UK Government

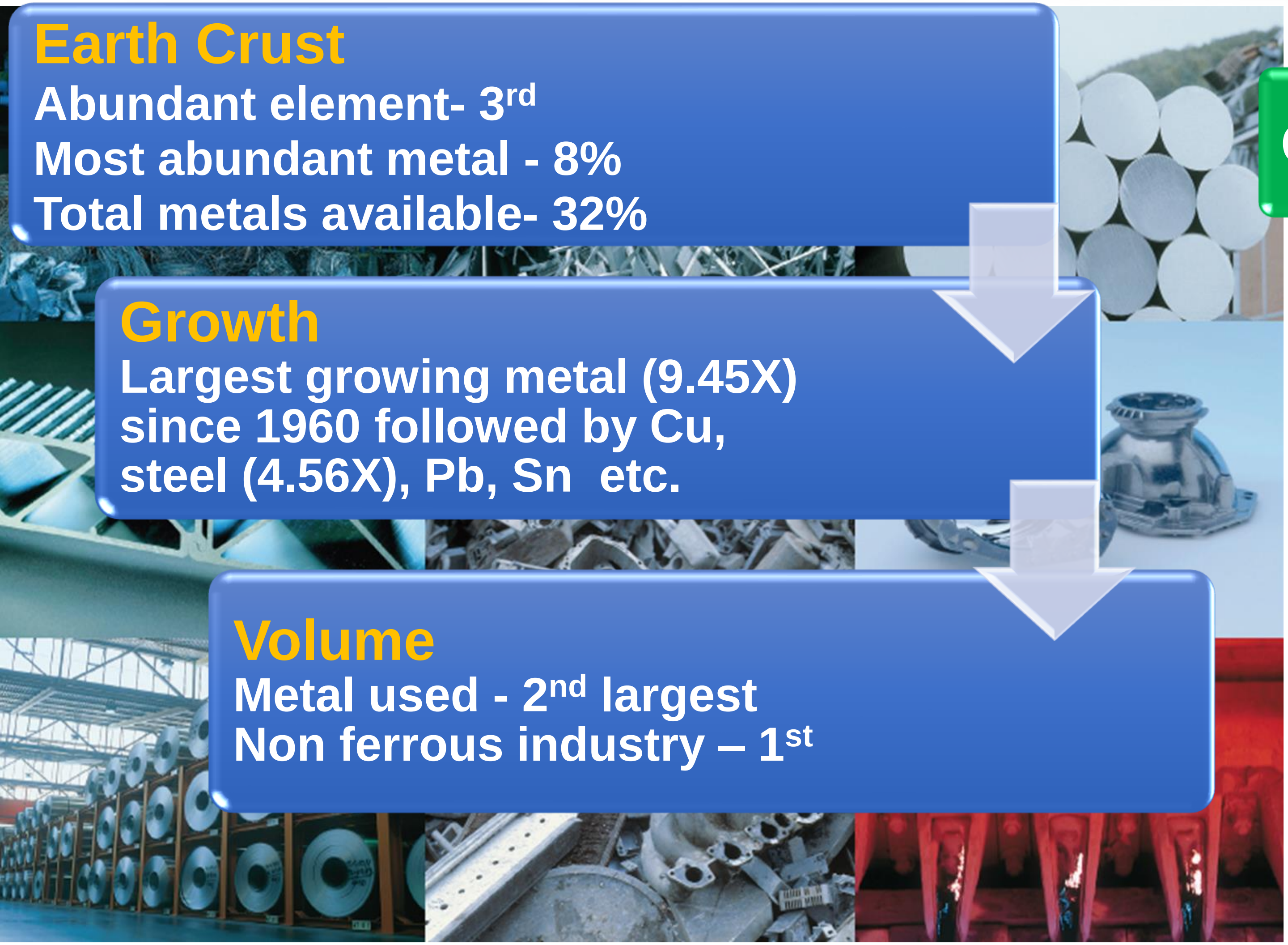
Bureau of Energy Efficiency
Ministry of Power, Government of India

Knowledge Exchange Platform

Emerging Technology for Aluminium Sector-Inert Anode Technology & Circular Economy

21st November 2022

Aluminium in Circular Economy



Earth Crust

Abundant element- 3rd
Most abundant metal - 8%
Total metals available- 32%

Growth

Largest growing metal (9.45X) since 1960 followed by Cu, steel (4.56X), Pb, Sn etc.

