BUSINESS MODEL FOR DECARBONIZATION OF A METALLURGICAL SECTOR COMPANY

Case Study: Kazakhstan Aluminium Smelter

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Kazakhstan 2024

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CONTENTS

List of figures

List of tables

EXECUTIVE SUMMARY

Decarbonizing the aluminum industry is crucial for meeting global climate targets and ensuring the sustainability of the metallurgy sector. The aluminum industry, categorised as hard-to-abate industry, emits around 1.1 Gt of GHGs a year1, contributing approximately 2% of global GHG emissions, primarily from the smelting process. Under a Below 2 Degree Scenario (B2DS), the aluminum industry would need to reduce its emissions to 250 Mt CO2e, from a 1.1 Gt CO2-e 2018 baseline and a projected 2050 Business as Usual scenario of 1.6 Gt CO2-e (meaning over 84% reduction is required).

This document is depicting a business model for an aluminium smelting industry of Kazakhstan metallurgy sector, Kazakhstan Aluminium Smelting (KAS) of Eurasian Resources Group (ERG), initiated by the German Government's GIZ as part of their project, "*"Towards Carbon Neutrality Strategy implementation in the private sector of Kazakhstan"*.

This business model has been developed based on information supplied by ERG (Appendix A and D) and from information gathered from international sources.

All gathered information on decarbonizing aluminium smelting have been analyzed with each option's technology readiness level (TRL) in the Background section 2. Broad mitigation options identified are:

- fuel switching and electrification: Renewable energy is a major option since up to 90% of GHG emission for aluminium smelting are from energy consumption.
- increasing energy and material efficiencies: energy efficiency, alternative smelting technologies, like inert anode technology that reduces carbon anode consumption, and CCS are the candidates for direct emission reduction.

A brief description of KAS followed by its process description, current emission data and company's current decarbonization strategy are given in sections 3 and 4. KAS produces around 265,000 tons of Aluminium and emits around 4 Mt CO_2e/yr (including emissions associated with the production of the consumed electricity).

Section 5 deals with decarbonization levers covering technology and financial & policy aspects. Levers have been listed based on KAS suitability and assessed by economic and emission data, calculations of which are shown in a spreadsheet in Appendix A. A marginal abatement cost curve (MACC) has also been drawn for the assessment. After assessment, the levers have been grouped by bringing relevant levers together.

Section 6 portrays the grouping of all selected levers with a timeline scenario. The three-stage timeline process is based on availability and suitability of each lever for KAS as outlined below (financial and regulatory measures are common to all three stages):

- stage 1 by 2035 to reduce up to 87% of GHG – main emphasis is on decarbonizing electricity/energy and operational efficiency;

[1] Making net-zero aluminum possible: An industry-backed 1.5°C-aligned transition strategy, Mission Possible Partnership, September 2022.

- stage 2 by 2045 to reduce up to 91% of GHG – emphasizing on fuel switching and development of inert anode; and
- stage 3 by 2060 to reach Net Zero goal with inert anode or CCUS.

Section 7 has listed all challenges / barriers faced by KAS and Kazakhstan in achieving their decarbonization goals. One of the major bottlenecks for effective decarbonization policies and actions in Kazakhstan is the lack of incentives for industries. Low prices in the fossil-based energy sector hinder private investments in low-carbon solutions. On the top, none of alternative technologies is commercial-ready today. It is then followed by conclusions and recommendations in Section 8. Overall, this decarbonization business model demonstrates KAS's environmental responsibility and its foresight in adapting to a low-carbon economy towards sustainable decarbonization.

Task

Prepare a decarbonization business model for Kazakhstan Aluminium Smelter JSC (KAS) of Eurasian Resources Group (ERG) to achieve at least 30% emission reduction (Scope 1 & 2) by 2035 from 2021 level and reaching Net Zero by 2060 or earlier.

1 BACKGROUND

Kazakhstan's developing economy is strongly tied to consumption of fossil fuels and natural resources; besides, the country is vulnerable to climate change impacts as well as subject to natural disasters. Its per capita emission is very high. In response to this, Kazakhstan elaborated a national long-term low emission development strategy [CNS (Carbon Neutrality Strategy) – approved in 2023]. Economic modelling in the CNS revealed that investments for reaching carbon neutrality by 2060 are needed.

There will be no escape but to adopt carbon reduction measures as per the Paris Agreement. According to IEA[2], “Failure to accelerate the transition along the lines of the pathway depicted in the NZE Scenario would virtually guarantee a high overshoot of the 1.5 °C limit, with serious consequences for humans, ecosystems and climate tipping points. In such circumstances, returning the global average temperature rise to below 1.5 °C by 2100 would require a large and costly deployment of CO_2 removal technologies and would not avoid the need to reduce fossil demand substantially in this decade. Raising climate ambitions and ensuring effective implementation must remain critical priorities.” In addition, EU’s ETS (Emission Trading System) and CBAM (Carbon Border Adjustment Mechanism) will impact some of Kazakhstan’s metal exports, particularly aluminium, unless drastic measures on carbon reduction are undertaken.

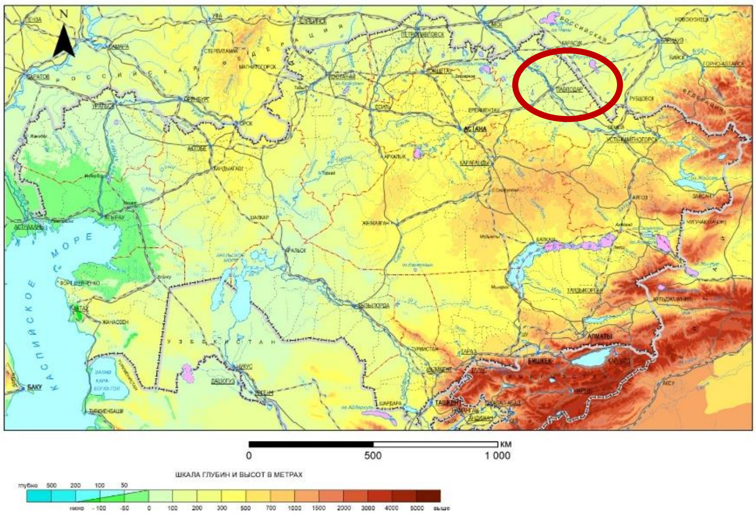
Within the International Climate Initiative (IKI), the German Government commissioned GIZ to implement the program “Capacity Development for Climate Policy in the Countries of Southeast, Eastern Europe, the South Caucasus and Central Asia, Phase III (CDCPIII)”. Among these projects the individual measure "Towards Carbon Neutrality Strategy implementation in the private sector of Kazakhstan" aims to support Kazakhstan’s commitment to transition towards a low-carbon economy, aiming for climate neutrality by 2060. As part of these efforts, the following specific tasks were identified By GIZ for this project:

1. Development of Decarbonization Business Models for a metallurgy industry
2. Elaboration of an lndustry White Paper
3. Capacity Development Hands-on-Trainings and Study Visits
4. lmplementation of Dialogue Measures

This document deals only with the first task, i.e., a business model.

During the first working mission to Astana during April 15-19, 2024, GIZ and Global Factor experts had separate meetings with the Ministry of Energy, the Ministry of Ecology and Natural Resources, the AIFC (Astana International Financial Centre), the Financial Settlement Centre, Kazakhstan’s Economic Research Institute, the project’s key national partners (namely, ECOJER and Qazaq Green), and selected Kazakh metallurgical companies. Astana mission has identified a particular company, named Eurasian Resources Group (ERG) to share data towards creating a business model for decarbonization. ERG has selected their aluminum industry for this decarbonization case study, namely the Kazakhstan Aluminium Smelter JSC (KAS) located at Pavlodar in Pavlodarskaya Oblast in the north of Kazakhstan as shown in the map. It is considered to be the flagship company in the domestic metals industry.

