot stage
	Kaolinite reduction	Research stage
Low-temperature technology	Ionic liquids	Development stage
Recycling technologies	Novel physical recycling techniques	Demonstration
	Aluminium mini mills	Pilot

Inert anode technology

Inert anodes can significantly improve the Hall-Heroult process for producing aluminium by eliminating the need for regular replacement of the carbon anodes currently used in Hall-Heroult cells. Ideal inert anodes are chemically nonreactive and are not consumed by the electrolysis reaction, and thus could ideally have the same lifetime as the smelting cell.

Materials that have been considered for inert anodes include metals, ceramics, and cermet, which are a mix of these two. In addition to eliminating the energy and material needs for frequently replaced carbon anodes, inert anodes can reduce the ACD in a Hall-Heroult cell, is a major determinant of electricity used by the cell. Figure 5 shows the reaction, input and output of the aluminium electrolysis cell with inert anodes.

$$\frac{1}{2}Al_2O_3 \rightarrow Al + \frac{3}{4}O_2$$

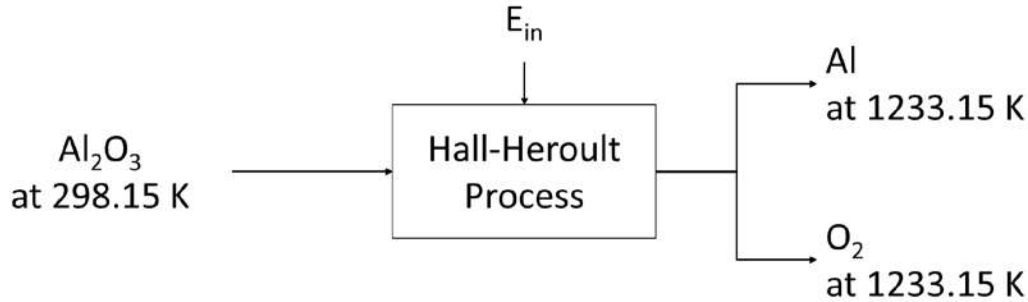

Figure 5 Inert anode technology

Benefits of inert anodes include:

- Energy savings of 3-4% within a modified Hall-Heroult cell (U.S. DOE 2007)
- Capital costs for inert anodes could be 10-30% lower than that for conventional anodes
- Eliminating greenhouse gases produced by electrolysis with carbon anodes (CO_2, carbon monoxide, and PFCs)
- Improving occupational health by eliminating the need to regularly replace carbon anodes in the smelting cells
- Improving plant operating efficiency by eliminating anode effects
- Reducing cell energy losses by 60% or more

Wetted cathode technology

The cathode in a Hall-Heroult cell is technically the negatively charged surface of the molten aluminium that is being formed by electrolysis, but usually ‘cathode’ refers to the solid carbon material upon which the molten aluminium collects. The molten aluminium is somewhat stable under normal operating conditions but bringing the anode closer to it causes large waves due to MHD forces. ‘Wetting’ refers to improved electrical contact between the molten aluminium and the carbon cathode material.

A completely wetted cell lining that was also inert to the cell bath would allow molten aluminium to be drained out of the anode-cathode spacing. This design could withstand a smaller ACD, leading to significant energy savings. Titanium diboride (TiB_2) is a durable, wetted cathode material that can withstand corrosive and high-temperature conditions within a cell.

Wetted cathodes face several design challenges, namely compensating for complications that arise with a smaller ACD and lower voltage operation. These include lost heat energy and impeded circulation and mixing of the molten bath. Finally, TiB2 and related composites can be very expensive. Several possible concepts for wetted cathode and draining cells is shown in Figure 6.