Volume

Metal used - 2nd largest
Non ferrous industry – 1st

- Green Metal
- Strategic Metal
- Metal of Future
- Infinite Metal

World Al Industry claim to become green house gas (GHG) neutral, by the year 2050

Status of the Emerging Aluminium Technologies

Technology	R&D needs	Demonstration needs	Deployment Milestones
Wetted drained cathodes	----	Ready for demonstration	Deployment to start by 2015 with full commercialization by 2020
Inert anodes	**Extensive testing at laboratory and batch scale**	**Ready for demonstration**	**Deployment to start in 2015 - 2020 with full commercialization by 2030**
Carbothermic reduction	Extensive research under way	2020 - 2025	Deployment to start between 2030 and 2040 with full commercialization by 2050
Kaolinite reduction	Research under way	2025 - 2030	Deployment to start between 2035 and 2040

No.	Report Section/Technology Name	Commercialization status
	Emerging Electrode Technologies	
1	Inert Anodes	Demonstration stage
2	Wetted Cathodes	Demonstration stage
3	Multipolar Cells	Development stage
4	Novel Physical Design for Anodes	Commercial with low adoption stage
	Alternative Reduction Technologies	
5	Carbothermic Reduction	Pilot stage
6	Kaolinite Reduction	Research stage
	Emerging Low-Temperature Reduction Technologies	
7	Ionic Liquids	Development stage
	Carbon Capture and Storage Technologies for the Aluminum Industry	
8	Carbon Capture Using Absorption Technologies	Development stage
	Emerging Aluminum Recycling Technologies	
9	Novel Physical Recycling Techniques	Demonstration stage
10	Aluminum Mini Mills	Pilot stage

https://www.globalefficiencyintel.com/new-blog/2017/technologies-energy-emissions-aluminum-industry

https://www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters

Advantages of Emerging Technologies

Technology	Energy Use (kWh/kg)	Alumina (kg)	Carbon Anode (kg)	CO_2 (kg) [CO] (kg)
Hall–Heroult	15.37	1.93	0.45	1.66
Wetted cathode	11.83	1.93	0.45	1.66
Inert anode	**16.82**	**1.93**	**0**	**0**
Carbothermic	10.15	1.89	0.67	1.56
Best technology	Carbothermic	Carbothermic	Inert anode	Inert anode

Inert Anode Material & Properties

To be successfully implemented, an inert anode must be

- Physically stable at service temperature
- Resistant to
  - cryolite
  - attack by pure oxygen
  - Thermal shock
- Electrochemically stable
- Electronically conductive
- Mechanically robust
- Easy to deploy & adapt (electrical connection to bus, startup, power interruptions)

What Materials May Inert Anode Consists of?

- The Ceramic Anode (SnO_2, $NiFe_2O_4$, NiO-LiO_2)
  - Inherent Instability
  - Doping required (Leaching)
  - High Corrosion rate
  - Low electrical conductivity / thermal shock and fragile
- The Cermet Anode (Fe-($\mathbf{NiFe_2O_4 + NiO}$), Cu-Ni- $\mathbf{NiFe_2O_4}$ –NiO, $\mathbf{NiFe_2O_4}$ –Cu, $\mathbf{Cu_2O - Cu}$, $\mathbf{Ni(NiFe_2O_4 - 10NiO)}$)
  - Metal being oxides and leached out
- The Metal Anode (AlCuSn, Cu-Ni-Fe, N-Fe-Co, Zn)
  - Unstable in the presence of oxygen @ high-temperature +Fluorides

Advantages & Challenges of Inert Anodes

Principal Advantages of Inert Anodes

- Cost Reduction
  - Absence of anode plant
  - Capital and operating cost reduction
- Environmental friendliness
  - Elimination of GHG emissions (smelter & carbon plant) (CO_2, CF_2, C_2F_6, PAH)
  - Carbon residues eliminated
- Improved Occupational Health
  - Operational easiness (reduced heat stress)
  - Reduced thermal disturbances

