

ASSESSMENT OF GLOBAL HIGH PURITY ALUMINA (HPA) MARKETS

SUMMARY REPORT

A Report Prepared by the CM Group for
Advanced Energy Minerals Limited for
Inclusion in a Prospectus.

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Glossary of Terms

ACH	Aluminium Choline Hydrolysis
AIH	Aluminium Isopropoxide Hydrolysis
Al ₂ O ₃	Aluminium Oxide
AQSIQ	General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China
ATH	Alumina Trihydrate
Bn	Billion
Ca	Calcium
CATL	Contemporary Amperex Technology
CGA	Chemical Grade Alumina
CHIPS	Creating Helpful Incentives to Produce Semiconductors (US Act, 2022)
CMP	Chemical Mechanical Planarization
CO	Carbon Monoxide
CRTs	Cathode-ray Tubes
ESG	Environmental, Social and Governance
FTA	Free Trade Agreements
FYI	For Your Information
GGII	Gaogong Industry Institute
GPF	Gasoline Particulate Filter
HC	Hydrocarbon Compounds
HPA	High Purity Alumina
HPA 3N	High Purity Alumina with Alumina Content of 99.9%
HPA 3N5-8	High Purity Alumina with Alumina Content of 99.95%-99.98%
HPA 4N	High Purity Alumina with Alumina Content of 99.99%
HPA 4N5	High Purity Alumina with Alumina Content of 99.995%
HPA 5N	High Purity Alumina with Alumina Content of 99.999%
ICC	ICC Sino
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometer
ICs	Integrated Circuits
IRA	The Inflation Reduction Act (US Act, 2022)
ITO	Indium Tin Oxide
LED	Light Emitting Diodes
LFP	Lithium Iron Phosphate
LiB	Li Ion Battery
LiCoO ₂	Lithium Cobalt Oxide
MOCVD	Metalorganic Chemical Vapor Deposition
MOU	Memorandum of Understanding
Na	Sodium
Nano Aa	Nano alumina, typically of size <200nm
NCM	Nickel Cobalt Manganese

NEVs	New Energy Vehicles
NMA	Non-Metallurgical Alumina
NMC	Nickel Manganese Cobalt Oxide
NOx	Nitrogen Oxide
OEM	Original Equipment Manufacturer
PDPs	Plasma Display Panels
PE	Polyethylene
PP	Polypropylene
ppb	Parts Per Billion
ppm	Parts Per Million
PVC	Polyvinyl Chloride
PVD	Physical Vapor Deposition
RBST	Chongqing Renbing Technology Co., Ltd.
ROW	Rest of World
SAC	Standardization Administration of the P.R.C.
SGA	Smelting Grade Alumina
SI	Southern Ionics
SiO ₂	Silicon Dioxide
TFT	Thin-film Transistor
Th	Thorium
TiO ₂	Titanium Dioxide
Tn	Trillion
TWC	Three-Way Catalyst
U	Uranium
UHPA	Ultra-High Purity Alumina
UK	United Kingdom
US	the United States
USGS	U.S. Geological Survey
Nano Alumina	<200nm alumina

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AEM HPA Summary Report

This report presents an independent assessment of global High Purity Alumina (HPA) markets, (Japanese, South Korean, US, EU and Chinese), focusing on high-end 4N/4N+ market sectors and their applications.

Executive Summary

- **Global demand for high-end 4N/4N+ HPA grew at a fast rate of 13.6% CAGR from 2013 to 2024, driven by strong demand in new industrial applications, in particular sapphire/LED manufacturing. Customer behaviour indicates currently tight market conditions.**
- **Global demand is forecast to continue to grow at double-digit CAGR (10.0%) over the 10-year period from 2025 to 2035, driven by continued strong demand from the key sapphire/LED market with additional growth areas of semiconductor and battery sectors.**
- **Strong global demand growth coupled with a sluggish supply response in the ROW will ensure markets remain tight and with a supply deficit forecast in 2026, and from 2029 to 2034.**
- **Prices are forecast to rise (in real terms) over the 10-year period to 2035, driven by strong demand and an emerging Rest-Of-World (ROW) supply deficit.**
- **China, the world's largest producer of HPA, is expected to be excluded from ROW markets, due to an inability of Chinese producers to meet the strict quality requirements demanded by ROW markets, coupled with prohibitively high trade barriers.**
- **The emergence of a new market sector for marginally lower HPA grades in the quality range 3N5-3N8 HPA attracts prices which are typically discounted by 40%-50% relative to 4N/4N+ prices, depending on the specific quality requirement and application.**
- **New ROW producers have a significant opportunity to enter the HPA 4N/4N+ market at this time due to attractive market conditions; and, using commercially proven, low-cost technologies, have an opportunity to establish themselves and take advantage of the high industry cost structure to generate strong margins.**

Market Overview

High Purity Alumina markets have only meaningfully emerged over the past two decades. This relative market immaturity together with a strong interdependence of customer and supplier, means they do not follow typical supply-demand fundamentals or behave like commodity markets (and are unlikely to do so over the outlook period to 2035) given the:

- 1) Small volumes associated with the key market segments,
- 2) Lack of transparency in prices and contracts,
- 3) Rapidly moving nature of high-tech applications, and
- 4) Non-fungibility of HPA, given the diverse range of products and applications.
- 5) Sales/purchase based almost entirely on customer tailored products.

HPA markets currently attract high prices and return solid margins and, in our view, are likely to continue to do so over the outlook period. We base this view on a strong demand growth outlook for several key HPA market sectors, a widening ROW supply deficit and several significant barriers to entry, particularly around access to commercially proven production technology and capex to build a plant.

Highly customized HPA is non-fungible and manufactured to precise customer specifications. Different customers require different product specifications, even if applications are similar (a critical point of differentiation between HPA and other industrial minerals and minor metals, which have typically larger, more liquid markets and follow pricing patterns more closely aligned with market supply-demand balances and cost curve pricing fundamentals). Customers will undertake a qualification process on the HPA to ensure it is suitable for their requirements. This will typically take one to two years.

A strong interdependence between customer and supplier ('sticky relationship') is significantly more influential on pricing than the cost of production, given the sensitivity to quality and performance, the symbiotic nature of the relationship and highly customized end-product. HPA prices are negotiated almost exclusively on a bilateral basis, reflecting the multi-faceted customer/supplier relationship, often including a deep level of technical exchange, including interchange of IP.

The highly specialized nature of HPA applications results in customer and supplier working closely together to develop solutions to unique materials challenges, creating strong and defensible barriers to entry. Consequently, we strongly emphasise formal 'qualification' as a prerequisite to commercial supply into HPA markets. The importance of achieving qualified status as an HPA supplier cannot be overstated - no matter how long it takes - given the precision required to produce highly specialised HPA products and the defensible competitive advantage qualification creates.

CM considers Chinese and ROW markets as separate on account of **(1)** the inability of Chinese producers to meet strict ROW 4N+ quality requirements, **(2)** the reluctance of ROW suppliers to accept the opaqueness associated with Chinese supply, **(3)** a strong desire by ROW customers to protect their IP, and **(4)** a strong drive by ROW HPA customers to increase transparency in their supply chains, especially for critical materials.

HPA Characteristics and Main Applications

High purity alumina (HPA) of grade 4N+ (> 99.99% alumina) is a specific form of aluminium oxide with a unique set of physical and chemical properties, which make it suitable for use in highly specialized commercial applications. The performance of HPA in these applications is inextricably linked to grade, quality (including impurity levels) and to the physical attributes of its crystalline structure.

Synthetic Sapphire

HPA is used to produce high-quality sapphire crystals, where specific quality and physical requirements must be met. Key requirements are:

- **High Purity Alumina (HPA)** - typically exceeding 99.99%. High level of purity ensures that the resulting sapphire crystal is also highly pure, avoiding impurities that could affect optical and physical properties.
- **Low Impurity Levels** - Impurities can negatively impact crystal growth and quality. HPA should have the lowest possible impurity content, particularly of metal and non-metals such as iron, titanium, cadmium and silicon.
- **High Crystallinity** - Highly crystalline HPA aids in forming high-quality sapphire crystals.
- **Thermal Stability** - Must exhibit excellent thermal stability; maintains stability and quality of crystal growth during the high-temperature crystal growth process of sapphire.

Synthetic sapphire has extensive applications in various fields: (LED, optics, optical communication, and military industries). Specific applications include LED substrates, optical chips, watch faces, smartphone home buttons, and camera cover plates.

Sapphire substrates - the primary material used in the production of high-brightness LED lights. Excellent thermal conductivity and stable optical properties allow LEDs to maintain superior performance under high-temperature and high-brightness operating conditions. LEDs represent the third lighting technology revolution for energy efficiency, environmentally friendly, long-lasting, and versatile light sources with a much higher energy conversion efficiency than incandescent and compact fluorescent lamps.

