KN02 - The Decarbonisation Journey of the Aluminium Industry – Opportunities and Challenges to Achieve Net-Zero

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Abstract

The aluminium industry plays a critical role in the decarbonisation of many sectors of society, but it is also a significant contributor to global greenhouse gas emissions. The challenge for the industry is to continue enabling positive developments while minimising negative environmental impacts. The production process for aluminium generates three primary sources of GHG emissions: CO_2 emissions from electricity production for the electrolysis process (65 %), direct emissions from the smelting process (12 %), and fuel consumption for calcination, melting, and heating purposes (23 %). However, decarbonisation of the entire supply chain through renewable energies, biomaterials, inert anodes, carbon capture and storage (CCS) etc., is possible. The paper provides a high-level overview of the steps, costs, and necessary policies to transform the aluminium industry to become carbon-neutral and achieve Net-Zero solutions. Furthermore, aluminium has the potential as an energy carrier due to its energy density, transport safety and economics, and storage capacity. The industry can contribute to the fight against climate change and help decarbonize society by providing massive amounts of aluminium required for Net-Zero emissions in transport, energy generation/storage/distribution, building, and packaging. Aluminium is the third most abundant element in the earth's crust, and its exploration is less abrasive to the environment than the extraction of alternative metals (e.g., copper). Aluminium smelters can help to transport renewable energy via aluminium instead of hydrogen, making it relevant for new greenfield smelters or regions with potential surplus renewable energies. The paper also highlights the low-carbon aluminium trends and industry targets, such as establishing a green premium for low-carbon aluminium products. However, accounting loopholes and relabelling of renewable electricity may hinder the creation of a substantial low-carbon aluminium premium early in the cycle.

Keywords: Net-Zero, Variable renewable energy (VRE), Carbon capture and storage (CCS), Hydrogen, Energy carrier.

1. Introduction

Reducing GHG emissions and mitigating climate change has become paramount to governments, societies and NGOs. The aluminium sector has been an early adaptor of concepts and transparency. The industry has focused on energy efficiency in the last 50 years, which made sense in terms of resource conservation and economics. The Club of Rome and the idea of peak oil marked the previous 50 years. The question hovered around the concept of conventional energy resource scarcity. However, we learned in the last 20 years that peak oil was delayed and that coal reserves are plenty for the following centuries. We also learned that absolute scarcity is the deposition level of CO_2 in the atmosphere. Hence, CO_2 emissions need to be the leading indicator, and energy efficiency can be a sub-category if supportive of CO_2 savings.

Aluminium production is an energy-intensive process that contributes to greenhouse gas emissions. It accounts for 4 % of global electricity consumption and 3 % of global GHG emissions, mainly from power generation. The specific CO_2 emissions from aluminium smelting range from 2.5 to 25 tonnes per tonne of aluminium, depending largely on the energy source used. The shift in the power mix, with a decrease in hydroelectric power and an increase in coal-based electricity, has contributed to the rise in CO_2 emissions from the aluminium sector over the past 40 years. The following chart (**Figure *1***) displays this trend:

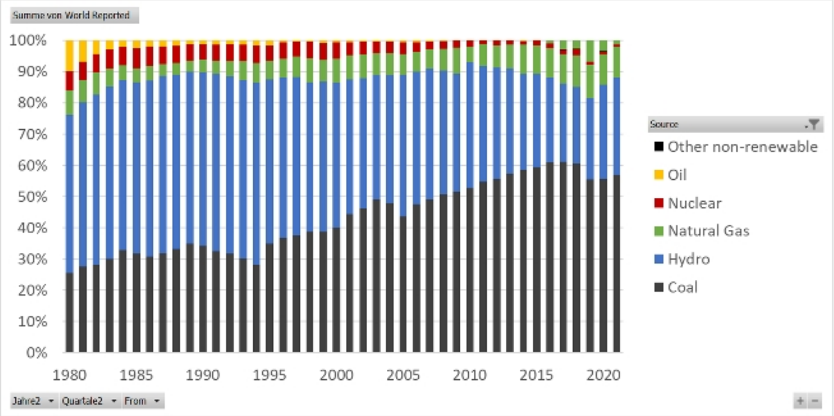


Figure 1. Primary aluminium smelting power IAI statistics 2022 [1].

Global efforts to address global warming led to establishing of the Intergovernmental Panel on Climate Change (IPCC), the Kyoto Protocol, and the Paris Agreement. The Greenhouse Gas Protocol was developed in the private sector to measure, report, and reduce company-specific emissions. The protocol introduced the concept of "scopes" to categorise direct and indirect emission sources.

The industry is now moving towards reporting total emissions along the entire value chain, including all three scopes. The International Aluminium Institute (IAI) has provided guidelines for reporting emissions at different levels, with Level 3 being the Cradle-to-Gate disclosure that covers the entire aluminium production process. The IAI has also published decarbonisation scenarios, such as the B2DS and 1.5DS, which set emission reduction targets for the industry.

Figure *2* shows the different scenarios that IAI has published on its website, “Aluminium Sector Greenhouse Gas Pathways to 2050” [2]. The blue line shows the historical development of the Cradle-to-Gate emissions for primary aluminium between 2005 and 2018. Based on IEA scenarios, the forecast scenarios use a top-down approach and calculate the emission targets based on the maximum bubble emissions from the sector. The B2DS (red triangles) targets 14.5 t/t in 2030 and 2.5 t/t in 2050, while the 1.5DS (red circles) achieves 11.5 t/t in 2030 and 0.5 t/t in 2050.

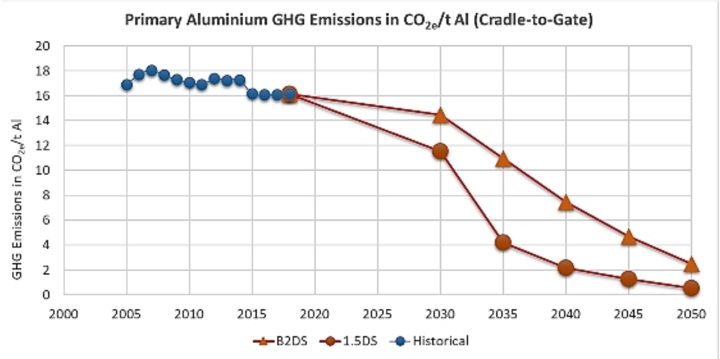


Figure 2. IAI decarbonisation scenarios for primary aluminium [2].

2. Aluminium Demand with Strong Potential

Aluminium can profit from the fight against climate change and play a central part in the decarbonisation of our society. Massive amounts of aluminium are needed for net zero emissions in transport, energy generation/storage/distribution, building and packaging. In most sectors and applications, aluminium is part of a long-lived asset, increasing the pool of aluminium-in-use. The good thing is that aluminium is the 3^{rd} most abundant element in the earth's crust, and the exploration is less abrasive to the environment than the extraction of alternative metals.

Aluminium, a versatile and lightweight metal, is poised for significant growth in demand over the coming decades. This surge can be attributed to three primary drivers: global population growth, increasing societal wealth, and the ongoing shift towards renewable energy sources for climate conservation. While the first two factors are relatively predictable, the impact of the energy transition on aluminium demand remains uncertain, with multiple scenarios and outcomes.

The aluminium industry's sustainability and carbon footprint are pivotal in these projections. A lower carbon footprint in primary aluminium production is correlated with stronger demand growth. This interdependence highlights the industry's intrinsic motivation to reduce its carbon emissions. The projection of aluminium demand and aluminium-intensive solutions will strongly depend on the decarbonisation success of the primary aluminium industry or, as CM group [3] has quoted it, “In this sense, we conclude demand and supply to be correlated; a low CO_2-e primary supply base implies stronger demand growth and vice versa.” Therefore, there must be an intrinsic motivation of the aluminium industry to reduce the CO_2 footprint of primary aluminium.

