A Low Carbon Pathway for the Aluminium Sector in the Republic of Türkiye

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Abbreviations and Acronyms

ALUTEAM	Aluminium Test, Training and Research Center
BAT	Best Available Technique
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon Dioxide
CST	Concentrated Solar Thermal
EBRD	European Bank for Reconstruction and Development
ETS	Emissions Trading System
EU	European Union
FTS	Frontier Technologies Scenario
GALSIAD	Entrepreneur Aluminium Industrialist & Businessman Association
GAMS	General Algebraic Modeling System
GHG	Greenhouse Gas
H_2	Hydrogen
IAI	International Aluminium Institute
IEA	International Energy Agency
LCP	Low-Carbon Pathway
LTS	Long Term Strategy
MoIT	Ministry of Industry and Technology
MPP	Mission Possible Partnership
MRV	Monitoring, Reporting and Verification
MVR	Mechanical Vapor Recompression
NDC	Nationally Determined Contribution

NO_x	Nitrogen Oxides
NPV	Net Present Value
O_2	Oxygen
OIZ	Organized Industrial Zone
OPEX	Operating Expense
PFC	Perfluorocarbon
R&D	Research and Development
SMR	Small Modular Nuclear Reactor
SPS	Stated Policy Scenario
TALSAD	Turkish Aluminium Industrialists Association
TIM	Türkiye Exporters Assembly
TOBB	Union of Chambers and Commodity Exchanges of Türkiye
TR	Türkiye
TUBITAK	Scientific and Technological Research Council of Türkiye
TUDOKSAD	Turkish Foundry Association
UAE	United Arab Emirates
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WoM	Without Measures Scenario

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Introduction

Advances in the international climate regime have been fostered by UN-backed, science-based emission reduction targets. Climate targets determined on a supranational level have been incorporated into binding policies through key initiatives such as the Paris Agreement and the European Green Deal agenda. The Paris Agreement is a landmark example of international cooperation on the mitigation of climate change, binding parties to limit their GHG emissions. The Agreement calls on counties to work together to adapt to the impacts of climate change, and to strengthen their commitments over time. This project aims at supporting the deployment of low carbon options for the industry in line with Türkiye's 2053 net zero target.

The European Green Deal, a package of policy initiatives, is the EU's ambitious and comprehensive plan to become the first climate-neutral continent and fundamentally transform the European economy. The Carbon Border Adjustment Mechanism, a key policy tool under the deal, aims to prevent carbon leakage and drive global emissions down. As part of these international agreements and initiatives, efforts are being made to address transition needs of the hard-to-abate (must abate) sectors, one of which is the aluminium sector.

Aluminium (and its alloys) is a key material with uses ranging from heavy manufacturing to everyday, fast-moving consumer goods. Producing primary aluminium is however a key source of CO_2 emissions, responsible for about 3% of the world's 9.4 Gt of direct industrial CO_2 emissions in 2021.[1] Even considering its high emissions, aluminium will only increase its relevance, especially as a key input for emerging technologies (e.g., electric vehicles), including decarbonization technologies.

Due to its properties, the metal in theory is infinitely recyclable. As a result, the global value chain operates a cycle of cascade recycling of new and old aluminium scrap alongside primary aluminium manufacturing starting from bauxite mining. The distinction between primary and semi-aluminium processing is especially significant for Türkiye, as the country has flourishing semi-aluminium processing operations with efficient yet very limited primary manufacturing. While the global literature rightfully focuses on decarbonization of primary aluminium (which accounts for the majority of emissions in the aluminium value chain), Türkiye's aluminium sector requires a tailor-made approach to focus on decarbonization of semi-aluminium processing and recycling of the metal.

This study also considered all the international low carbon roadmaps and targets. The methodology applied in this report has brought additional insights regarding the total cost of transition for the aluminium industry. Furthermore, this study stands out as one of the initial ones to incorporate the modeling[2] of semi-aluminium processing (remelting and refining) alongside primary aluminium production. Following the adoption of this roadmap, this report can serve as foundation to developing investment plan and platform that helps to accelerate implementation of actions recommended by bringing together relevant actors and sharing a common vision for the sector.

[1] International Energy Agency. Aluminium Track Report.

[2] Secondary production is the process of recycling aluminum scrap into aluminum which can be reused. Aluminum processing is the process of melting primary metal and scrap in furnaces into semi-finished products.

This project, financed by EBRD, with the Ministry of Industry and Technology as the beneficiary and carried out under the leadership of PwC Türkiye Consortium, aims to support and contribute to climate related policy actions in line with national and Türkiye's aluminium sector's decarbonization targets. The Steering Committee is formed in order to reflect the views of all sector stakeholders in the most accurate and complete way. The Ministry of Industry and Technology, The Ministry of Energy and Natural Resources, The Ministry of Environment, Urbanization and Climate Change, the Ministry of Trade and Scientific and Technological Research Council of Türkiye (TUBITAK) and related other public institutions as well as Turkish Aluminium Industrialists Association (TALSAD), Aluminium Test, Training and Research Center (ALUTEAM), Turkish Foundry Association (TUDOKSAD) and Entrepreneur Aluminium Industrialist & Businessman Association (GALSIAD) are the members of the Steering Committee.

During the development of this roadmap for Türkiye's aluminium sector, three different Steering Committee Meetings were organized to share the project outputs with the stakeholders and collect their feedback effectively. In addition to the meetings mentioned, many other focus stakeholder discussion meetings were also held to discuss model results and policy recommendations.

This report, as the key output of the project "Türkiye: A Low Carbon Pathway for the Aluminium Sector," aims to lay the groundwork for the aluminium sector in Türkiye to accomplish green transformation in a manner that complies with Paris Agreement objectives. To this end, insights in this report are connected to several other national policy documents. The roadmap provides a basis for the implementation of the Action 1.1.1 of the Ministry of Trade's "Green Deal Action Plan", which appoints the Ministry of Industry and Technology to "Develop a national level roadmap, that will support the reduction of greenhouse gas emissions in priority manufacturing sectors that may be subject to Carbon Border Adjustment Mechanism". This project also serves to achieve Türkiye's net zero target for 2053, and interim target as per updated NDC. This includes laying the groundwork for Green Technology Roadmaps (to be prepared in 2023-2024 period).

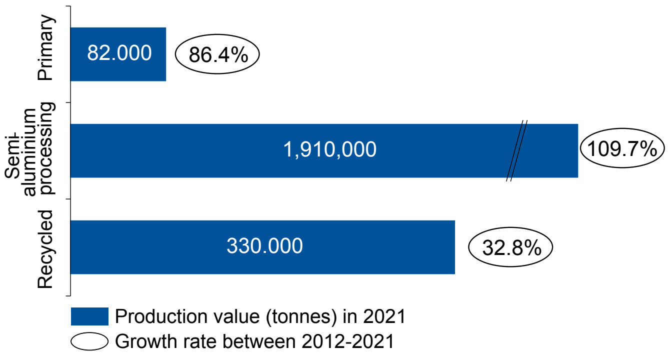
Executive Summary

Executive Summary: Key Findings & Results

Industry Status and Current Emission Performance

While it is home to one very efficient primary aluminium plant, overall Türkiye is not a key player in the global primary aluminium market. Türkiye's primary aluminium industry expanded its aluminium production by 86.4% over the period between 2012 and 2021, reaching 82,000 tonnes of annual production.[3] Semi-aluminium processing in the country increased an average of 8.6% per year between 2012 and 2021, rising 109.7% in total to reach 1.91 million tonnes.[4]

Figure 1. Türkiye's Aluminum Production by Production Route

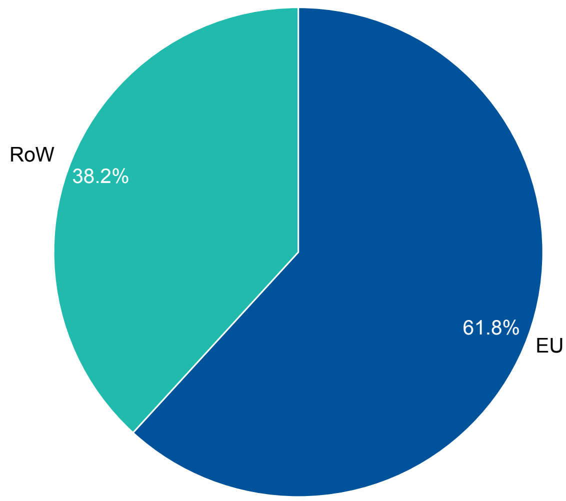


The supply of scrap aluminium, which is key to semi-aluminium processing (aluminium fabrication by extrusion, rolling, casting, forging, drawing, etc.), is not growing at a rate that meets demand. Production from recycled scrap increased by only 32.8% between 2012 and 2021, with a CAGR of 4.5%, reaching 330,000 tonnes, a rate lower than the overall increase in semi-aluminium processing.[5] As a result of insufficient primary metal production and limitations in domestic scrap availability, semi-aluminium processing relies heavily on imported aluminium scrap and primary and secondary ingots. The fact that recycled aluminium amounts are increasingly insufficient for semi-aluminium processing indicates a possible bottleneck in the sector's future emission mitigation efforts.

In 2022 Türkiye exported 6.7 billion dollars worth of aluminium to more than 100 countries. The majority of these exports sailed for the EU – 61.8% by value. This concentration leaves Türkiye's aluminium exporters especially exposed to the trade policies of their largest trade partner and consequently to the EU Carbon Border Adjustment Mechanism (CBAM).

On the primary aluminium front, thanks to its single primary manufacturer's extensive use of renewable energy, Türkiye is in a fairly good position, with emissions of 5.34 tonnes CO_2/tonne aluminium, compared to the global average of 17 tonnes CO_2/tonne and the EU average of 6.7 tonnes CO_2/tonne.[6] On the semi-aluminium processing front, benchmarking emissions is unfortunately not possible due to very limited country data. However, semi-aluminium processing is considerably less energy intensive compared to primary production, requiring nearly 10 to 15 times less energy than primary aluminium production,[7] and it has a lower emission intensity.

Figure 2. Distribution of Türkiye's Aluminium Exports, by Value, 2022



[3]ETI Aluminium
[4]TALSAD, TÜDOKSAD, PwC Analysis
[5]TALSAD, TÜDOKSAD, PwC Analysis
[6]Sector Representatives, IAI
[7]Padamata et al. "A Review of Secondary Aluminum Production and Its Byproducts". https://doi.org/10.1007/s11837-021-04802-y

Benchmarks and Technology Choices

The two key international aluminium decarbonization roadmap studies (used for benchmarking purposed in this report), prepared by the International Aluminium Institute (IAI) and Mission Possible Partnership (MPP), concentrate on primary aluminium production to tackle the larger source of emissions. Unfortunately, no international or national decarbonization roadmap for secondary aluminium production/semi-aluminium processing had been identified as of the writing of this report. Nevertheless, this report offers the following comparison of emission reduction (%) forecasts of the said international aluminium decarbonization roadmaps and the "Low Carbon Pathway for Türkiye's Aluminium Industry" (this body of work.)

Table 1. Emission Mitigation Targets in Primary Aluminium Production (CO_2 Emissions, %)[8]

Technology Archetype	2030	2040	2050/2053
IAI[9]	26	81.7	95.1
MPP[10]	20	80	90
TR Roadmap[11]	15.5	87	98

As semi-aluminium processing decarbonization levers differ from primary decarbonization levers, Türkiye is in a unique position it its decarbonization journey compared to other key manufacturers with high levels of primary production. This study finds that decarbonization of Türkiye's aluminium industry requires deployment of new frontier technologies to achieve higher levels of emission reduction in support of the country's overall decarbonization plans. Technologies that have been prioritized by the optimization model generated as part of this study (details of which will be provided in section 2 of this report), along with their emission reduction impact and investment requirement, are as follows.

Table 2. Technology Prioritization in the Low Carbon Pathway Scenario

	Expected Date of Entry	Technology Switching Year	Emission Reduction Effect	Investment Requirement
Primary Aluminium Technologies				
Gas Boiler	2028	2028	Medium	Low
CST Boiler	2032	2032	Medium	High
Hydrogen Calciner	2035	2047	Low-Medium	Low-Medium
Inert Anode	2040	2040	Very High	Very High
Semi-aluminium Processing Technologies				
Highly Advanced Reverberatory Furnaces	Available	2024	High	Medium
Electric Reverberatory	2040	2040	High	High
Crucible + Carbon Capture and Storage (CCS)	2040	2045	Low	Low-Medium
Rotary + CCS	2040	2046	Low	Low-Medium
Highly Advanced Reverberatory + CCS	2040	2047	Low	High

[8]The table was developed by consolidating the outputs of IAI, MPP and this project.
[9]Emission reduction is calculated based on 2018 data.
[10]Emission reduction is calculated based on 2020 data.
[11]Emission reduction is calculated based on 2023 data.

Potential for Emission Reduction Under Various Scenarios

Achieving sectoral decarbonization requires a well-planned chain reaction identifying and prioritizing key production technologies, securing funding for technology investments, and decarbonizing energy related emissions across all manufacturing paths. Accordingly, Türkiye's aluminium sector must define its short and long-term strategies to facilitate technological transition and identify investment needs if Türkiye is to meet its emission reduction targets in the next decades. To bring the aluminium sector close to net zero emissions by 2053, the key decarbonization levers identified by this study are: increased recycling (of aluminium), adoption of new, frontier technologies and transition to low-carbon energy.

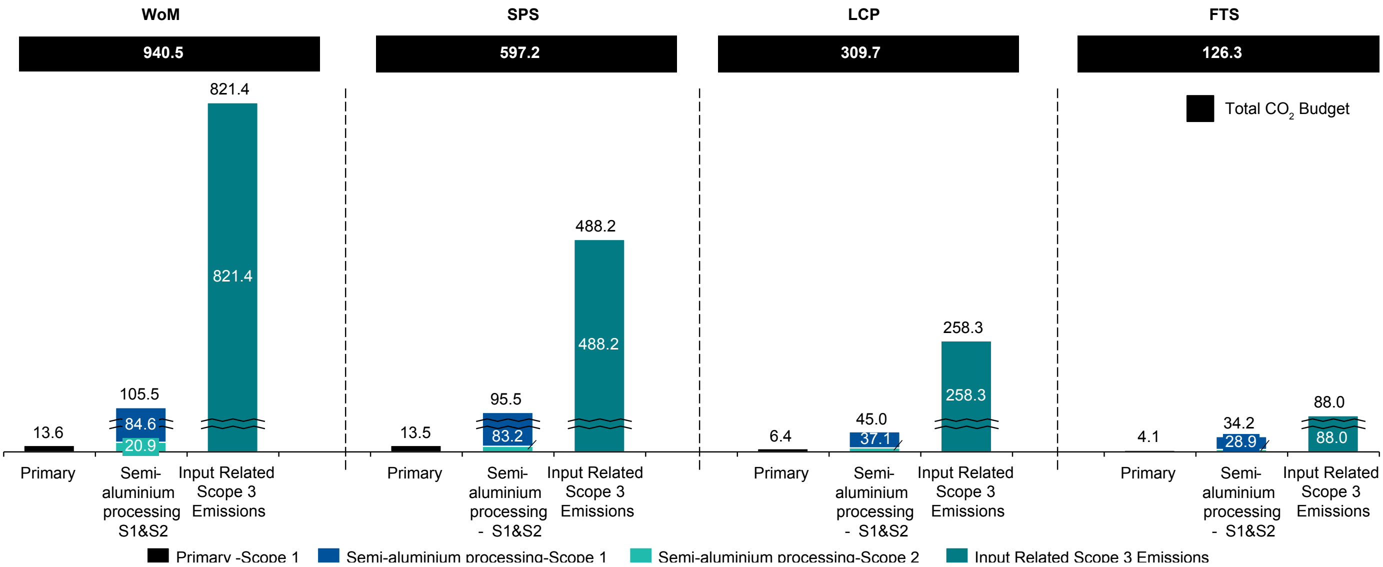
Specifically, this project uses four scenarios to forecast the varying "to-be" states for the sector. The **Without Measures Scenario (WoM)** assumes that the aluminium production process (i.e., technology used, energy distribution. and emissions) will remain more or less as it is today, without implementation of any additional decarbonization or climate-mitigation measures or deployment of decarbonization technologies. The **Stated Policy Scenario (SPS)** assumes that policies stated as of the writing of this report, such as Türkiye's Energy Plan and company-based efficiency improvements in facilities, will be implemented as stated in the future. The **Low Carbon Pathway Scenario (LCP)** assumes least-cost mitigation measures, under which all feasible low-carbon technologies as well as envisioned policies are introduced. And lastly, the **Frontier Technologies Scenario (FTS)**, the most ambitious decarbonization scenario, assumes that all frontier technologies found will be deployed in the aluminium production processes. The FTS also assumes a higher ETS price is implemented for Türkiye's aluminium industry.

The model finds that:

Carbon Budget: Based on modelling results, the cumulative carbon budget of Türkiye's aluminium sector between 2023-2053 is ~941 Mt CO_2 and 597 Mt CO_2 in the WoM and SPS scenarios, respectively. In mitigation scenarios, the cumulative carbon budget is expected to decrease to ~310 Mt CO_2 in the optimal LCP and decrease to ~126 Mt CO_2 in the more aggressive FTS.

Emissions: The total emission of the aluminium industry can be reduced by 75% in the LCP and by 98% in the FTS compared to the SPS in 2053. As demonstrated below, the main emissions of Türkiye's aluminium industry are input related scope 3 emissions from semi-aluminium processing.

Figure 3. Türkiye's Aluminium Sector's CO_2 Budget, Between 2023-2053 (Mt CO_2)



Primary Aluminium (Scope 1&2) Emissions

The results from LCP and FTS assume a similar technology transition for primary aluminium with different timeframes as follows:

LCP, the optimal scenario for Türkiye's primary aluminium industry, will achieve lower emissions in production by following the below transformation pathway.

- For the digestion process, LCP assumes a technology shift first to **gas boiler** in **2028** and later to **concentrated solar thermal (CST) boiler** in **2032**,
- For the calcination process, LCP assumes the use of a **hydrogen calciner** in **2047**,
- For the smelter process, LCP assumes a shift to **inert anode technology** in **2040**.

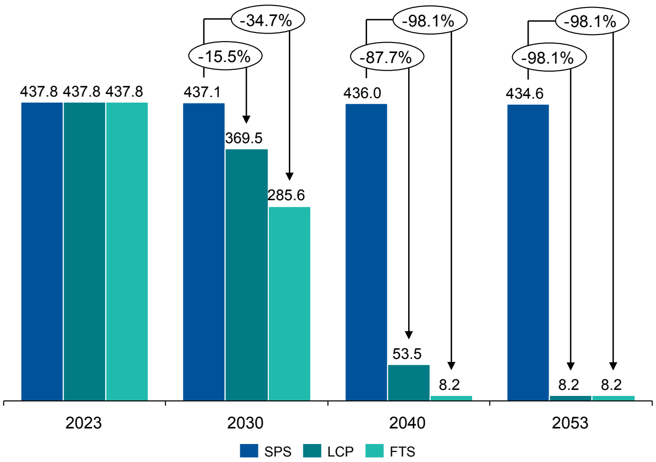
FTS assumes earlier penetration of the frontier technologies.

- For the digestion process, FTS assumes a technology shift first to **gas boiler** in **2025** and later to **CST boiler** in **2027**,
- For the calcination process, FTS assumes the use of a **hydrogen calciner** in **2036**,
- For the smelter process, FTS assumes a shift to **inert anode technology** in **2035**.

The emissions of LCP scenario, compared to the reference scenario SPS are projected to decrease by 15.5% by 2030 and 98% by 2053. In terms of total cumulative emissions, LCP scenario is expected to reduce emissions by 53% compared to SPS over the next 30 years.

The more aggressive FTS offers a 34.7% reduction by 2030 compared to SPS and could achieve a 98% emission reduction by 2053. Cumulative total emissions can be reduced by 70% in the FTS compared to the SPS over the next 30 years.

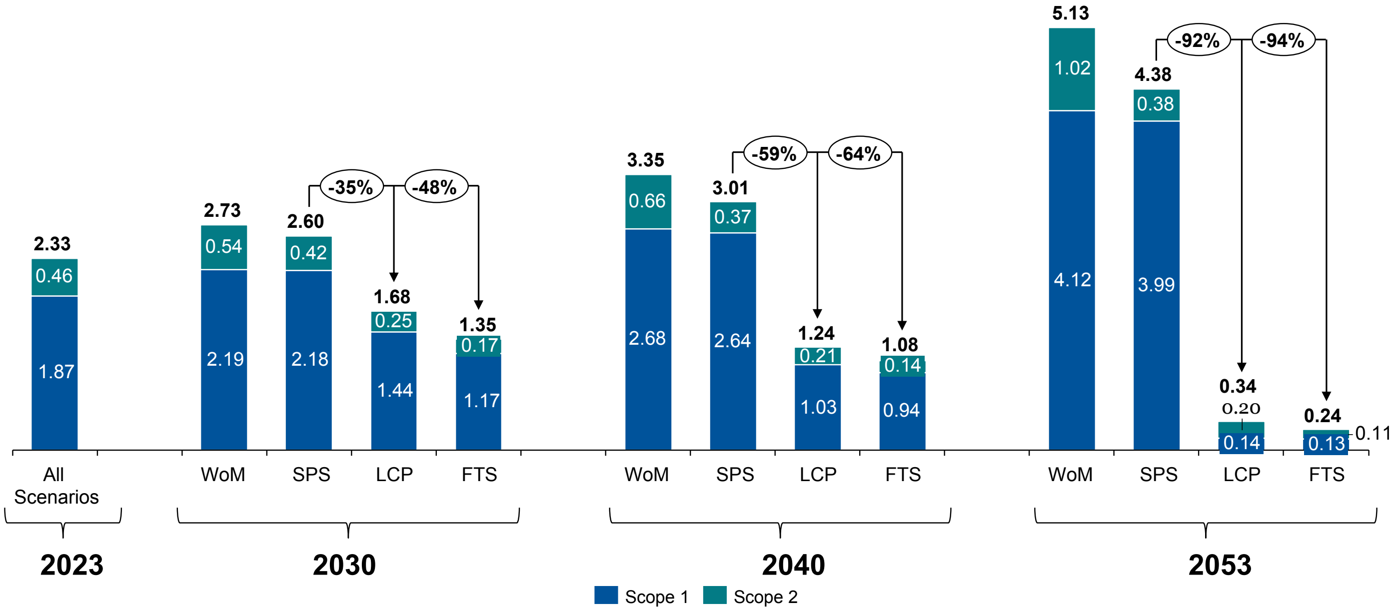
Figure 4. Emission Reductions Achieved by Various Scenarios Compared to SPS (Thousand Tonnes CO_2), for 2023, 2030, 2040, and 2053



Semi-Aluminium Processing (Scope 1&2) Emissions

For the semi-aluminium processing segment, it is expected that producers will shift to efficient furnace technologies with lower emissions. Emission reduction in this production route is achieved with technological transition to advanced furnaces and the integration of carbon capture and storage (CCS) technology.

Figure 5. Yearly Scope 1&2 Emissions Assumed Under Various Scenarios (Thousand Tonnes CO_2)



In **LCP scenario**, production shifts to mainly highly advanced reverberatory furnaces + CCS, which represent a share of 54% in 2053. This transformation is expected to reduce emissions by 35% by 2030 and 92% by 2053 in LCP as compared to the SPS reference scenario. In FTS scenario, the highly advanced reverberatory furnaces + CCS have the highest share of production with 47% in 2053, following by electric reverberatory with 32%, while the share of non-reverberatory furnaces, especially rotary furnaces, shifts into CCS technologies. For FTS, the emission reduction compared to SPS is 48% by 2030 and reaches 94% by 2053.