[2] Net Zero Roadmap 2023 Update, IEA



Source: National Atlas of the Republic of Kazakhstan. Volume 1: Natural conditions and resources. -Almaty, 2010

ERG is one of the leaders of the mining and metals industry in the world. It is the world leader in the production of high-carbon ferrochrome and one of the largest suppliers of iron ore, copper, cobalt and aluminium products in the Eurasian region. It is the only producer of high-grade aluminium in Kazakhstan. The Group is also one of the largest electricity producers (17% share of the country's market) with 2,550 MW of installed electric power capacity at its main plant in Aksu servicing Kazakhstan and Russia. ERG Kazakhstan aims to reduce specific GHG emissions of aluminium at least by 30% in 2035 compared to 2021 (scope 1 and 2). They also expect gradual advancement of carbon regulations in Kazakhstan, while target of establishing an effective global GHG price of $60 per ton by 2035[3].

The aluminium industry, categorised as hard-to-abate industry, emits around 1.1 Gt of GHGs a year[4]. Under a Below 2 Degree Scenario (B2DS), it needs to reduce its total emissions to 250 Mt CO_2e, from a 1.1 Gt CO_2-e 2018 baseline and a 2050 Business as Usual scenario of 1.6 Gt CO_2-e.[5] More than 60% of the sector's emissions are currently from the production of electricity, which, under a B2DS-aligned scenario, would need to be reduced to near zero.

Table 1[6] provides a visual summary of decarbonization technology options [known as Best Available Technologies (BAT)], highlighting the relative importance of each mitigation strategy in each of the six energy-intensive sectors. Broad mitigation options are:

a) fuel switching and electrification,
b) increasing energy effociency,
c) increasing material efficiency,
d) deploying CCS and CCU, and
e) implementing circular economy approaches.

Aluminium production from alumina involves *the Hall-Héroult process,* as detailed in section 4. It is very energy-intensive; hence electrification has the potential to significantly lower emissions if the electricity is from low- or zero-carbon sources. Other important mitigation options include higher material efficiency and circularity practices aimed at the recycling of existing stock. In the case of nonferrous metals, many of

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[3] ERG Kazakhstan Decarbonization Strategy, approved in 2024

[4] Making net-zero aluminum possible: An industry-backed 1.5°C-aligned transition strategy, Mission Possible Partnership, September 2022.

[5] Australian Aluminium Pathways | FACT SHEET #1, Australian Aluminim Council Ltd

[6] Elena Verdolini, Lorenzo Torreggiani, Sara Giarola, Massimo Tavoni, Marc Hafstead, and Lillian Anderson, Industrial Deep Decarbonization: Modeling Approaches and Data Challenges, Report 23-10, Aug 2023, Resources for the Future. https://www.rff.org/publications/reports/industrial-deep-decarbonization-modeling-approaches-and-data-challenges/

these decarbonization options are available and have been used on occasion in the past, but they have not been widely used because they are costlier than traditional techniques and, with low fossil fuel prices, are not economically attractive yet (IPCC 2022)[7]. However, due to the target to meet B2DS, concerted efforts are underway by aluminium industry to have BATs implemented.

Table 1. Summary of relevance of different mitigation options by hard-to-abate sector

	Fuel switching and electrification	Energy efficiency	Material efficiency	CCS/ CCU/ DAC	Circular economy
Steel	high	medium	high	medium	high
Cement and concrete	low	low	high	medium	low
Chemicals	high	low	medium	high	medium
Light manufacturing	high	high			
Aluminum and non-ferrous metals	High	low	medium	low	medium
Pulp and paper	high	high	low	medium	low

In line with Net Zero goals, the International Aluminum Industry (IAI)[8] has identified three broad pathways for emissions reduction whilst meeting growing demand:

1. **Pathway 1 - Electricity decarbonisation** (using renewable energy source). Globally, two-thirds of the sector's electricity needs are met by captive power stations owned and operated by aluminium producers, which are largely fossil fuel based. In Australia, all smelters are grid connected too allowing them to perform an enabling function in grid stabilisation which helps with increased penetration of variable renewable electricity as the grid transitions. Smelters also have the opportunity, as part of contract renewal, to source firmed renewable electricity from on or off grid sources.
2. **Pathway 2 - Direct emissions reduction** - the major sources of non-electricity related emissions in the aluminium sector are fuel combustion in alumina refineries and smelter anode consumption. So, energy efficiency, alternative smelting technologies, like inert anode technology that reduces anode consumption and CCUS are the candidates for direct emission reduction in aluminum industry. Hydrogen may also be a potential pathway, for parts of the process not suitable for electrification. Another key aspect is improving the efficiency. Mechanical vapor recompression, for instance, recycles waste heat, thereby enhancing energy efficiency. Integration of advanced technologies such as artificial intelligence and machine learning to optimize processes and reduce waste.
3. **Pathway 3 - Recycling & resource efficiency**. Infinite recyclability without loss of properties is one of aluminium's unique benefits. Globally, the recycling of post-consumer scrap today mitigates the need for almost 20 million tonnes of primary aluminium every year. Recycling uses only about 5% of

[7] IPCC (Intergovernmental Panel on Climate Change). 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

[8] International Aluminum Industry - international-aluminium.org

the energy and emits about 5% of the CO_2 compared to primary production making it a less energy-intensive method.[9]

The B2DS solution will require all three pathways. The relative weighting of each pathway, within a jurisdiction, will depend on resource endowment, geographical limitations, government policy, market and consumer forces and the maturity of the economy.

IEA's assessment on emission reduction scenario for aluminium industry is shown in **Error! Reference source not found.**1[10] to reach net zero by 2050. Among all the measures, energy efficiency, electrification and process shift (use of inert anode) will be dominating projecting 27% emission reduction by 2030. Activities will increase emission by 16% from 2030 level, hence the projection of 97% emission reduction is estimated till 2050. CCUS will have some role for decarbonizing aluminum industry. The use of CCUS is estimated to raise production cost by 38%. A carbon price of $210/t of CO_2 is required to incentivise the use of CCUS in smelting. This is significantly higher than the current carbon price in Kazakhstan, just over $1/t CO_2.[11]

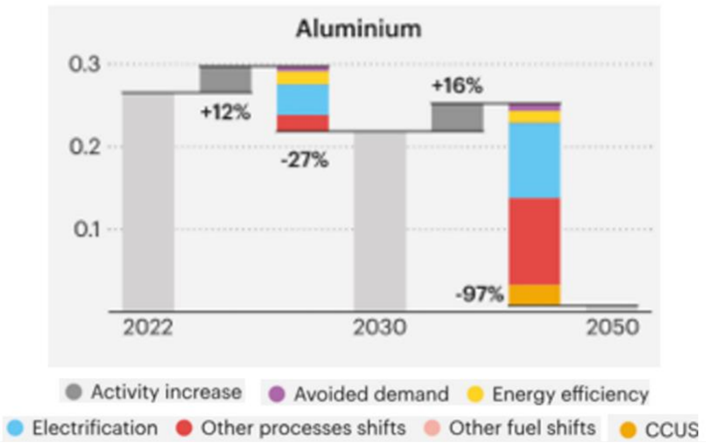

Figure 1. Emission reduction in aluminium industry towards Net Zero (source: IEA Net Zero Roadmap)

The low-emission production technologies are largely prototyped at scale and the necessary infrastructure required by the low-emission industry is partially in place. The expected year of commercial readiness of first low-emission production is 2030. World Economic Forum Report[9] mapped and assessed the main technologies' technology readiness levels (TRL) as shown in Fig. 2 below. If TRL reaches 9 then it falls under commercial scale availability. Apart from decarbonized electricity (TRL 9-11), all other technologies (H_2, CCUS, Inert anode, Mechanical vapour recompression) are at TRL 2-5. So, as mentioned earlier, KAS may try to collaborate with companies who are testing this technology in an R&D set up.