Major Challenges

- Wear Rate of Anodes
  - Low solubility & reactivity in electrolyte
  - High resistance to anodic oxygen
  - Low Anode corrosion (metal purity)
- Alumina Control
  - Alumina-saturated melts
  - Right side - pseudo-resistance curve
  - Risk of sludge formation
- Anode Effect
  - Sharp dissolution of anodes
- Heat Balance
  - No side ledge
  - Reduced heat loss

Hall-Heroult : Inert Anodes

$$\frac{1}{2}Al_2O_3 + \frac{3}{4x}C = Al + \frac{3}{4}(2-\frac{1}{x})CO_2 + \frac{3}{2}(\frac{1}{x}-1)CO$$

- Anode polarization voltage can be reduced to 0.15 V in IAT from 0.6V (HH)
- Theoretical energy requirement for an inert anode is higher by 2.95 kWh/(kgAl) since there is no energy from carbon anode oxidation
- Higher voltage of 0.89 V is required in IAT for a reduction in the absence of carbon oxidation energy
- Combining both effects (polarization and increased reaction voltage) will result in a voltage increase of 0.44 V
- Total voltage required for the inert anode technology is then 5.08 V which corresponds to 16.82 kWh/(kgAl)
- No changes to the alumina feeding system & no carbon dioxide emission

	DP	AOV	Electrolysis E_{req}	Anode E_{req}	Cell voltage	Electrolyte Voltage drop
HH	1.17	0.7	6.34	1.0	4.5	1.76
IA	2.19	0.2	9.26	0.2	5.1	???
δ	1.02	-0.5	2.92	-0.8	0.6	???

$$Al_2O_{3(diss)} = 2Al_{(l)} + \frac{3}{2}O_{2(g)}$$

Commercialisation of Inert Anode Technology

Elysis Moves Toward Commercialization of Inert Anodes

By Andrea Svendsen, Managing Editor

Elysis, the joint venture formed by Alcoa and Rio Tinto, is making great strides toward the commercialization of its proprietary inert anode technology, which is said to be able to produce aluminum without any direct greenhouse gas (GHG) emissions. This would help to meet the primary aluminum industry's need to reduce its carbon footprint. If fully implemented at existing smelters across Canada, the technology could eliminate the equivalent of 6.5 million tonnes of GHGs. In addition, it is expected to increase production by 15% and also to reduce operating costs by 15%, when compared to the traditional smelting process.

Technology Development

The Elysis™ inert anode technology is the realization of a long term dream of the aluminum industry, which has been working on its development since electrolysis was first invented. The concept itself is straightforward. In a traditional electrolysis cell, the alumina (essentially a combination of aluminum and oxygen) is placed in a cell with an electrode and carbon anode, where the process splits the aluminum and oxygen. The aluminum settles in the bottom of the cell, and the oxygen binds with the carbon in the anode, creating CO_2 emissions. With inert anode technology, the carbon element is removed. The absence of carbon means that when the aluminum is separated from the oxygen, only oxygen is emitted from the cell.

Despite the simplicity of the concept, realizing inert anode technology is actually very complex. "Literally every aluminum producer has taken a stab at this, investing incredible sums of money over many decades," said Vincent Christ (Figure 1), CEO of Elysis. "What this tells you is that making inert anodes viable is incredibly difficult, but ultimately the benefits are immense and worth the effort. Not only do inert anodes solve environmental problems, but they also have a major impact on reducing operation costs. Which is why, inert anode technology tends to be referred to as the holy grail of the aluminum industry."

Figure 1. Vincent Christ, CEO of Elysis.

As Christ points out, the barrier to entry is huge, a fact that is influenced by a number of factors. The first is finding the right materials for the inert anode, so that they provide efficient production with a high metal quality. "One of the ways to know whether you're on track or not is measuring quality of the metal that you produce," noted Christ. "A number of inert anode solutions have come along over the years. While these have shown some benefits, the inert anodes were often revealed to be not all that inert. As a result, the anode would pollute the metal, requiring additional purification steps to get it up to specification—which fails to solve the business case for inert anodes."