Input Related Scope 3 Emissions

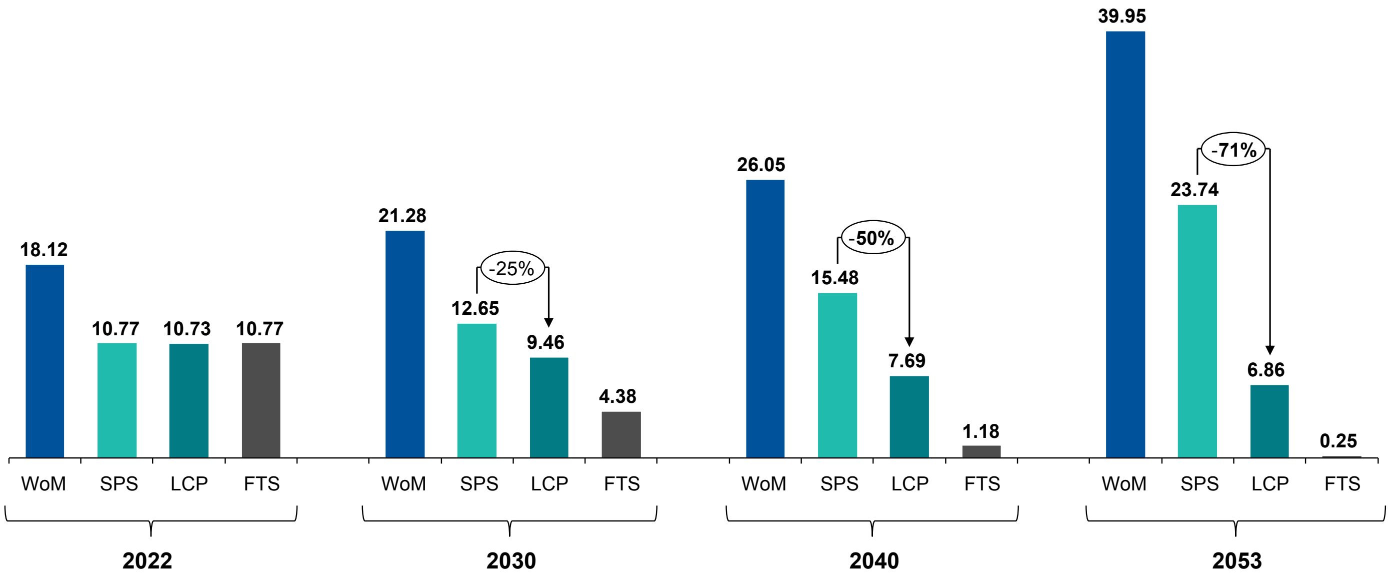
The use of scrap and the emissions of importing countries are significant to the reduction of Türkiye's embedded emissions. To reduce its input related scope 3 emissions Türkiye's aluminium sector could increase the amount of scrap used in production and prioritize countries with lower emissions when importing aluminium ingots.

For Türkiye's aluminium sector input related scope 3 emissions primarily consist of emissions embedded in the production of the primary metal (ingots) in the manufacturing processes of source countries. For 2022, Türkiye imported ~1.77M tonnes of unwrought aluminium from 66 countries. This amount of imported ingots corresponds to ~18 Mt CO_2 of input related scope 3 emissions.[12] With the implementation of emission reduction levers, the emission intensity of input related scope 3 emissions can be decreased by 67% (2.1 t CO_2/ t Al) in LCP scenario and by 98% (0.1 t CO_2/t Al) in FTS in 2053.

Currently, the percentages of primary ingots and scrap in production are 75% and 25%, respectively. It is forecasted that the scrap share in semi-aluminium processing will gradually increase to 35% in LCP scenario and to 50% in FTS by 2053. **Due to the increasing share of scrap and imports from countries having low emissions, there will be a decrease of between 71% and 99% in input related scope 3 emission by 2053 for LCP and FTS scenarios, respectively.**

[12]Total input related scope 3 emissions are calculated by multiplying the total amount of imported aluminium ingots with the average emission intensity of eight of the countries from which the most imports are obtained.

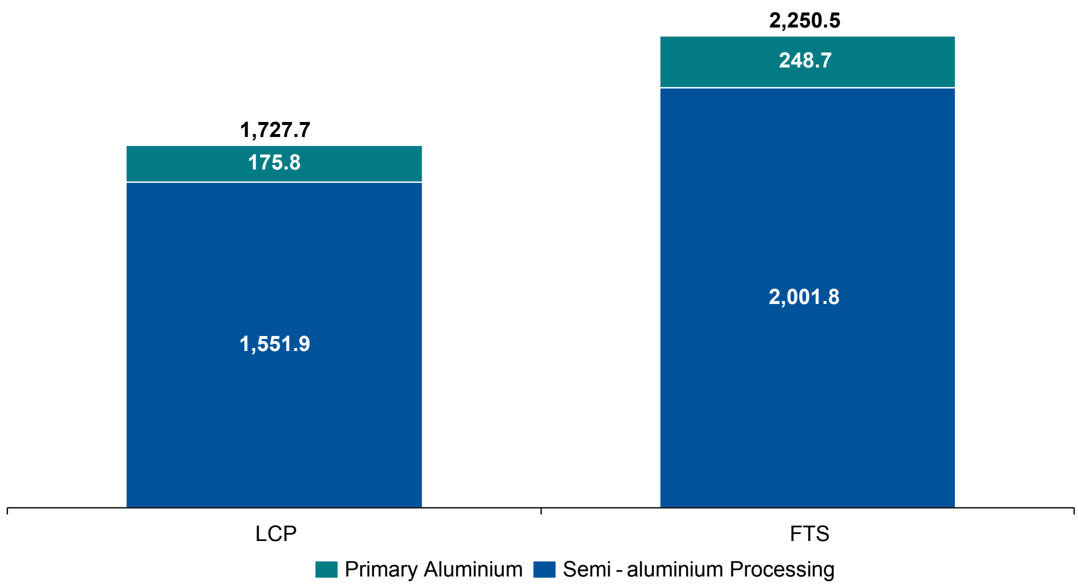
Figure 6. Input Related Scope 3 Emissions by Scenario and Year (Million Tonnes CO_2)



Investment Requirements for the Transition of the Industry

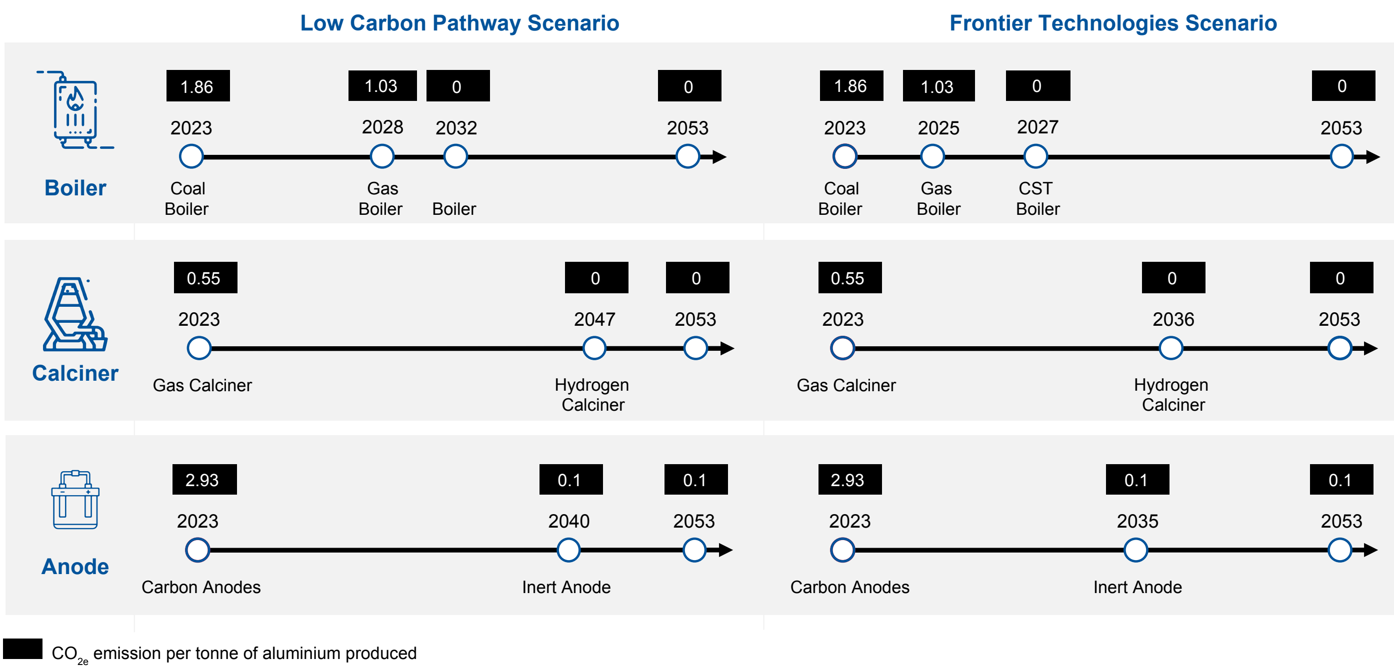
Achieving the emission reduction targets of Türkiye's aluminium sector requires a major technological transformation and there is a significant investment need associated with this transformation. The total investment cost of the transition of Türkiye's aluminium industry when calculated at net present value (NPV) with a 7% discount rate over the years, the total NPV costs are approximately 1.73 billion dollars and 2.25 billion dollars respectively for LCP and FTS. Since primary aluminium has lower share in capacity, semi-aluminium processing represents the largest share (88.9%) of the investment requirement.

Figure 7. Total Investment Needs by Scenario (2023-2053, NPV, Million Dollars)



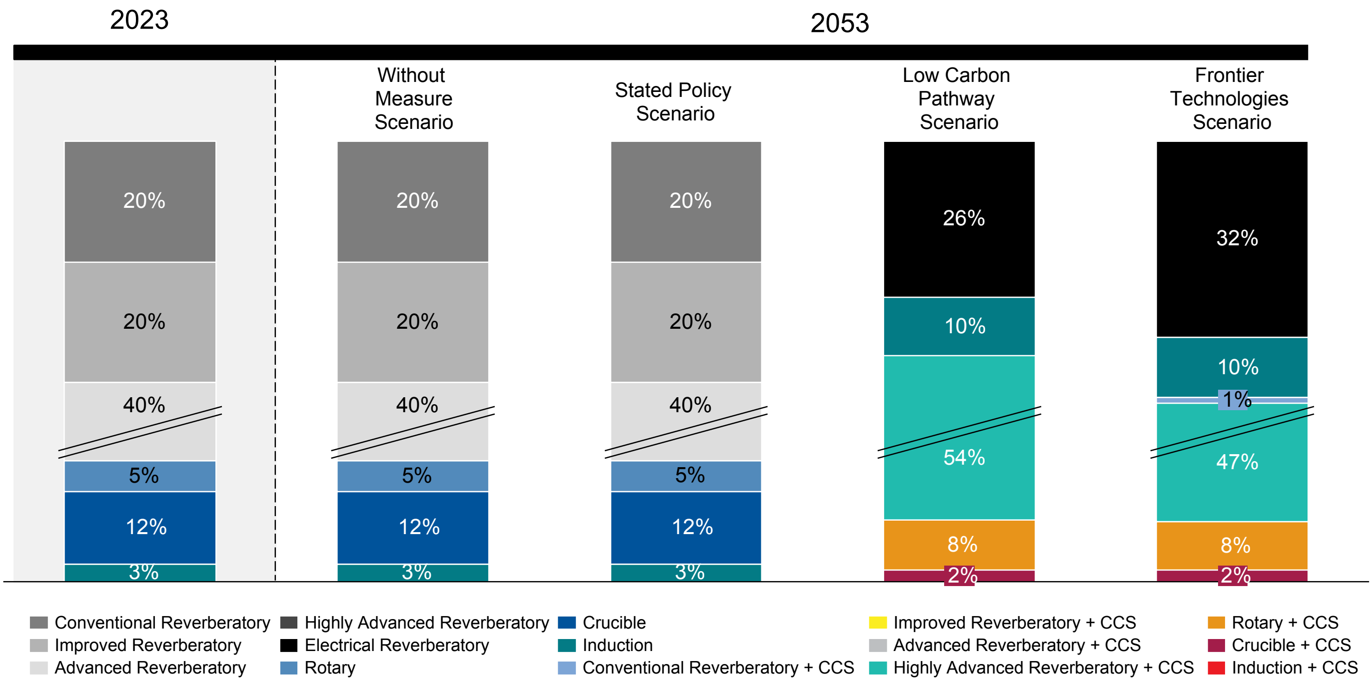
The technological transition for primary aluminium is the same for both mitigation scenarios and requires a nominal investment of ~500 million dollars. In LCP scenario, the first technology investment (gas boiler) is expected to be introduced in 2028, while FTS will attract the first investment three years earlier, in 2025. The technology requiring the largest investment is inert anode with a requirement of ~400 million dollars. **By applying a discount rate of 7%, the NPV of the total investments for these scenarios is 176 million dollars for LCP and 249 million dollars for FTS.**

Figure 8. Primary Aluminium - Technological Transformation



In semi-aluminium processing, the model favors highly advanced reverberatory furnaces, electric reverberatory furnaces, and CCS integration. Over years, some of the current furnaces are converted to these furnaces and new capacity/demand are fulfilled mostly with the same furnace types. In LCP scenario there is a 0.96 billion dollars brownfield cost due to the technological transformation of the furnaces that are currently being used. There is an additional 2.73 billion dollars greenfield cost for the construction of new furnaces. As it is assumed the share of renewable energy in energy consumption will reach 50% by 2053, there is a renewable energy investment cost of 0.67 billion dollars. **Thus, the total cost for LCP scenario is 4.37 billion dollars**. Due to more rapid and aggressive technological transformation and a higher renewable energy share the brownfield cost and renewable investment cost are significantly higher in FTS. 1.28 billion dollars of brownfield costs, 2.41 billion dollars of greenfield costs, and 1.14 billion dollars of renewable energy costs makes a total investment cost of 4.82 billion dollars.

Figure 9. Technological Transformation for Semi-aluminium Processing



The decarbonization trajectories of Türkiye's aluminium sector highlight the need to develop new financing mechanisms and plans. Therefore, measures to increase the mobilization of additional funds starting from the early years should be prioritized to enable the aluminium industry to achieve the necessary technological transformation in the medium to long term. Policymakers and financial institutions should collaborate and develop financing mechanisms for Türkiye's aluminium sector to access scaled capital flows to promote decarbonization investments.

Key Policy Actions in the Next 30 Years

Decarbonization of the aluminium sector requires targeted work across intertwined policy areas. The holistic policy set devised in this project is based on project experts' opinions, academic research on the best applications for aluminium sector decarbonization, sector specific information, assumptions shared by key project stakeholders (representing official organizational views), and model and scenario analysis results. The resulting policy recommendations are mapped to two key policy themes: A) input and technology and B) policy and market. The policy areas (may also be referred to as decarbonization levers) mapped to these high-level themes are summarized as follows.[13]

[13]A detailed assessment of the formulated policy recommendations is given in the long version Final Report prepared as part of this project.

Figure 10. Policy Recommendations for Decarbonization

High Level Policy Themes

Input & Technology	Policy & Market

Specific Policy Ares

Input & Technology:

1. Input Optimization
2. Technologies Reducing Direct Carbon Output
3. Carbon Capture, Utilization and Storage Technologies
4. Green Energy
5. Process Improvement
6. Inclusive Employment and Reskilling / Upskilling of Workforce

Policy & Market:

1. ETS
2. Trade Models
3. National Policy Documents
4. Green Transformation Finance
5. Cooperation
6. Circular Economy

Phases

- Phase 1: 2023-2025
- Phase 2: 2026 -2038
- Phase 3: 2039 -2053

Action Areas

- Regulation
- Investment
- Incentive & Finance
- Capacity Building

Stakeholders

- Responsible / Coordinating Institution
- Related Institutions

A) Input and Technology Related Policies

1. **Input Optimization:** Recycle post-consumer aluminium scrap, determine Türkiye's domestic scrap supply and prepare a scrap inventory to increase the use of recycled scrap, develop technologies for the use of raw materials that cannot be used for alumina production, secure domestic and international scrap supply, and import primary aluminium from countries and suppliers with low carbon footprints.

2. **Technologies Reducing Direct Carbon Output:** Reduce emissions from the existing alumina refining process and optimize the electrolysis process with lower anode carbon and energy consumption, change the boilers used in digestion in the alumina refining process to types with lower emissions, develop and use fuel switching with either electricity or green hydrogen, investigate and closely follow the work of various companies to develop inert anode cell technology and carry out the necessary feasibility studies, develop and integrate heat recovery systems for alternative use of waste heat generated in the calcination process, and prioritize use of lower emission furnaces in semi-aluminium processing by encouraging companies to invest in reverberatory furnaces and induction furnaces.

3. **Carbon Capture, Utilization and Storage (CCUS) Technologies:** Strengthen the financial, legal, and technical infrastructure to increase Türkiye's carbon capture, utilization, and storage capacity.

4. **Green Energy:** Establish infrastructure for renewable energy production to provide the energy required for the aluminium sector from renewable sources,

complete medium/long term planning and development at the national level and identify available, appropriate technologies to make green hydrogen commercially available and cost-effective and evaluate the use of low-emission small modular nuclear reactors (SMR) in primary production and semi-aluminium smelting processes.

5. **Process Improvement:** Establish digital monitoring systems integrated with energy management systems, use advanced automation in electrolysis cells and melting units for instant monitoring of parameters, develop processes and methods to increase energy efficiency in semi-aluminium processing, and deploy modern innovative maintenance approaches for production facilities to improve process efficiency and reduce energy use.

6. **Inclusive Employment and Upskilling/Reskilling of Labor Force:** Determine and coordinate the new qualification, skill, and training requirements of the green transformation of the aluminium sector, increase employment and qualifications of women and other groups requiring special employment policies to ensure equal opportunities for all, and prepare and implement training programs to respond to labour force requirements resulting from the green transformation.

B) Policy and Market Related Policies

7. **ETS:** Establish an ETS in Türkiye in line with EU legislation and establish proper mechanisms to incentivize green transformation for those operating in strategic sectors; allocate free allowances for facilities emitting below the sector average, especially for emission-intensive sectors with high carbon leakage risk; and prepare marginal abatement costs for technologies in the sector for rational decision-making within the scope of ETS or carbon pricing.

8. **Trade Models:** Analyze actual/expected trade shifts and market changes arising from increasing trade between countries that have not taken decarbonization steps and take measures to protect the international competitiveness of the sector, identify trade policy steps related to possible implementation of the EU CBAM, and ensure Türkiye's practices regarding monitoring, reporting, and verification practices are recognized by the EU in line with the principles of emission measurement and reporting under EU CBAM.

9. **National Policy Documents:** Carry out national feasibility studies regarding R&D and innovation from a holistic perspective, develop a clear, long-term vision for the sustainable energy transition of the aluminium sector, adopt a comprehensive industrial policy framework and associated emission targets aligned with national climate commitments, set mitigation goals for the industry in the Long Term Climate Change Strategy and the Climate Change Action Plan, ensure coordination to determine where the relevant legislation differs from the EU and assure full harmonization.

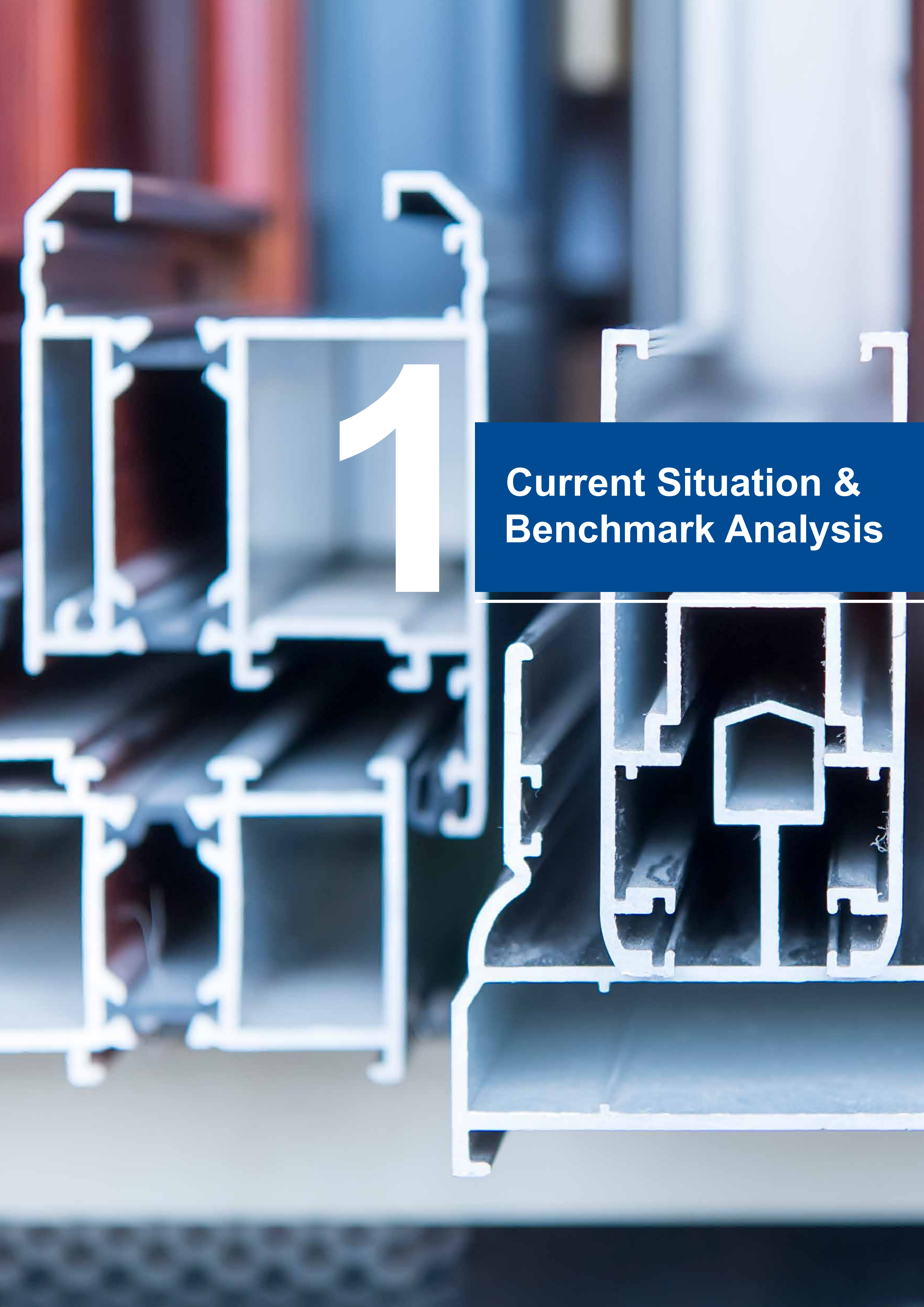
10. **Green Transformation Finance:** Provide public incentives for deployment of low-emission technologies, develop incentives by facilitating unlicensed renewable energy investments, and mobilize private capital for deployment of low-emission technologies.