Producing secondary aluminium from scrap (recycling) will play a crucial role in reducing industry emissions. Recycled aluminium is more than ten times less emissive than primary aluminium today and could near carbon neutrality if powered with decarbonized electricity.

[9] Aluminum decarbonization at a cost that makes sense, Mission Possible Partnership, 2023

[10] IEA – Net Zero Roadmap, 2023 Update

[11] World Economic Forum Report: Net Zero Industry Tracker 2022 in collaboration with Accenture

This business model evaluates all possible decarbonization measures including those mentioned above so far for KAS's suitability and assesses the CO_2 reduction potential for each with cost-benefit analysis.

Green financing to fund the new decarbonization measures is discussed and included in the model document.

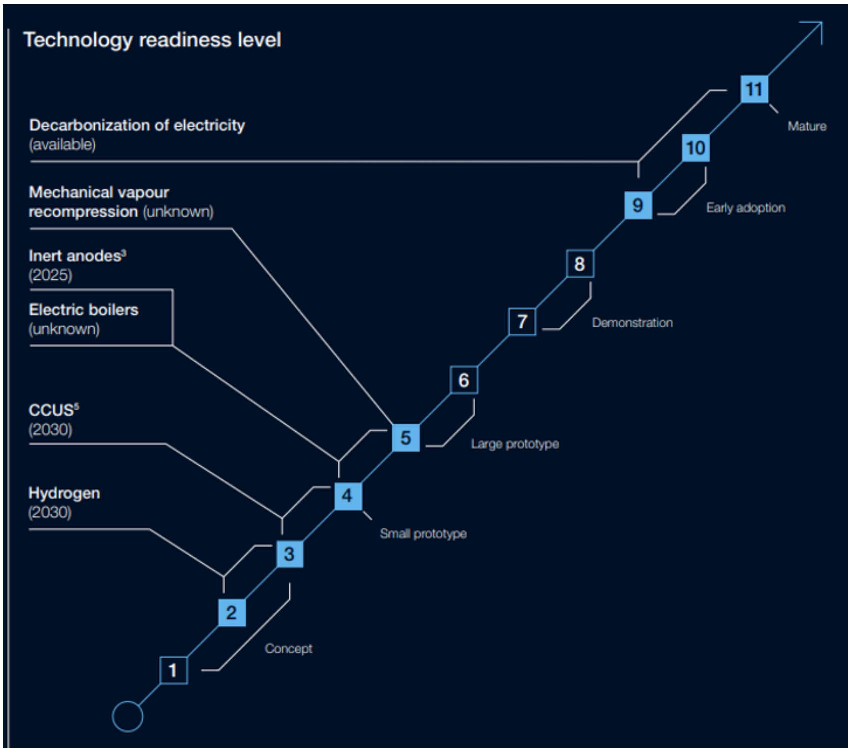

Figure 2. Technology readiness level for aluminium decarbonization technologies

2 INTRODUCTION TO KAZAKHSTAN ALUMINIUM SMELTER JSC

Kazakhstan Aluminium Smelter JSC (KAS) is the premier and only producer of high-grade primary aluminium in Kazakhstan. It is considered to be the flagship company in the domestic metals industry and ranks in the top 100 of the world's 200 largest aluminium organisations. The Company receives feedstock from Aluminium of Kazakhstan JSC (AOK), the only producer of marketable alumina in Kazakhstan. The two companies have formed an aluminium cluster to manufacture high-quality products and created thousands of jobs for the residents of the Pavlodar Region. KAS was incorporated on 17 March 2005.

The KAS uses a prebaked anode technology, one of the most advanced and environmentally friendly aluminium production solutions. KAS is located in Pavlodar and its production capacity totals ~265 ktpa (see Table 2) exporting to Southern Europe, Turkey, Kazakhstan, Russia and other CIS countries. Aluminium sales to Europe accounted for 79 percent of exports in 2021 and 2022 as per calculation from KAS Annual report 2022, p-52 data. Overall overseas sale in 2022 was 83%, total revenue is over KZT 309 billion[12] (USD 658 m).

Table 2. Production and Market Dynamics[13]

Plant	Product, ktpa	Dynamics in 2022
Kazakhstan Aluminium Smelter JSC (KAS)	Aluminium 2023: 261 2022: 249 2021: 262 2020: 265	Aluminium production decreased in 2022 due to since-resolved challenges around anode quality and the electrolysis process.

[12] KAS Annual Report, p-8 and p-52

[13] ERG Sustainable Development Report, 2022

3 PROCESS DESCRIPTION AND SOURCES OF GHG EMISSIONS

3.1 Process Description

ERG's another company, Aluminium of Kazakhstan (AK) is involved with the primary production of aluminum. This is a process that starts with the mining of bauxite, which is then refined into pure aluminum oxide (Al_2O_3) or alumina. KAS takes this oxide from AK as a feedstock for an electrometallurgical process known as *the Hall-Héroult process*, where it is dissolved in molten cryolite (Na_3AlF_6) to lower the melting temperature of the alumina to 650°C and subjected to electrolysis to produce pure aluminum. This method, while effective, is energy-intensive and a significant source of greenhouse gas emissions due to the carbon anodes used in the electrolysis process. Since we are dealing with KAS, this business model will be focussed only on its part of the process, i.e., producing aluminium from aluminium oxide.

There are two main processes of KAS operation, namely, electrolysis and anode manufacturing. The average global direct emissions from aluminum smelting, including carbon anode manufacturing, is up to 2.5 t CO_2e/t Al. The majority of Scope 1 emissions, ~1.5 t CO_2e/t Al, are process CO_2 emissions generated during carbon anode production.[14]

a) **Electrolysis.** The electrolysis occurs in the cells where the anodes are used, and their mass is consumed (evaporated) while letting the current through. This is part of electrolytic reduction where aluminum is deposited in liquid form on the cathode and oxygen is deposited on the anode. Oxygen reacts with the anode to form CO_2 gas while the aluminum is tapped in batches from the cell. The total emissions from KAS electrolysis are approximately 1.38 t CO_2e/t Al (Table 4 in next section). In addition to CO_2 emissions, the electrolysis process generates perfluorocarbon compounds (PFCs) in what is known as the anode effect. The anode effect occurs when the alumina dissolved in the cryolite melt falls to a concentration level too low to support the current flow at the nominal voltage for aluminum production. During these periods, which typically occur during 0.03–0.50 percent of the total electrolysis time, the voltage rises to a level where reactions are initiated that produce the PFCs. The average emissions of PFCs are ~0.038 t CO_2e/t Al and can be reduced to 0.02 or lower t CO_2e/t Al by implementing best practices (possibly it will require to change the cells – the main equipment of the plant).
b) **Anode Manufacturing.** The remaining emissions are associated with carbon anode manufacturing. This process requires the use of two main raw materials: calcined petroleum coke (CPC) and coal tar pitch (CTP). In the process, leftovers from dismantled anodes, called anode butts, are also recycled to reduce the use of raw material. The high temperatures remove excess moisture, extract all remaining volatile hydrocarbons, and modify the crystalline structure of the coke, resulting in a denser, more electrically conductive product. CPC can be generated on-site or sourced from third-party companies.