Once the inert anode has been successfully developed, a number of other concerns come into play, including the manufacturing process for producing the anodes and a redesign of the electrolysis cell. While the inputs (alumina and an anode) are the same, the electrolysis process with inert anodes is fundamentally different. Therefore, the cell needs to be designed to meet the specific requirements of the inert anode and achieve stable cell operation. With the development of a new pot cell design, the ancillary equipment for the handling of materials and management of the operation also needs to be redeveloped.

"Addressing these challenges requires specific competencies, notably a combination of deep science and the ability to transform the results of that scientific work into a commercial product or industrial solution," said Christ. "This is exactly what has happened with the Elysis joint venture."

Both Alcoa and Rio Tinto have their own R&D capabilities. For more than two decades, Alcoa had been developing an inert anode process at the Alcoa Technical Center outside of Pittsburgh, PA. Meanwhile, Rio Tinto has a long history of developing next-generation cell technologies, which have been utilized in smelters around the world. With investment support from the government of Canada, the government of Quebec, Alcoa, Rio Tinto, and Apple, which had facilitated the collaboration between the two aluminum companies, Elysis came into being in 2018. Since its launch, Elysis has blended these competencies in order to develop its breakthrough inert anode technology.

Elysis successfully produced its first commercial batch of aluminum using inert anodes at the Alcoa Technical Center in late 2019 (Figure 2), proving the sustainability, stable performance, and a strong business case for the technology. This first batch of metal was purchased by Apple. The sale of this first metal demonstrated the market potential for low-carbon aluminum, considering the growing demand for environmentally sustainable products.

Shortly after producing its first metal, Elysis began work on its Industrial Research and Development Cen-

Figure 2. Aluminum ingots produced using the proprietary Elysis technology. (Photo: Elysis.)

Rusal Develops Inert Anodes for a More Sustainable Future

By V. Mann, Rusal

Rusal is a leader in the development of unique and innovative inert anode electrolysis technology, having been the first company in the world to begin mass production of aluminum using inert anode technology in the pilot production cells at its Krasnoyarsk aluminum smelter. This technology provides a revolutionary environmental solution for the metal industry, which will eliminate direct greenhouse gas (GHG) emissions from aluminum production. The technology allows for the replacement of conventional carbon anodes with inert anodes made of ceramics or alloys. The carbon footprint of aluminum produced using inert anode technology is more than 85% lower than the industry average. One of the main benefits of this technology is the generation of oxygen in the aluminum production process: one cell using the inert anode technology can generate the same volume of oxygen as 70 hectares of forest.

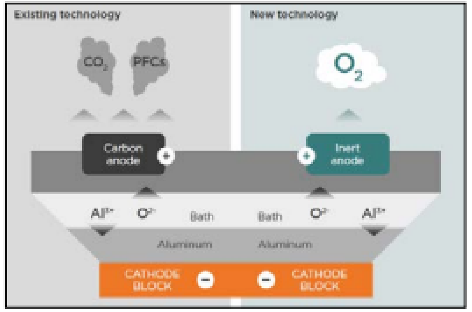


Figure 1. Comparison of aluminum production using the existing carbon anode technology versus the new inert anode technology.

Understanding Inert Anode Technology

Currently, all aluminum smelters use the electrolysis process, in which cryolite-alumina melts are processed in reduction cells with carbon anodes. The production of 1 tonne of aluminum consumes 0.5 tonnes of carbon anodes and emits 1.4 tonnes of CO_2. The rate of consumption for carbon anodes in the electrolysis process can be determined according to the following reaction:

$$\tfrac{1}{2}Al_2O_3 + \tfrac{3}{4}C \rightarrow Al + \tfrac{3}{4}CO_2 \qquad (1)$$

Inert anode technology is also based on traditional electrolysis, in which cryolite-alumina melt is processed into aluminum. However, in this case, the anodes do not use carbon. Instead, the anode is comprised of ceramic or other materials that do not interact with the anode gases and molten electrolyte. Because of this, these kinds of anodes are generally inert and produce oxygen instead of CO_2 or other emissions. Aluminum produced with inert anodes uses the following reaction:

$$Al_2O_3 \rightarrow 2Al + 3/2O_2 \qquad (2)$$

According to this reaction, when inert anodes are used in the electrolysis process, 0.9 tonnes of oxygen will be released per 1 tonne of aluminum produced. A comparison of the carbon and inert anode technologies is presented in Figure 1.