In the near future, with the development of the mini-LED market, HPA demand for sapphire is set to continue increasing.

Electronics & Semiconductors

In the semiconductor industry, HPA is used for:

- **Chemical Mechanical Polishing (CMP)** - for flattening and polishing the surfaces of wafers during the fabrication of integrated circuits.
- **Substrate Manufacturing** - exceptional electrical insulation properties and high thermal conductivity make HPA a suitable material for manufacturing substrates for integrated circuits (ICs), providing a stable and reliable base for electronic components.

- **Insulating Layers** – HPA’s high dielectric constant and electrical insulation properties are crucial in creating insulating layers that separate different conductive components in electronic circuits.
- **Ion Implantation** - acts as an implantation mask in the ion implantation process used to modify semiconductor materials. HPA can withstand high-energy ion bombardment and protect specific areas on the semiconductor wafer during the implantation process.
- **Sputtering Targets** - used to manufacture sputtering targets, essential in physical vapour deposition (PVD) processes. Targets deposit thin films of various materials onto semiconductor wafers during semiconductor fabrication.
- **High-Temperature Furnace Refractory** - HPA’s high thermal stability and resistance to thermal shock make it an ideal material for components within high-temperature furnaces essential in semiconductor fabrication.
- **Etching Chambers** – Can be used to protect etching chambers and internal components of etching equipment. However, the thermal expansion mismatch between the Al₂O₃ coating and the substrate often leads to cracking, compromising the coating's resistance to etching. Dense, high-purity Al₂O₃ bulk ceramics provide significantly superior resistance to plasma etching.
- **Etching Masks** - Resistance to strong acids and alkalis makes HPA suitable for use as etching masks in semiconductor etching. Masks accurately define areas for etching on the semiconductor substrate.
- **Ceramic Capillaries** – (aka ceramic nozzles or ceramic capillary blades): ceramic welding tools used for wire bonding and packaging in products such as thyristors, LEDs, surface acoustic wave devices, diodes, transistors, and IC chips. HPA (99.99%) is the main material for manufacturing ceramic capillaries and with the growing installation of wire bonding machines, the demand for ceramic capillaries is also increasing.
- **Epoxy Moulding Compound (EMC)** – In semiconductor devices, α-particles can be emitted from natural radioactive impurities in EMCs. When these particles enter the sensitive area of microelectronic devices, they can cause single-event effects, leading to abnormal CPU operation. Therefore, α-particle content in EMC has an impact on the stable operation of chips. Low-α spherical silica and spherical alumina are the main fillers used in EMC, accounting for over 80% of EMC's weight. Currently, the majority of the market is dominated by silica fillers, with over 70% of the market share. Alumina used in EMC is largely 99.7% pure alumina with strict impurity requirements. However, with more advanced 2nm chips starting to enter the market, the EMC requirement is increasing, with some producers requiring 3N plus HPA to be used as fillers.
- **Thermal Interface Material:** With fast-developing 5G connectivity and AI capability, electronic devices are becoming smaller and more integrated, highlighting heat generation issues and increasing the demand for efficient thermal management. As the thermal bridge between the chip and the heat sink, thermal interface materials (TIM) often require the addition of thermal conductive fillers to enhance their thermal conductivity due to inherent limitations. HPA is chemically stable, has excellent insulation properties, and is cost-effective, making it the primary choice as a thermally conductive insulating filler.

Li-ion Batteries

Cathode Materials (Coating and Doping)

In the rapidly evolving landscape of the global EV market, high-performance batteries continue to face a raft of challenges. The pursuit of enhanced battery performance in a demanding application often causes elevated stresses on battery materials and some serious concerns around both safety and cycle life. This is also an area of concern in other Li-ion battery application such as consumer electronics, powerbanks, and stationary storage systems.

In response to these challenges, innovative technologies, including HPA electrode coating and solid electrolytes, have emerged, although they remain in their infancy. Among these advancements, HPA coating has gained significant prominence, particularly in the realm of high-end batteries, as a pivotal solution to enhance performance and address safety and longevity concerns.

Using HPA as a coating material for Li-ion battery electrodes has proven to be instrumental in significantly improving capacity retention, cycle performance, thermal stability, and overall battery lifespan. HPA coating creates a protective barrier on the electrode surface, effectively curbing extraneous side reactions between the electrode material and electrolyte, specifically the growth of dendrites. By inhibiting dendrite formation and minimizing material degradation, HPA-coated electrodes display a superior performance.

The key benefits of HPA cathode coating are.

- **Delaying Lithium Dendrite Formation:** During the charging and discharging cycles, lithium ions undergo crystallization, resulting in the formation of needle-like structures at both electrodes. These crystalline structures have the potential to create a short circuit in the battery, posing safety risks. The application of an HPA coating is effective in mitigating the formation of lithium dendrites throughout the charging and discharging processes. Acting as a protective barrier, the HPA coating significantly impedes the formation and growth of lithium dendrites, diminishing the risk of short circuits.
- **Inhibiting Side Reactions:** A protective coating of HPA inhibits undesired side reactions between the cathode material and electrolytes. Such reactions have the potential to diminish the efficiency and cycling life of the battery. The HPA layer acts as a barrier, preventing substances in the electrolyte from undergoing further reactions with the cathode, ensuring the stability of the battery over its operational lifespan.
- **Enhancing Thermal Stability:** HPA coating contributes to the improved thermal stability of the battery. Aluminium oxide, characterised by its high melting point, thermal conductivity, and high electrical insulation, remains stable under thermal stress. It is also effective at dispersing and absorbing heat generated during the battery's operation. This helps prevent localised overheating, contributing to a more stable thermal environment.

HPA isn't the only material capable of providing the type of enhancement and protection required to improve battery performance. Alternative materials, such as titanium dioxide (TiO₂) and silicon dioxide (SiO₂) can also serve as electrode coatings. However, owing to the advantages of its high hardness, growing availability, and relatively low cost, HPA continues to stand out as the most prevalent choice for coating.

Cathode coatings are used extensively in many ternary lithium-ion batteries. Specifications for HPA coatings necessitate a purity level of 4N+ (99.99% or higher), with magnetic impurity content requiring less than 500 parts per billion (ppb).

Anode Coating

In the initial charge-discharge process of lithium-ion batteries, the formation of Solid Electrolyte Interphase (SEI) film through the reaction between electrode materials and electrolyte tends to reduce the first charge-discharge efficiency of the electrode material. Simultaneously, the detachment of the graphite layer results in the continuous destruction and regeneration of the SEI film. The progressively thickening SEI film contributes to an irreversible increase in the graphite electrode's capacity, leading to a decline in cyclic and rate performance.

The presence of a coating layer serves to prevent direct contact between the graphite surface and the electrolyte. This not only avoids the direct embedding of lithium ions and solvents, suppressing electrolyte decomposition, but also increases battery capacity, thereby improving cyclic performance.

Separators

The use of 4N HPA to coat Li-ion battery separators was once considered a major growth area. However, over the past three years, with advancements in battery technology and improvements in separator performance, there has been a decline in the purity requirement for the HPA used for the coating, seeing 4N HPA gradually replaced by more cost-effective 3N HPA and even cheaper boehmite.

Other Applications

LED Lighting

In addition to its use for manufacturing sapphire substrates for LED lights, HPA finds other applications in LED lights due to its many unique properties: -

- **Phosphor Coating** - In some LED applications, phosphors are used to produce different colours of light. HPA can be used as a coating material for phosphors, ensuring the durability and stability of the coating, leading to enhanced performance and longer lifespan of the LED.
- **Transparent Ceramics** - HPA is utilised in the production of transparent ceramics, which can be employed as protective covers or lenses for LED lights. Transparent alumina ceramics possess high hardness, scratch resistance, and thermal stability, protecting LED components.
- **Encapsulation** – HPA can be used in the encapsulation process to protect LED components from external environmental factors. The high purity ensures that the encapsulation material does not introduce impurities that could degrade LED performance.
- **Reflective Coatings** - HPA can be used in reflective coatings applied to LED components to enhance light reflection, increasing the overall efficiency of LEDs by directing light forward and reducing energy losses.
- **Heat Sink Materials** -HPA can be incorporated into heat sinks for LED lighting. Efficient heat dissipation is crucial in maintaining the optimal performance and longevity of LED devices.
- **Optical Components** - HPA's high purity and transparency make it suitable for various optical components, such as lenses and windows, used in LED lighting systems.

Polishing

Finely milled HPA is an essential abrasive material in a range of polishing processes, especially in chemical and mechanical polishing (CMP) applications. It is widely used in industries such as

electronics, glass manufacturing, metalworking and automotive manufacturing. During the polishing process, it is crucial to avoid scratches, necessitating high physical property requirements such as uniform particle size and hardness matching the product hardness.

Although 3N HPA and 4N HPA can meet the majority of polishing needs, for some high-end industries such as semiconductor and chemical mechanical planarization (CMP), a purity level of 4N or higher is required, with particle sizes reaching the nanometre scale.