KAS uses advanced and environmentally friendly aluminium production technology based on anode prebaking. The use of baked anodes eliminates tar emissions, including benzo(a)pyrene and other pollutants from the electrolytic cell. In addition, high-ampere electrolysers are used.[15] The significant share of

[14] Aluminum decarbonization at a cost that makes sense, Mission Possible Partnership, sponsored by Energy Transitions Commission (ETC), page 22-23, 2022

[15] KAS Annual Report 2022, p-20

domestic content, like in-house anode production and the use of domestic petroleum coke help it maintain competitive production costs.

The consumption of energy in smelting is significant, bulk is from electricity as shown in Table 3 below. This is the component causing the most GHG emissions in aluminium industry.

Table 3. KAS Energy consumption (KAS Annual Report, 2022, p-23)

Type of use	Energy source	2020, thousand TJ	2021, thousand TJ	2022, thousand TJ
Direct	Diesel	39	35	51
	Residual fuel	341	325	286
	Petrol	6	7	8
	Subtotal	386	367	345
	Electricity	13583	13610	12811
	(Electricity, MWh)	3773056	3780556	3558611
Total		**13969**	**13977**	**13156**

3.2 KAS total emissions

KAS's comprehensive emissions (Scope 1, 2 & 3) based on 2021 data, are shown in Table 4. It is evident that Scope 1 emission intensities (t CO_2e / t Al) of the plant are well below the global averages, which is a good sign in terms of GHG emissions, but question remains on switching electricity source to renewables, responsible for 89.43% of plant emissions. The rest 10.57% emissions are from electrolysis (9.40%) and anode baking processes (1.17%).

For accuracy of emission data, it is noted that the pre-commissioning and pilot operation of the automated monitoring system are to be installed at key sources of emissions (four gas scrubbers in the aluminium electrolysis shop and a gas scrubber in the electrode production shop).

Table 4. Comprehensive emissions data (Scope 1, 2 & 3) of KAS with production capacity of 265 ktpa of Aluminium

Process sections	t CO_2e	t CO_2e / t of Al	Global Ave: t CO_2e /t Al	% of emissions within the processes only (Scope 1)	overall % of emissions incl electricity (Scope 1, 2 & 3)	Overall plant-wise emissions % including electricity
Electrolysis (carbon anodes)	364,605	1.38	~1.8	85.75	9.07	
PFC (Perfluorocarbon compounds) during anode effect	9,647	0.04	0.02 to 0.5	2.27	0.24	Electrolysis 9.41
Diesel fuel (transportation)	3,707	0.01		0.87	0.09	
Other fuels	291	0.00		0.07	0.01	
Losses of the carbon in the anodes baking process	24,614	0.09	~0.50	5.79	0.61	Anode Baking 1.17
Oil fuel in the anodes baking	22,323	0.08		5.25	0.56	
Subtotal	425,187	1.60	~2.5	100.00	10.57	
Electricity	3595852	13.57	10 to 15		89.43	Electricity 89.43
Total	4,021,039	15.17			100.00	100.00

Values supplied by ERG, the rest are calculated in the columns (see Appendix A)

Note: Scope 3 emissions are not included due to the absence of proper ISO and GHG standardised methodology. These emissions are mainly the upstream emissions related to the production of the consumed coke and downstream emissions of smelting and value-added products' stamping.

3.3 Strategy

ERG, in general, systematically assesses the impact of the risks of the low-carbon (decarbonization) agenda on its operations. Their recent such assessment, approved in 2024, is as shown in (Appendix B)[16] along with key response measures. One of the measures to tackle CBAM has been identified to reduce carbon footprint of major export product, which is very relevant to aluminum industry. For 2024-2025, the plan is to develop a comprehensive risk management system that integrates these risks into investment and technological processes. A comprehensive list of KAS current risks and their mitigation actions is also provided in Appendix B. However, they still lack concrete measures associated with BAT other than the implementation of renewable energy projects. These are now considered for KAS under this business model.

The main strategic development initiatives of KAS focus on the following areas:

- operational efficiency;
- decarbonization.

Operational efficiency:

- The KAS's strategy is based on efficient operation, industry best practice, as well as on unlocking the potential for performance improvement.
- The KAS has developed projects to reduce the unit consumption of raw materials and electricity and enhance labour productivity.
- The anode baking process optimization, addition of 16 new electrolysers and designing a new workshop & supporting infrastructure are related to operational efficiency.

Decarbonization:

Aluminium produced in Kazakhstan has a high carbon footprint due to the large share of coal generation in the country and the high energy intensity of alumina production from local bauxite, the main raw material of KAS. The measures considered to minimise the risks in relation to CBAM payments can be classified into the following groups:

- improve the energy efficiency of KAS (with a focus on auxiliary processes);
- reduce the carbon footprint of raw materials consumed by KAS, largely alumina supplied by Aluminium of Kazakhstan JSC;
- ensure clean energy sourcing, including options for in-house green energy generation;
- diversification of markets with lower carbon footprint requirements – a possible temporary solution until own carbon footprint is reduced.

All these are reflected in the decarbonization levers as detailed below.

[16] ERG Kazakhstan Decarbonization Strategy, approved in 2024

4 DECARBONIZATION LEVERS

4.1 Technology Levers

KAS has initially supplied information on their identified measures for decarbonization as listed in Table 5[17]. It is evident that it includes the following levers:

a) **Renewable electricity**. It included a plan for stage-wise implementation of 180 MW WPP, 430 MW WPP, 600 MW WPP and 640 MW WPP projects. However, taking into consideration of wind power oscillations and the electricity demand of 450-470 MW of the KAS plant, ERG has a project plan in the pipeline for 1 GW project (very early pre-development stage, no specific partner chosen as yet). They are looking for good terms on risks (state guarantee take or pay), moderate requirments for the grid connection, partners with good financing options etc.). The ERG has come up with an estimated cost figure for 1 GW plant which is included in this business model.

Table 5. KSA identified preliminary measures for decarbonization

Project
180 MW WPP
430 MW WPP
WPP 640 MW, around 500 MW of maneuvering capacity
Electric vehicles
Anod baking furnace retrofit with H_2 fuel
WPP 600 MW + green H_2 + FC
Inert anodes

b) **Electrification of vehicles** – very small advantage compared to the total emissions.

c) **Anode baking furnace retrofit with H_2 fuel**. According to ERG, it is highly unlikely to implement H_2 fuel in the anode baking process. This in turn enhances the risks and challenges associated with its use, particularly in terms of safety and environmental impact, need to be carefully managed and mitigated. KAS is considering it for future.

d) **Green hydrogen** could potentially be used as a clean fuel to offset the use of fossil fuels in the production of the thermal energy needed for various processes in the aluminium smelter. In some aluminium recycling processes, hydrogen can be used as a reducing agent or as a protective atmosphere to prevent oxidation of the aluminum during melting.[18] Fuel cell electric vehicles (FCEVs) powered by hydrogen could replace diesel trucks for hauling alumina and aluminum, further reducing the carbon footprint. Hydrogen can be:

   i. Green if produced by elerolysis of water using renewable electricity,
   ii. Grey, produced from fossil fuels, mainly from natural gas, using steam methane reforming (SMR) process which is currently the widely practised route, or

[17] Supplied by ERG

[18] https://www.hydro.com/en/global/media/news/2023/worlds-first-batch-of-recycled-aluminium-using-hydrogen-fueled-production/

iii. Brown, produced from coal gasification, or
iv. Blue, produced by either b or c option accompanied by CCS.