However, a unique challenge arises in the aluminium sector: the competition between primary and recycled aluminium. Environmentally-conscious consumers often prefer recycled aluminium, potentially reducing demand for low-carbon primary aluminium. This dynamic can affect prices and premiums for more sustainable aluminium products.

The energy transition is expected to be a primary driver of aluminium demand, particularly in the transport and energy sectors. Projections indicate a significant increase in demand for aluminium semis, with transport (especially automotive) and electrical (particularly transmission and photovoltaic generation) showing remarkable growth potential.

CRU [4] forecasts a 39 % increase in annual aluminium semis demand from 86.1 Mt to 119.5 Mt over the current decade, with a 60 % increase in transport and a 50 % increase in electrical demand.

Aluminium's superior conductivity per kilogram compared to copper is a noteworthy advantage, particularly for high-voltage transmission lines and automotive wiring harnesses. Substituting copper with aluminium can reduce costs and minimise the environmental impact of mining.

Aluminium is set to play a critical role in producing renewable energy infrastructure. Studies project substantial aluminium demand for wind turbines, photovoltaic panels, and grid infrastructure, ranging from 190 million to potentially 500 million tonnes by 2050. Electrification efforts in grids and societies are further expected to boost aluminium demand. The leading indicator and figure for the production data are driven by the in-use-stock expectations described in Figure 3. The in-use stock is expected to increase between 2020 and 2050 from 1 150 Mt to 2 800 – 3 700 Mt levels. This increase of 140 % - 220 % must be supplied by primary metal, besides those metal streams lost by incineration, dross or disposal. Hence, primary metal demand stays strong, but with each tonne of primary metal, another tonne of recycling is available a few years later. The chart also reveals the shares of primary and recycling which starts at a ratio of 85 %:15 % in 1960, achieves 65 %:35 % in 2020 and arrives at 50 %:50 % in 2050.

Table 1. Aluminium semis* demand [Mt] in sectors based on CRU and own extrapolations [4].

	Product Lifetime	Steel	Copper	Plastic	Glas	Wood	2020 CRU	2030 CRU	2050 extra-polation
Construction	15 - 50 Years	🟩🟧				🟧	21,3	25,9	38,7
Electrical & Mechanic	25 - 50 Years		🟩				20,2	28,3	42,3
Tranportation	10 - 30 Years	🟩					19,9	31,7	47,4
Packaging	6 - 12 Months			🟩	🟧		15,0	20,5	30,6
Others	10 - 15 Years						10,1	13,4	20,0
		Opportunity	RISK				86,5	119,8	179,0

**Semis are intermediate products that need further processing, e.g., billets and slabs that are mechanically transformed into the final product.*

To enhance sustainability and reduce the industry's carbon footprint, aluminium stakeholders focus on circularity, material use reduction, and substitution. "Design for Recycling" is a growing trend, aiming to incorporate recycling considerations into product design and manufacturing processes.

Additionally, aluminium alloys made from post-consumer scrap are gaining attention as they contribute to resource efficiency. However, scrap sorting and impurity tolerance challenges must be addressed for broader adoption.

In summary, the aluminium industry is at a crossroads, driven by population growth, increased wealth, and the global shift towards renewable energy. Sustainability and reduced carbon emissions are central to its future, and aluminium's role in renewable energy infrastructure is poised for significant expansion. The industry's success will hinge on its ability to navigate these evolving environmental and market dynamics. Decarbonisation and Climate protection can be a huge booster for the aluminium industry.

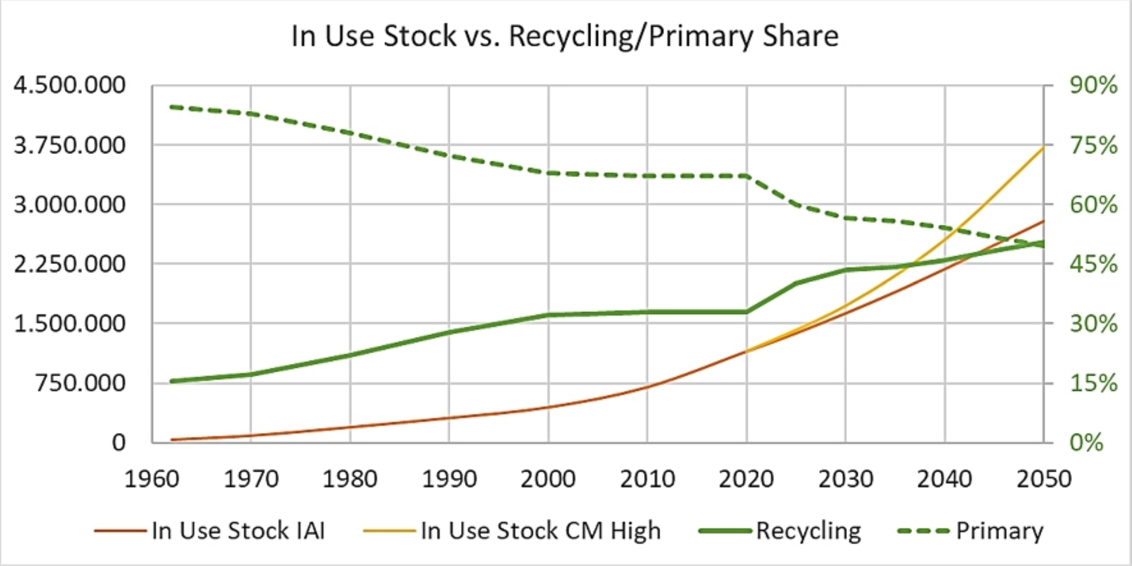


Figure 3. In-use stock and annual supply share from primary/recycling.

3. Greenhouse Gas Emissions and Energy Consumption in Aluminium Production

Figure 4 summarises the different scopes along the aluminium value chain, and its different GHG emission profiles for scopes 1, 2, and 3 (scope 3 limited to major parts as defined by IAI) displayed as t CO_2/t Al. The primary aluminium cradle-to-gate emissions are 15.9 t CO_2/t Al (as shown in Figure 4), with the smelter emission contributing almost 4/5 to this level on the global average. However, this share strongly depends on the power source and can be only 2/5 for a hydro-powered smelter, which would have a much lower overall CO_2 footprint.