Catalysts

γ -Al₂O₃ possesses excellent mechanical strength, good thermal stability, chemical stability, adjustable surface acidity and alkalinity, and various crystalline phase structures. In addition to the prominent sectors previously mentioned, high-purity γ -Al₂O₃ finds extensive application across various other industries, including petroleum chemicals and catalyst support in the chemical industry. γ -Al₂O₃ is used to coat catalytic converters on the exhaust pipe of automobiles to transform unsaturated hydrocarbons and nitrogen compounds into saturated compounds.

In China, with increasingly stringent domestic requirements for automotive exhaust emissions standards, under China's National VI emissions standard, gasoline vehicles generally install a Three-Way Catalyst (TWC) on the exhaust pipe to simultaneously treat CO, HC, and NO_x emissions. Additionally, a Gasoline Particulate Filter (GPF) is added separately to control particle emissions. Based on a single vehicle's TWC and GPF usage volume of approximately 1.8 litres and considering a reference production of 21 million vehicles in 2022, the demand for automotive exhaust carrier catalysts is about 38 million litres. Based on an estimated requirement of 35 t of γ -Al₂O₃ per one million litres, the annual demand for γ -Al₂O₃ is approximately 1,300 t.

Phosphor Powder

Phosphor powders are essential components in light-emitting diodes (LEDs), fluorescent lamps, cathode-ray tubes (CRTs), plasma display panels (PDPs) and other lighting and display devices. Possessing excellent thermal stability and high-temperature resistance, HPA is an ideal material in the preparation of phosphor powders.

Stability and High-Temperature Resistance of Phosphor Powders

Phosphor powders are typically prepared and used under high-temperature conditions, and HPA, as a stable substrate for phosphors, ensures stability even at elevated temperatures.

Carrier for Phosphor Powders

HPA is often used as a base or carrier for phosphor powders. Its high purity and excellent optical properties ensure the purity and stability of the phosphor colour. Phosphor particles can be composited with HPA through methods such as coating, doping, or blending to adjust specific luminescent properties.

Stabilisation of Luminescent Centres

HPA can stabilise the luminescent centres in phosphor powders, ensuring their stable position. This stabilization helps improve the efficiency and stability of the phosphor, which is crucial for the optical performance of the phosphor.

Dispersion and Uniformity of Phosphor Powders

As a component of phosphor powders, HPA can influence the dispersion and uniformity of phosphor particles. By controlling the particle size and distribution of HPA, the uniformity and optical properties of the phosphor powders can be enhanced.

Ceramic Matrix for Phosphor Powders

HPA can act as the ceramic matrix for phosphor powders, providing stability and reliability of the phosphor pigments during long-term use.

Ceramics

HPA ceramics have extensive applications in the fields of electronics, chemical engineering, biomedical and aerospace industries. HPA ceramics refer to ceramic materials with an Al_2O_3 content of over 99.9%(3N). Due to their high sintering temperature ranging from 1650 to 1990°C and a transmittance wavelength of 1-6 μm , they are commonly used in various applications:

- **Replacement for Platinum Crucibles:** Due to high sintering temperature and good transmittance, they replace platinum crucibles in certain applications.
- **Sodium Lamp Tubes:** Utilized for their transparency and resistance to alkali metal corrosion in sodium lamp tubes.
- **Electronics Industry:** Used as integrated circuit substrates and high-frequency insulation materials in the electronics industry.
- **Medical** - In the medical field, aluminium oxide is extensively used in the manufacturing of artificial bones, joints, artificial teeth, and more. Aluminium oxide ceramics possess excellent biocompatibility, biological inertness, physicochemical stability, high hardness, and wear resistance, making them ideal materials for creating artificial bones and joints.

Alumina ceramic substrates, made from high-temperature sintering of alumina (Al_2O_3) powder, are an advanced electronic ceramic material that plays a crucial role in the promotion and application of 5G technology. They significantly enhance circuit signal processing efficiency, optimize heat dissipation, and improve circuit stability and reliability, effectively meeting the stringent demands for high-frequency and high-bandwidth signal transmission.

Transparent Ceramics

Transparent ceramics refer to ceramics that allow light to pass through. Typically, ceramics are opaque due to refraction and scattering effects caused by defects like micro-pores within the ceramic material, making it difficult for light to pass through.

Presently, transparent alumina ceramics are not only used in high-pressure sodium lamps but have also found applications in new lighting technologies like metal halide lamps as discharge tubes. Additionally, they serve as bio-ceramics, e.g., in ceramic brackets for orthodontics.

The key to preparing alumina ceramics lies in eliminating residual pores. Pores have the greatest difference in refractive index with transparent ceramics, so the quantity and size of pores have a significant impact on scattering losses. Factors affecting the transparency of ceramics include porosity, grain boundary structure, surface finish, grain size, crystal structure, and impurities. 4N+ alumina is widely utilized in transparent ceramics due to its high purity.

Ceramic Targets

Metal oxides, such as aluminium oxide (Al_2O_3) or zirconium oxide (ZrO_2), are examples of inorganic non-metallic materials in the category of metal oxides. These materials possess many ceramic characteristics, including high hardness, high melting points, and chemical stability.

In magnetron sputtering, ceramic targets are used to produce specific thin films. Aluminium oxide targets can be utilized to manufacture corrosion-resistant and wear-resistant coatings.

Thermal Sprays

Thermal spraying is the process of heating and melting coating materials, atomising them into extremely fine particles with high-speed airflow and then spraying them onto a surface at high velocity to form a coating. Different coating materials are selected based on desired properties, such as wear, corrosion, oxidation, heat and electromagnetic wave resistance. Thermal spray coating has become a major market for spherical alumina (3N and 4N.)

Thermal spraying technology primarily uses heat sources such as flames, electric arcs, and plasma to heat the spraying material to a molten or semi-molten state. The particles are then accelerated to impact the substrate, forming a coating. Compared to other surface treatment processes, thermal spraying has a broader range of applicable materials. Given the limitations of aluminium alloys, such as low hardness, poor wear resistance, and rapid failure upon damage, the high wear resistance of thermal spray coatings effectively compensates for these shortcomings.

Thin-film Deposition/Vacuum Coating

Vacuum coating refers to the technology of evaporating or sputtering metal or non-metal materials onto the substrate surface under vacuum conditions to form a thin film. Vacuum coating materials are used in vacuum coating processes that evaporate, sputter, or deposit onto the substrate surface to form thin films.

Vacuum coating materials can be applied to substrate surfaces through methods such as sputtering, evaporation, ion plating, physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), and pulsed laser deposition (PLD). Possible substrate materials include plastic, film, paper, metal, and alloys. Alumina films possess excellent electrical insulation and chemical stability, effectively isolating current in microelectronic devices to prevent issues like short circuits and significantly enhancing the hardness and wear resistance of surfaces, extending the product's lifespan.

Emerging New Applications

Sodium-ion Batteries

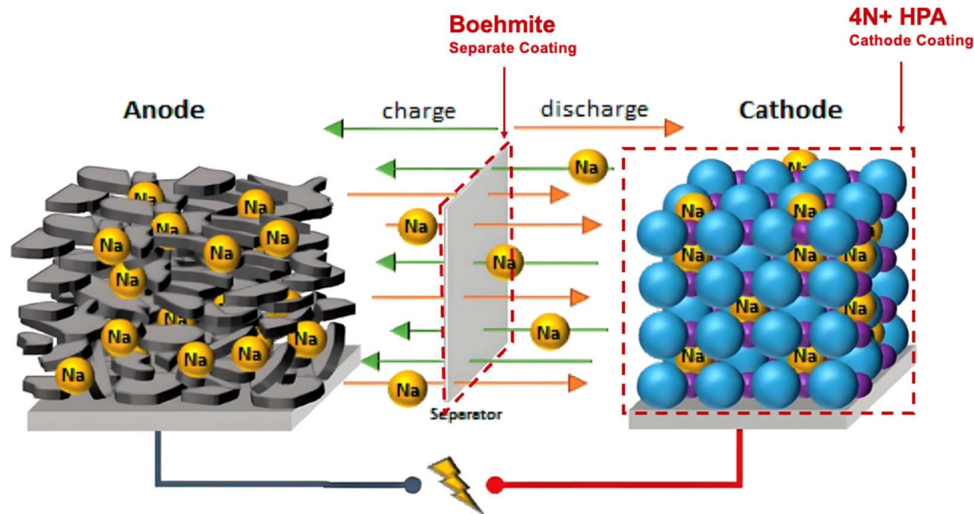
Lithium-ion batteries have been widely used in small electronic devices and power batteries for new energy vehicles. However, lithium-ion batteries still have several drawbacks, including safety concerns, raw materials sourcing (Li) and over-capacity.

In our view, the current applications of HPA in lithium-ion batteries, including separator coating, electrode coating and cathode material encapsulation, could extend to sodium-ion batteries in the future.