11. **Cooperation:** Create funding opportunities to carry out projects on energy and materials, increase cooperation and interaction of companies in the implementation of internationally accepted standards and encourage involvement in international organizations, involve aluminium producers in government-level sector roadmap studies of the transition to low-carbon production, and establish a common database for monitoring the aluminium industry with the participation of ecosystem stakeholders.

12. **Circular Economy:** Use green technologies to recover metal from slag and recycle residual waste; carry out studies for recycling precious metal components in red mud; develop a national, inclusive, holistic circular economy action plan specific to the aluminium sector; develop high-quality, value-added, recyclable aluminium products to contribute to the decarbonization of aluminium-using end-user sectors; and develop methods and practices for by-product and waste management.

A more detailed discussion of the policy actions can be found in the section “3. The Roadmap for Decarbonization of the Aluminium Sector” of this report and in the detailed “Policy Recommendations Document” prepared as part of this project.

The policy actions recommended in this report are also to serve as key inputs for the on-going development of Türkiye’s economy-wide LTS, as well as subsequent development of its second NDC. It would be critical to ensure policy coherence and consistency across different government strategic documents and send strong market signals to project developers, financiers and investors on which pathway Türkiye is committing to decarbonize its aluminium sector, alongside other key sub-sectors of its overall industry sector, in the context of achieving its overall economy-wide net zero target.



1 Current Situation & Benchmark Analysis

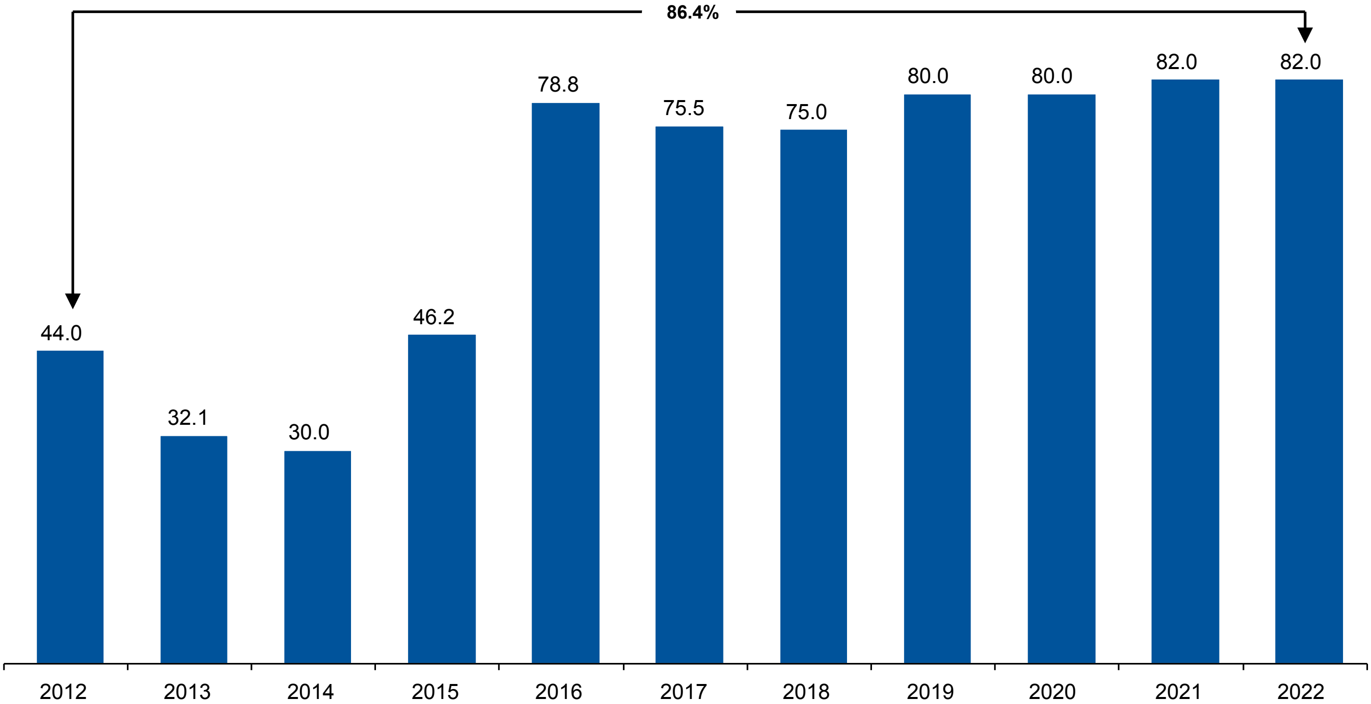
1. Current Situation & Benchmark Analysis

1.1. Overview of Türkiye's Aluminium Sector

1.1.1. Capacity and Production

The sole primary aluminium producer in Türkiye is ETİ Aluminium in Seydişehir, Konya. The facility expanded its aluminium production to 78.8 thousand tonnes in 2016 from its capacity of 44 thousand tonnes in 2012. After the additional capacity being added in 2016 there were no major changes to the overall capacity of the facility. With the latest increases in capacity the current production capacity is 82 thousand tonnes in 2022.[14] While primary aluminium manufacturing has an intrinsic value in and of itself, this production volume does not make Türkiye a significant primary aluminium player at the global level, nor it is enough to support the growing semi-aluminium processing sector in the country. Türkiye is largely dependent on imports for primary aluminium with imports accounting for 1.85 million tonnes of aluminium, corresponding to %91.2 of domestic demand.[15] Although Türkiye's primary aluminium industry has doubled its production capacity with the new technology investments in 2015, import dependency to primary aluminium is expected to continue in the medium-long term[16].

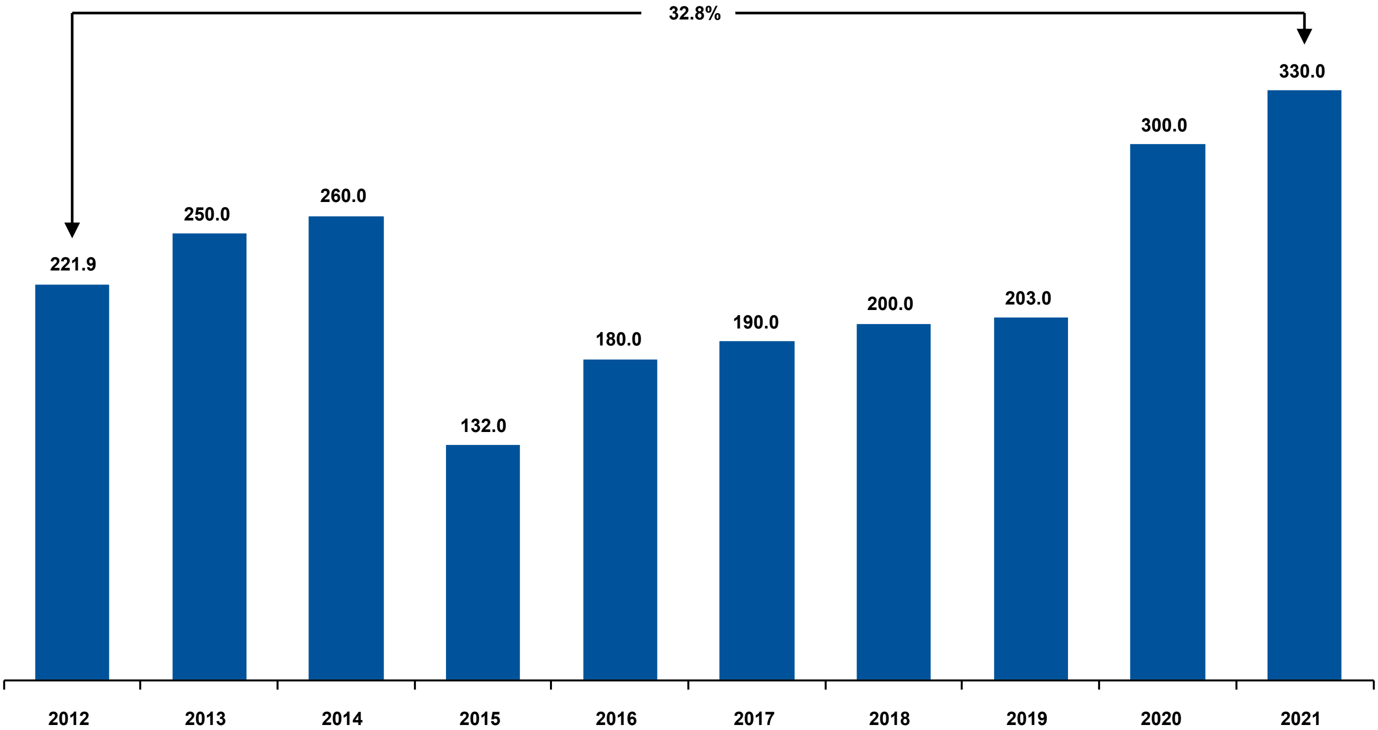
Figure 11. Primary Aluminium Production in Türkiye (Thousand Tonnes)[17]



[14] ETI Aluminium
[15] TALSAD. PwC Analysis
[16] ETI Aluminium
[17] TALSAD, PwC Analysis

The supply of scrap aluminum, crucial for both semi-aluminum processing and emission mitigation endeavors, is failing to keep pace with the growing demand. Production from recycled scrap increased by 32.8% between 2012 and 2021, with a CAGR of 4.5%, reaching 330,000 tonnes, but lagged behind the overall increase in semi-aluminium processing. This trend indicates the scrap aluminium collection and processing infrastructure in Türkiye is not yet mature enough to meet increasing demand, and therefore there are limitations to scrap use.

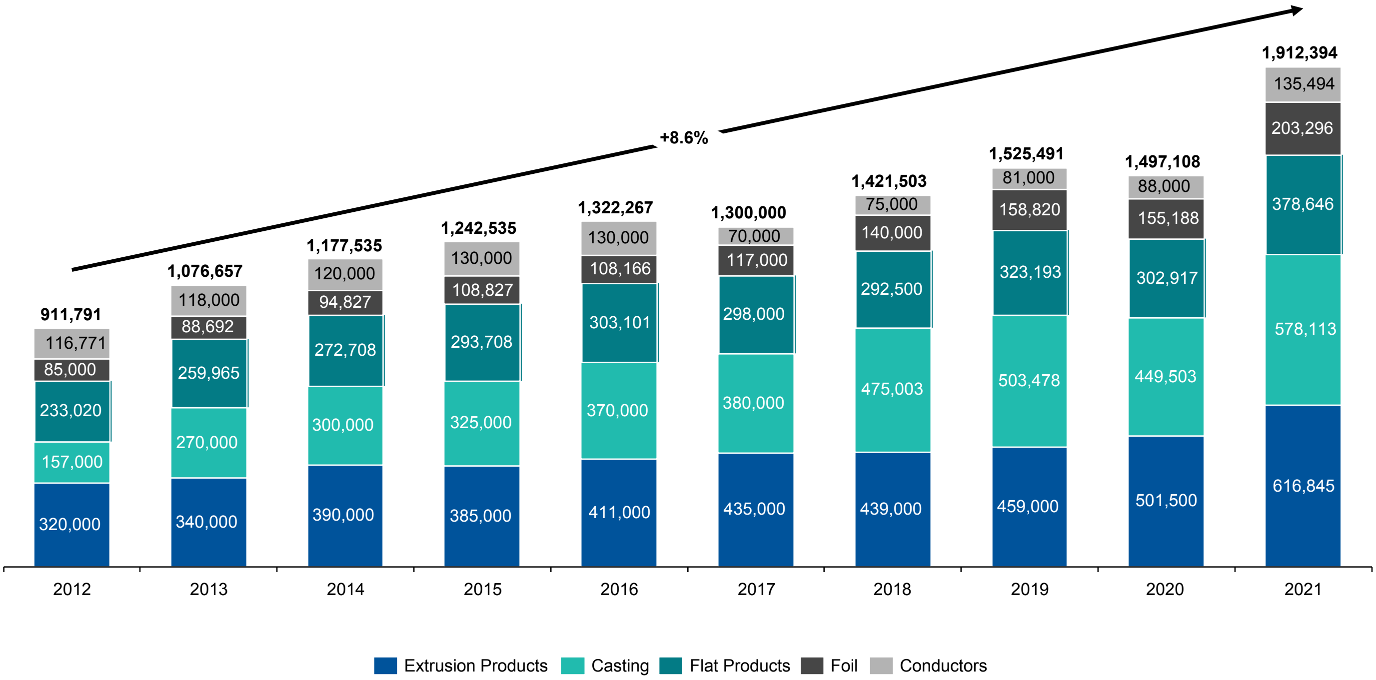
Figure 12. Recycled Scrap Aluminium Supply in Türkiye (Thousand Tonnes)[18]



Türkiye does have a significant presence in semi-aluminium processing including rolling, extrusion, forging, drawing, and casting. Semi-aluminium processing in the country has increased by an average of 8.6% per year between 2012 and 2021, rising 109.7% in total, reaching 1.91 million tonnes. The growth in production during the period was mainly driven by **casting** (268.2% total growth with a CAGR of 15.6%) and **foil products** (139.2% total growth with a CAGR of 10.2%), suggesting strong domestic and foreign demand for these product groups. The 92.8% growth in **extrusion products** (CAGR of 7.6%) also made a significant contribution to the growth of the sector. In the same 2012 to 2021 period, **flat products** grew significantly by 62.5% with a CAGR of 5.5%, while **conductors** expanded by only 16% with a CAGR of 1.7%, falling behind other product groups. Despite the different trajectories over the period, the significant increase in all product groups in 2021 is important in terms of revealing the performance of Türkiye's aluminium sector.

[18] TALSAD, TUDOKSAD, PwC Analysis.

Figure 13. Semi-aluminium Processing in Türkiye (Tonnes)[19]



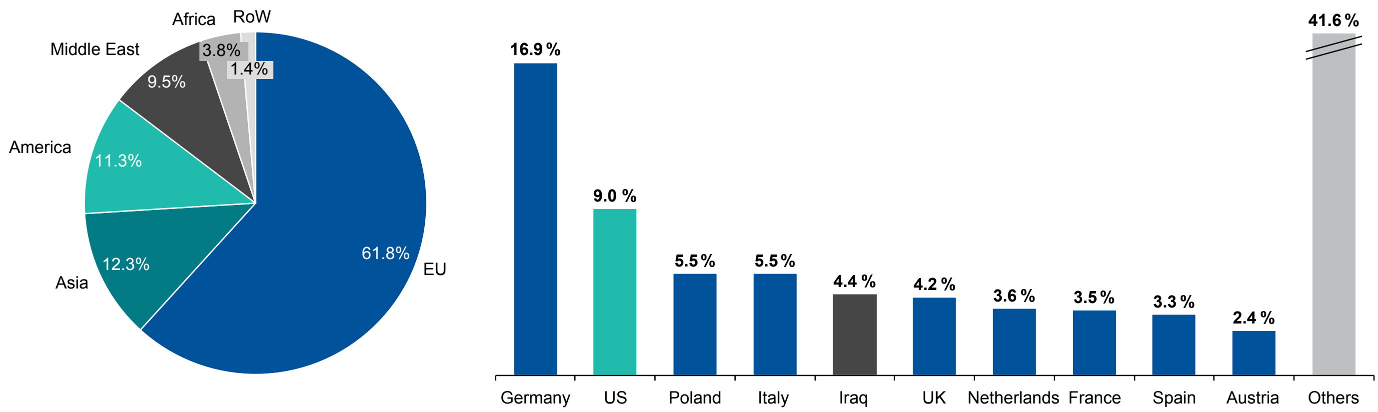
1.1.2. Türkiye's Aluminium Trade and EU Share

In 2021, aluminium consumption in the domestic market is 871,000 tonnes, equivalent to 45.6% of total production, and the increasing semi-aluminium processing in Türkiye is concentrating on exports. Türkiye's exports of finished and semi-finished aluminium products, which have recovered from the pandemic-related headwinds, increased significantly to 6.7 billion dollars in 2022.[20] Although export routes are quite diverse, 61.8% of exports measured in value are shipped to EU countries.[21] Germany, the USA, Poland, Italy, and Iraq were the top five destinations for Türkiye's aluminium exports in 2022. In addition, it is noteworthy that seven out of the first 10 export routes are those of EU members.

Türkiye appears to have been successful in leveraging its geographic proximity to the European market to its advantage, as evidenced by the high share of exports to the EU. Overall, the level of Türkiye's aluminium exports to developed countries, particularly to EU countries, reflects the strength and competitiveness of Türkiye's aluminium sector in global markets, however it also exposes the industry to external economic shocks and demand fluctuations in those markets. The distribution of exports in the last 10 years indicates that Türkiye's aluminium exports are increasingly spreading to wider regions.[22] Nevertheless, Türkiye should further diversify export routes and product offerings to mitigate external risks.

[19] TALSAD, TUDOKSAD, PwC Analysis.
[20] Trademap, PwC Analysis
[21] ibid
[22] TALSAD. Aluminium in the World and Türkiye, 2021 Edition

Figure 14. Distribution of Türkiye's Aluminium Exports by Region and Country, 2022[23]



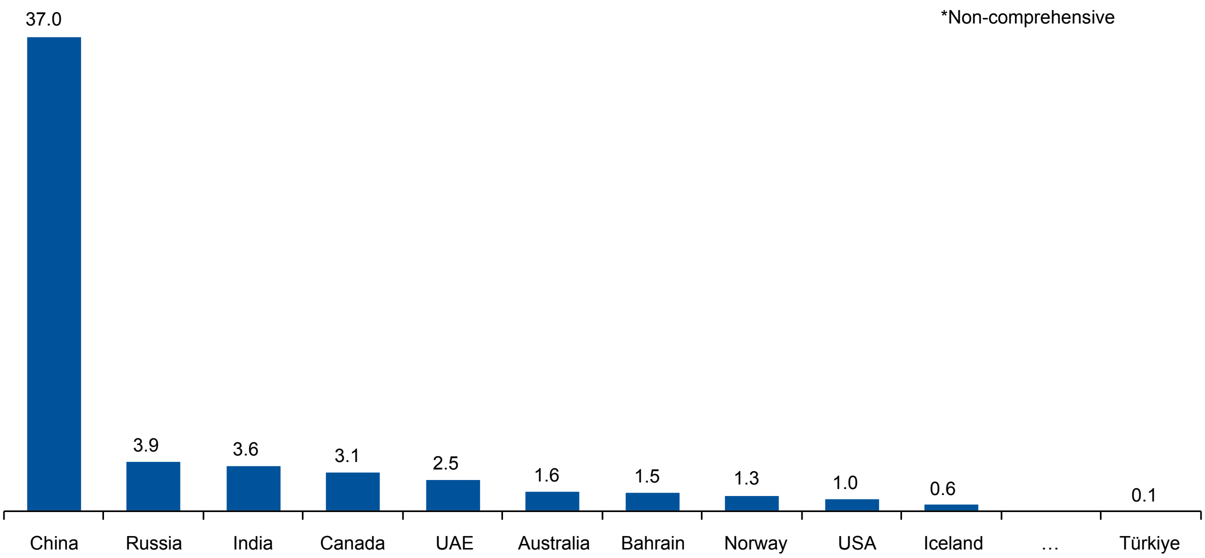
1.2. Benchmarking Industry Activities

1.2.1. Benchmarking Physical Capacity for Producing Aluminium

China is the world leader in primary aluminium production, accounting for nearly 60% of global supply. Although the majority of its production is allocated to domestic markets to support the strong domestic manufacturing industry, China also exports aluminium in semi-fabricated forms. The second largest producer Russia, with 3.7 million tonnes of annual primary aluminium production, relies heavily on hydropower. India, whose production is predominantly coal-powered, is in the third place. Canada, the UAE, Australia, Bahrain, Norway, the USA, and Iceland are other key producers of primary aluminium.[24]

Having one primary manufacturing plant with 82,000 tonnes of annual capacity, Türkiye is not among the top players in primary aluminium production. The scarcity of domestic primary aluminium supply forces Türkiye to rely heavily on primary metal imports for the manufacturing of final aluminium goods.

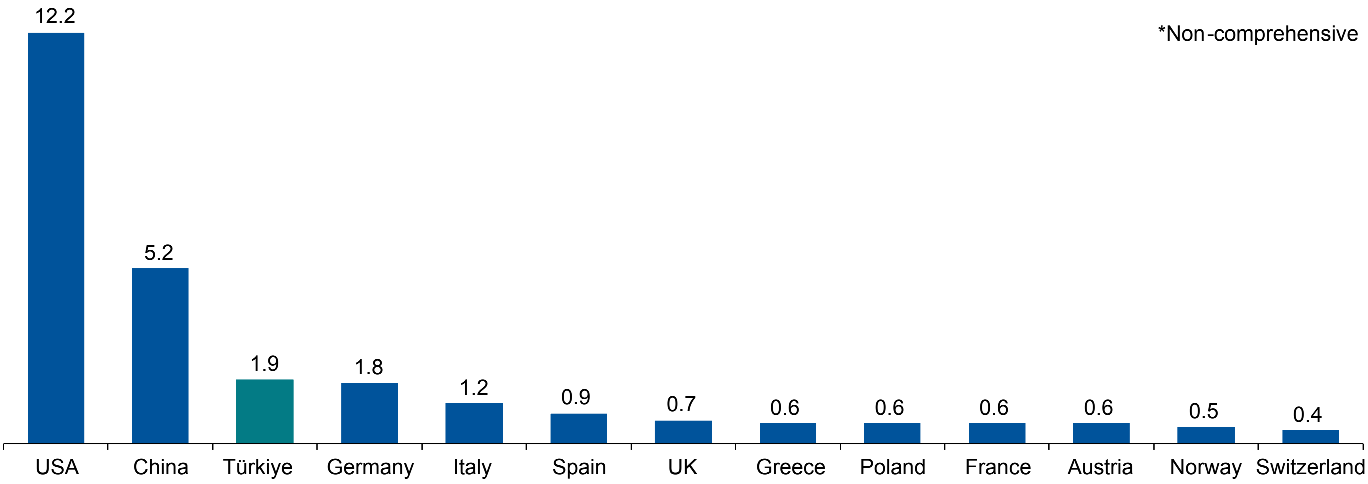
Figure 15. Capacity of Leading Primary Aluminium Producing Countries, 2020 (Million Tonnes)[25]



[23]Trademap, PwC Analysis
[24]OECD, The Aluminium Value Chain
[25]Harbor Aluminium, Aluminium Production by Country

The USA, which is not among the lead players in primary aluminium, ranks first in semi-aluminium processing (44.8% of global semi-aluminum processing) with a total output more than twice that of its closest rival, China. Türkiye also has a strong semi-aluminium processing capacity. This significant semi-aluminium processing capacity is mainly supported by imported ingots. TALSAD figures show that ingot imports have grown from 0.9 million tonnes to ~1.77 million tonnes, with a CAGR of 7.8% between 2012-2021.[26] Considering that semi-aluminium processing demands significantly less energy than primary production, Türkiye's sectoral emission intensity is lower than that of primary-heavy countries.