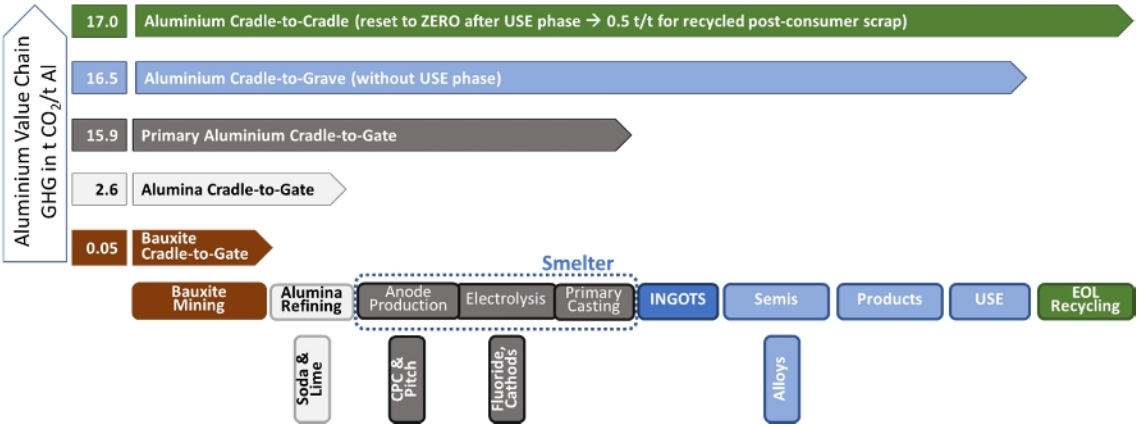
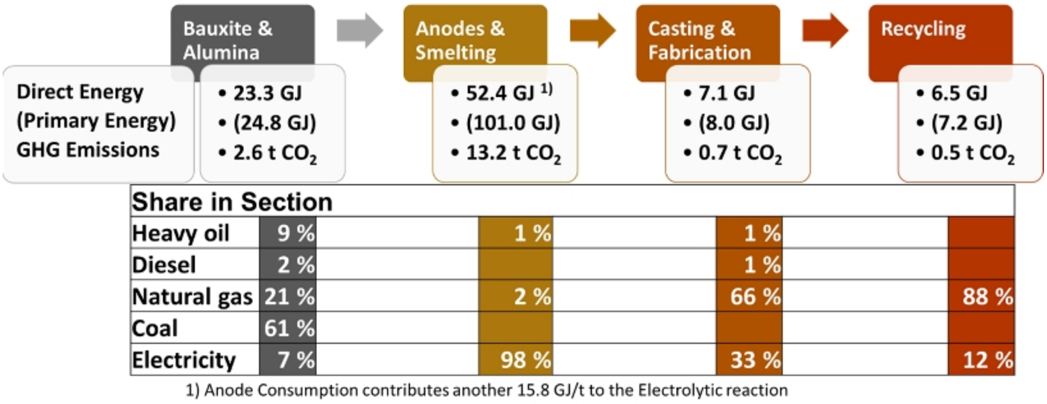


Figure 4. Aluminium value chain with GHG emissions for different scopes (the data are own calculation derived from IAI [20] and Argonne [19]).

Figure 5 summarises the energy consumption and CO_2 emissions for the individual production blocks along the aluminium value chain. Inside the white boxes are three numbers representing the energy consumption and CO_2 emissions for the individual stage. The values are presented per tonne of aluminium for the global average aluminium production. The energy values in brackets are primary energy consumption (including the conversion losses for purchased/produced electricity). A sub-note also refers to the extra energy embedded in the carbon anodes and released in the exothermic reaction of alumina with carbon. Energy and emission intensity go hand in hand. The most significant energy consumer and GHG emitter is the 2nd part of the value chain with the smelter block. The table in Figure 5 shows the fuel category and intensity for each part of the value chain. The percent share represents the amount of energy each source provides for this part of the value chain. Every block needs to sum up to 100 %.



Share in Section	Bauxite & Alumina	Anodes & Smelting	Casting & Fabrication	Recycling
Heavy oil	9 %	1 %	1 %	
Diesel	2 %		1 %	
Natural gas	21 %	2 %	66 %	88 %
Coal	61 %			
Electricity	7 %	98 %	33 %	12 %

1) Anode Consumption contributes another 15.8 GJ/t to the Electrolytic reaction

Figure 5. Value chain indication with energy consumption and CO_2 emissions (the data are own calculation derived from IAI [20] and Argonne [19]).

Coal is dominant for the alumina refinery part. It is mainly China and other Asia with a predominant share of coal consumption for the boiler house and coal gasification for the calcination process. Gas is dominant in Casting, Fabrication and Recycling, while electricity is the major factor in smelting.

Figure 6 shows the development of the specific energy consumption (blue line) for alumina refining (left) and aluminium smelting (right) and the total energy demand for the sector (orange line) expressed in TWh. While the production level (alumina and aluminium production derived from aluminium consumption [1] [21]) increases by 36 %, the total energy demand would only increase by 17 %. The forecast assumes [5] that the sector will improve at the same rate over the last 40 years, achieving the best performance today as the average in 2050. There might be further improvement options with the application of heat recovery, industrial heat pumps, vapour recompression and other solutions, but other aspects, like the anticipated deterioration of bauxite qualities, will offset some of the additional improvements.

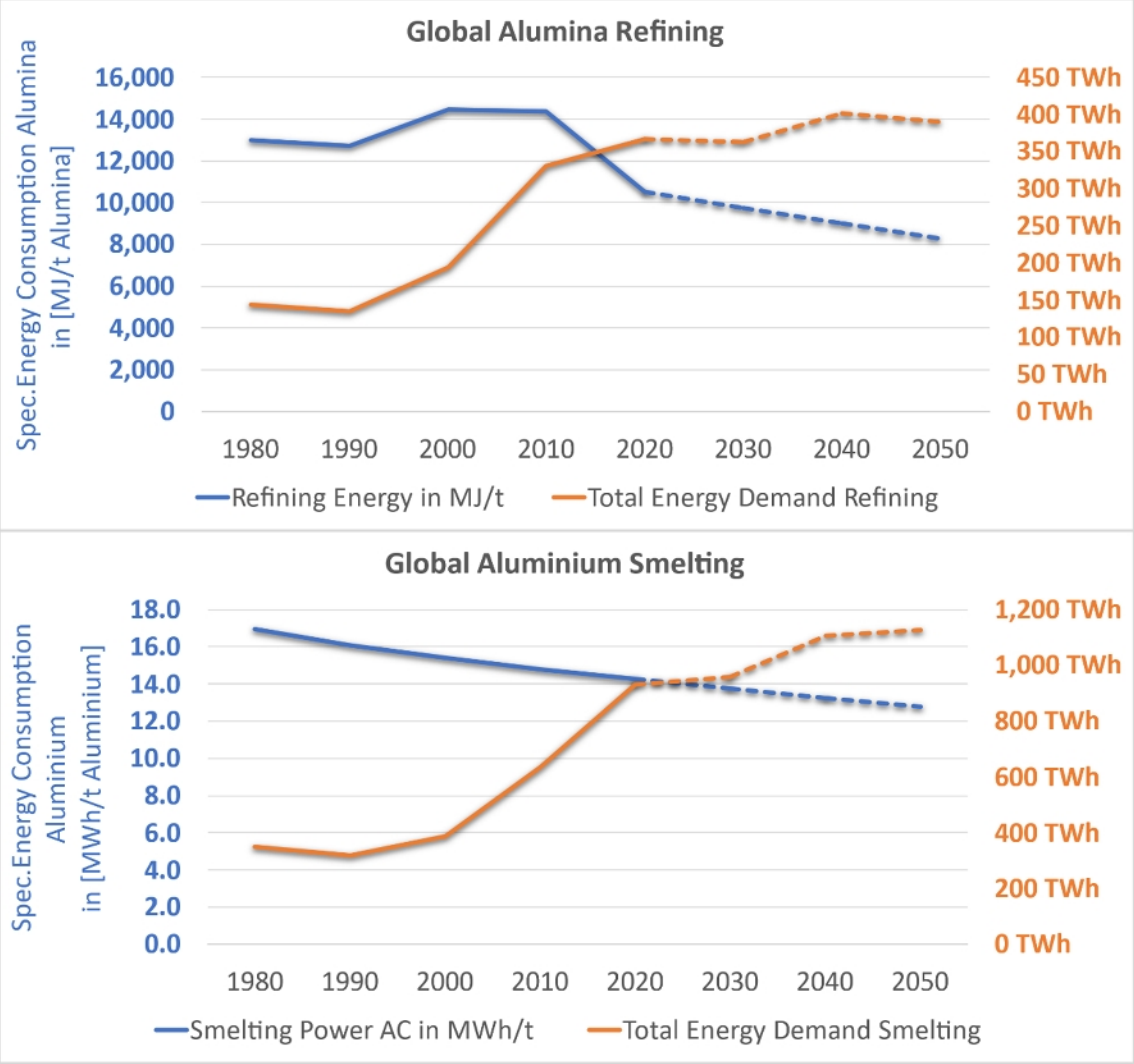


Figure 6. Specific and absolute energy consumption in alumina and aluminium production.