The preferred category is the Green Hydrogen followed by Blue Hydrogen for the metallurgy application. Green Hydrogen is completely emission free and the cleanest option. However, challenges such as H_2 production cost and infrastructure requirement need to be addressed for widespread adoption. Further details are available in the White Paper.

e) **Inert anode:** Inert-anode technology, coupled with wetted cathodes, offers the greatest opportunity to reduce GHG emissions. However, there is currently no industrial-scale inert anode–based technology for aluminum smelting, though multiple companies are exploring the idea, and a commercial-scale plant is expected to be developed by 2030. ELYSIS (a joint venture among Alcoa, Apple, Rio Tinto, and the Canadian government) is running industrial trials at the Alma smelter in Canada. Apart from these two examples, there is very little public information on inert anode operational performance, and estimates on when this will be adopted on an industrial scale vary vastly. However, according to IAI, the overall cost impact of replacing traditional anode by inert anode technology in aluminum smelting is likely to be positive in the long term, despite higher initial investment costs.

All these technology levers formed the basis for the choice of suitable decarbonization measures for the business model as discussed in section 5.3.

Let us now examine further international context on KAS levers. Mission Possible Partnership[19] has identified some broader decarbonization levers for aluminum industry. These are listed below (also see Table 6):

1. *Hall-Héroult* (HH) process with 100% green electricity;
2. *Hall-Héroult* (HH) process with 100% green electricity with CCS
3. *Hall-Héroult* (HH) process with 100% green electricity with CCS and electric anode baking with CCS;
4. Inert anode.

It is evident from Table 6, the 1st lever, *Hall-Héroult* (HH) process with 100% green electricity, is the only matured technology, while others are in the pipeline of progress. KAS is rightfully addressing this as discussed above. Two levers involve CCS, which is still in infancy. CCS technology involves capturing carbon dioxide and storing them underground permanently. Successful implementation of CCS requires suitable storage sites, efficient capture technologies, and supportive policies to incentivize investment. The lack of all three elements in Kazakhstan makes it unattractive for investors. It requires a case-by-case study before coming to a final decision for KAS. Further details on CCS can be found in the White Paper or Global CCS Institute report.[20] That report has pointed out that the projection of CCS's wide implementation period is during the decades from 2030-2050, but preparation must be started now with feasibility and/or pilot testing.

[19] Aluminum decarbonization at a cost that makes sense, Mission Possible Partnership, sponsored by Energy Transitions Commission (ETC), 2022

[20] Global CCSI's report on "Global Status of CCS 2023 scaling up through 2030

Table 6. Smelter technologies with potential for a low-CO_2 footprint[21]

Process CO_2 | Anode production | Low | High

	Hall-Héroult (HH)	HH + carbon capture and storage (CCS)	HH with CCS and electric anode baking with CCS	Inert anode
Approach	Global average smelter using 100% green electricity	Typical smelter using 100% green electricity with CCS	Typical smelter using 100% green electricity with CCS, electric anode baking with CCS, and petcoke calcination with CCS	Retrofit current HH, reusing potrooms holes, though cell needs to be redesigned
Emerging example	En+ Group, Hydro, Rio Tinto	Alvance, Hydro, Rio Tinto	N/A	Alcoa and Rio Tinto (ELYSIS), En+ Group
Aluminum smelter emissions, tCO_2 per t aluminum[1]	2.0 1.5 0.5	1.0 0.5 0.5	0.7 0.5 0.2	0.3
Logic or limitation	Multiple players including Chalco, Emirates Global Aluminium (EGA), and Hongqiao are exploring renewable-energy sources to fossil-fuel generation sources	Technology is still in its infancy Assuming 70% CCS efficiency, no PFC[2] capture and no reduction in carbon anode production emissions	Technology is still in its infancy Assuming 70% CCS efficiency, no PFC capture and green electricity for electric anode	Technology developments in the past 10 years
Maturity				ELYSIS commercial demonstration by 2026

Note: Figures may not sum, because of rounding; excluding transport and raw material input; assuming perfluorocarbon control with best available technology (BAT).

[1] Metric tons of carbon dioxide per metric ton of aluminum across Scopes 1 and 2, including process CO_2 emissions, process non-CO_2 emissions, and anode fabrication emissions including raw materials (0.5).

[2] Perfluorocarbon. Assuming BAT marginal emissions of 0.02 t of CO_2e/t of aluminum.

4.2 Financial and Policy Levers[22]

The decarbonization of the aluminum value chain needs to be a concerted effort between financial institutions, political institutions, producers, buyers, intermediaries and equipment providers. To successfully meet a 1.5°C scenario or even B2DS (below 2 degree scenario), a set of financial and regulatory levers could help to stimulate investment in ultra-low-carbon aluminum production as summarized below. Details are outlined in Appendix C.

Major part of the decarbonisation lever require special favourable terms to become feasible and attract financing. A study shows on retrofitting a coal-fired smelter in China with inert-anode technology and

[21] Aluminum decarbonization at a cost that makes sense, Mission Possible Partnership, sponsored by Energy Transitions Commission (ETC), 2022

[22] Aluminum decarbonization at a cost that makes sense, Mission Possible Partnership, sponsored by Energy Transitions Commission (ETC), 2022

connecting it to the grid would have a negative NPV (Net Present Value) of $1.2 billion when assuming electricity intensity of 16 MWh/t Al (Appendix C, p-16). The carbon price has 60% impact.

If state support measures won't be implemented in Kazakhstan, metallurgic plants here may loose their export competetivness and large portion of their today's external markets.

A. Finance levers
   - Financial institutions need to be part of the decarbonization of the aluminum value chain to reduce their financed emissions and at the same time mitigate climate risk by decreasing interest rates, increasing loan duration, or increasing loan to value of loans for players' decarbonization efforts through issuing:
     - green loans
     - green bonds
     - transition bonds
     - sustainability-linked loans or bonds

B. Policy levers
   - **Setting up carbon prices or taxes**. These can take multiple forms, such as locally regulated taxes, exchange-traded emissions systems like those currently installed in several parts of the world, and fees on imports, such as the European Union's cross border adjustment mechanism (CBAM). However no clear rules on Scope 2 emissions for the CBAM are ready yet.

     KAS is a regulated subject in the Kazakhstan Emission Trading System (ETS). Authorities (Ministry of ecology and it's subordinated entity Zhasyl Damu) operate the system and issue certain amount of CO_2 quotas annually to distribute them for free between companies. The amount of the free allocations is defined based on the benchmark set by Ministry of ecology. Actual CO_2 emissions are calculated and verified on an annual basis. KAS have to buy additional quotas to cover the difference between actual emissions and quotas received. Currently, it is almost balanced. For further information please check with Kazakhstan ETS website.[23]

     However, the Kazakh Government has declared to speed up the pace for the decrease of the free allocation quotas starting from 2026 (stated in the National Development Plan 2029 signed by the President in July 2024). Also, The Ministry of Ecology has already begun working on bringing the European and Kazakh systems closer together. Starting in 2026, it is planned to expand it by types of economic activity and greenhouse gases. "Along with fulfilling the obligations under the Paris Agreement, this will allow our exporters to avoid paying the full border carbon tax in the EU," the Minister added.[24]

     So, for this very reason along with CBAM, it is doubly important that KAS considers decarbonization measures seriously.