Figure 16. Capacities of Leading Semi-aluminium Processing Countries, 2021 (Million Tonnes)[27]

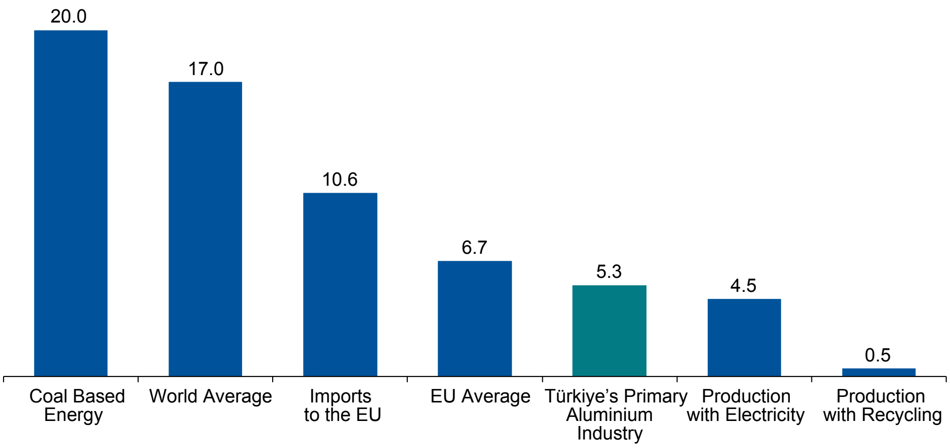


1.2.2 Benchmarking CO_2 Emissions

Key primary aluminium production steps are bauxite mining, alumina refining, aluminium smelting, and casting. Emission levels at the ETI Aluminium facility are relatively low as the energy required is predominantly sourced from the hydro power plant. In addition, ETI is moving forward to lower its remaining emissions from electricity by investing in the installation of new solar facilities. Compared to the world average, Türkiye's current performance (5.3 tonnes CO_2/ tonnes aluminium) looks significantly positive, but the plant's emission levels are still high compared to the average for aluminium production with electricity. The gap with electrified production average indicates that there are further policy options to reduce the carbon emissions for Türkiye's primary aluminium industry.

[26]The data provided by TALSAD within the scope of this project.
[27]www.lightmetalage.com, PwC Analysis

Figure 17. CO_2 Emissions Intensity of Primary Aluminium Production (t CO_2/t Al)[28]



Due to the limited availability of data on semi-aluminium processing globally and in Türkiye, direct benchmarking has unfortunately not been possible. Emissions in semi-aluminium processing, the predominant production in Türkiye, are mostly associated with scope 1 emissions due to the usage of natural gas in furnaces and electricity-related scope 2 emissions. Concentrating production in semi-aluminium processing could potentially make it easier for Türkiye to achieve low carbon emissions in the aluminium sector compared to some other key manufacturers with primary-heavy portfolios. Switching to more efficient furnace types that will reduce fuel use is a critical policy step towards decarbonization of semi-aluminium processing. Furthermore, considering that semi-aluminium processing is also electricity-intensive, decarbonizing grid emission intensity emerges as a critical policy step for Türkiye's aluminium sector.

Input related scope 3 emissions from Türkiye's final products (embedded in ingot imports) is dependent on the emission intensity of countries from which the primary aluminium is imported. Therefore, the direct emissions of countries from which Türkiye imports primary metal is also of significance to Türkiye's producers. As for the decarbonization of semi-aluminium processing, Türkiye will require increasing volumes of aluminium scrap to achieve lower levels of decarbonization in the aluminium industry.

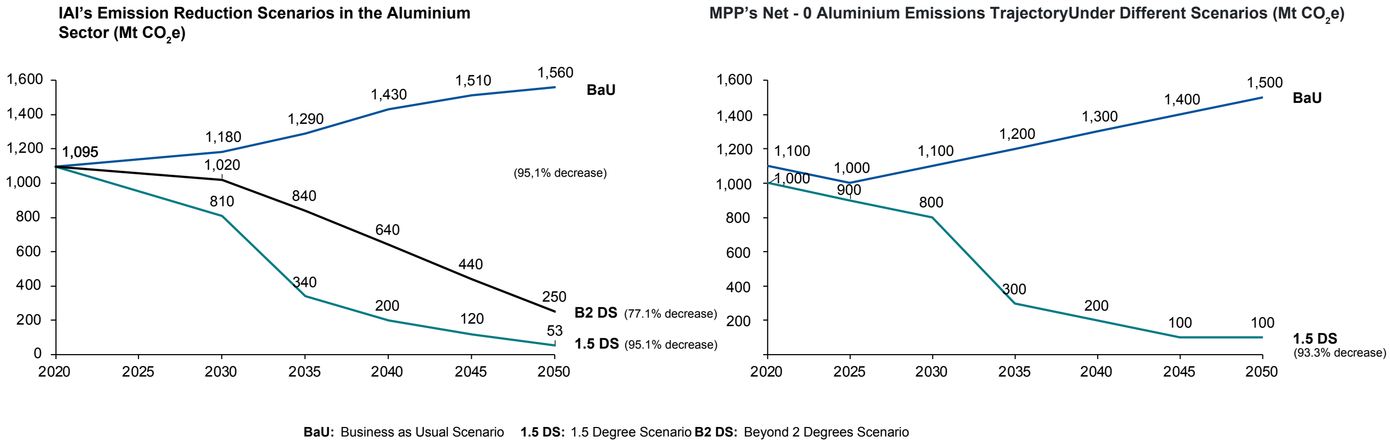
1.2.3. Benchmarking Aluminium Decarbonization Strategies

The two flagship reports on global decarbonization of the aluminium industry that have been used in this study are those of the IAI[29] and MPP[30] studies. The IAI study sets forth two scenarios. The beyond 2 degrees scenario is based on the IEA'S beyond 2-degrees scenario, while the 1.5 DS scenario sets out credible and realistic approaches to emissions reductions for the aluminium industry. The MPP's 1.5-degree scenario explores the energy, infrastructure, financing, and policies required for the aluminium industry to reach net zero. IAI scenarios estimate by 2050 there will be a 77.1% emissions reduction for the B2DS scenario and a 95.1% emissions reduction for the 1.5 DS scenario compared to 2020 levels. The MPP study forecasts 93.3% in emissions reduction compared to 2020 levels by the same year.

[28]This figure has been generated by consolidating the data from sector representatives and the IAI.
[29]IAI, 1.5 Degrees Scenario: A Model To Drive Emissions Reduction
[30]MPP, Making Net Zero Aluminium Possible

The aluminium decarbonization roadmaps presented by these institutions have focused on certain key decarbonization levers. Initially, the studies underscore **power decarbonization** as a fundamental step for decarbonization as electricity consumption in aluminium production is very high. In addition, **recycled aluminium** plays a critical role in and is estimated to account for over 50% of global aluminium supply by 2050, up from 33% in 2020.[28] However, these two essential levers are not sufficient to bring aluminium emissions to zero. Therefore, deploying near-zero emissions refining and smelting technologies such as new **low-carbon anodes**, as well as integrating **carbon capture, usage, and storage (CCUS)** into the production process to address remaining emissions, is essential in the later stages of decarbonization efforts.

Figure 18. Aluminium Decarbonization Roadmaps of International Institutions[31]



The climate-based emission mitigation targets of the world's leading aluminium producers (e.g., Rio Tinto, Alcoa, Hydro) reveal that most companies have set long-term net zero commitments and interim targets to move towards their long-term targets. Companies usually set 2050 as their net zero target, with interim targets to reduce scope 1 and 2 emission levels.

[31]IEA, MPP

2 Modelling and Scenario Analysis for Aluminium Sector Decarbonization

2. Modelling and Scenario Analysis for Aluminium Sector Decarbonization

A key lever of this project is the modelling and scenario analysis work that forecasts and quantifies the impact of different combinations of policies and technologies on the future emissions of the sector. To carry out the modelling work the following analyses had to be completed first place:

- Demand and supply projections of Türkiye's aluminium sector up until 2053 and,
- Key decarbonization levers and technologies that will achieve decarbonization in the sector, differentiated for the primary aluminium and semi-aluminium processing routes.

For the 2023-2053 period the model generates possible pathways for decarbonization of the aluminium industry in Türkiye, running two sets of scenarios to forecast and benchmark the sector's future emissions. These scenarios are:

1. **Reference scenarios** were generated as "reference" or "counter" points against which the mitigation scenario's performance is evaluated in terms of emission reduction. Under the reference scenario umbrella, two scenarios have been generated i) WoM and ii) SPS. The WoM, scenario assumes a "no policy" baseline where no explicit mitigative action is taken and no technological transformation takes place. The other reference scenario, the SPS, was generated to explore the potential effects of the policies declared as of the writing of this report, including renewable energy investments, process efficiency improvements, EU CBAM constraints and introduction of a national ETS. In essence, SPS was generated to project emissions where stated policy steps are taken but no technological transformation is achieved.

2. **Mitigation scenarios** were generated to forecast the impact of radical policy action and investment in technology to address the emission levels of the sector. The two mitigation scenarios used in this project, i) LCP and ii) FTS, assume varying levels of mitigative policy actions and adoption of low carbon technologies. The LCP is designed to be the (cost-effective) optimal scenario for decarbonization of Türkiye's aluminium sector. The more aggressive FTS is differentiated from the LCP by earlier introduction of frontier technologies. In addition, the FTS assumes a higher national ETS price.

This study finds that key decarbonization levers for Türkiye's aluminium sector, regardless of the scenario employed, are higher recycling rates, adoption of frontier technologies, and transition to low-carbon power.

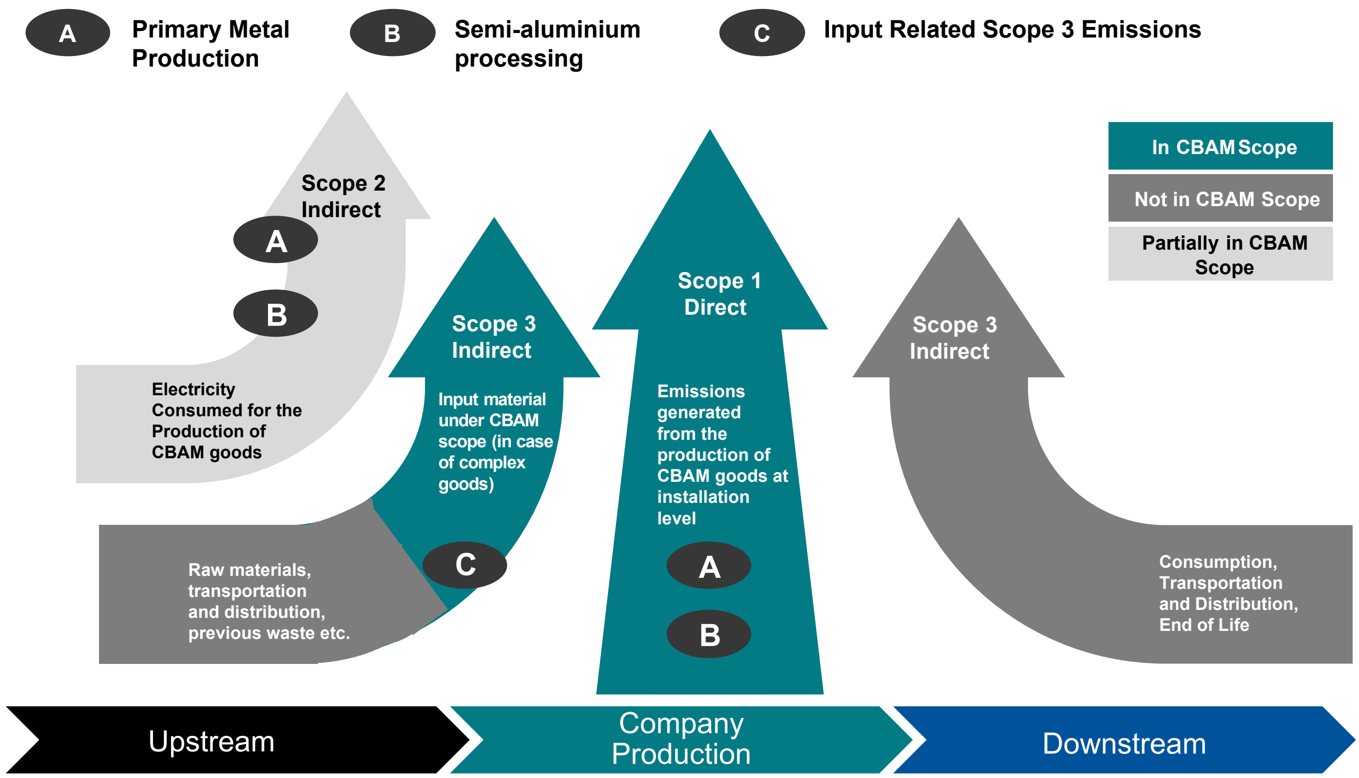
For primary aluminium production new technologies for **smelting, digestion, calcination processes**, their respective emission reduction impacts, and costs have been analyzed. Technologies that will result in decarbonization of thermal energy generation, fuel switches (to achieve lower emissions), and low-carbon anodes come to the fore for refineries and smelting plants, promising near-zero emissions.

For semi-aluminium processing, **adoption of new furnace technologies**, lower grid emissions, and lower emission inputs are the key decarbonization levers. Specific years of entry for the new furnace technologies are decided together with industry experts and sector associations.

Following the scope of emissions holistically, the emissions model developed in this study covers scope 1, scope 2 and input related scope 3 emissions[32] for the aluminium sector.

[32]Scope 1 emissions are emissions from sources that an organization owns or controls directly: from factories, facilities, warehouses, offices, vehicle fleets owned by the company. Scope 2 emissions are emissions that an organization causes indirectly when the energy it purchases, and uses is produced. Lastly, input related scope 3 emissions are emissions that are not produced by the company and are not the result of activities from assets owned or controlled by them but are produced by those the company is indirectly responsible for up and down its value chain.

Figure 19. Scope of Emissions



Scope 1 and scope 2 emissions for both primary and semi-aluminium processing are modelled in GAMS (the General Algebraic Modeling System)[33] optimization software. To accurately reflect the emission factors, separate optimization models were generated for the primary aluminium and semi-aluminium processing routes. On the other hand, input related scope 3 emissions are only modelled for the semi-aluminium processing route, based on trade statistics projections.

Decarbonization of Türkiye's aluminium industry requires deployment of new, radical technologies to achieve higher emission reduction levels in support of the country's overall decarbonization plans. Technologies that have been prioritized by the optimization model generated as part of this study (details of which will be provided under section 2 of this report) are as follows.

[33]It is a high-level modeling language and optimization system designed for mathematical modeling and solving complex optimization problems. It allows users to express their problem using algebraic equations and constraints, making it easier to translate real-world scenarios into mathematical models. The system then utilizes various optimization algorithms to find the best solution to the formulated problem.

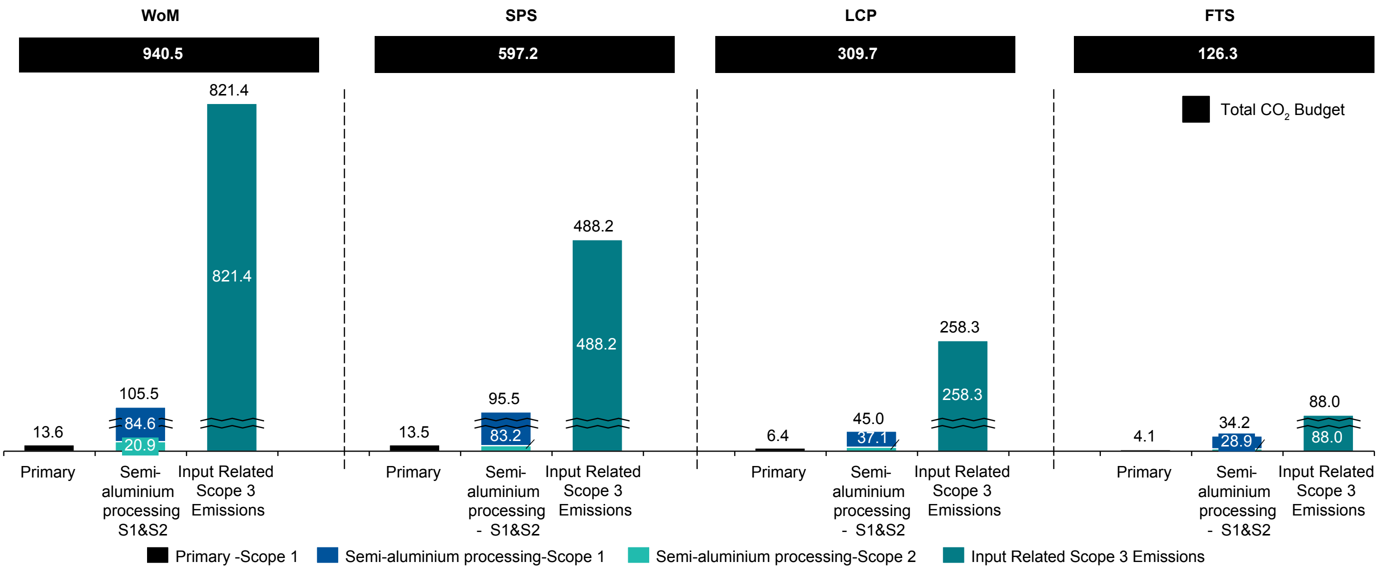
Table 3. Technology Prioritization in the Low Carbon Pathway Scenario

	Expected Date of Entry	Technology Switching Year	Emission Reduction Effect (tCO_2/t Al)	Investment Requirement (Dollars/t Al)	Emission Reduction Cost Per Unit (Dollars/tCO_2)
Primary Aluminium Technologies					
Gas Boiler	2028	2028	0.7	30.9	43.8
CST Boiler	2032	2032	0.9	1000.3	1057.0
Hydrogen Calciner	2035	2047	0.5	214.8	298.5
Inert Anode	2040	2040	2.8	4851	1714.1
Semi-Aluminium Processing Technologies					
Highly Advanced Reverberatory Furnaces	Available	2024	1.2	850	705.3942
Electric Reverberatory	2040	2040	1.3	1050	820.3125
Crucible + CCS	2040	2045	0.2	345	2748.184
Rotary+ CCS	2040	2046	0.3	385	1013.158
Highly Advanced Reverberatory +CCS	2040	2047	0.4	1135	1352.941

Summary of Emission Results from the Model

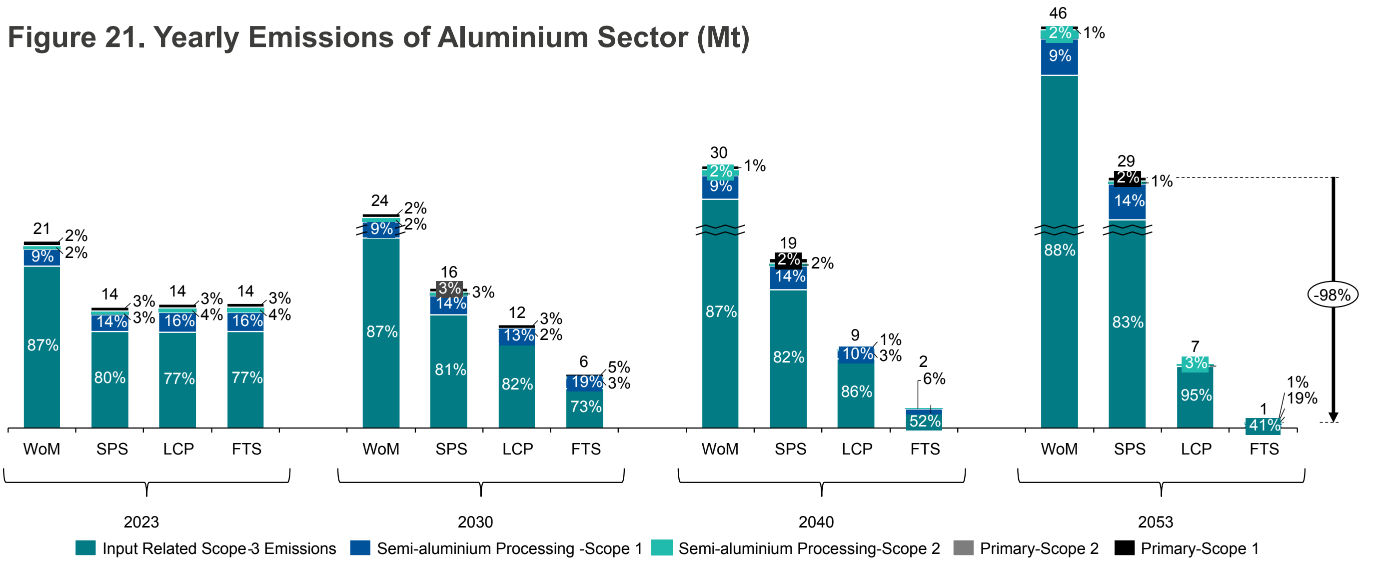
When everything is considered, it is anticipated that Türkiye's aluminium sector's total scope 1, scope 2 and input related scope 3 emissions will reach 940.5 Mt between 2023-2053, assuming no improvements are made (WoM Scenario). In SPS the total emissions of the industry will reach approximately 597 Mt in the same period. With the incorporation of decarbonization levers such as integration of new technologies into production, increasing scrap, and decarbonization of energy, total emissions of the sector are expected to decrease to ~310 Mt CO_2 and ~126 Mt CO_2 in 2023- 2053 for LCP and FTS, respectively.

Figure 20. Total Emissions of Aluminium Sector (2023-2053, Mt)



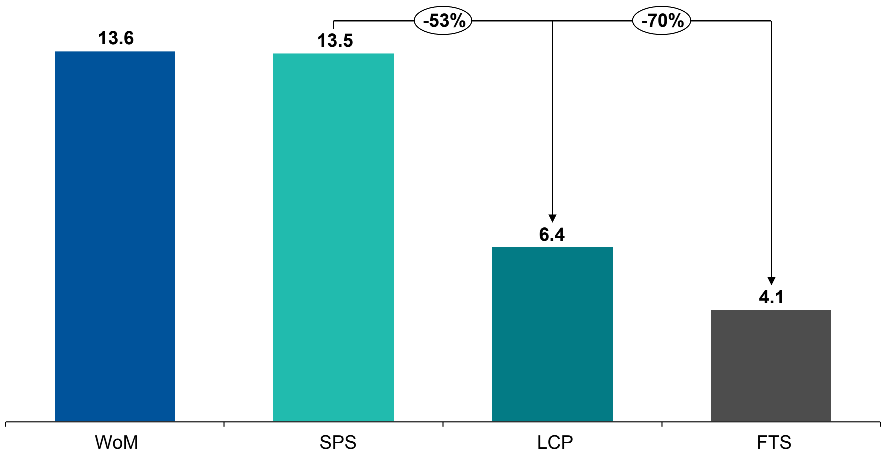
The total emission of aluminium industry can be reduced by 75% with LCP scenario and by 98% with FTS compared to SPS scenario in 2053. When total emissions by year are analyzed, with LCP scenario by 2030 emissions LCP scenario decrease by 27% to 16 Mt CO_2 compared to SPS, while with FTS emissions decrease by 62% to 6 Mt. In 2040, emission reductions reach 53% and 88% for LCP and FTS scenarios, respectively. By 2053, LCP scenario achieves a 75% emission reduction with 7 Mt in emissions and FTS results in 98% emissions reduction with 1 Mt in emissions.