4. Decarbonisation Strategies for the Aluminium Industry

Decarbonising the aluminium sector is a critical endeavour in the fight against climate change. The sector's energy-intensive processes and significant carbon emissions make exploring innovative solutions for its transformation imperative. Key challenges lie in addressing the emissions associated with the alumina refining and aluminium smelting processes. Renewable energy sources, particularly hydroelectric, geothermal, solar and wind power, hold promise in driving this transformation.

In 2019, primary aluminium production emitted approximately 15.9 tonnes of CO_2 per tonne of aluminium, with an energy demand of 75.7 GJ per tonne. The application of renewables in 2020, primarily hydro and other renewable sources, accounted for a portion of the energy supply. Notably, China stood out in other renewables, albeit coal still dominated the energy mix. A significant amount of energy usage, about 426 TWh, was allocated to heat across various stages of the aluminium value chain.

The heat requirements can be categorised as low-temperature and high-temperature heat, each with distinct challenges. While low-temperature applications can leverage waste heat, concentrated solar power, heat pumps, and electric boilers, high-temperature processes such as alumina calcination and carbon anode baking necessitate more complex solutions like bio-gas, hydrogen, or electricity. The introduction of renewables in these high-temperature processes is crucial, given their potential for substantial emissions reduction.

Aluminium smelting, accounting for about 930 TWh of electricity, poses challenges in achieving energy efficiency due to its energy-intensive electrolysis process. While renewable energy adoption has improved, there's still a long way to go to replace conventional energy sources, particularly coal.

Alumina refining also presents opportunities for decarbonisation. Benchmark technologies are achieving energy consumption levels as low as 8 000 MJ/t, showcasing the potential for improvement. Technological advances like industrial heat pumps, vapour recompression, and concentrated solar power can contribute to decarbonising the alumina refining process. The continuous nature of these operations allows for the integration of intermittent renewable sources, but the intermittency challenge must be addressed through storage or backup solutions.

Transport emissions within the aluminium value chain, particularly long-distance shipping, require attention. Decarbonisation measures such as hydrogen and e-methanol could hold promise in mitigating these emissions. The shift to electrification for internal transport within smelters also offers opportunities, especially for tasks handled by cranes and automated vehicles.

The journey towards decarbonisation is not without challenges. The sector's historical performance improvements must be accelerated to meet ambitious emission reduction targets. Additionally, the evolving quality of raw materials could impact the potential gains from efficiency improvements. Investment in research and development is crucial to unlocking new pathways for decarbonisation and energy efficiency.

The focus then shifts to aluminium smelting, where electricity consumption for the electrolysis process is the primary source of energy consumption and CO_2 emissions. The global average specific electricity consumption for primary aluminium production has decreased by 15 % in the last 40 years, with best-in-class smelters achieving even lower levels. Potential improvements through heat recovery and better magnetic compensation are being explored, accompany the need for flexibility services.

Direct emissions from the electrolysis process, attributed to carbon anodes, contribute 2.0 tonnes of CO_2-e per tonne of primary aluminium, with 9 % attributed to anode consumption and 3 % to the "anode effect." These emissions can be eliminated by implementing inert anodes or combining CCS and bio-based materials. While inert anodes show potential for greenfield projects, CCS offers a feasible option for existing smelters, providing GHG-free aluminium for various industries.

Despite the challenges and uncertainties surrounding using inert anodes, ongoing research and collaborations, such as the ELYSIS project, promise to improve productivity and reduce production costs. Additionally, CCS represents a crucial step in achieving faster decarbonisation goals, with a long-term vision of bio-based materials potentially leading to carbon-negative smelters.

In conclusion, the aluminium sector's energy transformation and decarbonisation are critical for achieving sustainability goals. By adopting renewable energy solutions, exploring technologies like inert anodes and CCS, and optimising various processes, the aluminium industry can play a pivotal role in reducing global greenhouse gas emissions and driving the transition to a low-carbon future.

4.1 Renewable Energies as the Solution Vector for the Aluminium Industry

Renewable energy has become pivotal in reshaping various industries, and the aluminium sector is no exception. Over the years, renewable energy sources, primarily hydroelectric power, have played a crucial role in developing aluminium smelting. Historical smelters were often situated near hydroelectric dams, a trend that continues today. This synergy is evident in projects such as Iceland's Fjardaal aluminium smelter and the shift of smelting operations to China's Yunnan River region. However, the landscape has evolved beyond electricity pricing to include environmental considerations like CO_2 footprints. A noteworthy stride towards sustainable practices in aluminium production involves integrating Variable Renewable Energies (VRE) like wind and solar power. The sector has witnessed significant progress in applying VRE to alumina refining and smelting. Wind Power Purchase Agreements (PPAs) in Norway and photovoltaic (PV) supply for smelters in the Middle East stand as prime examples of these efforts.

To achieve environmental goals, industry strategies have targeted specific challenges. One major victory is the substantial reduction in perfluorocarbon (PFC) emissions. Over the past 30 years, despite a threefold increase in production, emissions dropped by 60 %. This achievement resulted from retiring older Søderberg technologies and embracing modern computer-controlled point feed technologies. This not only reduced emissions but also enhanced productivity and energy efficiency.

The Western world, particularly the U.S., successfully collaborated voluntarily with primary aluminium producers and environmental agencies. This approach significantly reduced PFC emissions, a notable achievement in mitigating greenhouse gas emissions. China pursued a different strategy, focusing on reducing specific energy consumption. This involved closing or upgrading smaller, less efficient smelters, compelling them to meet energy consumption benchmarks or halt production. This strategy has effectively driven energy efficiency, leading to China's highly efficient smelter base. Despite this, there is room for improvement in transitioning to low-carbon aluminium production.

Renewable energy potentials are not uniformly distributed worldwide, impacting renewable-powered smelters' feasibility. Regions with extensive hydroelectric, high onshore wind speeds, or abundant solar irradiation can offer lower-cost zero-carbon electricity. However, the intermittency of renewables presents challenges for energy-intensive operations like aluminium smelting, which demands constant power supply due to its continuous operation nature.

The search for new smelter locations demands consideration of various factors. Excellent PV and wind resources, abundant land, access to CO_2 storage or inert anode technology, hydrogen storage options, and deep-sea ports are vital prerequisites. Interestingly, hydrogen and aluminium share similarities as energy carriers, sparking competition and potential collaborations between the two sectors. Despite these successes, barriers persist on the path to full decarbonisation. These barriers span technical challenges, economic constraints, accounting complexities, regulatory hurdles, and political considerations. Addressing these barriers requires a comprehensive approach involving innovation, policy adjustments, and global collaboration.

5. Aluminium as an Energy Carrier

Aluminium is the most energy-intensive metal at scale, and hence, it exhibits a colossal energy carrier potential. When comparing hydrogen and aluminium as energy carriers, it is evident that aluminium has clear advantages in energy density, transport safety & economics, and storage capacity. Haller et al. [6] advocate even using aluminium as seasonal storage. While this might be too ambitious, it shows the potential of aluminium, and it becomes evident that aluminium must be seen in this context as an energy carrier. The export of Wind and PV via hydrogen hubs can be improved with aluminium smelters (it is unlikely to produce hydrogen in continent A → transport it to continent B → produce electricity in continent B → produce aluminium in continent B), which then export aluminium to continent B instead of hydrogen. This is very relevant for new greenfield smelters or smelters already existing in regions of potential surplus renewable energies.