   - **Offering government grants**. For example, a CA $1.8 billion grant (US $1.4 billion) from the Canadian government is making possible an ArcelorMittal investment in the steel industry to convert a blast furnace to an electric-arc furnace, resulting in a CO_2e emissions reduction of three million metric tons (or 60 percent emissions reduction). The Canadian government has also provided support to Alcoa and Rio Tinto for development of the ELYSIS technology.

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[23] https://icapcarbonaction.com/en/ets/kazakhstan-emissions-trading-system

[24] https://www.inform.kz/ru/sistema-torgovli-vybrosami-rasshiritsya-k-2026-godu-minekologii-rk_a3939996

- **Developing carbon contracts for difference (CCfD)**. For example, Germany is currently considering providing €43 billion funding for CCfD for use in heavy industry (for example, steel, cement, and chemicals). This will be a ten-year agreement resulting in an offset in CO_2e emissions of 20 million metric tons per year. A similar CCfD scheme has been implemented in the UK to accelerate the renewable-energy transition and has already supported 16 GW of low-carbon electricity.

  If no similar measures of the state support implemented for Kazakhstan, metallurgic plants here may loose their export competetivness and external markets.

- RES corporate PPA (Power Purchase Agreement)

  In general, if an operation has its electricity supplied from a national or regional grid, it can enter into a PPA with a renewable energy provider to buy its electricity directly from the generator for an agreed price. One method of achieving this is through a direct retail or "sleeved" PPA, whereby an off-taker, like KAS or ERG can enter into an agreement directly with a renewable energy producer, fixing the price but paying a fee to the utility, via which the electricity will pass through to cover its cost of managing the grid to resolve any balancing issues (i.e. if the renewable energy source fails to produce enough electricity on a given day, the off-taker can purchase additional power from the utility). As an example, in 2019, RWE closed a PPA with Deutsche Bahn to supply electricity from its Nordsee Ost offshore wind farm, also close to Heligoland. Starting with 2024, Deutsche Bahn (German Rail) is powered by electricity from RWE Renewable's Amrumbank West offshore wind farm. The relevant power purchase agreement (PPA) has been signed by Deutsche Bahn and RWE Supply & Trading, RWE's trading subsidiary. The PPA will begin in 2024 and run until 2039. In Australia too such PPA systems have started functioning. A potential drawback to this is that it requires the wind farm or solar plant to be hooked up to the same grid as the mine, which is not always practical.

  For Kazakhstan there is another barrier. All RES built in Kazakhstan supply electricity to the wholesale market meaning they can't just switch to the industrial consumer without losing this right received through a competitive selection or inter-governmental agreement.

  Alternatively, a virtual PPA can provide a good solution if it is not possible for the off-taker and the renewable generator to be connected to the same grid. A virtual PPA can take many different forms but, most commonly, it is effectively a financial instrument between a renewable generator and an off-taker, which has the effect of providing the latter with a stable energy price over the term of the PPA. In practice, the off-taker is still being supplied with energy from a mix of sources under a sleeved or virtual PPA but can reap the benefits of the low cost of renewable power, without using a renewable source. This requires a functioning and well-operated grid, so it might not always be economically viable, but is already being used in a number of countries.

C. Demand levers

- *Reaching offtake agreements*. Offtake agreements often help secure funds for decarbonization, reducing the investment risk. Buyers and sellers can reach an agreement to purchase a defined quantity of low-carbon-footprint product at a predefined price or at the cost of the production price.
- *Stakeholder Engagement*: Collaborating with governments, investors, and consumers to create a demand for low-carbon aluminum products.

4.3 Comprehensive Decarbonization Levers for KAS

As indicated earlier, though some measures have already been undertaken by KAS, but to achieve their target of 30% GHG reduction by 2035, they need to adopt further concrete actions. Based on the above information and discussions with ERG, we can now choose particular decarbonisation measures / levers to be suitable and realistic for KAS. The assessment process involved listing and prioritising those levers based on importance for achieving net zero goals, costs, implementation probability and KAS's strategy.

To reach net zero targets, KAS also have a strategic plan in all other technological, regulatory and financial levers. All probable levers suitable for KAS are listed below, with estimated cost, in Table 7. The yellow highlighted data in the Table 7 have been supplied by ERG. The cost calculation for both Capex and Opex are in the Appendix A.

The broad categories of measures as shown in Table 7 are:

a) **Fuel switching and electrification**. It contains the main item of decarbonization of electricity. As evident from Table 7, it has the potential to reduce 87% of total emission. Also included anode baking furnace retrofit with H_2 fuel till inert anode is establised.

b) **Increasing energy and material efficiency**. Hall-Héroult (HH) process with 100% green electricity, anode baking process optimization and progressing towards inert anode establishment are considered under this category.

c) **Deploying CCS and CCU**. CCS is shown for information only. However, as discussed in Section 5.1, successful implementation of CCS has some difficult issues which prevent its widespread use. It needs collaborative approaches for all the steps (capture, transport and storage / utilization) and requires initiative with funding supports from the government. Although the plants and operataional costs are shown to be reasonable, there is no in-depth geological study of resorvoirs for storage or EOR (enhanced oil recovery) or other utilization. The distance from the KAS plant to the probable storage site, say Torgay, identified by a peliminary study[25], is over 1180 km, and government regulations are absent in Kazakhstan. Governmental help is vital to assess CCUS feasibility So, ERG, with Kazakhstan government support, may start with a pre-feasibility study on CCUS now so as to taking a step forward towards readiness by 2050 when CCS is supposed to be a commercially viable technology. Another aspect of utilization may need to be explored, e.g., producing food grade CO_2 or other value-added chemicals from CO_2. It also requires a proper feasibility staudy first, which is a possible option.

d) **Financial and Policy Levers**. These are considered must in order to have successful and meaningful implementation of technologies as outlined in section 5.2.

[25] Yerdaulet Abuov , Nurlan Seisenbayev, Woojin Lee, CO_2 storage potential in sedimentary basins of Kazakhstan, Int Journal of Greenhouse Gas Control, vol 103, Dec 2020, 103186 https://www.sciencedirect.com/science/article/abs/pii/S1750583620306113

Table 7. Assessing Decarbonization Levers for KAS based on Emission Reduction Potential

Broad Category	**Project Name**	Carrent TRL	mUSD	mUSD	years	Abated CO_2	
			CAPEX	**OPEX**	**Lifetime**	**000 x tpa**	**%**
Operational Efficiency	Anode baking process optimization	10	6	-1	20	1	0
Fuesl Switching and electrification	1 GW WPP (decarbonization of energy)	11	979	-64	25	3515	87
Deploying CCS***	CCS	3-4	245	32	30	345	9
Material efficiency	Inert anode established	4-5	1223	0	30	350	9
Fuel switching and Energy efficiency	Anode baking furnace retrofit with H_2 fuel	7	75	9	25	22	1
Financial and Policy levers	Details are in the report text	?	?	?		?	?

*** It is listed here for information, but will not be considered for near future due to the reasons explained in the report

Supplied by ERG

(For calculations, please see the spreadsheet in Appendix A).