Given the resemblance in negative electrode materials and electrolyte types between sodium-ion and lithium-ion batteries, the application of HPA in sodium-ion batteries is expected to have similar benefits. These may include enhancing stability, improving cycling life, and enhancing safety. Such

applications have the potential to drive advancements in sodium-ion battery technology, making it more competitive and widely applicable, particularly in energy storage and other domains.

Figure 1 Application of Boehmite & HPA in Sodium-ion Batteries



Source: Flash Battery Designs, CM Group

Although the decline in lithium carbonate prices in 2023 and 2024 has slowed the development of the sodium battery industry, sodium batteries still have broad development prospects. Overall, from 2024 to 2027, the domestic sodium battery industry is still in the nurturing period and has the potential to enter a period of high growth after 2027.

Semi-Solid-State and Solid-State Batteries

There is growing interest in semi-solid-state and solid-state batteries due to their potential to address safety, energy density and performance concerns associated with traditional liquid electrolyte-based batteries. Both semi-solid-state and solid-state battery technologies are now at the development stage and their fundamental theories are not fully mature, making it difficult to guide and support large-scale production.

Solid-state batteries face technical challenges that need to be overcome. For instance, the ionic conductivity of solid-state electrolytes is significantly lower than that of liquid electrolytes, resulting in increased internal resistance, reduced cycle life and diminished rate performance. High costs are a significant factor hindering the commercialization of solid-state batteries. The industry chain for liquid lithium-ion batteries is highly mature at present, allowing the production of well-performing lithium-ion batteries at a low cost. In contrast, the industry chain for solid-state batteries is not yet well established.

Neither semi-solid nor solid-state batteries typically have a separator, as the electrolyte in these batteries is in a solid state and does not require a separator to prevent electrical contact between

the electrodes. Therefore, the utilization of HPA as a separator coating is not anticipated in these two battery types.

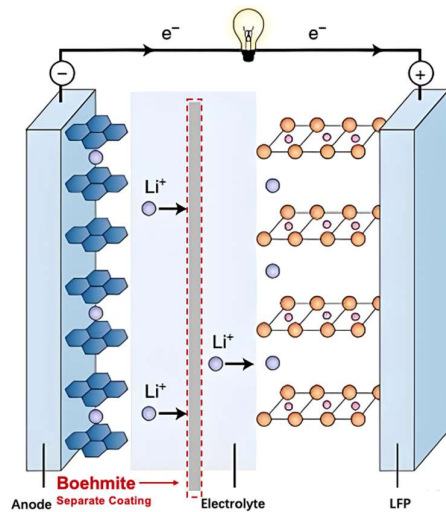
However, HPA still holds promise for various applications, primarily within the solid electrolyte and as a coating for electrodes.

- **Electrolyte Matrix**
- **Electrode Coating**
- **Electrolyte Additive**
- **Enhanced Structural Support**

With technology improvements inevitable, we believe the global battery sector is likely to see a division among lithium-ion batteries, sodium-ion batteries and solid-state batteries, depending on the specific needs of specific applications.

- **Entry-Level Vehicles** - may opt for affordable sodium-ion batteries and lithium iron phosphate (LFP) batteries. While they have slightly lower energy density, their advantage lies in cost-effectiveness, making them suitable for entry-level electric vehicles for commuting purposes.

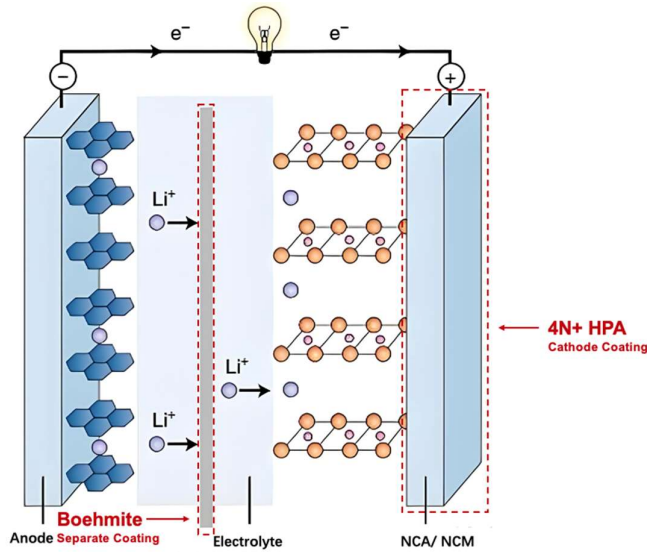
Figure 2 Application of Boehmite in LFP Batteries



Source: *Journal of Nanomaterials*, CM Group

- **Mid-Range Vehicles** - expected to predominantly use lithium iron phosphate (LFP) batteries and ternary lithium-ion batteries (NMC, NCA). Ensures a reasonable balance between energy density and cost control.

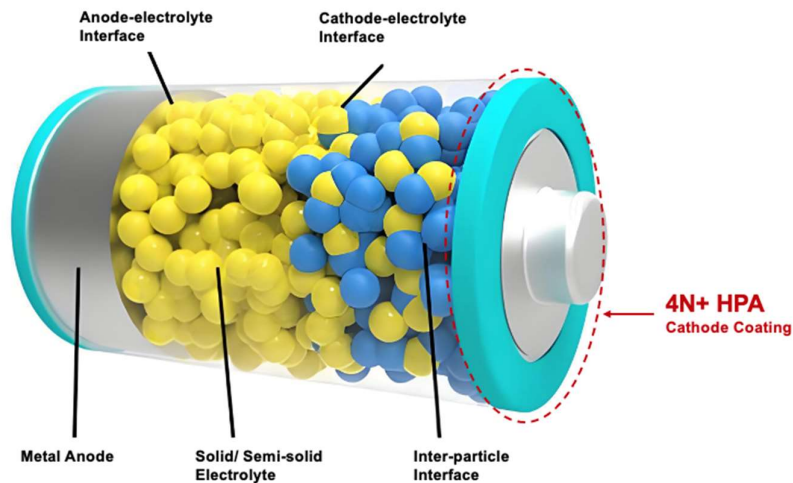
Figure 3 Application of Boehmite and HPA in Ternary Batteries



Source: Journal of Nanomaterials, CM Group

- **Entry-Level Luxury Vehicles** - projected to primarily utilize ternary lithium-ion batteries (NMC, NCA) and semi-solid-state batteries. Allows for a higher energy density while maintaining a balance between performance and cost.

Figure 4 Application of HPA in Solid-state/ Semi-solid-state Batteries



Source: Chexun, CM Group

We take a bullish view regarding HPA application in the global battery industry of the future, especially for 4N+ products and see great potential in the coating of high-nickel cathode materials as well as use in electrolytes of semi-solid and solid-state batteries. In contrast, we see 3N demand as unlikely to grow further in this sector, considering the replacement of boehmite in separator coatings and the development of solid-state (no separator) batteries in the future.

Micro LED and Mini LED

Micro LED technology refers to a high-density array of tiny LEDs integrated on a single chip. Each pixel can be individually addressed and illuminated by TFT (thin-film transistor) driving, with pixel distances in the micron range. It is considered the next generation display technology after OLED, offering both superior display quality and lower power consumption.

Table 1 Comparison of Main Display Technology

Display Technology	Traditional LCD	OLED	Mini LED	Micro LED
Technology Type	Backlit LED	Self-emissive	Self-emissive	Self-emissive
Brightness (lumen)	500	500	-	5000
Luminous Efficiency, Contrast Ratio	Low	High	High	High
Thickness (mm)	Thick, >2.5	Thin, 1-1.5	Thin, <0.05	Thin, <0.05
Lifespan (hours)	60,000	20,000-30,000	80,000-100,000	80,000-100,000
Flexible Display	Difficult	Easy	Easy	Difficult
Number of LEDs	100	-	10,000	1,000,000
Cost	Low	Medium	High	High
Power Consumption	High	About 60%-80% of LCD	About 30%-40% of LCD	About 10% of LCD
Viewing Angle	160°×90°	180°×180°	180°×180°	180°×180°
Operating Temp.	40-400°C	30-85°C	-100-120°C	-100-120°C
Industrial Progress	Mass production	Mass production	Initial scale production	Research stage

Source: CM Group

Currently, Micro LED faces technical challenges in mass transfer, driver IC, epitaxial wafers, maintenance, and repair. Moreover, it is costly and still in the stage of technological accumulation, making large-scale production difficult. Before achieving widespread use of Micro LED, Mini LED serves as a promising alternative.

The pre-process of Mini LED manufacturing includes three main steps: substrate, epitaxy, and chip processing.