Figure 21. Yearly Emissions of Aluminium Sector (Mt)



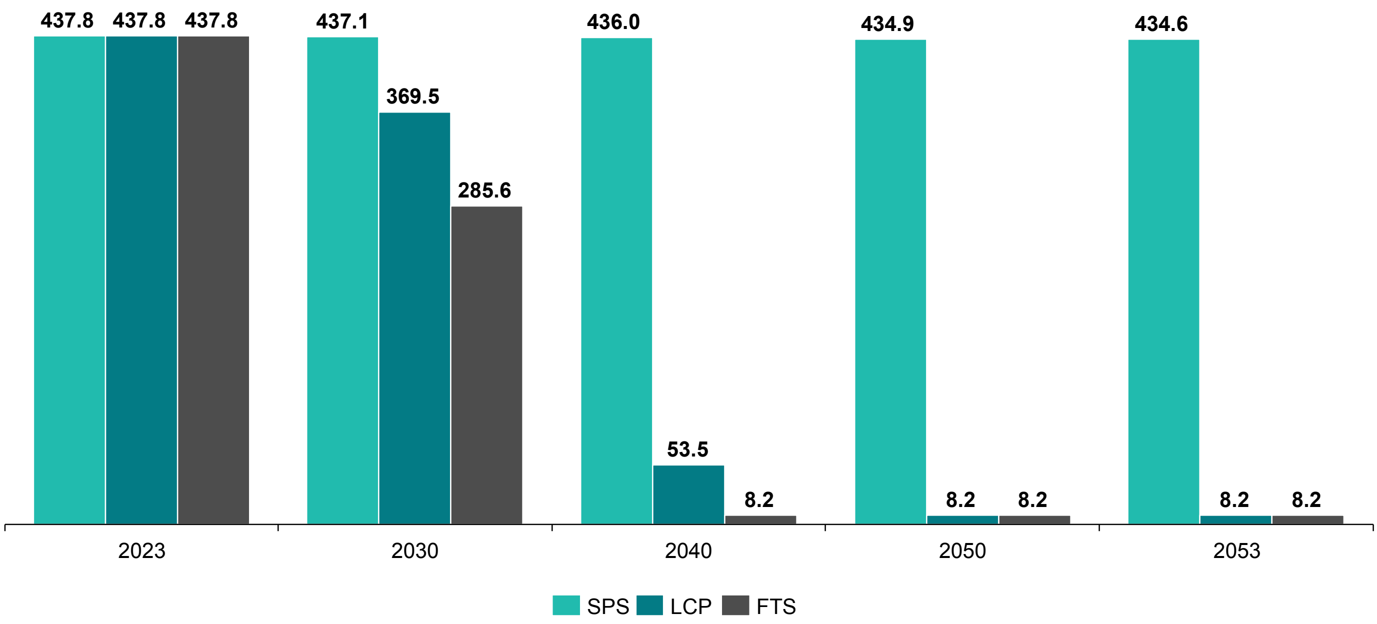
According to model results, the LCP and FTS pathways in primary aluminium production bring similar transitions in different timeframes, with FTS introducing disruptive technologies earlier. As a result of transition, total emissions from the primary aluminium sector in the 2023-2053 period decrease by 53% to 6.38 Mt with LCP scenario and by 70% to 4.10 Mt with FTS compared to SPS.

Figure 22. Cumulative Emissions of Primary Aluminium (2023-2053, Mt)



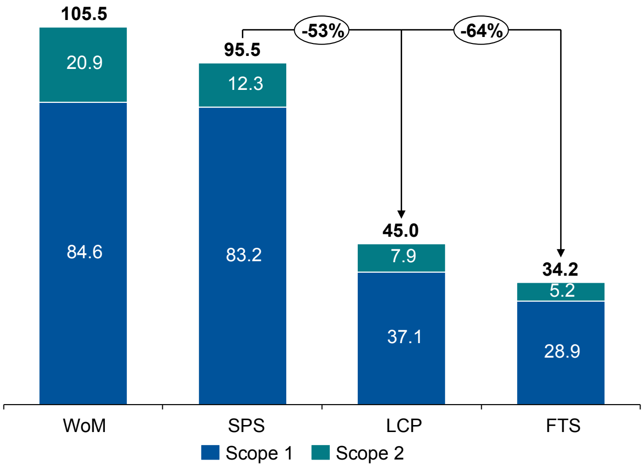
With technological transformation, the emissions of LCP scenario, compared to the reference scenario, SPS, are projected to decrease by 15.5% by 2030, 35% by 2040, and 98% by 2053. The more aggressive FTS offers a 34.7% reduction by 2030 compared to SPS and could achieve a 98% emission reduction after the 2040s.

Figure 23. Yearly Emissions of Primary Aluminium (Thousand Tonnes CO_2)



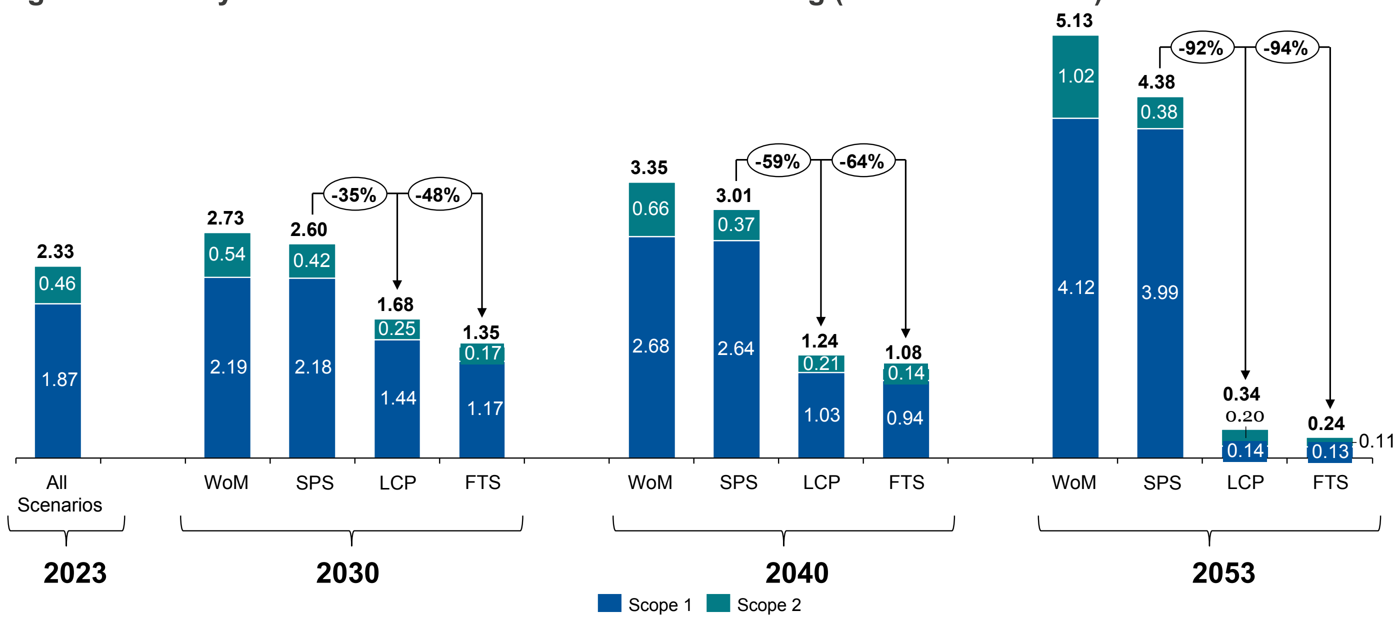
In the semi-aluminium processing optimization model, highly advanced reverberatory furnaces + CCS have the highest share in the mitigation scenarios. As a result of this transformation, LCP scenario can achieve a 53% reduction of the total CO_2 budget for cope 1 and scope 2 emissions in semi-aluminium processing, and the more aggressive FTS is expected to decrease total scope 1 and scope 2 emissions of semi-aluminium processing by 64% compared to SPS.

Figure 24. Total Emissions of Semi-aluminium Processing (2023-2053, Mt)



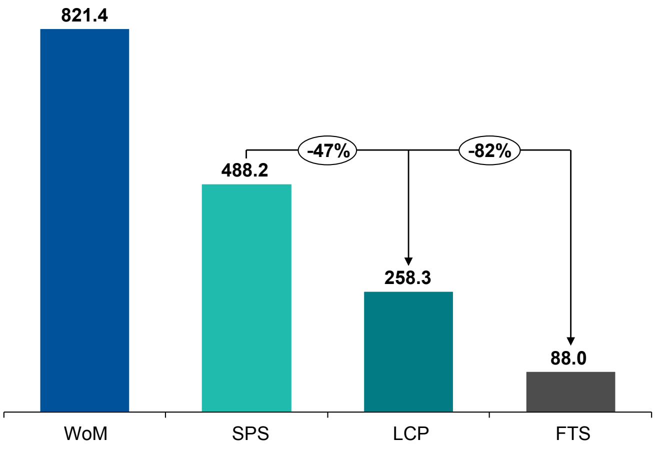
In 2022, total emissions accounted for 2.33 Mt in the current furnace distribution. In 2030, the technological transformation in furnaces provide a 35% reduction in LCP scenario, and a 48% reduction in FTS scenario. By 2040, emission reductions reach 59% and 64% for LCP and FTS scenarios, respectively. In 2053, LCP scenario achieves a 92% reduction compared to SPS, decreasing emissions to 0.34 Mt. In the more aggressive FTS scenario, a 94% reduction is achieved compared to SPS and total annual emissions are reduced to 0.24 Mt in the same year.

Figure 25. Yearly Emissions of Semi-aluminium Processing (Thousand Tonnes)



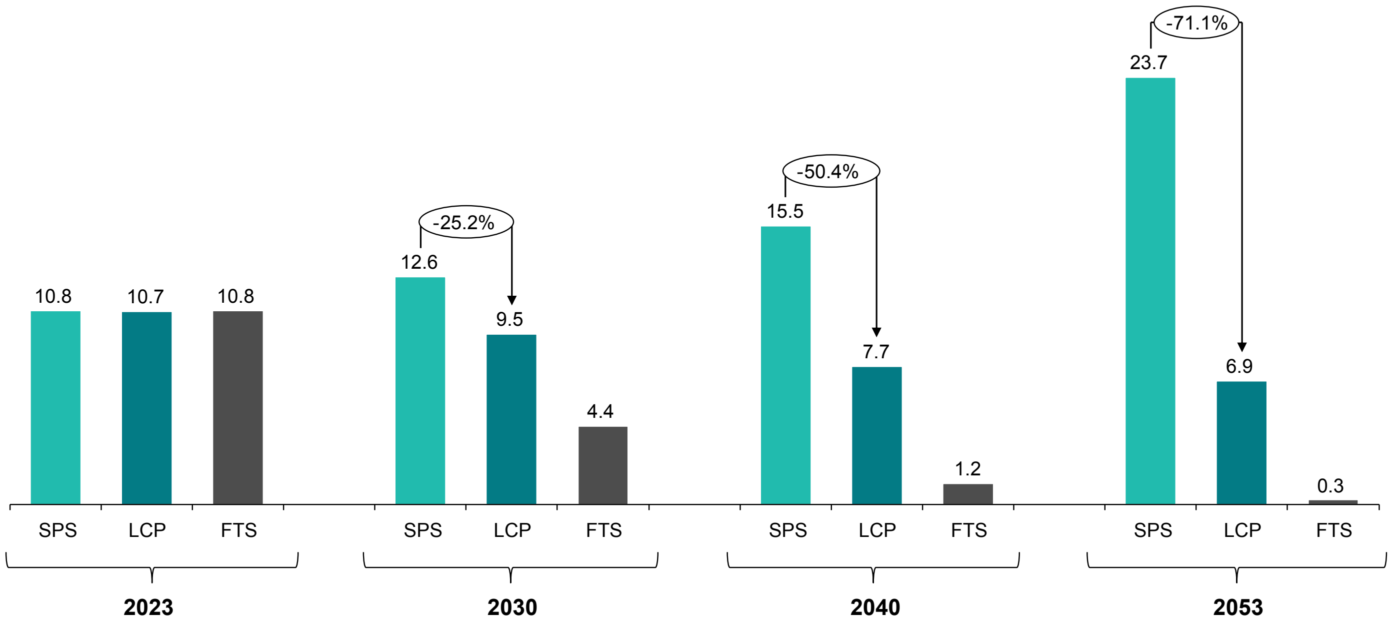
Input related scope 3 emissions, which are the highest source of emissions in aluminium production, were analyzed by considering actions such as changing the ratio of scrap to primary metal in primary production and switching imports to low carbon producing countries. LCP scenario can achieve a 47% reduction in the total CO_2 budget for the input related scope 3 emissions, and the more aggressive FTS is expected to decrease the total CO_2 budget for the input related scope 3 emissions by 82% compared to SPS.

Figure 26. Total Input Related Scope 3 Emissions of Semi-aluminium Processing (2023-2053, Mt)



Increasing the share of scrap and importing from low emitting countries is expected to reduce input related scope 3 emissions by 71%-99% in 2053. The emission reduction of the mitigation scenarios increases over the years to reach a significantly lower amount in 2053. In 2030, the mitigation scenarios achieve emission reductions of 25% and 92% for LCP and FTS, respectively, compared to SPS. By 2040, the reduction rate reaches 50% for LCP and 92% for FTS.

Figure 27. Yearly Input Related Scope 3 Emissions of Semi-aluminium Processing (Mt)

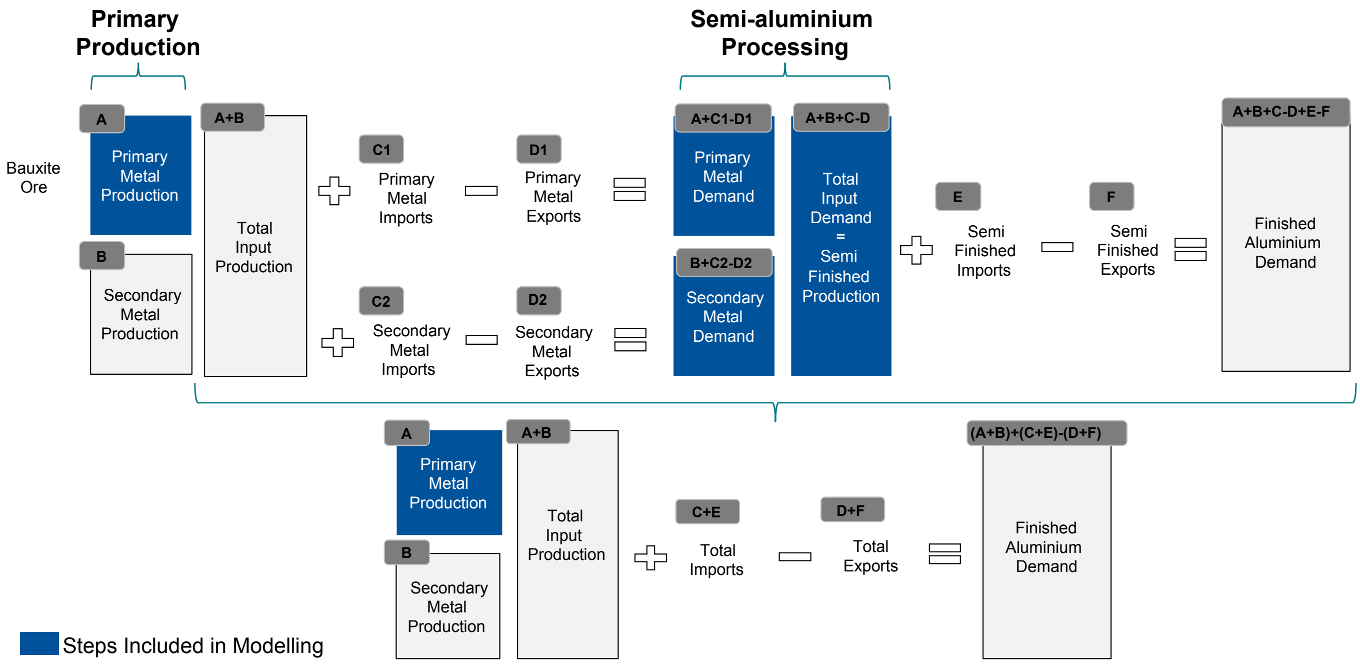


2.1. Sectoral Growth Projections

2.1.1. Methodology & Assumptions

The future 30 years of aluminium production in Türkiye (between 2023 and 2053) was forecasted, using the supply-demand model developed for the project. Separate assumptions were hold and results were obtained for the primary and semi-aluminium processing routes. The production projections in primary route were modelled based on the current primary aluminium producers. Projection for the semi-aluminium processing route were, on the other hand, based on historical growth rates. Methodology for projection work and key assumptions are detailed below.

Figure 28. Projection Methodology



The following assumptions were made in developing the supply-demand projections.

Assumptions for Demand

- Future demand growth was estimated by **considering historical trends**. Noting the global industry growth rates, per capita consumption of various countries, and based on the oldest data available (2012), the CAGR[34] between 2012-2019 was taken as a reference and industry demand was assumed to grow at 3.8% CAGR until 2038. After 2038 demand growth was projected to converge with growth forecasts for the Europe and Middle East regions and decrease gradually to 3% by 2053.[35]
- As of 2022, the share of primary metal in production was calculated to be **75%**, while the share of scrap usage was **25%**. Based on the assumption the industry will invest in recycling, by 2053 the primary metal share will fall to **65%**, while the share of scrap usage will gradually rise to **35%**.

Assumptions for Capacity & Production

- Annual production capacity for Türkiye's primary aluminium industry currently 82,000 tonnes. Semi-finished aluminium production capacity is calculated by applying demand and trade assumptions.

[34]Removing the pandemic effect
[35]CM Group

Assumptions for Trade

- Based on averages for the last 10-years, the **import/ domestic consumption** ratio for semi-finished products was kept constant **(33%)**. The **export/production** rate for semi-finished products was **assumed to be 60%** and gradually **reduced to 47%** by 2034 after considering **EU CBAM and ETS effects** (Annex 1).

2.1.2. Supply/Demand Projection Outcomes

Primary Aluminium Production

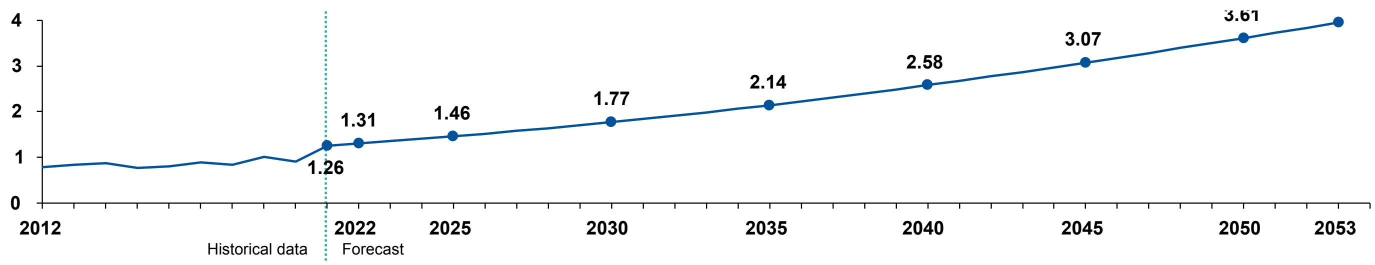
Annual production capacity for Türkiye's primary aluminium industry currently 82,000 tonnes. No further investment plans for additional production capacity were assumed. Therefore, primary aluminium production was kept constant at 82,000 tonnes until 2053 for Türkiye.

Semi-Aluminium Processing

Domestic Demand Forecast

Historical trends show that aluminium demand in Türkiye has been on an upward trajectory, with demand in 2021, the latest year for which data is available, standing at 1.26 million tonnes. The CAGR for the aluminium demand growth was found to be 3.86% between 2012 and 2019 (removing the pandemic effect from the historical data).[36] In line with global benchmarks and consultations with sector experts, the historical growth rate (3.86%) was carried over for the period 2023-2038, and then gradually reduced to 3% by 2053. **With these assumptions, total aluminium demand is forecasted to reach 3.95 Mt in 2053 in Türkiye.**

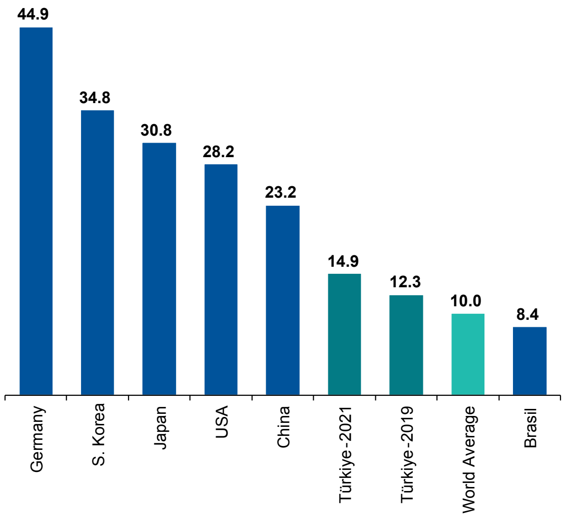
Figure 29. Aluminium Demand Forecast (Million Tonnes)

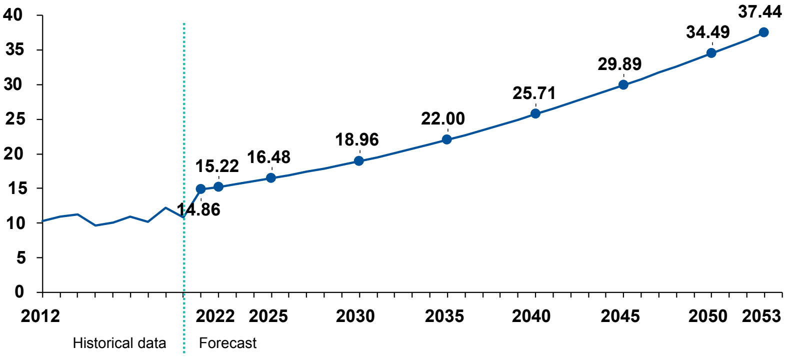


Aluminium consumption is assumed to rise with the ongoing population growth, growing transportation, defense, and aviation industries, and the expectation of stable growth in construction and overall infrastructure investments in the country. Accordingly, **the aluminium consumption per capita in Türkiye, which was 14.9 kg in 2021, is predicted to reach 37.44 kg in 2053.** The per capita consumption of aluminium forecasted for 2053, which is currently higher than the global average, will only come close to South Korea's consumption in 2023.