Researchers have been trying to develop a viable inert anode technology since the Hall-Héroult electrolysis process was invented well over a century ago. However, significant progress has only been made in the last few decades. The main difficulty in advancing this technology has been in regards to the development of an inert anode material that is able to meet a number of requirements for electrolysis, including a high electrical conductivity, corrosion resistance in fluoride melts and oxygen environments, mechanical resistance, and reasonable cost. Based on these requirements, the main candidates considered for implementation in inert anodes are ceramic anodes containing metal oxides, metal alloys, and cermets (i.e., oxide-metal compositions). As all primary aluminum manufacturers are currently working towards reducing GHG emissions, the development of inert anode technology has become even more pertinent. As a result, a number of aluminum companies, research institutions, and universities have been actively pursuing and making strides towards the goal of achieving mass production of aluminum with inert anodes.

Development of Inert Anodes at Rusal

With its history of innovation and research, Rusal has been investing in the development of inert anodes for years, including the testing of various materials and the trialing of several types of reduction cells. In 2015, Rusal successfully produced aluminum using its innovative and proprietary inert anode electrolysis technology. The aluminum was produced in pilot production cells at the Krasnoyarsk aluminum smelter.

Currently, the daily production rate of one pilot cell using inert anodes at Krasnoyarsk is approximately 1 tonne of aluminum at an amperage of 140 kA. As of today, Rusal has produced several thousand tonnes of aluminum using this inert anode technology, some of which have already been delivered to customers as test shipments.

Combined with the use of sustainable energy sources, the inert anode pilot cells emit less than 0.01 tonnes of CO_2 equivalent per one tonne of metal (under Scope 1 and Scope 2 of the Center for Corporate Climate Leadership's GHG inventory guidance, which includes direct and indirect GHG emissions). These emissions represent only one thousandth of the current industry average of CO_2 emissions per one tonne of aluminum (12 tonnes of CO_2 per one tonne of aluminum), enabling Rusal to produce aluminum with one of the lowest carbon footprints in the industry.

A key result of this development is the stable production of aluminum using inert anodes at an industrial scale. This aluminum is sold under the new brand ALLOW INERTA (Figure 2), which emits very low emissions at all of its production stages—from bauxite extraction to the casthouse. In total, ALLOW INERTA aluminum has a carbon footprint that is more than 85%

Inert Anode Technologies Worldwide Status

AUTOMOTIVE

Rio Tinto and Ford Sign MOU for a Net Zero Future

July 27, 2022

Rio Tinto and Ford Motor Company signed a non-binding global memorandum of understanding (MOU) to jointly develop more sustainable and secure supply chains for battery and low-carbon materials to be used in Ford vehicles. The multi-materials partnership will support the transition toward a net-zero future by supplying Ford, one of the world's largest automakers, with

SMELTING

Elysis Moves Toward Commercialization of Inert Anodes

March 1, 2022

By Andrea Svendsen, Managing Editor. Elysis, the joint venture formed by Alcoa and Rio Tinto, is making great strides toward the commercialization of its proprietary inert anode technology

- The Russian company RUSAL operates with pilot cells based on metal anodes.
- A Chinese company has pilot cells using cermet anodes (made of metal/ceramic material)
- Elysis is a relatively new consortium of Alcoa, Rio Tinto, Apple and the Canadian authorities, & they are claiming they will have a commercial process in place in 2024.
- In Europe, Arctus metals in Iceland is conducting inert anode R&D

APPLICATIONS & DESIGN SMELTING

ELYSIS and Apple Collaborate to Use Carbon-Free Aluminum in the New iPhone

March 24, 2022

ELYSIS, the joint venture between Alcoa and Rio Tinto, is strengthening its ties with Apple. The company has produced t first commercial-purity primary aluminum at industrial scale, which will be used in Apple products. The breakthrough technology produces oxygen instead of greenhouse gases (GHGs), and the achievement marks a major milestone in the production of [...]