- **Substrate:** The substrate material is often sapphire. Involves the growth of a sapphire crystal, slicing, polishing and other steps. 4N+ HPA is commonly utilised in the growth of sapphire crystals, with a small quantity also being employed for polishing.
- **Epitaxy:** Process of producing specific single-crystal thin-film epitaxial wafers on the substrate using Metalorganic Chemical Vapor Deposition (MOCVD).
- **Chip Processing:** Involves several steps like etching, sputtering, vapor deposition, photolithography, testing and sorting. These steps create metal electrodes. Traditional LCDs typically use edge-lit backlighting, and one unit of backlight source requires around 30-50

LED chips. However, with Mini LED as the backlight source, the demand for LED chips per unit is expected to increase to over 10,000 chips.

The continuous penetration of Mini LED backlighting will significantly boost the demand for LED chips and related materials along the industrial chain, including sapphire substrate. The current production cost of Mini LED and Micro LED remains relatively high. However, over time, the cost difference between Mini LED, Micro LED, and traditional LEDs is expected to decrease. Therefore, we hold an optimistic outlook for the application of HPA in this field.

HPA Demand and Forecast

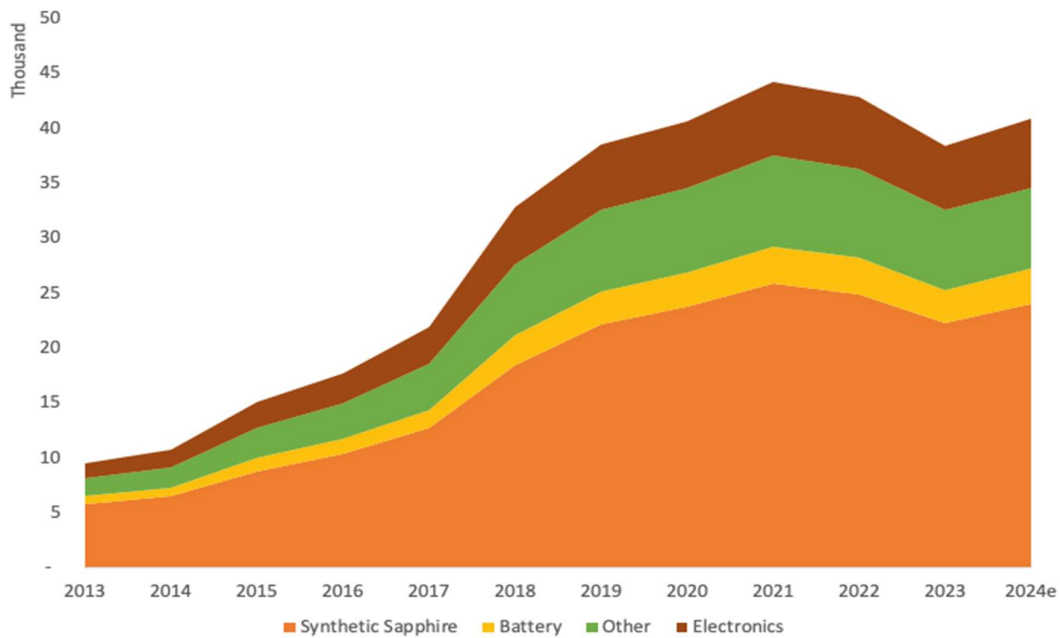
HPA Demand and Sector

Between 2013 and 2021, world consumption of HPA underwent a remarkable and substantial growth, with consumption increasing from 9.9kt in 2013 to a notable 43.8kt in 2021. This growth was primarily driven by the growing demand for HPA in the production of sapphire, electronics and lithium-ion batteries.

However, during 2022-2023, factors such as the COVID-19 pandemic and economic downturn impacted the consumption for HPA, principally in China, and most notably in major consumer industries such as sapphire, LED, phosphor powder, and those related to the property sector. This resulted in a year-on-year decline in HPA demand in 2022 and 2023 before recovering in 2024 to 40.5 kt.

Overall, the compound annual growth rate (CAGR) from 2013 to 2024 was 13.6%

Figure 5 World HPA Historical Consumption by Downstream Sector 2013-2024e, t



Source: CM Group

It is worth noting that the battery and electronics sector, as an emerging market in recent years, accounted for 11.2kt of HPA consumption in 2024, compared to only 3.0kt in 2013, almost a fourfold increase.

HPA Demand by Region

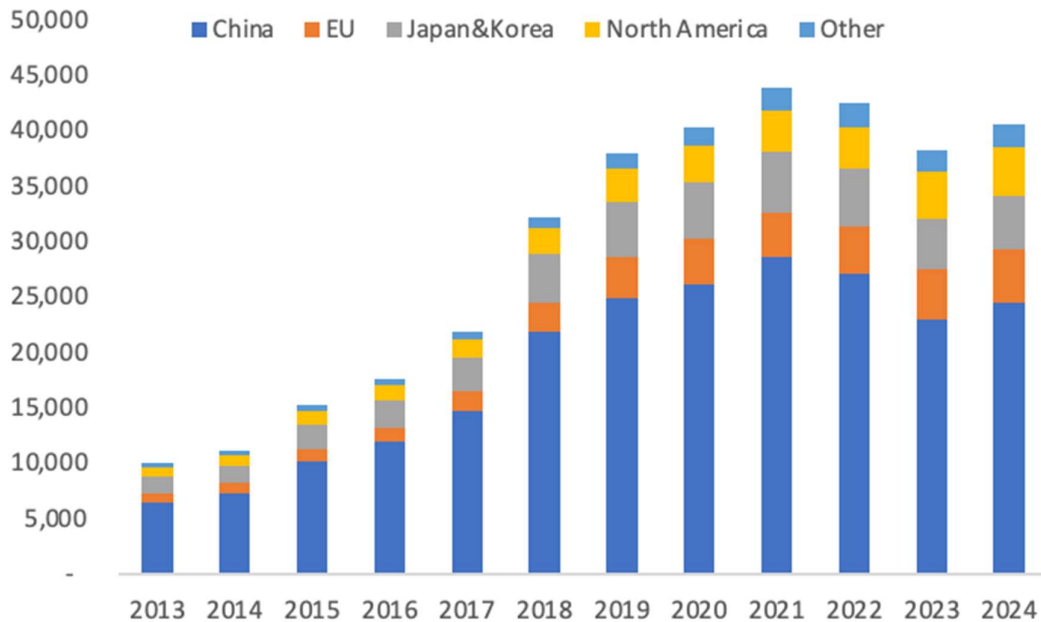
China’s HPA market is the largest and is approximately the same as ROW markets combined. It also behaves differently, given the different market forces at work. Different grades of HPA in various downstream sectors highlight a more multifaceted market. While purity remains a critical factor in choosing HPA for specific applications, as it does elsewhere, downstream customers place importance on different characteristics and properties. As a result, even when HPA shares the same level of purity, it can find utility in different applications and supply different customers, which can subsequently impact pricing. Demand is dominated by the sapphire sector at about 70% followed by electronics (semiconductors) and batteries.

In Japan and Korea, demand is spread more broadly with electronics being the largest sector at about 30%, followed by sapphire, batteries, and speciality/advanced ceramics. The use of HPA in sapphire manufacture in Japan is in the form of specialised higher quality, lower-volume manufacturers rather than Chinese mass manufacture. Quality requirements and prices are high for raw material at the high end of the range for 4N5 or even 5N material in some cases.

With the demise of sapphire production in the US, much of the consumption of HPA is now in applications such as catalysts, advanced ceramics including military and medical uses, and translucent ceramics for optics. There is also some use in the semiconductor industry and in CMP polishing.

HPA has a broad range of applications in the EU market, such as sapphire, advanced ceramics, CMP polishing, catalysts, and as fillers in semiconductor substrates.

Figure 6 4N+ HPA Demand by Region 2013-2024(t)



Source: CM Group

Forecast

We forecast strong HPA demand growth led by the key LED sapphire, semiconductor and battery coating market sectors. Specifically, we note the trend toward larger wafer sizes driving strong growth in the LED sapphire market.

Table 2 Base Case – Forecast Global Demand Growth for 4N/4N+ HPA, 2024-2034 (tpa, %)

Market (tpa)	2024e	2025f	2026f	2027f	2028f	2029f	2030f	2031f	2032f	2033f	2034f
Sapphire	21,526	23,397	25,333	27,756	30,528	33,430	37,368	41,837	46,648	51,277	56,401
Battery	3,423	3,716	4,014	4,393	4,830	5,289	5,911	6,616	7,375	8,100	8,901
Electronics	7,810	8,477	9,159	10,015	11,009	12,057	13,473	15,079	16,803	18,457	20,285
Others	7,765	8,432	9,115	9,976	10,970	12,012	13,425	15,028	16,751	18,402	20,227
Total 4N+ Demand	40,523	44,021	47,620	52,140	57,336	62,787	70,178	78,561	87,577	96,236	105,815
(%)	2024e	2025f	2026f	2027f	2028f	2029f	2030f	2031f	2032f	2033f	2034f
Sapphire	NA	8.7%	8.3%	9.6%	10.0%	9.5%	11.8%	12.0%	11.5%	9.9%	10.0%
Battery	NA	8.5%	8.0%	9.4%	10.0%	9.5%	11.8%	11.9%	11.5%	9.8%	9.9%
Electronics	NA	8.5%	8.0%	9.4%	9.9%	9.5%	11.7%	11.9%	11.4%	9.8%	9.9%
Others	NA	8.6%	8.1%	9.5%	10.0%	9.5%	11.8%	11.9%	11.5%	9.8%	9.9%
Average	NA	9%	7%	11%	11%	9%	12%	12%	12%	9%	10%

Source: CM Group

The combination of highly specialised product, qualification of suppliers and the requirement for targeted technical support and close collaboration results in the need for customers and suppliers to forge strong relationships. This is a critical characteristic of the ROW HPA 4N/4N+ market and a cornerstone to achieving the high prices on offer.