[36] Removing the pandemic effect

Figure 30. Aluminium Consumption (Kg) Per Capita in Selected Countries and Türkiye[37]

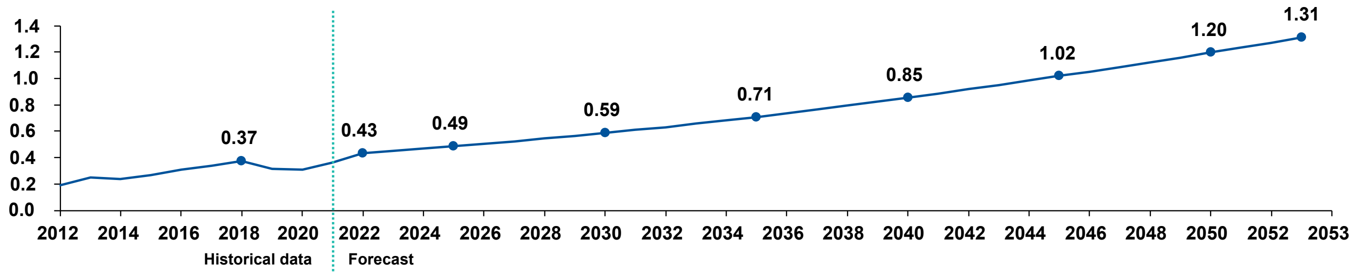




Import Forecast

Türkiye's aluminium imports reached 0.37 million tonnes in 2018 and import levels have since declined. In aluminium import projections, the import/demand ratio was kept constant (0.33), considering Türkiye's increasing product demand. **Under these assumptions, imports of semi-finished aluminium products are expected reach 1.3 million tonnes 2053.**

Figure 31. Semi-finished Products Import Forecast (Million Tonnes)

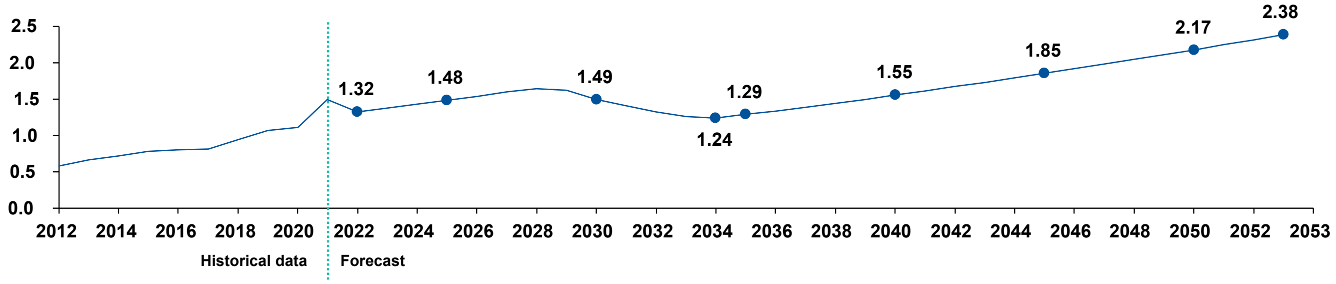


[37]TALSAD, TUDOKSAD, PwC Analysis.

Export Forecast

Export projections assume the domestic ETS to be operational from 2025 and EU CBAM to be operational from 2026 on. Considering that the destination receiving the largest amount of Türkiye's aluminium exports is the EU (60.8%), the CBAM impact will be considerable under any circumstances. As detailed in Annex 1 of this report, **EU CBAM's impact on Türkiye's aluminium exports to the EU is expected to take place over several years, ultimately resulting in a more than 20% decrease in exports after the 2020s**. With these assumptions, total exports of the aluminium sector remain between 1.32-1.55 million tonnes between 2022-2040, reaching 2.38 million tonnes by 2053.

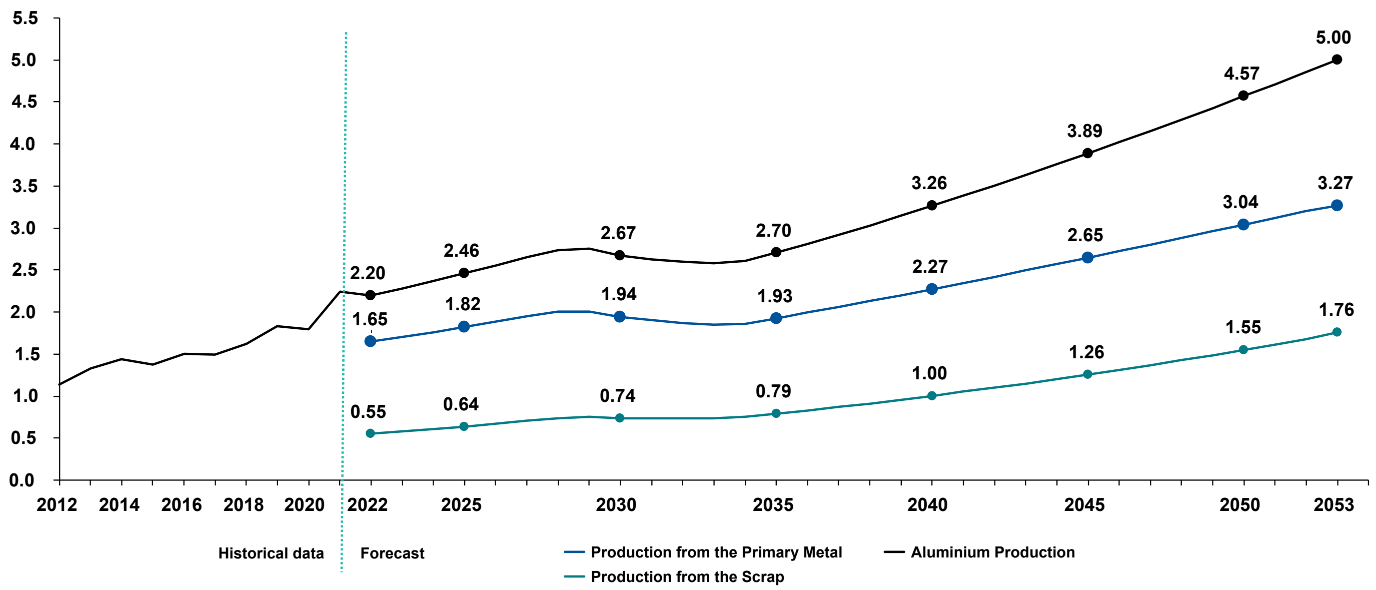
Figure 32. Semi-finished Products Export Forecast (Million Tonnes)



Production Forecast

The production forecast is derived from the demand, import, and export forecast for the sector. Essentially, the part of total demand (domestic and foreign) that cannot be covered by imports is assumed to be covered by domestic production. Consequently, the forecast for Türkiye's aluminium production finds production levels soar following the upward trend of the total aluminium demand.

Figure 33. Semi-finished Products Production Forecast (Million Tonnes)



The EU CBAM impact is expected to manifest as a decrease in production and export of semi-finished aluminium products. The EU CBAM impact begins to be seen in 2026 and reduces the growth rate immediately. After the phase out of the free allowance in 2034, production is forecasted to rise as a result of estimated growth until the end of the projection period (2053).

Total aluminium production, which stands at 2.2 million tonnes as of 2022, is projected to reach 5 million tonnes, with 3.27 million tonnes of production from primary metal and 1.76 million tonnes of production from scrap in 2053. Currently, the distribution of primary metal and scrap use in production is 75% and 25%, respectively. Evaluations made in concert with experts and based on global trends reveal an increase in the use of scrap in production is expected. Accordingly, the distribution in production is expected to gradually shift to 65% primary metal and 35% scrap.

2.2. Primary Aluminium Modeling Results

Primary aluminium production is responsible for the majority of emissions in the aluminium value chain.[38] For this reason, global (and local) decarbonization roadmaps predominantly focus on decarbonization of the primary aluminium route. Having only one primary aluminium manufacturing plant, Türkiye requires a more nuanced decarbonization plan focusing mainly on the semi-aluminium processing. On the other hand, the model generated for the primary production reflects the “as-is” and “to-be” of Türkiye’s primary aluminium industry and has been developed after consultations with the industry representatives.

The primary model uses the aluminium technology archetypes determined by MPP and explores 144 technological combinations for each industrial process. Four scenarios, namely WoM, SPS, LCP and FTS, are used to store different parameter combinations such as the introduction years for innovative technologies, grid decarbonization, and the ETS impact. The consequent model outputs cover the emission impact, phases, and investment requirements of technological transformation for mitigation scenarios.

In this context, in LCP scenario, which is the optimal scenario, technological transformation starts in 2028 with transition to gas boilers. Then, there is a transition to CST boilers in 2032, inert anode technology in 2040, and hydrogen calciner in 2047. As a result of this transformation, total emissions under LCP scenario decrease by 53% compared to SPS and decline to 6.38 Mt CO_2 in 2053. The NPV of investment cost of this transformation is calculated to be 176 million dollars in total for the 2023-2053 period.[39]

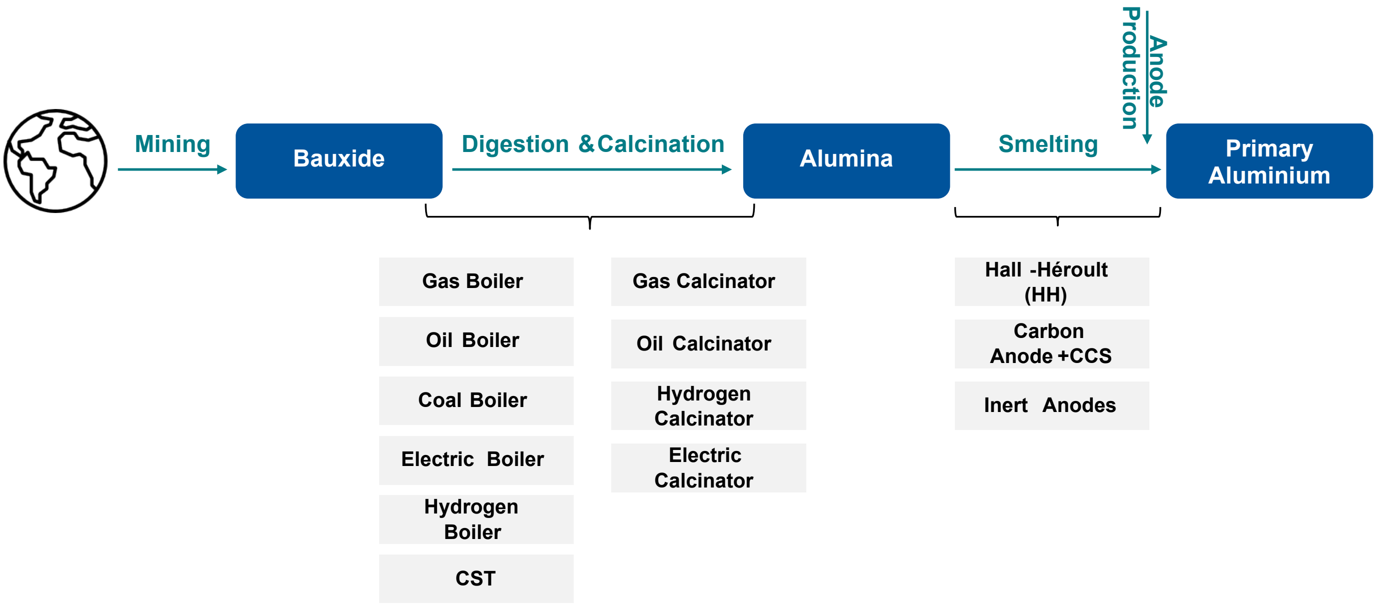
The same technological transformation is envisaged for the more aggressive FTS, with early penetration routes for the above-mentioned technologies. As a result of this transformation, FTS will achieve a 70% emission reduction compared to SPS for the period between 2023-2053. In 2053, emissions for FTS will be 0.1 t CO_2/t Al, while the sector’s cumulative emissions will be reduced to 4.1 Mt. The total investment cost of this transition is calculated to be 245 million dollars (NPV).

2.2.1. Low Carbon Primary Aluminium Technologies

Our modelling approach is based on process level analysis of available and new technologies. Process-based technologies were evaluated with reference to the MPP[40] framework. These technologies are considered potential future states Türkiye’s primary aluminium sector can use to achieve low carbon production.

[38] IEA
[39] Discount rate used is 7%.
[40] Retrieved from www.missionpossiblepartnership.org/wp-content/uploads/2022/10/Making-1.5-Aligned-Aluminium-possible.pdf

Figure 34. MPP Technologies by Process



Low temperature (100°C-320°C) coal, gas, or oil boilers are currently used by the industry to generate steam for digestion. In addition to the traditional boilers, three new boiler types are considered to be the new technology the industry can use to reduce emissions.[41] They are the electrical boiler, which is commercially available according to global sources, the hydrogen boiler, which will be commercially available in 2027, and the CST boiler, which will be commercially available in 2027.[42]

Conventional calciners rely on gas or oil combustion to generate heat at temperatures ranging from 1000°C to 1300°C and are currently used extensively by industry. Hydrogen and electricity-based calcination are the new technologies under development to reduce emissions in the calcination process. It is expected hydrogen and electric calciners will be commercially available in 2030 according to global sources.[43]

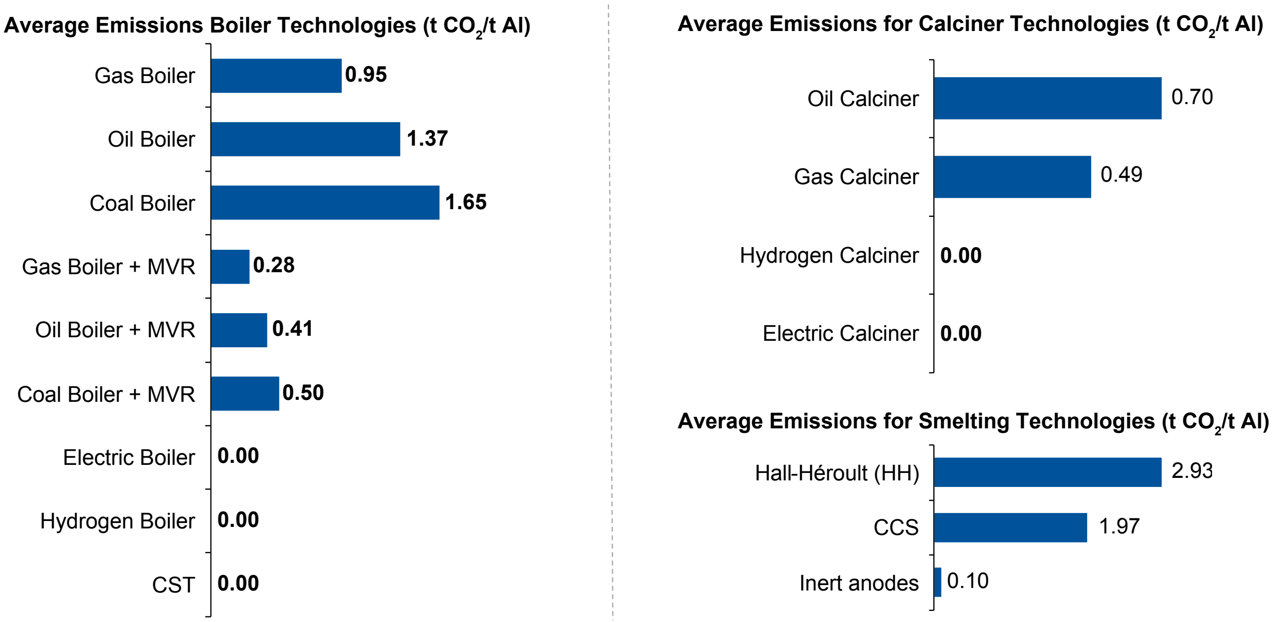
The Hall-Héroult process, which is the most used process for aluminium smelting, involves dissolving alumina in molten cryolite (a naturally occurring mineral) at high temperatures, typically around 950°C.[44] This process generates CO_2 and PFC emissions, which result from the reaction of oxygen released from alumina with the anode effects.

Two technologies come to the fore when considering the reduction of direct emissions that occur in the smelting process. They are CCS integration into current Hall-Héroult (carbon anode) technology and the new inert anode technology. The year of deployment for both technologies is forecasted to be 2030 by global sources. It is predicted that the CCS technology integrated into Hall-Héroult can capture 90% of the CO_2 emissions that occur in the smelting process. Inert anode technology,[43] on the other hand, involves replacing the carbon anode with an anode (e.g., ceramic oxide) eliminating the emissions associated with the reaction.

[41] MPP
[42] Concentrated Solar Thermal
[43] MPP
[44] Retrieved from www.temperaturedetectors.com/www.meltingtemperatures.com/hall-heroult_process.html
[45] Retrieved from www.enplusgroup.com/en/what-we-do/projects/Inert-anode/

The emission levels for the new and emerging technologies in the three main processes of primary aluminium production are shown in the figure below.

Figure 35. Emission Levels of Primary Aluminium Technologies[46]



In forecasting technology entry years, discussions were held with industry experts and company representatives. In addition, the estimations regarding the introduction years of technologies were evaluated at Steering Committee meetings. Scenario-based technology entry years for primary aluminium production are detailed in Figure 36. For primary aluminium, FTS scenario assumes the same entry years for Türkiye as the MPP study for all technologies except the HH+CCS and inert anode technologies. For LCP scenario, it is assumed that technologies can be deployed in Türkiye five years after they are commercially available globally.

[46] MPP

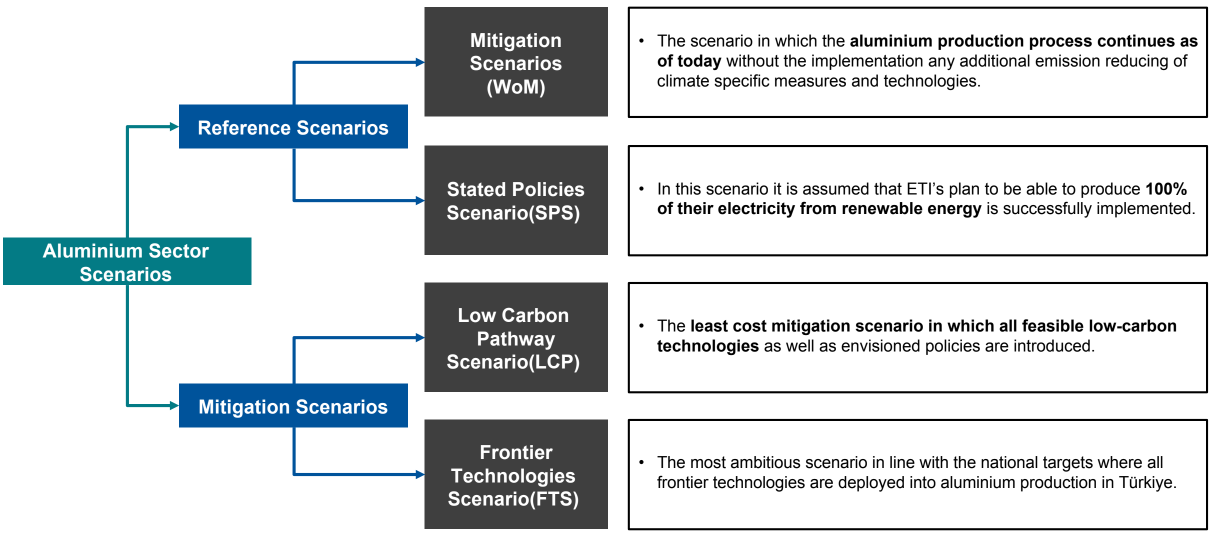
Figure 36. Primary Aluminium Technology Entry Years

MPP		Frontier Technologies Scenario (FTS)	Low Carbon Pathway Scenario (LCP)
Technology	Commerciably Available Year	Commerciably Available Year	Commerciably Available Year
Digestion Technologies			
Gas Boiler	2023	2023	2028
Oil Boiler	2023	2023	2028
Coal Boiler	2023	2023	2023
Electric Boiler	2023	2023	2028
Hydrogen Boiler	2027	2027	2032
CST (Concentrated Solar Thermal)	2027	2027	2032
MVR (Mecanic Vapour Recompression)	2027	2027	2032
Calcination Technologies			
Gas Calcinator	2023	2023	2023
Oil Calcinator	2023	2023	2023
Hydrogen Calcinator	2030	2030	2035
Electric Calcinator	2030	2030	2035
Smelting Technologies			
Hall -Héroult (HH)	2023	2023	2023
HH+CCS	2030	2035	2040
Inert Anodes	2030	2035	2040

2.2.2. Scenario Analysis and Modelling Approach

In the scenarios developed for primary aluminium, no technological transformation is foreseen for the baseline scenarios. The SPS reference scenario is different from the WoM reference scenario as it considers stated policies such as renewable investments and ETS implementation. In the mitigation scenarios, the entry years of the technologies entering the system are different, as shown in the previous section. FTS provides more aggressive results compared to the optimal LCP Scenario.

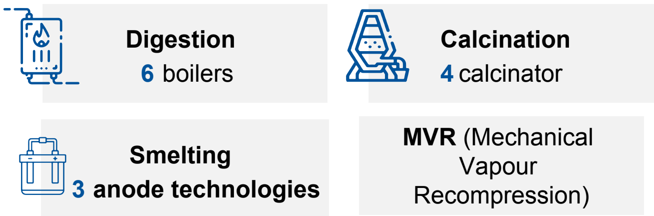
Figure 37. Primary Production Scenarios



The optimization model, which runs on GAMS software, uses a mathematical model to select technologies to be implemented and years of implementation to find an optimal path to a lower carbon emission trajectory for Türkiye's primary aluminium industry. MPP data was used to break down primary aluminium production into its processes and further analyze the sector. The three main processes are digestion, which uses boilers, calcination, which uses calciners, and smelting, which uses anodes. To better assess the situation, the current production technologies of Türkiye's primary aluminium production industry were examined. Currently, coal boiler, gas calciners and carbon anodes are used in primary aluminium producers in Türkiye.

As a part of modelling study, the starting CO_2 emission levels from the current primary aluminium production process were calculated in line with consultations made with industry representatives. Then, the alternative technologies were examined: there are six different boilers, four calciners, three anode technology combinations, and an additional mechanical vapour recompression system. So, in total, there are one hundred and forty-four technology combinations to evaluate.

Figure 38. Technology Options for the Primary Aluminium Processes



The model attempted various combinations of these technologies to achieve decarbonization. It considered CAPEX, OPEX, fuel costs, CO_2 emissions, efficiencies, future market projections, and years of commercial availability of these technologies when making optimization decisions. The model approached this problem by trying to minimize the NPV of the total cost of transition, which includes CAPEX, OPEX, fuel cost, and carbon budget due to ETS implementation. The output of the model indicates the years of implementation of the technologies, which can then be converted into a timeline for decarbonization of primary aluminium production in Türkiye.

2.2.3. Results and Insights from the Model

Although Türkiye's primary aluminium emissions from the anode and the electrolysis are higher than the global average, reduced emissions from the alumina refining process makes the total emissions of the country slightly lower than the global average emissions.[47]

Based on the discussions with industry representatives, with further planned investments on renewable energy, scope 2 emissions of Türkiye's primary aluminium industry are expected to gradually decrease and reach zero by end the of 2023.

According to information from a primary aluminium producer, the share of renewable energy in electricity used increased from 51% in 2021 to 94% in 2022. Subsequently share of grid and coal went down to 5% and 1% respectively. The rise of renewable energy in the production plant has cut down company's emissions to 5.52 CO_2 per tonnes of aluminium produced, which 5.27 comes from scope 1 emissions and 0.25 from scope 2 emissions in 2022. If the company successful in implementing 100% renewable energy in their production plant, the company's total emissions will fall to 5.27 which is all scope 1 emissions at the end of 2023.

[47]Industry representatives, International Aluminium Institute, Expert view

Due to the reason that Türkiye's primary aluminium industry's emissions mainly result from process emissions, an optimization model is designed to reduce these emissions. Primary aluminium production is modeled by considering different technologies in production processes. In this regard, 3 different production processes, which have significant emission intensity in the primary aluminium production process, were evaluated under calcination, digestion and smelting phases. Current production technology combines; coil boiler, gas calciner and carbon anodes which is used to examine the current situation in Türkiye in primary aluminium production.