RUSAL begins testing of new generation of inert anode pot

Moscow, 10 June 2020 – RUSAL (SEHK: 486; Moscow Exchange: RUAL), a leading global aluminium producer, announces that it has commenced testing operations for a pilot industrial electrolytic cell with inert anodes, which has an improved design and a record low carbon footprint.

CIRCULAR ECONOMY

- The circular economy is a new way of creating value and prosperity in the Aluminium Sector.
- It works by extending product lifespan through improved design and servicing and relocating the waste from the end of the supply chain to the beginning
- **In effect, using resources more efficiently by using them over and over, not only once.**

Sectors	Aluminium	Copper	Zinc
Automotive	High Impact	Medium Impact	High Impact
Aviation	High Impact	High Impact	Medium Impact
Biotechnology	Low Impact	Low Impact	Low Impact
Chemicals	Medium Impact	Medium Impact	Medium Impact
Construction	High Impact	High Impact	High Impact
Defense manufacturing	High Impact	High Impact	High Impact
Electrical and Electronics	High Impact	High Impact	Medium Impact
Food Processing	High Impact	Medium Impact	Low Impact
IT and BPM	Low Impact	Low Impact	Low Impact
Leather	Medium Impact	Low Impact	Low Impact
Media and Entertainment	Low Impact	Low Impact	Low Impact

Sectors	Aluminium	Copper	Zinc
Mining	Low Impact	Low Impact	Medium Impact
Oil and Gas	High Impact	Medium Impact	Medium Impact
Pharmaceuticals	Medium Impact	Medium Impact	Low Impact
Ports	High Impact	High Impact	High Impact
Railways	Medium Impact	Medium Impact	High Impact
Renewable energy	Medium Impact	High Impact	High Impact
Roads and highways	Low Impact	Low Impact	Medium Impact
Space	High Impact	Medium Impact	Medium Impact
Textiles and garments	Medium Impact	Medium Impact	Medium Impact
Thermal	High Impact	High Impact	Medium Impact
Tourism	Low Impact	Low Impact	Low Impact

Key: High Impact | Medium Impact | Low Impact

Importance of Circular Economy in Indian Aluminium Sector

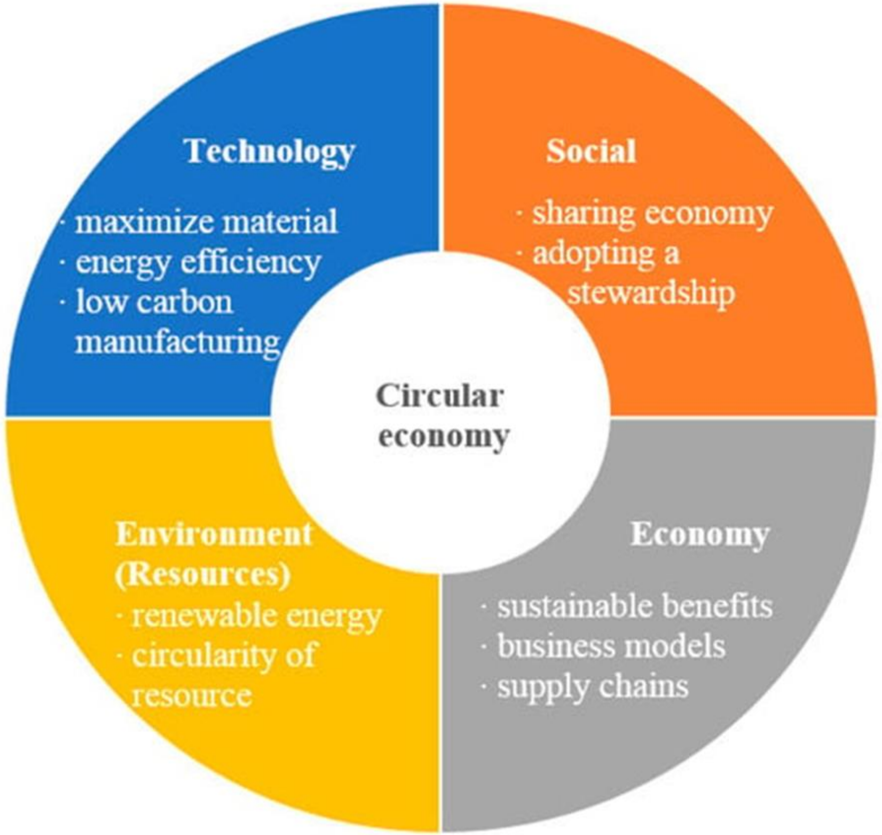
- Dwindling bauxite resources (Q/Q)
  - 800-600mT recoverable
  - Bauxite definition
- Environment Pollution
- Coal/Power Availability
- Higher input material/energy cost
- Highly volatile Al/Al_2O_3 prices