The pricing approach taken by CM for the emerging, lower-grade and more niche 3N5-3N8 sector falls within the larger HPA market sector given the nature of the production processes involved, despite the slightly lower dependence on purity levels. Pricing is therefore set by discounting price down from 4N/4N+ prices, rather than adding a bonus markup from a standard 3N 'industrial mineral' price.

Products in the 3N5-3N8 quality sector are priced at a discount to HPA 4N prices, where the discount is typically in the range of 40% to 50% when compared with Standard Sapphire Puck pricing, although the discount could be greater, depending on the purity and the specific application.

Supply, Supply Outlook and Production Methods

Supply by Region

Rest of World (ROW)

Production in 2024 of 4N/4N+ HPA outside China is considered to be closely approximated to actual capacity. Total supply is estimated to be of the order of 15,300 tpa mainly from Japan, France and Germany. Sumitomo is currently the market leader, has recently added further capacity and is considered the most likely to continue to do so of the established producers.

Table 3 Capacities of ROW HPA Producers in 2024, tpa

Group	Country	Location	Capacity t
Sumitomo	Japan	Chuo-ku, Tokyo	5,200
DONGWOO FINE-CHEM (Sumitomo)	South Korea	Pyeongtaek-si, Gyeonggi-do	1,600
Nippon Light Metal	Japan	Minato-ku, Tokyo	1,100
Taimei	Japan	Chuo-ku, Tokyo	500
Sasol Chemicals	Germany	Brunsbüttel, Germany	4,200
Baikowski	France	Poisy, Auvergne-Rhône-Alpes	1,200
Baikowski	USA	Malakoff, TX	900
Advanced Energy Mineral Limited	Canada	Cap-Chat, Quebec	300
Polar Performance Materials	Canada	Oakville, ON	300
Total			15,300

Source: Public Sources, CM Group

China

Fuelled by surging demand for HPA over the past decade, China's HPA supply base responded rapidly, experiencing a remarkable surge that, in the end, outstripped demand. Total 4N+ capacity has expanded from 12.8 ktpa in 2013 to a 64.7kt in 2024. Concurrently, production figures have risen from 3.1kt to an estimated 28.9kt over the corresponding period. Stated capacity utilisation is consistent with other similar sectors in the Chinese economy and capacity may be overstated.

The majority of capacity expansion occurred during the period spanning 2015 to 2019, when investors held optimistic expectations for HPA's potential in various downstream sectors, particularly sapphire.

Previous production of HPA was mainly focused on medium to low-end grades, with 3N and 4N products collectively constituting 82% of total HPA production in 2013. With technology improving, we see the situation changing because Chinese producers are now capable of producing more high-end products.

With the demand rebounding, pulled by mini-LED, China's overall HPA production in 2024 reached 28.9kt, up 8% y-o-y.

Table 4 4N+ HPA Supply by Country / Region, 2014-2024 (t)

Calendar Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
China	3,554	7,410	9,962	16,487	21,575	26,928	26,582	30,818	30,360	26,810	28,935
ROW	7,668	8,678	9,578	9,778	10,288	10,628	12,378	12,803	12,803	11,273	11,693
Total	11,222	16,088	19,540	26,265	31,863	37,556	38,960	43,621	43,163	38,083	40,628

Source: CM Group

Supply Outlook

On the supply side, our analysis estimates current global supply at 40,628 tpa (Table 5), with China the largest producer, at approximately 29,000 tpa of HPA '4N-grade and above', although in our view, Chinese producers cannot consistently meet the quality requirements of ROW 4N/4N+ producers and do not provide any technical support.

Table 5 Forecast Global 4N+ HPA Supply by Country / Region, 2024-2034 (t)

Calendar Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
China	28,935	31,625	32,885	33,995	34,995	35,995	39,545	43,460	46,060	48,960	50,860
EU	4,345	4,770	4,770	5,620	6,470	6,470	6,470	6,470	6,470	6,470	6,470
Japan & Korea	6,235	6,235	7,235	8,235	8,235	8,235	8,235	8,235	8,235	8,235	8,235
North America	1,113	2,193	2,643	3,543	5,343	6,193	6,643	6,643	6,643	7,093	7,093
Other	-	-	-	800	2,500	4,000	5,000	5,000	5,000	5,000	5,000
Total	40,628	44,823	47,533	52,193	57,543	60,893	65,893	69,808	72,408	75,758	77,658

Source: CM Group

Our supply-side research identified few potential new ROW producers likely to enter the market. New producers, or high credibility aspirants, are limited to Advanced Energy Minerals (Stage 1 – 3,000 tpa, Stage 2 – 6,000tpa), Polar Performance Materials (1,000tpa) in Canada, and Alpha HPA in Australia, where construction has commenced at its Gladstone (Australia) site for a nameplate capacity of 5,230t/yr HPA plus additional aluminium chemicals. Alpha HPA's ramp-up is likely to take several years.

Production Methods

There are several ways to produce HPA, which are described below.

Modified Bayer Process

The Bayer process is traditionally used to extract alumina from bauxite ore. The Modified Bayer Process is a variation of the conventional process used for producing alumina in which high-quality feedstock is used, and additional purification steps are incorporated to enhance the purity of the final product. Dissolution of aluminium hydroxide in a sodium hydroxide solution is followed by precipitation, washing and calcination to obtain HPA with high purity levels. This is a mainstream technology to produce HPA in China, especially by producers in Shandong, where Chalco Shandong refinery is located and acts as a main raw materials (hydrate) supplier to them.

Aluminium Isopropoxide Hydrolysis (AIH)

AIH is a hydrolysis-based method in which aluminium isopropoxide is hydrolysed in a controlled manner to produce HPA, allowing for precise control over the reaction conditions and the formation of highly pure alumina particles. The resulting HPA can be further processed to achieve the desired particle size and purity. Sumitomo and Sasol also use this method to produce HPA.

Hydrothermal Crystallisation

Hydrothermal methods involve the controlled crystallization of aluminium-containing precursors under high-pressure, high-temperature conditions. An aluminium-containing solution or gel is subjected to hydrothermal treatment, promoting the growth of pure HPA crystals. The crystals are then washed, filtered and calcined to obtain the final HPA product. (One of the HPA production methods used by Baikowski.)

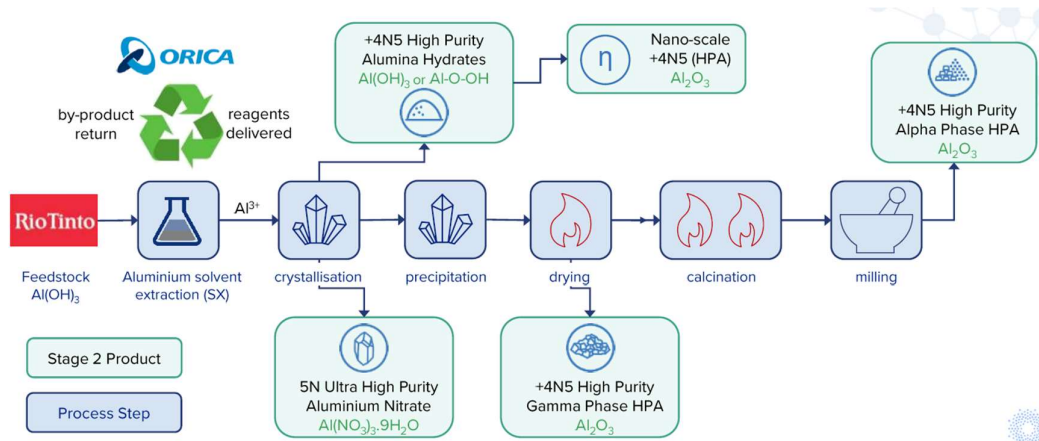
Aluminium Choline Hydrolysis (ACH)

Aluminium choline is hydrolysed to produce HPA. Choline base is an organic strong base used as a solvent, catalyst and corrosion inhibitor in the chemical industry. Choline hydrolysis involves the hydrolysis of aluminium alkoxides using choline chloride. Choline chloride acts as a catalyst in the hydrolysis reaction, leading to the formation of HPA. The obtained HPA can be further processed to achieve the desired characteristics.