Figure 39. Türkiye's Process-based Emissions Compared to Global Averages (t CO_2 /t Al)

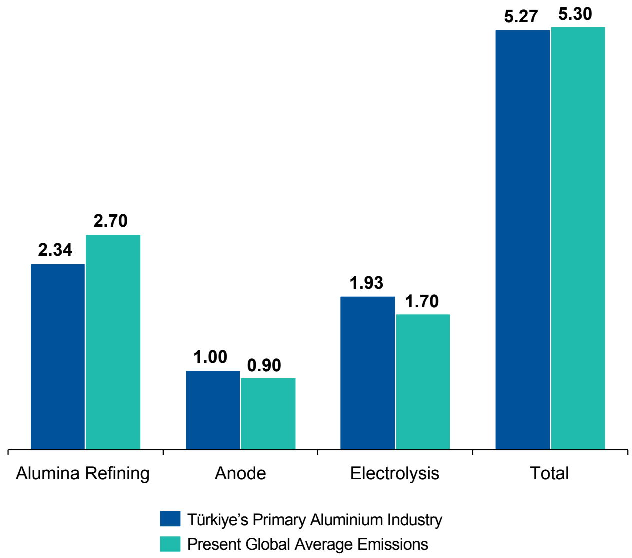
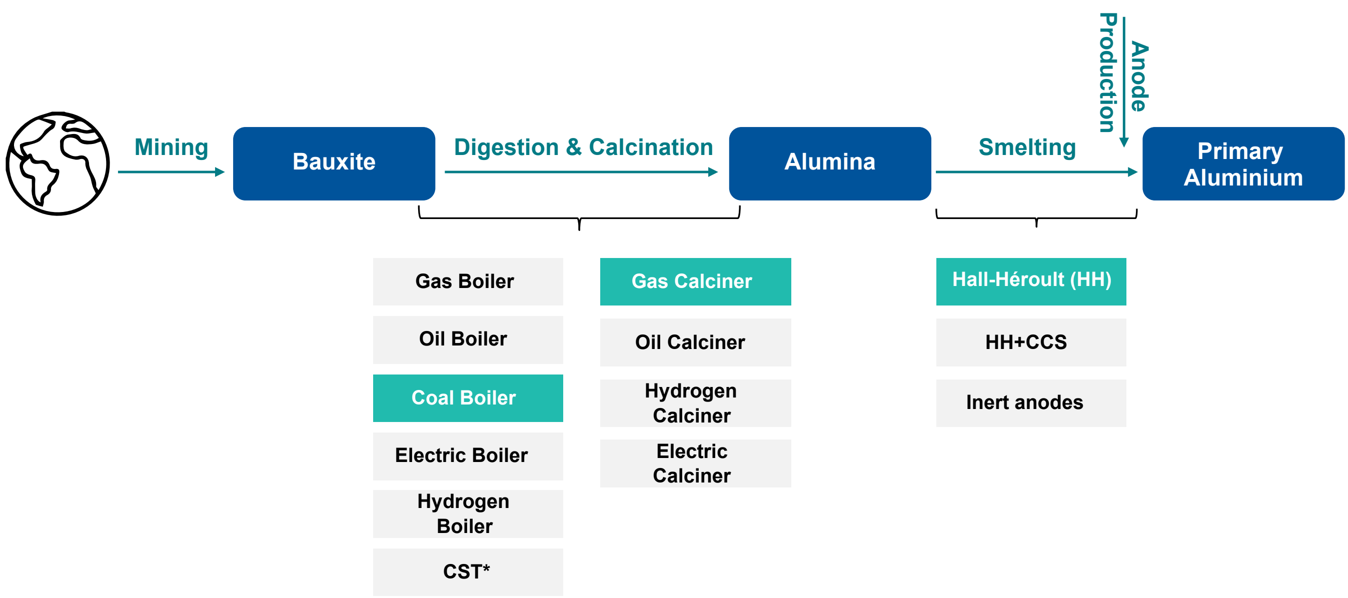


Figure 40. Current Technologies by Process

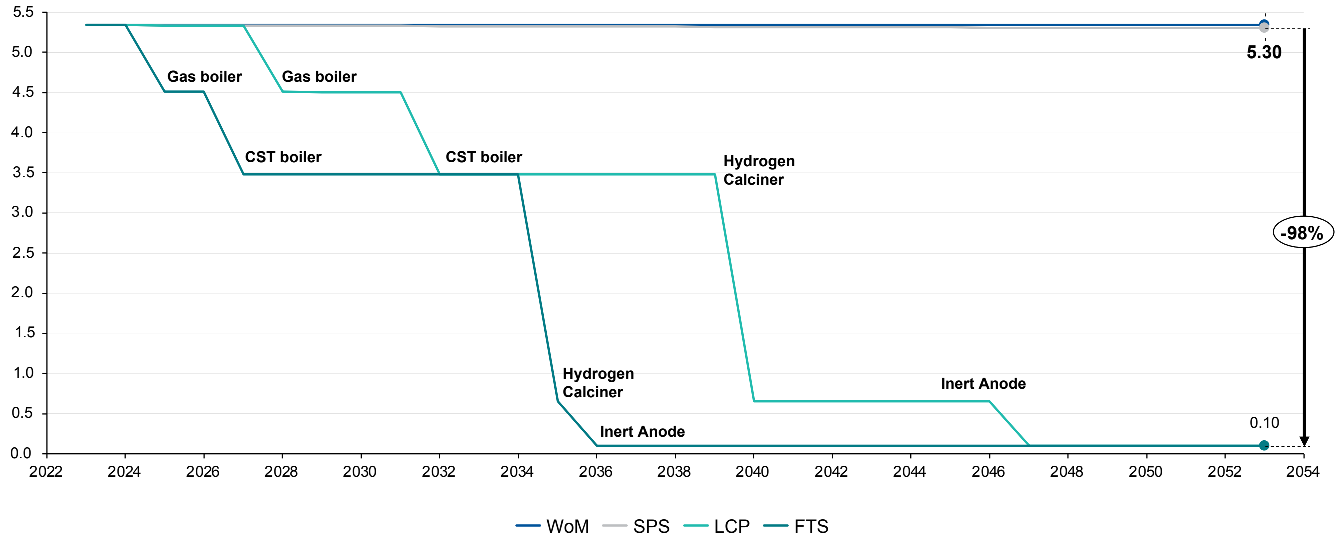


Emissions

In the WoM scenario, one of the reference scenarios for Türkiye's primary aluminum sector, the emission intensity level is equal to the current emission intensity level throughout the forecast horizon as no technological transformation is foreseen. In the mitigation scenarios, emission intensity is expected to decrease by 98% in 2053 with technological transformation.

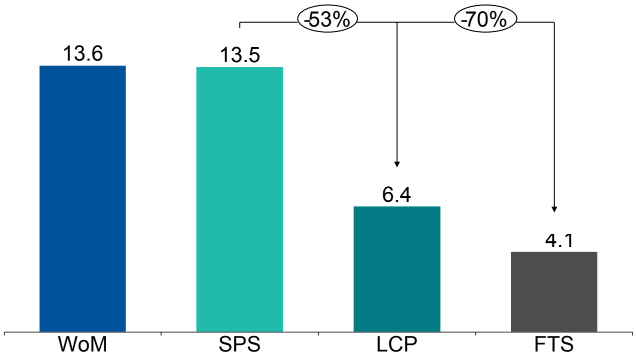
For the emission intensity in WoM scenario, which assumes current state will continue, the emission intensity accounts for 5.34 tonnes CO_2 per tonne aluminium. With integration of new technologies, emission intensity falls by 0.10 by 2053 for LCP and FTS. Both scenarios will follow the same technological transformation roadmap with different technology introduction years. For that reason, the emission intensity of FTS reaches 0.10 in 2036 while LCP scenario reaches the same intensity in 2047.

Figure 41. Emission Intensity (t CO_2 /t Al)



Emissions are the highest in WoM, where the model indicates release of a total of 13.5 Mt of CO_2 between 2023-2053. Total emissions in SPS scenario are almost the same as in WoM scenario. In LCP scenario, which achieves a significant decrease of emissions with the introduction of new technologies, total emissions between 2023-2053 decrease to 6.38 Mt of CO_2. In FTS, with more aggressive technological transformation, emissions in the same period are calculated to be 4.10 Mt. Accordingly, cumulative total emission can be reduced by 53% in LCP scenario and by 70% in FTS scenario compared to SPS scenario over the next 30 years.

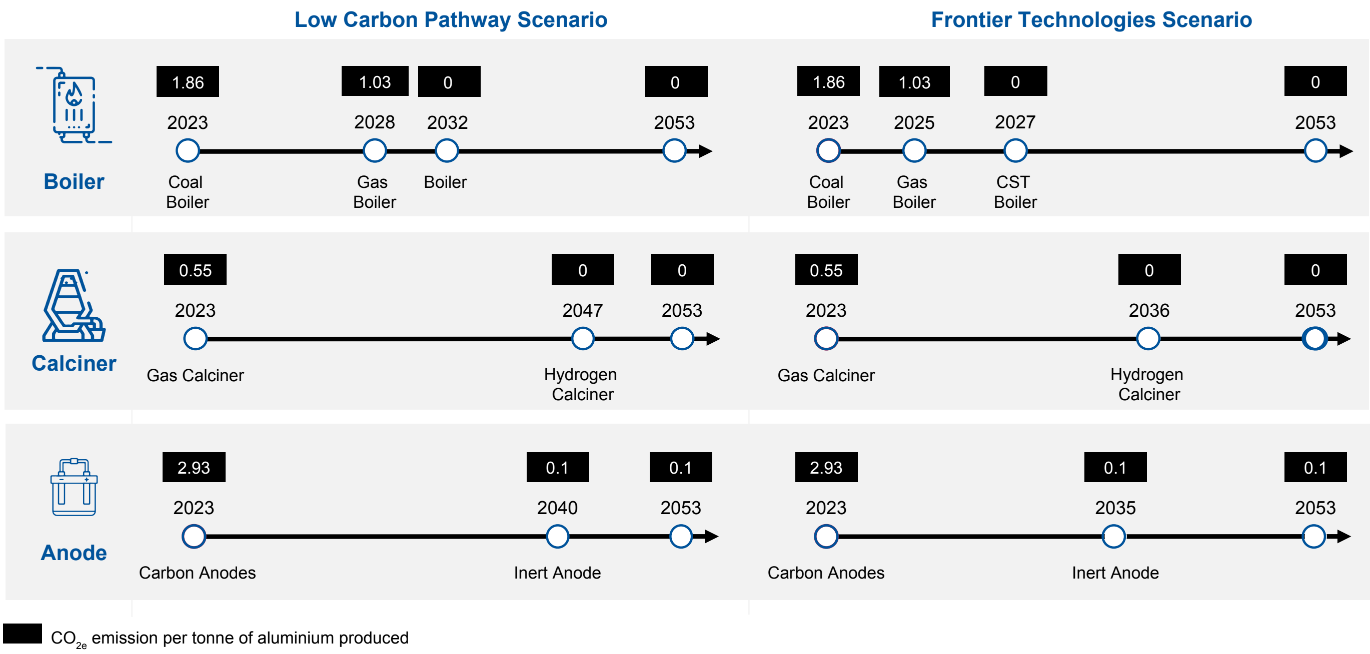
Figure 42. Cumulative Total Emissions in Primary Production (Mt CO_2)



Technological Transformation

The reduction in emissions in the mitigation scenarios is achieved by integrating new technologies into production processes. The optimization model identified different technology utilization pathways for different scenarios. In the model, in both mitigation scenarios the same technologies were selected but with different entry years. This technological transformation starts with the conversion to a gas boiler and then to a CTS boiler in the milling process. Then, in the calcination process, the traditional gas calciner is converted to hydrogen calciner in 2047 in the LCP scenario and in 2036 in the FTS scenario. Finally, in the smelting process, which causes the highest emissions, the carbon anode is replaced by inert anode technology. The introduction of inert anode technology is projected as 2040 for LCP and 2035 for FTS.

Figure 43. Technological Transformation for Primary Aluminium Production



2.3. Semi-Aluminium Processing Modelling Results

The model for the technological transformation of semi-aluminium processing considers various furnace types. The current (and future) furnace type distribution in Türkiye, along with their costs, efficiencies, and emissions, were generated through extensive consultations with sector experts and industry representatives specifically for this project. As a result, four scenarios were developed for the model, based on furnace type-related variables and parameters.

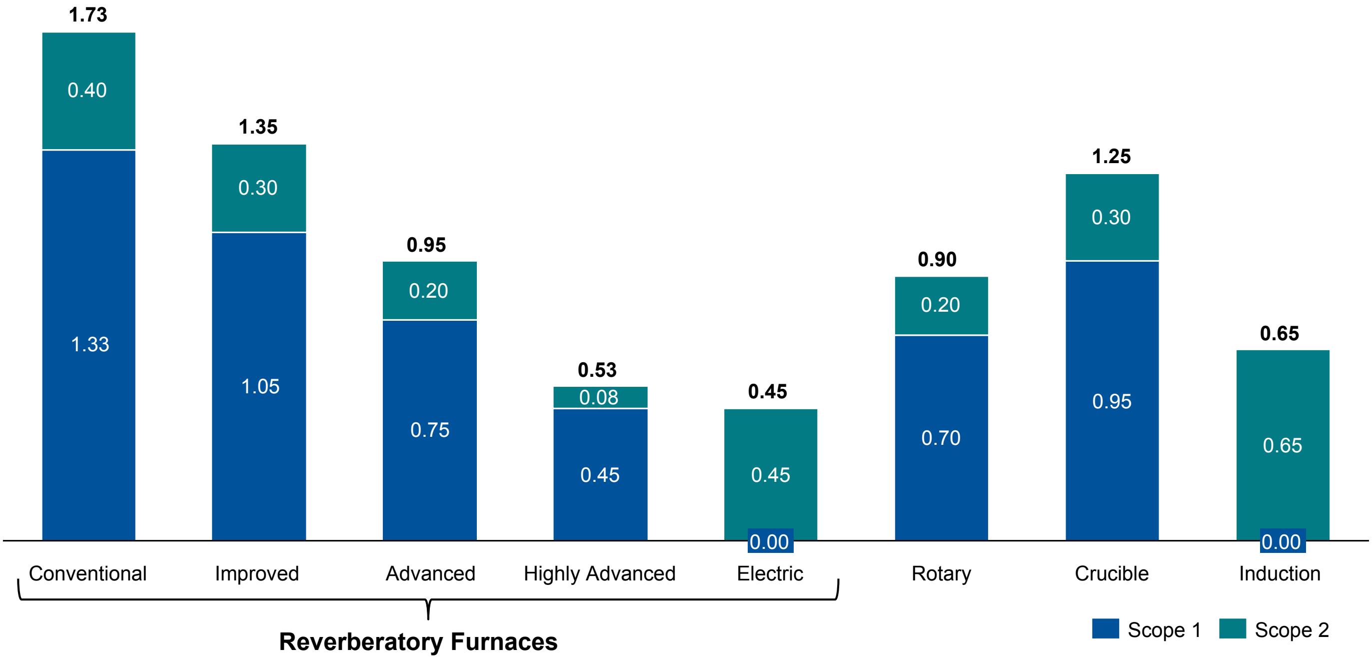
Technological transformation was permitted only in the mitigation scenarios, namely LCP and FTS. For LCP scenario the model suggested the technological transformation should move towards highly advanced reverberatory furnaces + CCS and electric reverberatory furnaces. This scenario can achieve a reduction of 53% of total CO_2 budget over the next 30 years compared to SPS. For LCP scenario, emission intensities decrease by 92% in 2053 compared to the SPS scenario. LCP scenario requires a 1.55 billion dollars investment for the technological transformation to more advanced furnaces calculated in NPV. FTS scenario proposes a similar transition, but the integration years are earlier than in the LCP scenario. In 2053, high advanced reverberatory + CCS and electric reverberatory have the highest share of production, respectively, and CCS is envisaged to be used for non-reverberatory furnaces. This scenario offers a 64% reduction in CO_2 budget for the next 30 years and 94% emission intensity reduction in 2053 compared to the SPS. FTS scenario requires a 2-billion-dollar investment in NPV for the technological transformation, ~500 million dollars higher than LCP due to more aggressive transition to advanced furnaces.

2.3.1. Low Carbon Semi-Aluminium Processing Technologies

Semi-aluminium processing refers to the process of converting primary metal or aluminium scrap into semi-finished and finished aluminium products. Furnaces, where the process of converting both primary metal and scrap to molten aluminium takes place, are the key sources of emissions in the semi-aluminium processing phase.

Four furnace types are used in semi-aluminium processing: reverberatory furnaces, crucible furnaces, rotary furnaces, and induction furnaces.[48] Each furnace type has different production technologies, capacities, and areas of use. **Currently, 80% of production in Türkiye is carried out by reverberatory furnaces.** The average emissions for different furnace types are given below.

Figure 44. Emission Levels of Furnace Types (t CO_2/t Al)[49]



[48]Detailed explanations of these furnace types are provided in Annex 2.
[49]Expert view, PwC Analysis

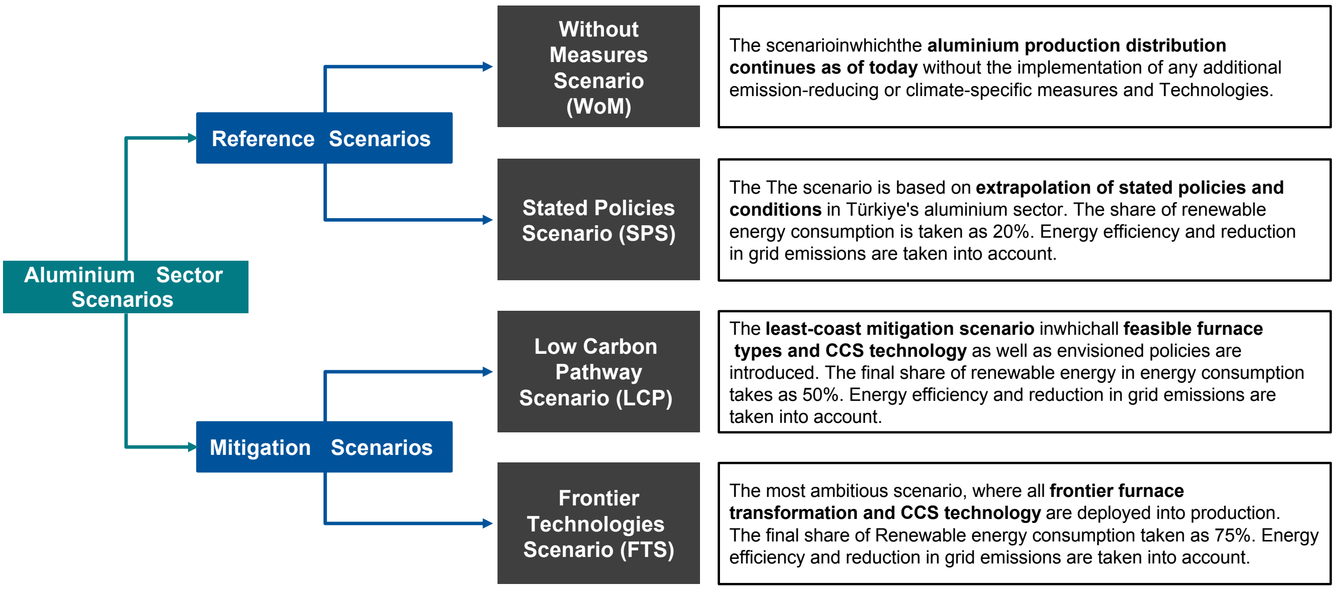
Reverberatory furnaces use natural gas and electricity in the production process. In non-reverberatory furnaces, the main energy source of rotary and crucible furnaces is natural gas, while the main energy source of induction furnaces is electricity. Therefore, while rotary and crucible furnaces have both scope 1 and scope 2 emissions, in induction furnaces emissions result only from electricity.

2.3.2. Scenario Analysis and Modelling Approach for Semi Aluminium Processing

The scenarios generated for semi-aluminium processing modelling are detailed in the figure below. For the semi-aluminium processing route, reference and mitigation scenarios are differentiated by furnace type distribution and level of efficiency. Other important assumptions for semi-aluminium processing modeling are the following:

- Commercial integration of CCS will be available for furnaces after the 2040s,
- The year of integration of the electric reverberatory furnace in Türkiye's aluminium industry is assumed to be 2040.

Figure 45. Semi-Aluminium Processing Scenarios



The semi-aluminium processing model was developed based on furnace types. There are eight different furnaces considered in semi-aluminium processing, as explained in the previous section: five types of reverberatory furnaces, rotary furnaces, crucible furnaces, and induction furnaces. All the furnaces except the electric reverberatory and induction furnaces use natural gas as their primary energy source, and thus have higher scope 1 emissions.

To start, the current situation of Türkiye in terms of distribution of furnaces, CO_2 intensities of these furnaces, and the carbon budget were examined to build the model's baseline and develop alternative future states for the industry. Based on consultations with project experts and industry representatives, the current distribution of production between reverberatory furnaces and non-reverberatory furnaces was assumed to be 80% to 20%. The CO_2 intensities of furnace types and their approximate share of production in Türkiye can be found in the figure below.

Figure 46. Distribution and Emissions of Semi-aluminium Processing by Furnace Type[50]

Emission reduction effect of CCS integration (outlined box)

	Furnace Type	Scope 1 Emissions (t CO_2/ton Al)	Scope 2 Emissions (t CO_2/ton Al)	Total Emissions (t CO_2/ton Al)	Current Share in Türkiye (%)
Reverberatory Furnaces	Conventional	1.20 / 1.33	0.40	1.20 / 1.73	20
	Improved	0.95 / 1.05	0.30	0.95 / 1.35	20
	Advanced	0.68 / 0.75	0.20	0.68 / 0.95	40
	Highly Advanced	0.41 / 0.45	0.08	0.41 / 0.53	0
	Electric	0.00	0.45	0.45	0
Other Furnaces	Rotary	0.63 / 0.70	0.20	0.63 / 0.90	5
	Crucible	0.86 / 0.95	0.30	0.86 / 1.25	12
	Induction	0.00	0.65	0.65	3

The model is developed by using GAMS software as a linear, multi-objective optimization model. The model minimizes the total NPV of investments (new and switching) while considering production and emission targets. It takes CAPEX, OPEX, ETS price, CO_2 emissions of furnace types, renewable energy share, efficiency gains per year, and the grid emission reduction projection into consideration.

The model uses the production caps set by industry experts and organizations. It assumes the 80%/20% split between production from reverberatory and non-reverberatory furnaces will continue in the future. There is also a production cap under non-reverberatory furnaces. The production from rotary furnaces is assumed to be capped at 12.2% of total production, whilst production from induction furnaces can reach a maximum of 7.8% of total production. Results are used to create a roadmap for the decarbonization of the semi-aluminium processing sector of Türkiye.