5.1 Cost Sensitivity of Aluminium Smelters

Nowadays, many industries are committed to switching to renewable energies and reducing their carbon footprint for their Scope 2 emissions, leading to lower carbon footprints of their products and services. However, most of these industries are less sensitive to power costs. Aluminium smelters earn EBITDA of 10 – 50 USD/MWh, while energy-intensive chemical plants range between 250 and 1 500 USD/MWh, and electro-intensive data companies like Google and Meta achieve 3 000 – 10 000 USD/MWh. Energy Prices in most countries may range from 25 USD/MWh to 250 USD/MWh, with energy-intensive players buying at the lower end of the range. However, a chemical plant may be able to pay another 25 USD/MWh for green electricity, whereas a smelter would be out of business already.

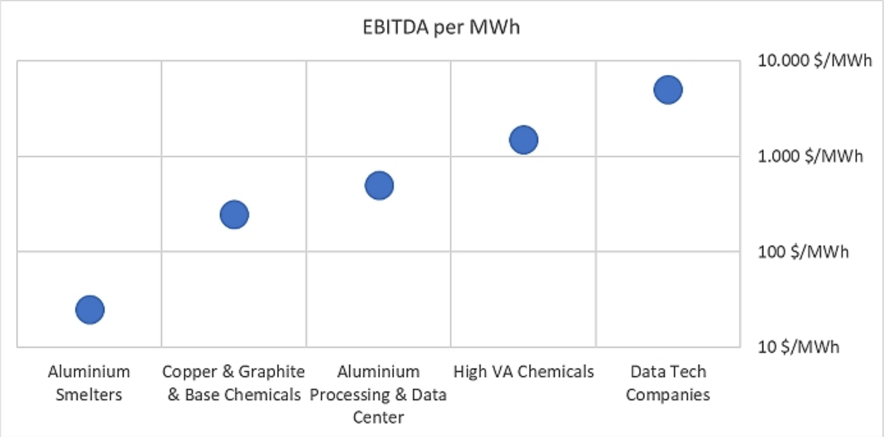


Figure 7. “Electrical Food Chain” (own calculation).

The essentials of this graph can be summarised as follows:

- Aluminium Smelters are at the low end of the "Electrical Food Chain." Smelters could be successful in a stranded situation without electrical competition
- Grid-connected smelters could be successful if the grid was populated with abundant cheap and dispatchable power (e.g., Canada, Norway)
- Hydrogen will compete with smelters for power but likely even lower on the "Food Chain" → Hydrogen and aluminium smelters could be complimentary successful,

5.2 Renewable Energy for Smelters

Aluminium smelters are among the most cost-sensitive industries in terms of electricity prices. Hence, smelters have been established in regions with abundant and cheap electricity resources. In the past, it did not matter whether this source was hydro, coal, gas or nuclear. However, this has changed, and the CO_2 footprint of electricity has become a second parameter besides the price of electricity. Now, smelters have started to search for alternatives, and the only abundant natural resource is wind and solar, with all their limitations and challenges. Smelters began with the local introduction of renewable energies from rooftop PV or onsite Wind turbines. More significant projects of up to 5 % with local renewables are the PV project of EGA and the Wind project at ALUAR. [7] [8]

5.3 Power Purchase Agreements (PPAs) for Aluminium Smelters

PPA is the new BUZZ word in the energy-intensive industry worldwide when it comes to integrating renewable energies. However, so far, very few PPAs have been signed between RE generators and smelters. The only country with significant volumes has been Norway, where Wind PPAs of >10 TWh per year have been signed by Norsk Hydro and Alcoa at very competitive prices. Norway's significant advantage for RE PPA lies in its cheap integration costs (massive hydropower to compensate for volatile renewable energies), low wholesale market price, cheap land, and the Government guarantees for such projects [9].

Firming and Shaping (methodologies like storage, dispatchable power and others to match variable renewable energy generation with demand profiles) is seen as the biggest problem for integrating RE PPAs in the supply strategy of energy-intensive industries. A study from the European Commission states, "While RE PPAs do not entail upfront investment costs, they are still quite problematic due to the long contract duration, especially when this is coupled with the price risk stemming from regulatory uncertainty. In fact, while in an RE PPA the price of the energy component is agreed upon by the parties, network costs and other non-recoverable taxes charged to electricity consumers still depend on national legislation" [10]. European transmission operators estimate the current costs for "shaping & firming" at 5-20 USD/ MWh [11]. European initiatives started to cope with these risks and lobby for public support in two major projects being, the "GREEN POOL" and "GREEN FLEX FACTORY".

5.4 PPA Price versus Levelized Cost of Electricity (LCOE). The Hidden Cost Components

In the coming years, in some countries, LCOE costs for Wind and PV will likely reach 25 – 35 $/MWh. However, the total costs for RE in a system are typically two or even three times higher and include the costs for grid expansion and backup capacities. Governments are challenged with the decision to distribute these costs. Besides these regulatory costs, the European Commission also found that PPA offers are impacted by market prices or tariffs and not just by the LCOE: "The negotiation over the energy price component is affected by the market price for electricity. RE generators may always choose between signing a PPA or selling the electricity on the market; hence, any deal will look at the relevant market price, although a discount may apply as the offtaker ensures a stable demand for many years. Reportedly, as the market price affects the deal, indirect EU ETS costs (that are accounted for in the market price) also affect the price of RE *PPAs*" [10].

5.5 Grid-Connected Smelters in Liberalized Power Markets

Grids are becoming greener with constantly increasing amounts of renewable energies worldwide. This could mean smelters can sit back, relax and enjoy the decarbonisation ride. However, it can be witnessed that grid-connected smelters in liberalised markets had difficulties surviving. Europe EU27, as well as the US, have seen a dramatic exodus of smelting capacity over the last 30 years. Unbundling of generation and transmission is step one, followed by choice of market design, e.g., energy-only market or capacity mechanism. The options might be different, but the challenges are always the same. Who pays for the cost of the system, and who guarantees the security of supply? In liberalised, unbundled markets, aluminium smelters already play a significant role in stabilising the grid and receiving substantial remuneration for this service. European smelters receive for their different frequency restoration or interruptibility services up to 12 USD/MWh in compensation. [5]

5.6 Competitive Power Prices Require Government Intervention

Power Prices are soaring worldwide, and aluminium smelters, among the most cost-sensitive industries, face uncompetitive energy prices and require political support to stay in business. Europe and the US have witnessed that challenge over the last 30 years, and 50 % of European smelters have been shut down while European aluminium imports strongly increased. This trend has changed in recent years, and public scepticism towards aluminium smelters has shifted to political support for this industry. Parts of the industry changed the narrative of aluminium production from being an immobile power guzzler to a flexible saviour of the power grid. This could be achieved with the constructive involvement of aluminium smelters to support the energy transition with power flexibility.

6. Flexibility is the New Scarcity

Volatile renewable energy will be abundant in the future, but the challenges will be guaranteed power and demand flexibility. Hence, a flexible smelter can shape the future of a country and become the "GOOD NEIGHBOUR" that receives special tariffs for their contribution to grid stability without others being jealous. Transforming a smelter into a virtual battery is getting strong political support in many countries, from Australia to Europe. [12] [13] [14] [5].

Aluminium smelters have become a cornerstone and active participant in energy networks worldwide. The range of services that smelters can (and do) provide is very wide. Figure 8 gives an overview of the different balancing services, their degree of maturity and the time scale of these services.

Aluminium smelters can be switched off within seconds without a more significant loss or problems to re-start production. In a controlled manner, potlines are often turned down more than once a week for regular maintenance of the pots. Already in the 1970s, the German aluminium smelters were equipped with automatic switches which were connected to frequency controllers. The smelters were used as black-out protection and were cut-off automatically when the grid frequency fell below a specific threshold. This service was part of a special power tariff regime. Nowadays, these services are reimbursed as interruptibility fees. Typically, the time range for this service is from immediate (or 15 minutes) to last for 1 to 2 hours.