Global Trends – E^3

Economy - **Cost Reductions**

Energy - **Reduced Energy Consumption**

Environment - **"Carbon Footprint" Reduction**



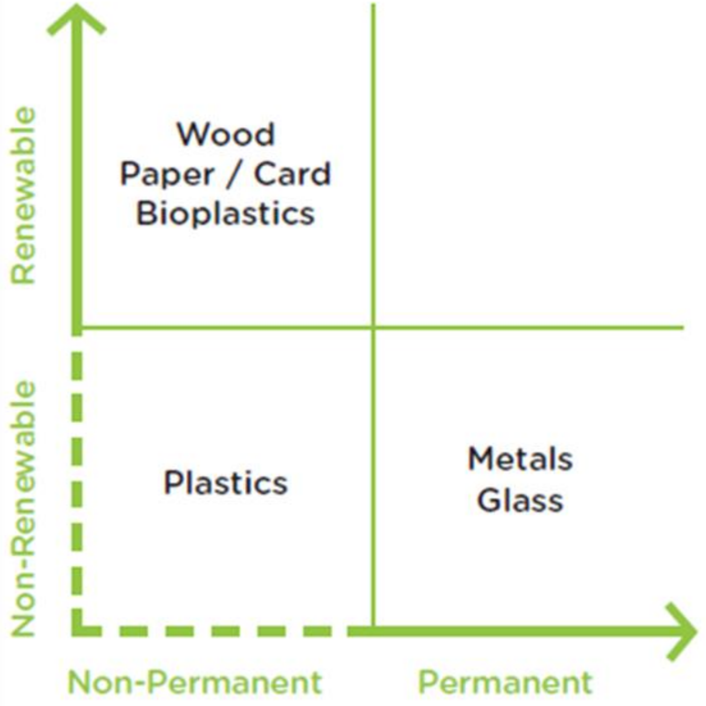
Aluminium Permanent Metal : A circular economy game changer

"Permanently available materials are those for which efforts are made to retain for use in society the energy and raw materials invested in their production at the end of the product life, either through reuse or recycling, with no loss of quality no matter how many times the material is recycled."

(Source: British Standard Institution (BSI) standard 8905:2011)

Why are 'Permanent Materials' important?

Permanent materials now have a greater focus because of increased consumption and growing populations. This brings the need for materials that are infinitely recyclable in order to serve these demands and this concept is known as a 'Circular Economy'.



Renewable materials such as wood, paper/card or bio plastics are made from natural resources that can be re-built by biological processes.

Permanent materials are classified as materials that once produced can be recycled or reused without the loss of quality, regardless of how often the material is recycled.

Aluminium in Circular Economy

Moving to a circular economy

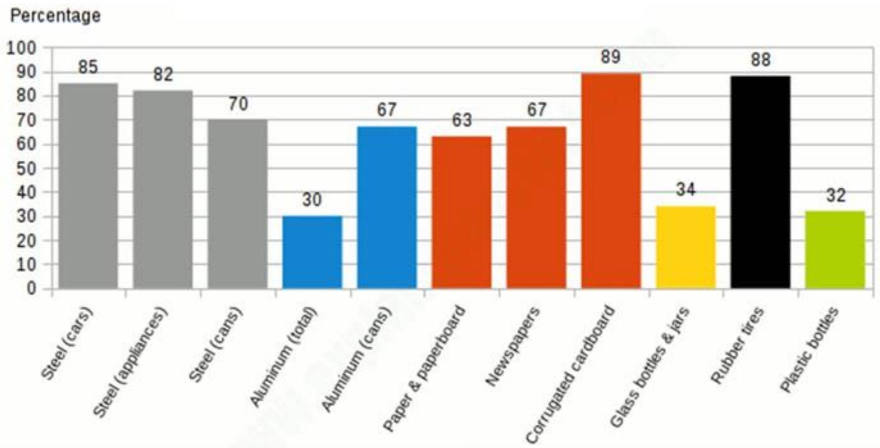
- Aluminium has a life cycle that few materials can match