A Marginal Abatement Cost Curve (MACC) has been constructed for all the technology levers using KAS's resources as shown in Fig. 3 to assess their potential (calculations for MACC are in Appendix A). Decarbonization of electricity has been singled out in terms of amount of CO_2 (~3.5 m tpa) abated and cost of CO_2 ($22/t CO_2e). KAS has rightfully concluded that the main decarbonization efforts in the next decade will be focused on the decarbonization of the electricity by:

- Creating green clusters of industrial consumption and renewable energy generation (new WPP connected to the grid in Pavlodar/Aksu).
- Procurement of the clean electricity from the PPA (Power Purchase Agreement).

Anode baking process optimization has negative cost implicating economic gain, although it is negligible in terms of substantial CO_2 abatement. It should be accompanied by all other operational efficiency measures such as automation & advanced control systems and adopting lean manufacturing principles across the plant operation. Electrification of vehicles & equipment is another way to gain competitive advantage.

CCUS is showing to be capable of abating 345,000 t CO_2 with a cost of $193/t, but as discussed above it will not be considered right now. Inert anode can abate 350,000 t CO_2 with a huge cost of $499/t while anode baking furnace retrofit with H_2 fuel can abate 22,000 t CO_2 with a higher cost of $889/t. The assumption parameters which lead to these high costs (Appendix A) need to be re-evaluated. However, the message is clear that all these will have to be incorporated into the plan towards Net Zero goals.

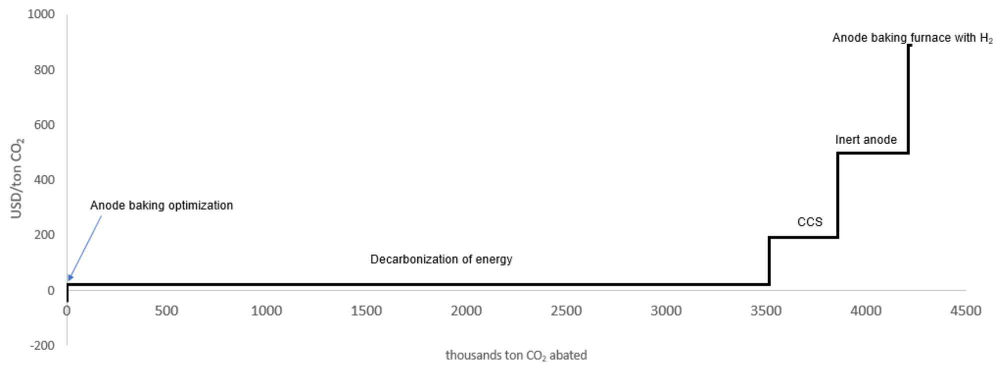

Figure 3. Marginal Abatement Cost Curve (MACC) for Decarbonization Technologies of KAS

5 ROADMAP FOR IMPLEMENTATION – Timeline Approach

Based on the KAS strategy and MACC, the timeline groups of decarbonization levers are assessed in terms of opportunities and barriers as explained in Table 8. The timeline summary diagram of all the probable decarbonization levers is shown in Fig. 4 along with target period and potential emission reduction amounts. Each timeline group in the figure has been selected in such a way that it reflects the overall timeline of decarbonization groupings shown in Table 8. This timeline clearly articulates the target 87% reduction by 2035, 91% by 2045 and Net Zero by 2060. It is believed KAS and ERG policymakers will look for further detailed study and plan to implement them.

Table 8. Timeline Grouping of selected decarbonization levers for KAS

Group/Levers	Opportunities	Barriers	Remarks
Timeline Group 1 – by 2035			
1 GW WPP (decarbonization of energy)	This is the best way that countries like Kazakhstan can get advantage of substantially reduce emissions in metallurgy industry. This statement is supported by the MACC shown in above section. ERG is seriously considering getting access to up to 1 GW WPP.	ERG favours outsourcing electricity or partnership here mainly due to the huge initial costs reason. CBAM scope 2 rules are unclear.	MACC's cost indicated very low cost, so It looks achievable by 2035.
Operational efficiency	Streamlining production processes through process optimization, automation and advanced control systems supports the enhancement of efficiency and lowers resource consumption, and adopting lean manufacturing principles minimizes waste and boosts productivity, directly impacting operational costs.	Overall, KAS needs some incentives from government to implement these in their aluminium smelting operation	All operational optimizations fall into the same category as the anode baking process optimization, hence doable and looks achievable by 2035.
Financial and Regulatory Mitigations	KAS/ERG can create a strong business case to lobby for green financing, setting up internal carbon pricing, liaising with EU CBAM and government for grants and pursuing CCfD to offset emissions	Again, lack of incentive from government may be the reason	This is within the reach provided understanding of the problem from the governmental authority, looks achievable by 2035.
Timeline Group 2 – by 2045			
Inert Anode development	Inert-anode technology, coupled with wetted cathodes, offers the greatest opportunity to reduce GHG emissions with high efficiency. It eliminates the CO_2 and PFCs (perfluorocarbon compounds) associated with the consumption of the carbon anodes, as well as the need to manufacture a carbon anode in the first place. Since the technology is in the process of development in the world, KAS can start initial investment into this technology towards future sustainability of the Al manufacturing.	Commercial unavailability of the inert anode technology is the main barriers. The MACC shows a very high cost of $499/t CO_2	Inert anode technology is not yet commercially available. It may take time, however, companies like Alcoa and Rio Tinto (ELYSIS), En+ Group have been progressed in this direction. Investing in R&D and collaboration with other players around the world is highly recommended. It could be ready well before 2045

Group/Levers	Opportunities	Barriers	Remarks
Recycling aluminium	Scrap-based aluminium production using 100% renewables can decarbonize the sector by up to 62% of emissions. For KAS operations, there is not much advantage of recycling in mitigating emissions.	Scarcity and hence the cost of scrap aluminium in Kazakhstan (less than 30,000 tons of Al scrap in the market in KZ)	Investigate and promote aluminium recycling networks. Will not be included in decarbonization list as it is mainly for saving raw alumina.
Anode baking furnace retrofit with H_2 fuel	Replacing current oil-based technology by green hydrogen is an ideal solution for anode backing process	Non-availability of commercial green H_2 and lack of a proper baking technology using H_2. The MACC is also showing a very high cost of \$889/t CO_2	It is anticipated that green hydrogen may be available within a decade and the situation looks favourable by 2045.
Financial and Regulatory Mitigations	Same as under Group 1	Same as under Group 1	Same as under Group 1
Timeline Group 3 – by 2060 or earlier			
Inert anode established	The benefits of this technology are stated above. By 2045, KAS would be able to access to the commercially available inert anode technology	Commercial unavailability of the technology and lack of all incentives as above	If all go well, KAS would be able to establish this anode technology in their facility by 2050 onwards.
CCUS (if inert anode is not established)	CCS/CCUS is the final but necessary low-carbon technology for decarbonization, without which it would be impossible to reach B2DS, according to IEA. Apart from geological storage, CO_2 can be used for EOR and for producing food grade CO_2 & chemicals	Technology is still in its infancy for aluminium industry. Identification of proper storage site (based on assessment by reservoir engineers) and high cost are other two barriers. Lack of R&D to investigate for both capture technology and storage site is also a factor.	According to Global CCS Institute, it is being implemented across all other industries, including steel manufacturing. KAS / ERG should start a pre-feasibility study for CCUS incl for food grade CO_2. For further details please see the Whitepaper and GCCSI web site (https://www.globalccsinstitute.com/).
Financial and Regulatory Mitigations	Same as above under Group 1	Same as above under Group 1	Same as above under Group 1