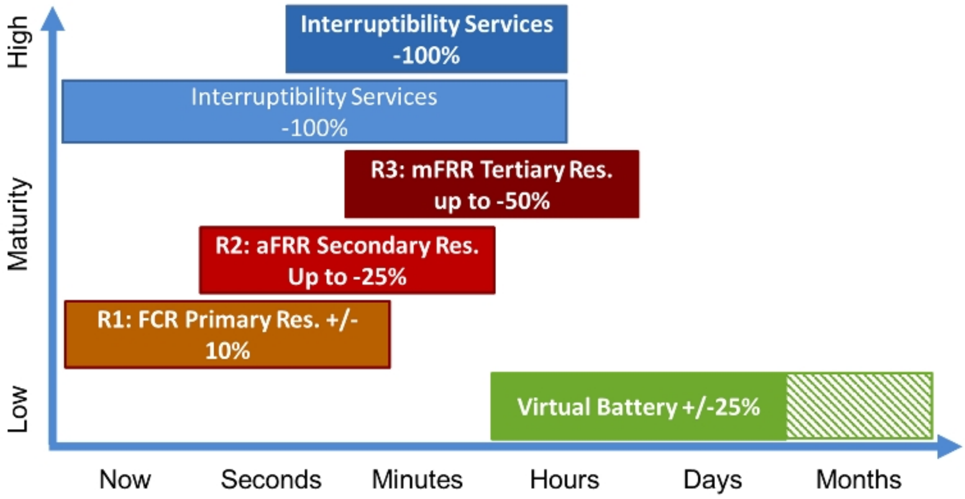


Figure 8. Aluminium smelters participating in balancing services [5].

6.1 Demand Response as a Contribution to a Green Society

Due to its energy-intensive production process, the aluminium industry, a significant contributor to global greenhouse gas emissions, faces the decarbonisation challenge. One avenue being explored is the integration of demand response and flexibility measures within aluminium smelters, which could contribute to more efficient energy usage and aid in integrating renewable energy sources into the grid.

Aluminium production involves the electrolytic reduction of alumina in molten cryolite, requiring massive amounts of electrical energy. Traditionally, smelters have operated with stable and constant energy consumption profiles to maintain process stability and maximise production efficiency. However, the need for flexible energy consumption becomes evident as the energy landscape shifts towards increased reliance on variable renewable energy sources (VRE).

Integrating demand response (DR) in aluminium smelters has gained attention as a strategy to enhance grid stability and enable the successful integration of renewable energy. DR allows industrial consumers, such as aluminium smelters, to adjust their energy consumption patterns in response to grid signals, market prices, or supply-demand imbalances. This benefits the grid by providing load-balancing capabilities and offers economic incentives to participating smelters.

Several methods of demand response in aluminium smelters are being explored:

1. **Load Interruption**: Smelters can participate in load interruption schemes by temporarily shutting down entire potlines during periods of high grid demand. This approach requires careful planning and coordination to ensure process stability and prevent equipment damage. While this method offers substantial flexibility, the duration of interruptions is typically limited due to process constraints.
2. **Amperage Modulation**: Smelters can adjust the amperage, which controls the production rate, to temporarily reduce energy consumption. This method can be implemented more frequently and with shorter response times compared to load interruption. However, it requires careful management to maintain process stability and avoid production disruptions.
3. **Grid Frequency Management**: Aluminium smelters can contribute to grid stability by providing ancillary services, such as frequency containment reserves. Smelters can respond rapidly to grid frequency variations by slightly adjusting the potline amperage up or down.

The benefits of demand response in aluminium smelters are multi-fold:

a. **Grid Stabilization**: Demand response provides a valuable tool for grid operators to manage supply-demand imbalances and frequency variations, especially as renewable energy penetration increases.
b. **Integration of Renewable Energy**: Flexible aluminium smelters can absorb excess renewable energy during periods of high production and curtail consumption during energy scarcity, aiding the integration of renewable sources into the grid.
c. **Economic Incentives**: Participating smelters can receive financial compensation for offering demand response services, potentially reducing their overall energy costs.
d. **Environmental Impact**: Aligning energy consumption with higher renewable energy availability periods, aluminium smelters can indirectly reduce their carbon footprint.
e. **Infrastructure Support**: Demand response can alleviate stress on the grid during peak demand, potentially delaying or eliminating the need for costly grid infrastructure upgrades.

However, implementing demand response in aluminium smelters also presents challenges:

a. **Process Stability**: Ensuring that demand response activities do not compromise the stability and efficiency of the aluminium production process is crucial.
b. **Technical Adjustments**: Certain technical adjustments, such as managing heat balance and addressing the impact of amperage modulation on the production process, are necessary.
c. **Synchronization**: Coordination with grid operators and clear communication channels are essential to ensure that demand response actions align with grid needs.
d. **Economic Viability**: Smelters must assess the economic viability of participating in demand response programs, considering factors like compensation, equipment wear, and potential revenue.

In conclusion, demand response in aluminium smelters presents a promising pathway to enhance grid stability, integrate renewable energy sources, and reduce carbon emissions. While challenges exist, advancements in process control technologies, communication systems, and collaborative efforts between industry stakeholders and grid operators can facilitate the successful integration of demand response into the aluminium production process.

6.2 A Flexible Aluminium Smelter

Traditionally, smelters were designed to be operated at constant power inputs. While this was easily achievable in a world based on conventional power, it will not be competitive in a world powered by volatile renewable energies. In recent years, concepts were developed to enhance smelters towards more flexible operation. A key concept for this adaptation is the modulation of the cell heat losses in correspondence to changes in the power input. In this way, it is possible to achieve power modulations in the order of +/- 25 % over a period of 12 to 48 hours. The costs to upgrade smelters for flexible operation would be in the order of 1 MUSD per +/- 1 MW flexibility. Additional benefits could arrive from energy optimisation and heat recovery to create additional value from this newly captured heat flux. [15] [16] [13] [5].

Some demand response, ancillary services or interruptibility can be delivered from almost every smelter without technological or process control changes. However, more significant energy shifts and stronger and faster reactions of the aluminium smelter require investigating and adapting technical features and control concepts of smelters. Another aspect is the question of whether the demand response service is symmetric (equal up and down), asymmetric (up and down different) or only one-sided (e.g., only reduce amperage/production). Figure 9 gives an overview of the main aspects that need to be addressed when enabling a smelter for bigger volumes in demand response.

The concept of a virtual battery option for a green smelter offers a dynamic and innovative approach to managing energy consumption and production in the aluminium smelting process. Traditionally, smelters have operated as baseload consumers, benefitting from a stable energy input for the electrolysis process. However, with the changing landscape of energy generation and the need for more flexible consumers, the virtual battery concept has emerged as a solution to address the challenges posed by volatile electricity generation, grid stability, and environmental concerns.

Smelters have historically focused on maintaining stable energy input to ensure process efficiency. Large fluctuations in energy supply can negatively impact smelter operations, reducing process efficiency, financial losses, and even equipment failure. The virtual battery concept aims to allow smelters to modulate their power consumption, essentially turning the smelter into a flexible asset that can respond to changes in electricity prices, supply, and grid stability.

The development of the virtual battery concept involves several key technologies and strategies. One of these is the Sidewall Heat Exchanger (SHE) technology. This technology enables the modulation of power input to the smelter by controlling the heat loss through the cell sidewalls. Smelters can control the heat loss between 50 % and 150 % of the standard heat flow by regulating the fan speed and heat extraction. This technology addresses thermal imbalances that can arise from power modulation and ensures the stability of the cell's operation.

Another critical aspect is the management of auxiliary utilities, including rectifier stations, Gas Treatment Centres (GTC), and compressed air supply. These utilities must be upgraded or optimised to support increased line currents during power modulation periods. Additionally, the virtual battery concept explores opportunities for heat recovery from the smelting process, which can further enhance the smelter's energy efficiency and contribute to reducing its carbon footprint. This recovered heat will also be essential when applying CCS technology in a smelter.