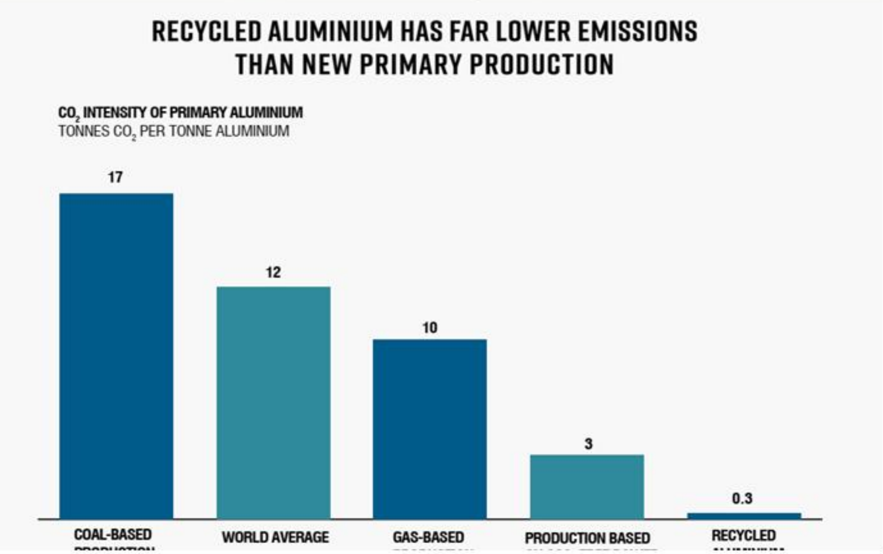
Aluminium can be recycled endlessly

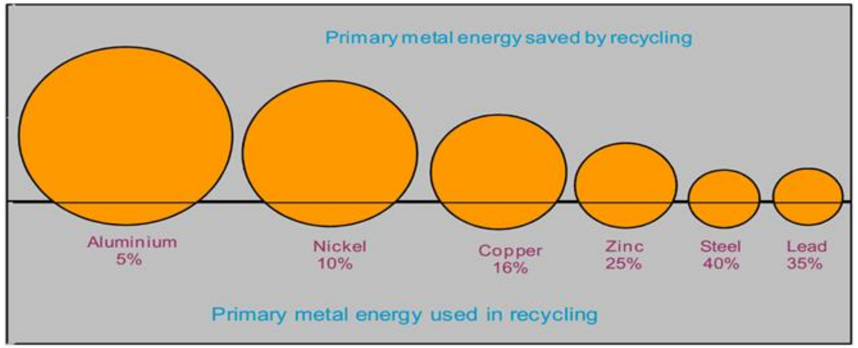
- Aluminium is an energy bank, which makes sense environmentally and financially

Aluminium in the circular economy

- Aluminum can be defined as the most circular material with infinitely and 100% recyclable
- Recycled aluminium is not different from what is obtained by the original mineral (bauxite), and its characteristics are unchanged
- 0.4 – 0.6 kW /h is required to produce 1 kg of new aluminium from scrap







Conclusion

- Substantial progress made in inert anode development, particularly regarding anode wear & metal purity
- The commercial aspects are yet to be proven, and the operation of inert-anode cells will be very challenging.
- **It is impossible to say when, or even if, this may be a proven technology.**
- Aluminium sector needs to be at the forefront of the circular economy model, given its pervasive applications.
- Bauxite is finite; the circular economy is the environmentally and economically viable way towards its conservation
- In today's world, nothing is a waste, and all so-called wastes can be converted into resources for wealth creation by the adoption of a circular economy

Thank You

Anupam Agnihotri
Director

Jawaharlal Nehru Aluminium Research Development & Design Centre, Nagpur
director@jnarddc.gov.in
+91 9404084435 (M)
+91 7104220763 (LL)

www.jnarddc.gov.in

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