Aluminium Solvent Extraction

Organic solvents are used to selectively extract aluminium from a solution, separating it from impurities. Solvent extraction is considered one of the most environmentally responsible and efficient methods. However, relatively high technical barriers exist, and currently, no manufacturers in China use this technology. Alpha HPA, based in Australia, employs this method at its Gladstone facility to produce HPA (>99.99% pure HPA products). Simultaneously, the company engages in the complete recycling of its key reagents as valuable by-products.

Figure 7 Solvent Extraction

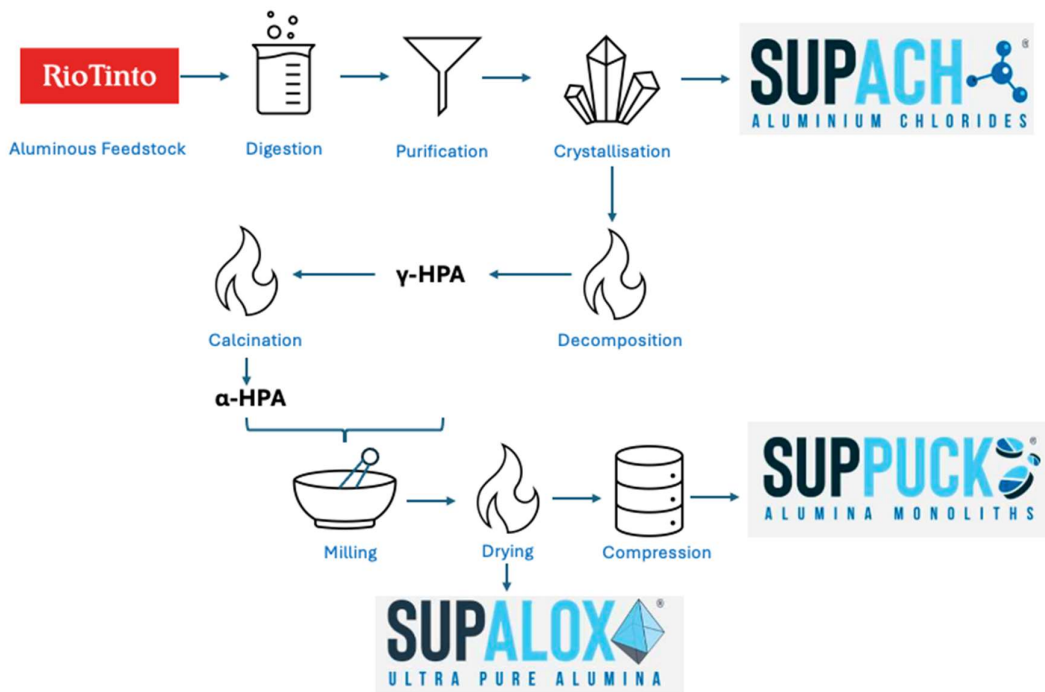


Source: Alpha HPA

Chlorine Leach-CLCP

Chlorine Leach-CLCP technology is the method used by AEM, which extracts alumina from an aluminous feedstock. AEM's CLCP process directly chlorinates and purifies/crystallizes the aluminous feedstock, followed by conventional thermal treatment and mechanical processing. Moreover, the CLCP method can produce products including alpha-alumina and gamma-alumina, with a high degree of manufacturing flexibility in product specifications (such as particle shape, size distribution, and purity). In addition, the CLCP process generates almost no solid waste, and the by-product aluminium chloride can be used as a commodity in the water treatment industry.

Figure 8 Chlorine Leach-CLCP



Source: CM Group

Table 6 Comparison of Commercially Operating HPA Technologies

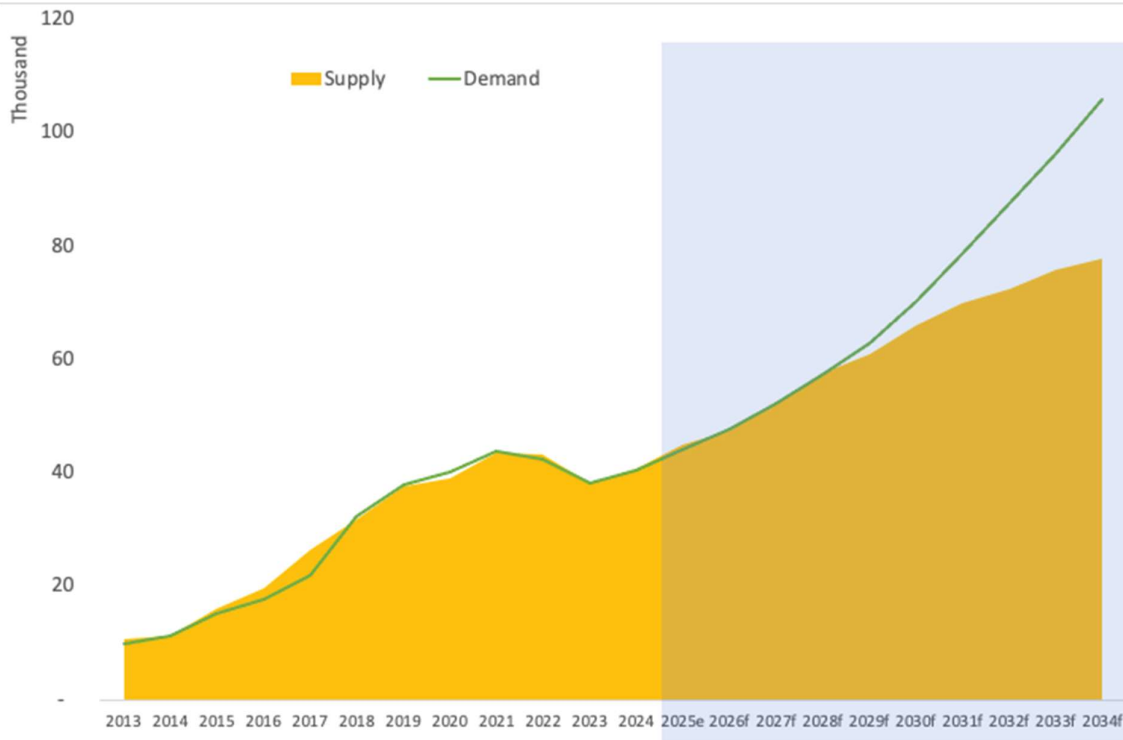
Technology	Raw Materials	Strength	Weakness	Cost
Modified Bayer Process	Al_2O_3 , $Al(OH)_3$	Low Cost	Old Tech, Low Productivity, Energy Consuming, Pollution	Low
Aluminium Isopropoxide Hydrolysis (AIH)	Primary Al. $(CH_3)_2CHOH$	Best Quality, Environmentally Friendly	High Cost	High
Hydrothermal Crystallisation	Primary Al	Short Process Flow	Safety Risk	Medium
Re-Crystallization	$Al(OH)_3$; H_2SO_4 ; $(NH_4)_2SO_4$	Low Entry Threshold	High Impurities	Low
Aluminium Choline Hydrolysis (ACH)	Primary Al	Mature Tech, Low Entry Threshold	High Cost	High
Aluminium Solvent Extraction	Al_2O_3 , $Al(OH)_3$	Wide product mix, low cost, proprietary technology	Yet to be proven at full commercial scale	Low
AEM CLCP	Aluminous, Al_2O_3 , $Al(OH)_3$	Low Carbon Emission, By-product can be recycled	New producer	Low

Source: CM Group

Supply Demand Balance and Pricing

Through 2013 to 2017, there was oversupply as stock levels rose to support, in particular, the rapidly growing sapphire/LED sector. This moved into undersupply through 2018 to 2021, with continued rapid demand growth prior to easing in 2022 and 2023. In 2024, production recovered by around 7% reaching 40,628 t and HPA 4N+ markets were considered largely balanced, although a small surplus of around 100 t was added to existing inventories. Discussions with customers indicate tight market conditions currently and a concern about securing supply for new projects.

Figure 9 Global HPA Supply Demand Balance by Product 2013-2034,



Source: CM Group

With solid demand growth forecast across all sectors and the likely emergence of new markets, such as mini-LED and micro-LED, a deficit in HPA is forecast to gradually widen. It is estimated that by 2034, there will be a shortage of 28,000 t of 4N+ HPA.

The charts below provide CM’s price forecasts by product and by regional market, based on market characteristics for each region combined with the outlook for each product. Prices are shown on a 2024 basis.