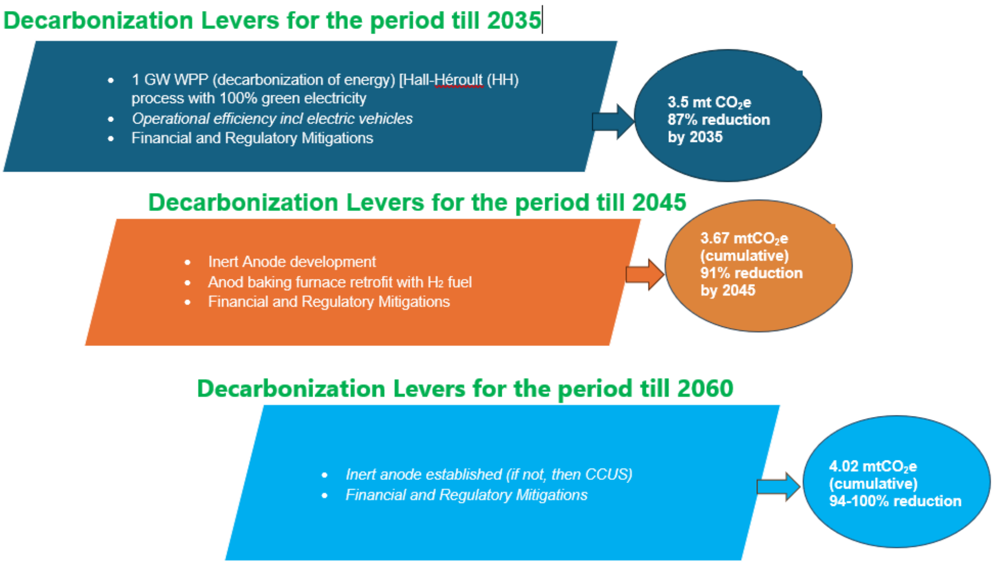

Figure 4. Timeline Diagram for all selected Decarbonization Levers for KAS

6 MAIN CHALLENGES/ BARRIERS AND RECOMMENDED ACTIONS

As indicated earlier, decarbonization is a collective effort of all stakeholders. For KAS, the following barriers have been identified:

a) Technological:
- Low readiness of the inert anode's technologies
- High prices for 100% dispatchable zero carbon energy
- High Capex and Opex as discussed in Section 5.3 and Tables 7

b) Financial:
- High debt rates
- Hard to comply with requirements towards corporate renewable PPA from the financial institutions
- Absence of state guarantees for green financing. International development banks are happy to finance green project when there is a transparent guaranteed investment return scheme in place.[26] In 2022, ERG developed their Green Finance Framework with the aim of providing a standard for the attraction of investments in Kazakhstan through green financing instruments. This includes the requirements and conditions for attracting green finance, as well as lender / investor reporting requirements. The Framework is aligned with the Green Bonds Principles (GBPs) of the International Capital Market Association and the Green Loan Principles (GLPs) of the Loan Market Association, Asia Pacific Loan Market Association and Loan Syndications & Trading Association. For further information, see: erg.kz.

c) Regulatory:
- In general, there is no effective state support for the energy efficiency measures.
- International competitiveness/CBAM is another challenge for metal exporting industries, particularly for aluminum. Uncertainty of the scope 2 inclusion into the CBAM coverage, as well as concrete scope 2 method and formulas to be implemented starting from the moment of inclusion.

According to the Kazakhstan Net Zero report[27], "The scale of transformation in the power sector necessary to reach net zero emissions by 2060 has to be met by massive investments into the power system. Under the current conditions, the sector is unattractive to private investors, and most of the costs would have to be borne by the state. This would create a trade-off between decarbonization and other socioeconomic priorities". It has also concluded that to stimulate private investment in green transformation, the government has four major instruments:

1) the economically optimal tariff policy that will allow markets to determine electricity prices;
2) carbon pricing which will internalise the environmental costs of fossil-based power generation and stimulate investments in renewable energy;

[26] ERG Sustainable Development Report 2022

[27] Kazakhstan: Towards Net Zero by 2060, DIW ECON, 2022

3) the government can attract green investment by providing preferential treatment for such projects (e.g., feed-in tariffs for renewables), tax cuts, subsidies, interest discounts, etc and
4) improving framework conditions and sending clear signals on the future policies will reduce uncertainty and risks perceived by domestic and international investors.

All four elements are interconnected. Each can stimulate some investment, but all four need to be combined to efficiently mobilise private financing for the decarbonisation.

7 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The developed business model provides a holistic view of a Kazakhstan metallurgy industry, namely aluminium manufacturing, which falls under a hard-to-abate sector of greenhouse gas emissions and will serve as a valuable tool for strategic decision-making and for long-term sustainable growth.

Decarbonization of aluminium smelting from alumina has been analysed. A profile describing Kazakhstan Aluminium Smelting (KAS) of Eurasian Resources Group (ERG), has been built through data provided by ERG, followed by analysis of its needs. All possible decarbonization measures available in the world have been explored for KAS applicability. Carbon emission and cost for each measure have been calculated and a MACC has been plotted. Then a decarbonisation pathway has been developed. Throughout the development of the business model, it was ensured, through exchanges with ERG, that it aligns with the specific needs and challenges of the metallurgical sector.

The model has identified 3-stage decarbonization activities required for KAS to reach Net Zero goal before 2060 from its current emission of 4 Mt CO_2e. The 1st stage will mainly involve with full decarbonization of the electricity along with operational efficiency and electric vehicles by 2035 to lower emission level by up to 87% (3.5 Mt CO_2e) from 2021 level; 2nd stage on fuel substitution, inert anode development, and anode baking furnace retrofit with H_2 fuel by 2045 to lower emission level by 91% (over 3.67 Mt CO_2e cumulative); and the 3rd stage on low-carbon emissions technologies, like establishment of inert anode technology or CCUS by 2060 to reach Net Zero. Financial and Regulatory Mitigation activities be applied in all stages.

Green financing to fund the new decarbonization measures is assessed and included in the model document.

Recommendations

Based on the above findings and based on World Economic Forum's identification of priorities for the sustainable aluminium sector, the following recommendations are drawn for KAS to decarbonize their operations:

1. Acquire access to / own decarbonised electricity to satisfy the constant demand of ~ 500 MW power or yearly required energy ~3800 GWh. 1 GW plant is in the KAS plan.
2. Promote and further expand aluminium recycling networks..
3. Further develop MACC (Marginal Abatement Cost Curve) for all the decarbonization levers identified in Sections 5 & 6 by modifying assumption parameners.
4. Invest in R&D to boost the number of low-emission projects identified above to accelerate the learning curve, drive costs down and bring forward the commercial readiness of clean technologies. Look for collaboration with companies for joint R&D.

5. Develop clean hydrogen production and CCUS feasibility study.

6. The following financial and policy levers are recommended here for KAS:

    - Develop business case for low-emission aluminium production to liaise with the government for implementation of the four instruments mentioned in Section 7.
    - Lobbying / Pursuing for geenfunding – Green Loans, Green Bonds etc. via ERG Green Financing Framework.
    - Setting up internal carbon pricing and continue ERG env stewardship projects.
    - Negotiating with the government for economically favourable policy/ies for captive power plants.
    - Regular liaising with EU's CBAM and/or other international regulatory authorities. Consider the fees on CBAM in Al production cost.
    - Pursuing government grants for decarbonization measures.
    - Pursuing for creation of carbon contracts for difference (CCfD) resulting in an offset in CO_2e emissions.
    - Reaching offtake agreements for green aluminium with buyers and feedstocks suppliers.