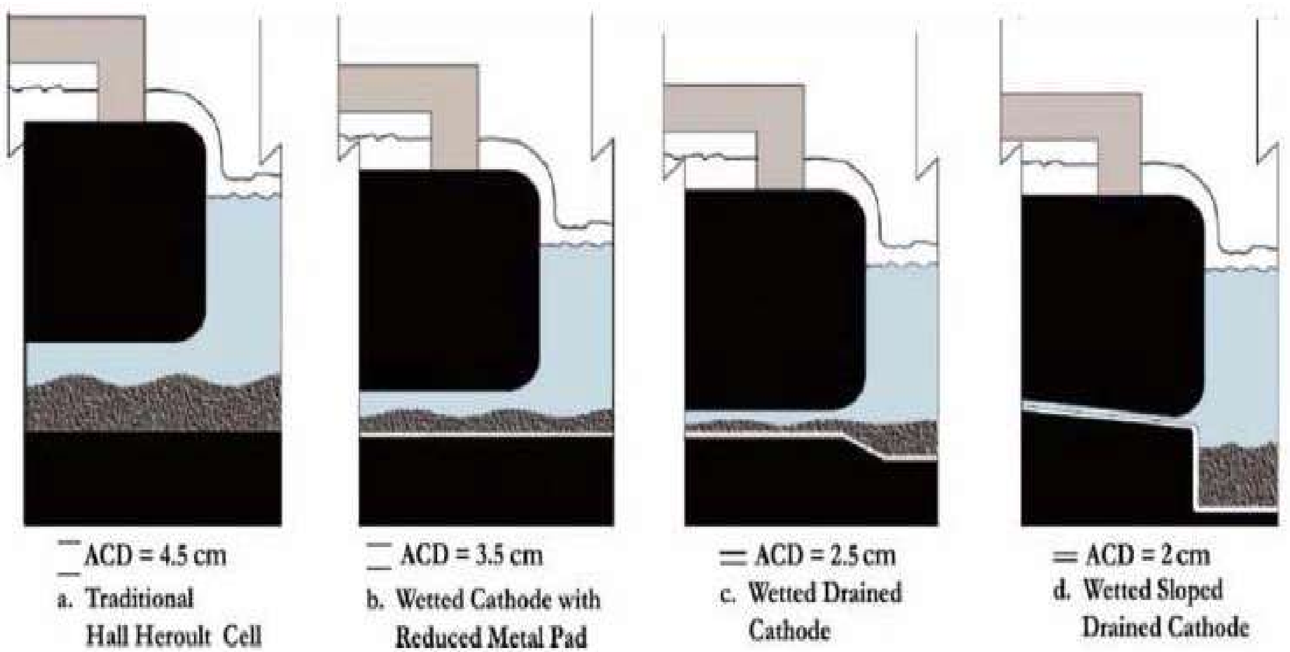

Figure 6 Possible combinations for wetted cathode and draining cells

shows that carbothermic is the best technology in terms of energy and alumina consumption, whereas inert anode technology is the best with the lowest carbon footprint amongst all the technologies.

Table 2 Comparison of emerging technologies for aluminium smelting

Technology	Energy use (kWh/ kg of Al)	Alumina (kg/kg of Al)	Carbon anode [carbon] (kg/kg of Al)	CO2 [CO] (kg / kg of Al)
Hall-Heroult	15.37	1.93	0.45	1.66
Wetted cathode	11.83	1.93	0.45	1.66
Inert cathode	16.82	1.93	0	0
Carbothermic	10.15	1.89	[0.67]	[1.56]
Best technology	Carbothermic	Carbothermic	Inert anode	Inert anode

Conclusion

To conclude, India's vision for aluminium's growth includes the following:

- Updating the status of aluminium as a core industry
- Bringing reforms in coal and bauxite mining
- Strengthening aluminium scrap recycling
- Energy policy for energy-intensive sectors
- Export policy for the downstream industry

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Dr. Anupam Agnihotri is working as Director, Jawaharlal Nehru Aluminium Research Development and Design Centre, Nagpur.Under UNDP, he has served as a visiting faculty to the

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