The virtual battery concept can be implemented in different operational modes, each with its own benefits. These modes include market-based operation, where the smelter responds to electricity price fluctuations to optimise energy consumption; real-option trading, which leverages the smelter's flexibility to participate in energy markets and grid stability services; and green operation, where the smelter's energy consumption is optimised based on emission profiles of the power mix.

The value proposition of the virtual battery concept is multifaceted. It benefits smelters by reducing electricity costs through strategic energy consumption and addresses the grid stability challenges posed by renewable energy integration. In countries like Germany, Australia or South Africa, where renewable energy penetration is increasing, smelters that can provide demand response and grid support become crucial components of the energy transition.

While the virtual battery concept offers significant potential benefits, there are challenges to its implementation. Regulatory and policy considerations, such as energy pricing and market structures, play a role in incentivising smelters to adopt flexible operation. The economic viability of implementing the required technologies and upgrading auxiliary utilities must also be carefully assessed.

In conclusion, the virtual battery option for a green smelter represents a groundbreaking approach to transforming traditional aluminium smelters into flexible, responsive assets contributing to grid stability, energy efficiency, and environmental sustainability. By embracing innovative technologies like the sidewall heat exchanger and optimising auxiliary utilities, smelters can unlock the potential for reduced electricity costs, increased revenue from energy markets, and a more resilient and adaptable role in the evolving energy landscape. As the world transitions to a cleaner and more dynamic energy future, the virtual battery concept could position smelters as essential players in achieving a sustainable and efficient energy ecosystem.

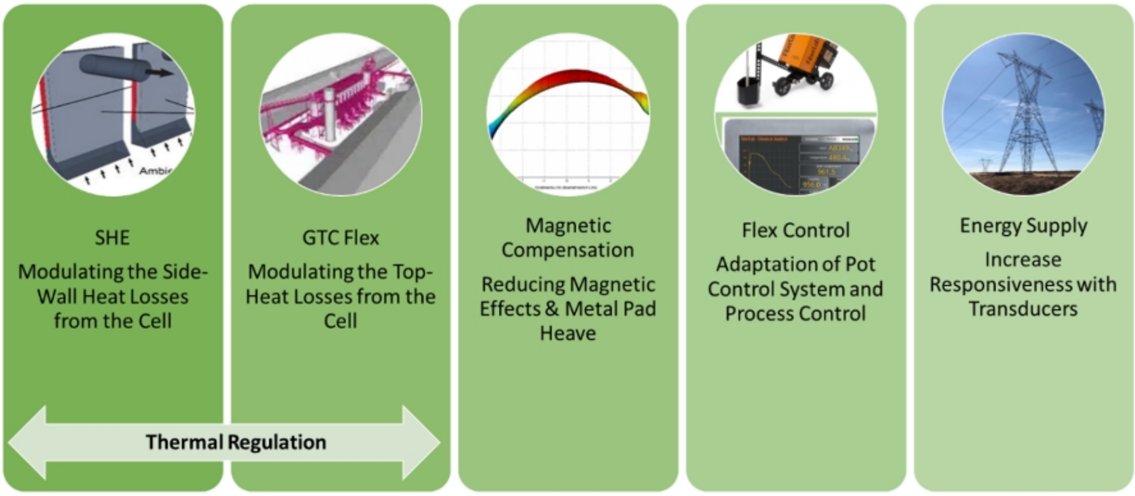


Figure 9. Increasing smelters demand response capabilities [5].

Critical aspects of a flexible smelter:

Thermal Regulation:
The biggest problem and concern for smelters participating in demand response is the heat equilibrium of the process. As the process requires a very low superheat (10 °C), it does not carry much extra energy. A deviation of the energy input results in heating and cooling (with eventual freezing) of the process, as the heat losses are passive in conventional smelters. Roughly 50 % of the heat escapes through the top of the cell with the exhaust flow, while 25 % escapes through the sidewalls. Flexible smelters must address these two major heat losses and modulate the heat loss when modulating the heat input. A smelter in New Zealand experimented successfully with a modulation of the GTC (exhaust draft) to stabilise the process for a daily hour-long 10 % modulation of the potline [5]. SHE (sidewall heat exchangers) are the enabling elements for more significant volumes of modulation, as the sidewalls are the sensitive part of the process. SHE and GTC Flex are the elements to adjust the heat loss in accordance with the heat requirements in modulation.

Magnetic Compensation:
Modern aluminium smelters are operated at high DC currents, reaching 300-600 kA. Strong magnetic fields in the potlines are associated with high currents with impacts on the process. The aluminium cell is equipped with a layer of 15-20 cm liquid aluminium metal (the metal pad), which acts as a cathode in the process. While ions carry the energy transport in the bath, it is carried by electrons inside the metal pad. A travelling electron exhibits a deviation inside a magnetic field (Lorentz Force), and this leads to a movement of the metal pad (10-20 cm/s) and a metal pad curvature (5-10 cm upheaval). A change in amperage will automatically lead to a change in the metal pad curvature, eventually creating short circuits. Hence, magnetic compensation might be a requirement for successful modulation.

Flexible Control:
The abrasive environment inside the liquid bath makes it difficult to observe the process (e.g., continuous temperature measurements). Standard process control relies on a few continuous measurements (voltage and amperage) and regular measurements (24-48 hours intervals) of temperature, liquid levels and bath chemistry. While this control works sufficiently for standard process control, it is insufficient for power modulation. A smelter participating in power modulation must know reasonably well about every cell's energy state, especially the superheat. Iffert [17] stated in his PhD thesis already in 2008:

"Looking into the future of the aluminium industry, it will be of high importance for different regions of the world to enable strong power modulation of reduction cells. Therefore, it is increasingly important to know every cell's energy and mass status accurately. Hence the introduction of superheat measurements will be a necessity for most smelters in the next 15 years."

Energy Supply:
The energy supply is typically designed for a specific line amperage and line voltage. Headroom for production increases, and anode effect voltage is typically 5-10 %. The system is built in an (n-1)-redundancy mode with typically 4 to 6 rectifier groups supplying the line current. This extra group is necessary for maintenance services without reducing line currents. However, it is acceptable to use all n-groups in times of upward modulation for power modulation as this is just an option to scam excessive power and not a process requirement. Most smelters operate with diode rectifiers (thyristors are only exceptions), where amperage is controlled with step-changers in the transformer, adjusting the voltage level of the potline and regulating the amperage. Finer adjustments of the voltage are made with the use of transducers, which work electro-magnetically, while step-changers work mechanically. Step-changers experience some wear, so balancing services need to account for this. In the case of demand response services from smelters, the energy supply creates some hard barriers for the potential. It might need some changes (additional rectifiers or transducers) to exploit the full potential.

7. Low-Carbon Aluminium Trends and Industry Targets

Climate Protection and fighting global warming has become a megatrend in recent years. Financial institutions and customers increasingly support companies with a clear strategy to reduce their GHG footprint. The aluminium sector is among the first industries to establish a green premium for products in a B2B context. Currently, customers pay 10- 50 USD/t upcharges for low-carbon aluminium, which is likely to increase with low-carbon aluminium becoming a necessity to supply companies like BMW, Nestle or Heineken. Industry targets are getting redefined to include all emissions from Cradle-to-Gate, covering Scope 1, Scope 2 and (partly) Scope 3.