Table 7 ROW HPA Spec 1 Price Forecast (US\$/kg)

Region	2024	2025	2026	Long-term
Japan	20	21	30	38
EU	18	21	30	38
South Korea	19	21	30	38
USA	23	21	30	38

Source: CM Group

Table 8 ROW Milled HPA (4N5+ standard D50 ~ 1um) Price Forecast (US\$/kg)

Region	2024	2025	2026	Long-term
Japan	25	25	32.5	40
EU	22.5	25	32.5	40

Source: CM Group

Table 9 ROW HPA Pucks Price Forecast (US\$/kg)

Region	2024	2025	2026	Long-term
Japan	28	29	41	46
EU	36	36	41	46

Source: CM Group

Table 10 ROW Gamma HPA Price Forecast (US\$/kg)

Region	2024	2025	2026	Long-term
Japan	16	18	22	30
EU	20	18	22	30

Source: CM Group

Table 11 ROW Nano HPA Price Forecast (US\$/kg)

Region	2024	2025	2026	Long-term
Japan	45	45	50	50
South Korea	50	50	50	50

Source: CM Group

Production Costs

ROW

CM estimates production costs by estimating raw materials, energy, labour, and 'other' costs based on different production processes and locations, as well as taking into consideration different product grades and purities.

Table 12 Costs Breakdown of 4N5 unmilled product by Different Regions in 2024, US\$/t

	Raw Materials	Energy	Labor	Other	Total
CANADA	2,160	1,296	865	1,496	5,817
Australia	3,713	2,228	1,487	2,572	10,000
USA	5,548	7,433	1,118	2,488	16,586
Japan	5,838	9,122	888	2,797	18,644
FRANCE	6,282	8,784	1,052	2,844	18,962

Source: CM Group

China

China produces HPA using four methods, namely:

- Modified Bayer Process
- Aluminium Isopropoxide Hydrolysis (AIH)
- Hydrothermal Crystallization, and
- Aluminium Choline Hydrolysis (ACH).

Costs vary based on the technology used and the final product specifications. As estimated by CM's field study and calling surveys, weighted averages costs for specific HPA products (unmilled) in China are:

- 3N(unmilled) RMB 38,000/t (US\$5,278/t)
- 4N (unmilled) RMB 41,200/t (US\$5,722/t)
- 4N5 (unmilled) RMB 42,800/t (US\$5,944/t)
- 5N (unmilled) RMB 52,000/t (US\$7,222/t)

The products above refer to unmilled products with particle size above 20+ μm . Typically, milling the particles to below 1 μm can result in an additional cost increase of up to 100%.

Table 13 Chinese Costs Breakdown of 4N+ by Different Technologies 2024, US\$/t

	Choline Hydrolysis	Hydrothermal	Isopropoxide Hydrolysis	Modified Bayer
Output of Product	3,390	3,100	10,865	9,570
Raw material	3,827	2,735	3,055	2,243
Energy	1,823	1,550	2,391	1,262
Labor	643	634	633	638
Other	1,111	868	1,073	731
Average Cash Cost	7,404	5,788	7,151	4,875

Source: CM Group

Global Industry Cost Structure

A strong interdependence between customer and supplier ('sticky relationship') is significantly more influential on pricing than the cost of production, given the sensitivity to quality and performance, the symbiotic nature of the relationship and highly customized end-product. HPA prices are negotiated almost exclusively on a bilateral basis.

Cost curves can be a useful means of comparing relative costs between producers of similar products in different jurisdictions and technologies. However, their usefulness can be limited in circumstances where markets are small and opaque, trades are infrequent and significant differences between products and product specifications exist, which is the case for 4N/4N+ HPA.

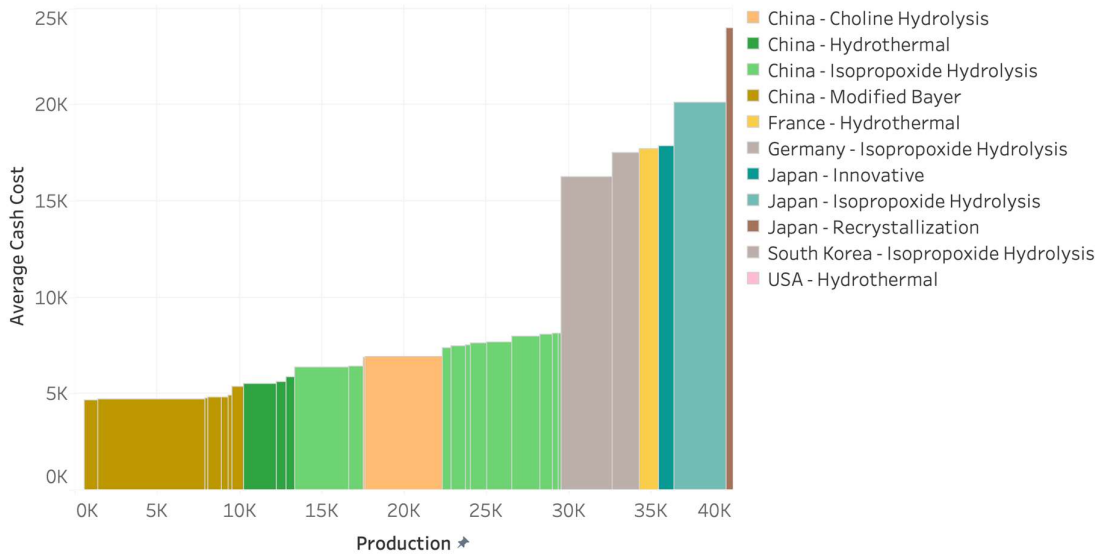
Figure 10 presents CM's global HPA cost curve for manufacturers in 2024, noting the inherent differences and limitations in the capabilities between technologies to produce particular HPA products.

In China, each of the four production processes used commercially has its own set of advantages and disadvantages. On average, the iso-propoxide hydrolysis process exhibits the highest production cost, followed by the choline hydrolysis process and the hydrothermal process. By contrast, the modified Bayer process stands out as the lowest production cost among the four methods, driven by lower raw materials input costs and lower energy costs, albeit more polluting.

Outside China, producers in Japan, South Korea and the EU have costs estimated to be significantly higher than producers in China, on account of higher energy and labour costs. That said, product quality remains a key differentiator between Chinese and ROW producers, as does technical support and innovation. In our view, this significantly limits the comparability between Chinese and ROW producers' costs.

New ROW producers entering the HPA 4N/4N+ market and utilising low-cost technologies have an opportunity to take advantage of the high-cost structures currently exhibited by existing ROW producers which, in our view, are likely to continue producing at high cost and therefore contribute to prices remaining at or above current levels over the outlook period.

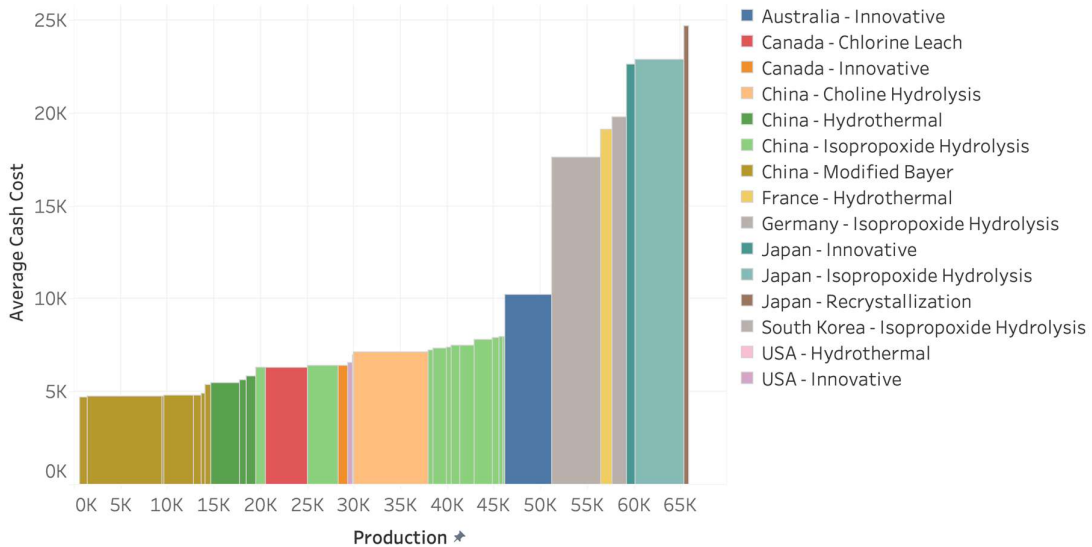
Figure 10 Global HPA Commercial Scale Production Cost Curve by Technology 2024, US\$/t



Source: CM Group

Over the next decade, as new ROW commercial producers (and processes) enter the market, we forecast a clear step emerging in the global cost curve (qualities notwithstanding), between new, low-cost production processes and older, higher cost producers (Figure 11). New producers entering the market at low cost (<US10,000/t) will be well positioned to take advantage of prices being influenced by older, higher-cost producers.

Figure 11 Forecast Global HPA Commercial Scale Production Cost Curve by Technology 2030, US\$/t



Source: CM Group