7.1 LME Green Aluminium Premium

The LME contract for High-Grade aluminium is the benchmark for the aluminium price in the western world. The beauty of this contract is that it supplies ample liquidity to the market and allows forward hedging over several years. Many smelters have LME-linked power contracts, which reduce the risk for the smelters and give the (often state-owned) power companies the potential to benefit from market up-cycles. Regional and product-specific elements are covered with an additional product premium negotiated in a physical deal or following an index mechanism. "GREEN" aluminium would best be valorised with an additional "GREEN" premium. The problems with a substantial green premium (> 10-20 % of LME) are plenty of loopholes in the accounting schemes for scope 2 emissions. Greening scope 2 on paper is relatively easy today, which increases the supply of low-carbon aluminium without additional renewable energies.

7.2 Accounting Loopholes

A substantial low-carbon aluminium premium (>10 % LME) can only emerge if there is scarcity in the system. With the current accounting loopholes, it is impossible to create this premium. Double accounting of renewable electricity increases the supply of low-carbon aluminium without the burden of higher costs. Loopholes are the choice between market-based and location-based approaches.

Alumina and aluminium producers need visibility for low-carbon products. Although some examples of low-carbon aluminium contracts are established between producers and customers, creating test markets for near-zero carbon alumina and aluminium with a sufficient price signal for first movers to do the necessary CAPEX is still necessary.

Accounting standards need to be harmonised, and common rules and certification processes must be established. It is necessary to create awareness and transparency for schemes and eliminate loopholes to ensure trust by all participants in the system as part of the level playing field.

A fast-changing environment, over-capacities and trade distortions challenge the industry. At the same time, it is necessary to fund substantial R&D projects. Hence, it is necessary to get public funding for different R&D avenues, e.g., flexible smelters and refineries; MVR and CST powered refineries; CCS and inert anodes for smelting process; integrated alumina/aluminium hubs with renewable energy and hydrogen; new (green) recycling concepts etc.

8. Policy Implications and Recommendations

Policymakers worldwide are grappling with the challenge of accelerating the energy transition, slashing carbon emissions, and averting carbon leakage. Achieving a complete energy transition demands a fundamental shift in how we perceive and manage our energy systems. The transition from a fossil fuel-dominated energy framework, established over centuries, to a sustainable one is more extensive than current policies envision.

Energy, a cornerstone of modern industrial societies, is integral to competition. While nuclear power often receives subsidies, renewable energies often do not. This is due to the renewable energy sector's push for a free market and the government's lack of clear strategies for fostering renewable energy industries. Some blame also rests with energy-intensive industries prioritising cheap power over supporting the integration of variable renewable sources.

German and US think tanks offer contrasting perspectives on the energy transition. Agora Industry from Germany proposes a state-driven process for international climate cooperation, while the US-based CSIS advocates a trade-focused decarbonisation approach. These differing views are emblematic of the broader decarbonisation narrative. The same divergence is seen in the aluminium industry's decarbonisation storylines, where claims of green products outpace actual low-carbon production.

CSIS suggests government intervention and trade-focused policies to drive heavy industry decarbonisation. Recommendations include increasing renewable energy share in the grid, enhancing grid capacity, encouraging cross-border renewable energy flow, and boosting recycling rates. The study also emphasises governments' role in promoting sustainable aluminium production, minimising waste, and establishing common life cycle assessment standards. CSIS suggests an upper limit of around 40 USD per megawatt-hour for aluminium companies transitioning to renewable power.

The aluminium industry confronts global competition, cyclicality, and environmental concerns. Governments must support renewable energy PPAs, ensure stable regulatory frameworks, and facilitate competitive electricity and firming costs. International standardisation of CO_2 accounting principles, establishing low-carbon aluminium premiums, and supporting low-carbon refineries and smelters are crucial. Short-term goals include integrating renewables through PPAs and incentivising flexibility services.

Greenfield investments will benefit from favourable locations in the long term while existing facilities need incentives for low-carbon practices. The cost of decarbonisation involves additional upfront CAPEX and ongoing OPEX. Direct emissions in smelting could be curbed by a carbon price of 100 USD/t CO_2, incentivising carbon capture or inert anodes. Governments should subsidise renewable energy integration and infrastructure development, while producers must decarbonise their processes.

In the end, a collaborative effort among markets, governments, and industries is vital to realising the decarbonisation potential of the aluminium sector. This includes financial support, regulatory frameworks, and technological innovations that drive the industry toward a greener future.

9. Conclusions

Aluminium metal is de facto an energy carrier, which makes it possible to transport electricity (captured in the metal) around the globe and store it for many years (if necessary) in the metal. The advantages of aluminium as an energy carrier are its easy and safe handling, cheap transport and good storability. The characteristics mentioned above were essential for the erection of smelters in the past 100 years. Smelters were used to unlock isolated and stranded energy potentials and ship this energy in the form of metal to the marketplace. Although aluminium was not utilised to recover its stored energy, this business model made a lot of sense as aluminium demand was (and still is) rising fast. Traditionally, these isolated spots were hydropower regions in the mountains of North America or Europe (e.g., the birth of the French aluminium industry was in the Maurienne valley, which had six hydro-powered aluminium smelters at its peak time) where aluminium smelters were used to convert hydro-power into a marketable product. The same reasoning created the base for the German smelters in North-Rhine-Westphalia. The smelters were built alongside the development of lignite power in the region. These days, the electricity demand was too low to justify the mines, and thus, aluminium smelters were attracted to convert, once again, electricity into a commodity metal. This model also created the aluminium industry in Iceland, Canada and the Middle East. Even the Chinese aluminium story can be put in this basket. China created a model in which it could convert its local, low-grade coal into a tradeable and exportable asset. What can we learn from the past for the future? The nature of this business model will not change in the future, independent of carbon regimes and efforts to decarbonise the aluminium industry. The biggest competitive advantage of aluminium is its excellent usability as an energy carrier. Hence, new greenfield smelters will be built in regions with excessive green power, and existing smelters need to provide extra services to the grid to prove their value to society.

The aluminium industry is on its way to improving its energy and carbon footprint. Success was achieved in improving specific energy consumption and is forecasted to achieve further reduction steps in the future, but that won't be enough. In his TMS 2021 presentation, Andrew Furlong concluded that "Energy efficiency (alone) will not take us to net zero emissions." [18]

There will be different strategies for existing facilities and new greenfield investments. Existing facilities are generally (partly) written off and bear a lower cost pressure than greenfield investments. However, their location is fixed, and thus they need to deal with their current environment. This needs to be addressed by policies to create low-carbon incentives for existing facilities and low/zero-carbon incentives for greenfield investments. The advantage of greenfield investments is the ability to choose the best location and act with the highest degree of freedom for the design.

Markets, Politics and Industry need to get a feeling/vision for the decarbonization cost of the industry, which consists of additional upfront CAPEX and ongoing OPEX. In the long run, the costs need to be borne by the market, while during the first transition, it could be necessary that the extra costs are subsidized by Governments.

What can/should be paid by the customer/user?

- ➢ Direct Emissions in Smelting are roughly 1.5 t CO_2/t Al. Additional GHG emissions from other Scope 1 and Scope 3 (upstream) contribute a minimum of 1 t CO_2/t Al, resulting in 2.5 t CO_2/t Al. Thus, a price tag of 100 \$/t CO_2 would result in extra costs of 250 \$/t or 10 % of the current LME market price for primary metal. This would be the order of magnitude for CCS and could decarbonise this part of the value chain. It would also represent an incentive for inert anode projects and low carbon alumina.

What should be paid/supported by Governments?

- ➢ The integration of renewable energies into aluminium smelting and alumina refining should be supported by Governments with direct subsidies (CFDs), CAPEX and financial guarantees.
- ➢ Infrastructure for renewable energies (transmission grids and hydrogen hubs) should be supported and financed by Governments to create competitively priced backup capacities

What should be paid/borne/developed by Producers?

- ➢ Producers are required to decarbonize the upstream production with competitive renewable heat, bio-gas and electricity
- ➢ Producers need to develop and supply flexibility and other demand response services in response to their access to competitively priced VRE

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