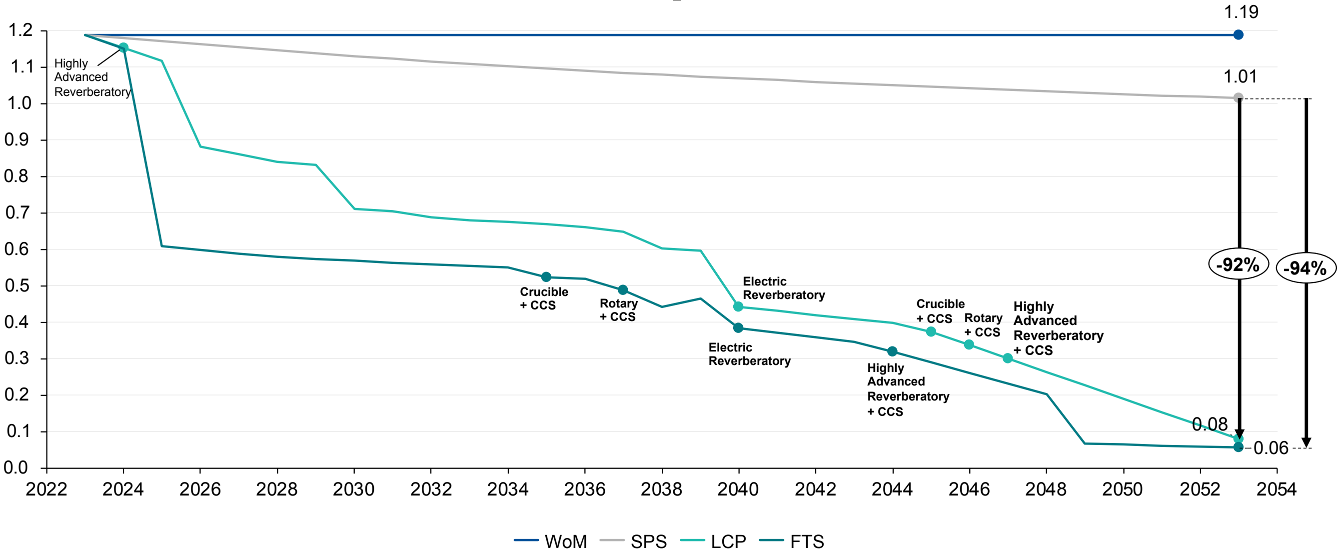
2.3.3. Results and Insights from the Model

Emissions

In the project, an optimization model was developed to determine year-based furnace distributions under four scenarios. Nine furnace types and CCUS integration were evaluated. WoM scenario, which assumes the production furnace distribution continues as it is today, has the highest emission intensity (1.19 t CO_2/t Al), as expected. In SPS emissions fall to 1.01 t CO_2 / t Al as a result of process efficiency and reduction in the grid emission factor. Emission intensity for scope 1 & 2 emissions can decrease by 92% in LCP and by 94% in FTS in 2053.

[50] Expert view, PwC Analysis

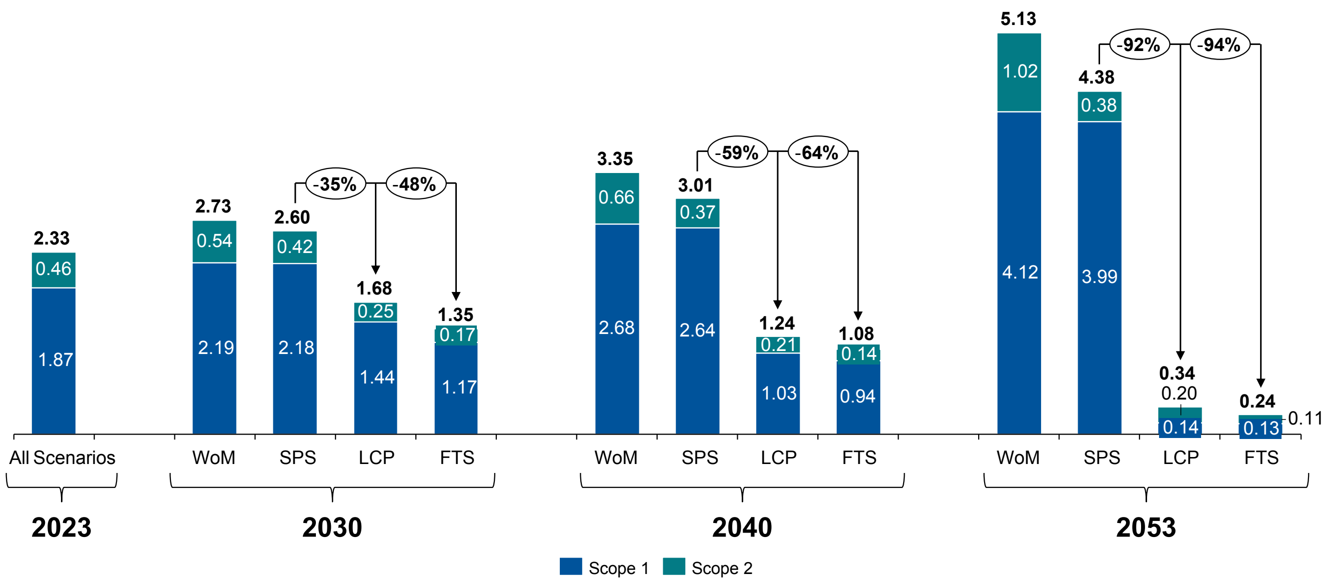
Figure 47. Emission Intensity (Scope 1 & 2) (CO_2 t/t)



It is foreseen that after 2030 the technological transition to advanced furnaces and the introduction of CCUS technology will bring lower carbon results. Scope 1 emissions are expected to decrease due to the transition to advanced and highly advanced furnaces, and scope 2 emissions are expected to decrease due to the gradual reduction in electricity grid emissions.

In 2022, in the current furnace distribution, total emissions equal 2.33 Mt, of which 1.87 is scope 1 and 0.46 is scope 2. By 2053, the total annual emissions of WoM and SPS scenarios will be 5.13 and 4.38, respectively. In the mitigation scenarios, LCP achieves a 92% reduction compared to SPS and emissions decrease to 0.34 Mt in 2053. In the more aggressive FTS, a 94% reduction is achieved compared to SPS and total annual emissions are reduced to 0.24 Mt in 2053.

Figure 48. Yearly Total Emissions (Scope 1 and 2, Mt)



Technological Transformation

Emission reduction in semi-aluminium processing is directly related to the distribution of furnace types in production. After extensive consultations with project experts and industry representatives, the furnace distribution in production is assumed to be 80% reverberatory furnace and 20% other furnaces. The distribution of reverberatory furnaces in production is 20% conventional, 20% improved, and 40% advance reverberatory, while the distribution of the remaining furnaces in production is 5% rotary, 12% crucible, and 3% induction.

In WoM and SPS scenarios, furnace distribution is assumed to continue as it is, while in the mitigation scenarios, the model is run to find the optimal furnace distribution. The reverberatory furnaces, which account for 80% of production, are distributed with an aim to minimize emissions and costs. Induction, crucible, and rotary furnaces are distributed within the 20% share in total production. In LCP scenario, which is the optimal scenario, the furnace type with the highest share of production in 2053 is the highly advanced reverberatory furnace, with a 54% share. It is followed by electric reverberatory with a 26% share, induction with a 10% share and rotary + CCS with an 8% share. The furnace type with the lowest share of production is crucible + CCS with a 2% share of production.

In FTS, where transformation is more aggressive, highly advanced reverberatory furnace + CCS has a 47% share of production, while the electric reverberatory share increases to 32%. Induction furnaces have the same share in both mitigation scenarios.

Figure 49. Current Furnace Distribution by Production

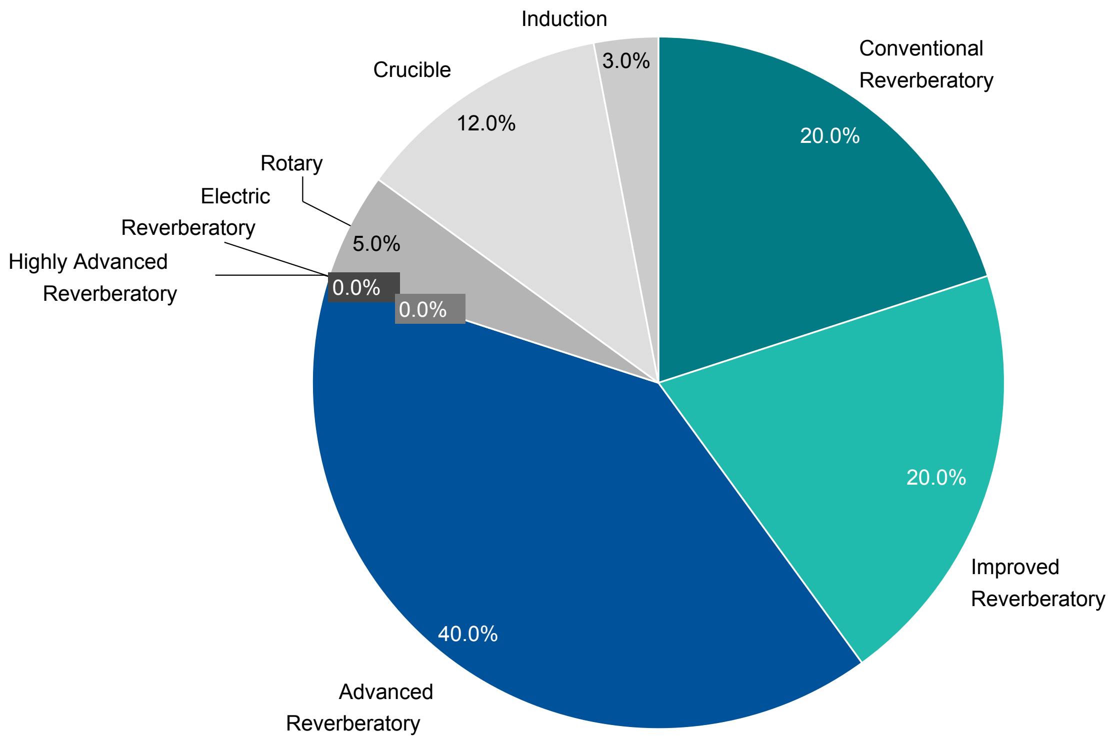
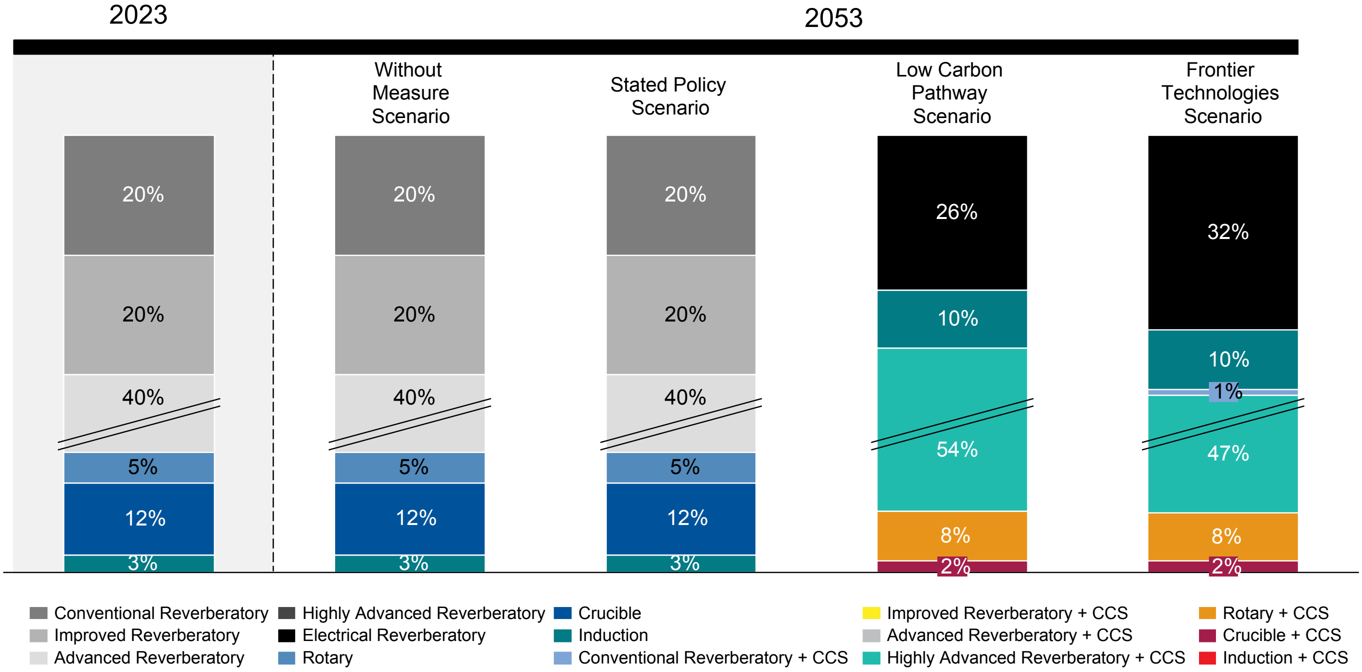


Figure 50. Technological Transformation for Semi-aluminium Processing

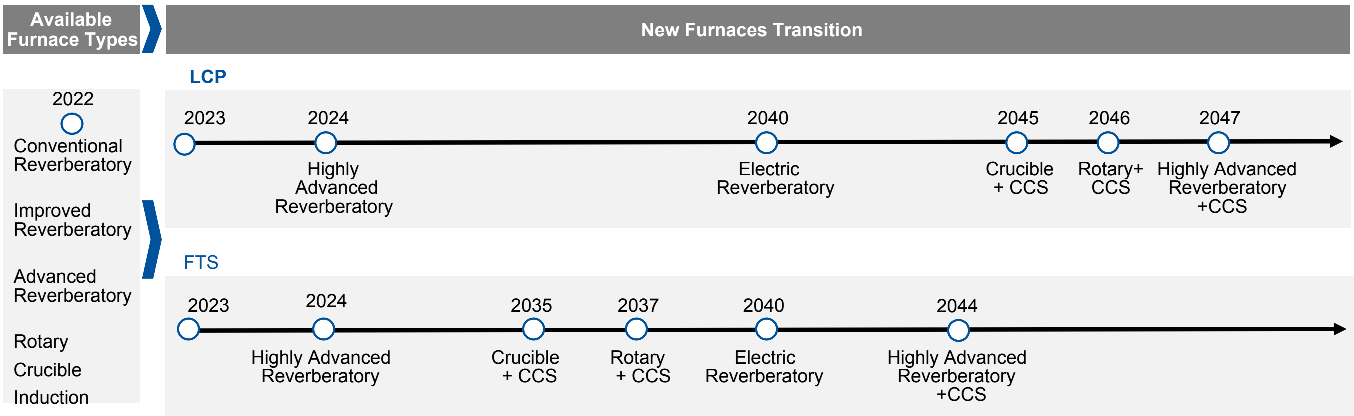


The two mitigation scenarios introduce similar transitions of furnaces in different timeframes, with earlier CCS integration in FTS. Highly advanced reverberatory furnaces are commissioned in the first year of the planning horizon due to the emission reduction target.

In LCP scenario, the first change in furnaces is the highly advanced reverberatory furnace in 2024. The electric reverberatory furnace is commissioned in 2040, the first year this furnace type can be commercially available in Türkiye's aluminium industry. The first transition in non-reverberatory furnaces is the CCS integration into the crucible furnace. CCS integration is also applied to rotary and highly advanced reverberatory furnaces at one-year intervals.

In FTS scenario, the highly advance reverberatory furnaces and electric reverberatory furnaces are commissioned in 2024 and 2040 respectively, the same as in LCP scenario. On the other hand, CCS integration in non-reverberatory furnaces start earlier than LCP, with deployment of crucible + CCS furnaces in 2035. This transition is followed by rotary + CCS in 2037 and highly advanced reverberatory furnace + CCS in 2044.

Figure 51. Furnace Transition for Semi-aluminium Processing



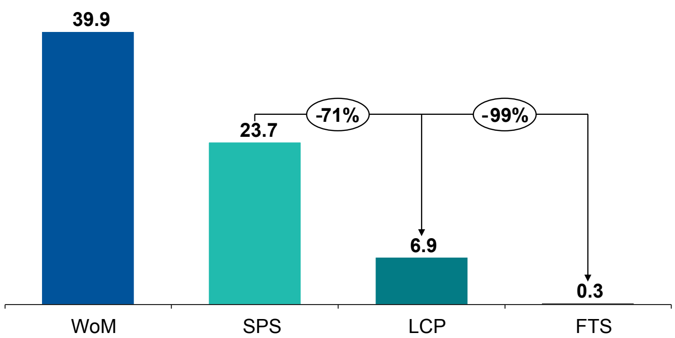
2.4. Input Related Scope 3 Emissions

Currently, Türkiye imports around 1.77 million tonnes of unwrought aluminium from around the globe.[51] These imports cause around 18 million tonnes of CO_2 input related scope 3 emissions which are embedded in the imported aluminium almost 85% of the total CO_2 emissions of Türkiye's aluminium industry. The emission reduction for the input related scope 3 emissions will come from the increase in scrap usage and the shift to importing from lower CO_2 emitting producers. Four scenarios for input related scope 3 emissions have been devised, with different scrap usage levels and primary metal import routes.

Current average emission intensity of imported ingots is calculated to be 10.6 t CO_2/t Al. In LCP scenario it is assumed the input related scope 3 emission intensity for imported ingots can decrease by 67% to 2.1 t CO_2/ t Al in 2053. For FTS, emission intensity of imported ingots can be reduced further, to 0.1 t CO_2/ t Al, with the technological improvements in source countries. On the other hand, it is assumed the share of scrap in semi-aluminium processing, which is currently 25%, will increase to 35% in LCP and 50% in FTS scenarios.

Total emissions from imported ingots are expected to reach 39.9 Mt in WoM, whereas total emissions in SPS decrease to 23.7 Mt CO_2. In the reduction scenarios, significant reductions of 6.9 Mt CO_2 and 0.3 Mt CO_2 were achieved in LCP and FTS, respectively. Total emission reduction due to an increase in the share of scrap and importing changes is expected to be 71% and 99% for LCP and FTS respectively.

Figure 52. 2053 Emissions by Scenario (Mt CO_2)



[51]Comtrade, PwC Analysis

2.4.1. Scenario Analysis and Modelling Approach

Input related scope 3 emissions in semi-aluminium processing refers to the greenhouse gas emissions that occur in the aluminium upstream and downstream activities in the value chain. The biggest contributing factor to these emissions is the production of ingots for use in semi-aluminium processing. For embedded emission calculations, primary metal and scrap distribution were changed based on the scenarios. In addition, the emission factors of the countries from which Türkiye imports ingots were also considered. The scenarios for input related scope 3 emissions are given in Figure 57. Using these limits, the input related scope 3 emissions for different scenarios are calculated.

International trade databases were examined to find Türkiye's aluminium ingot trading partners. The top countries that Türkiye imports primary metal from are Russia, Malaysia, Iran, India, Bahrain, Qatar, the UAE, Oman, Tajikistan, and Kazakhstan.

Figure 53. Input Related Scope 3 Emissions Scenarios

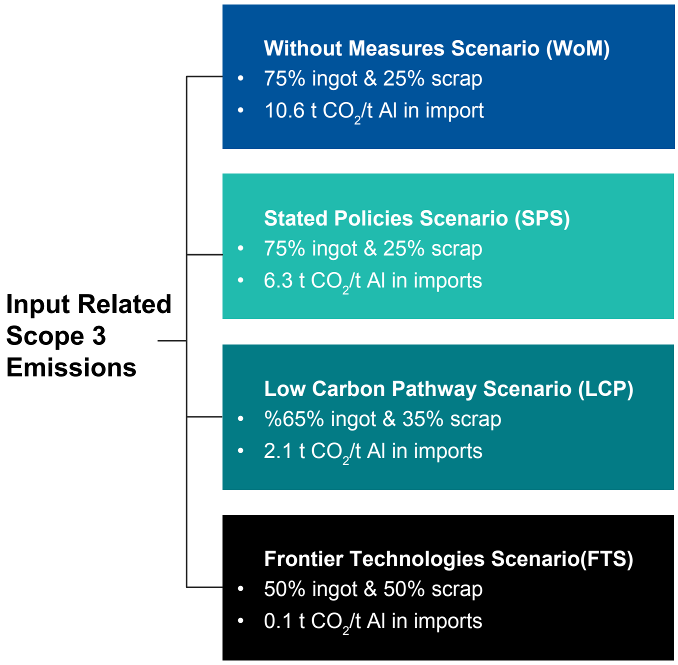
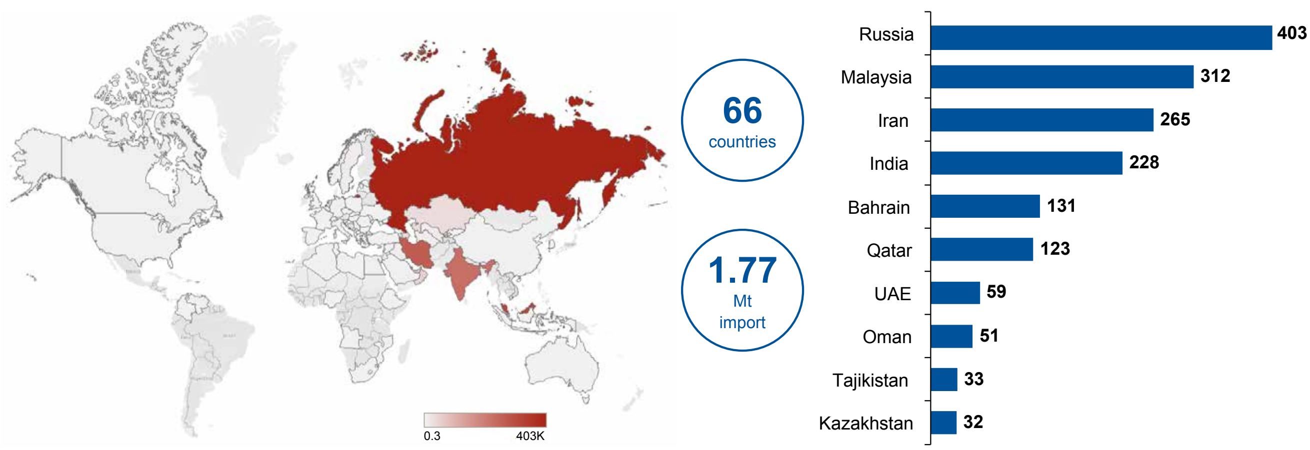


Figure 54. Countries From Which Türkiye Imports Ingots[52]

Türkiye's Unwrought Aluminium Import by Country (2022, Tonnes)

Top 10 Countries for Türkiye's Unwrought Aluminium Import (2022, Thousand Tonnes)



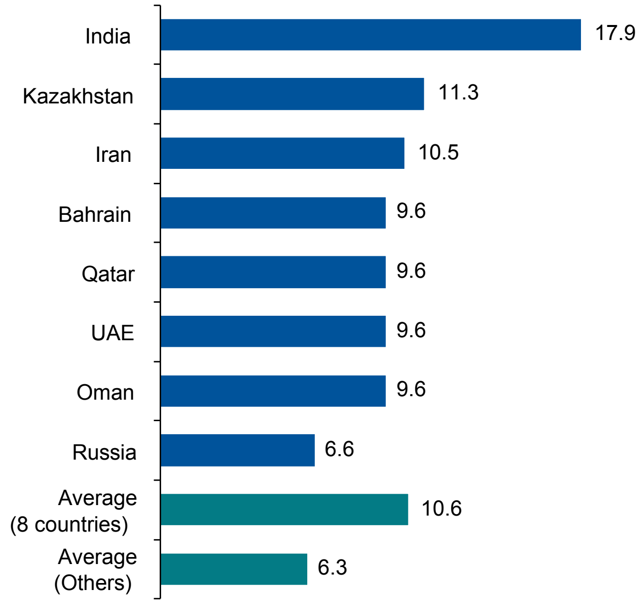
[52]Comtrade, PwC Analysis.

For the input related scope 3 emission intensities, MPP data were used for the countries discussed from which Türkiye imports aluminium ingots. After identifying the countries Türkiye trades with, CO_2 emissions were determined for various company archetypes in those countries. In the absence of publicly available data, it is not possible to determine exactly which archetypes Türkiye's companies trade with, so an average of the countries' CO_2 emissions was used. The archetypes were then matched with manufacturers in these countries and CO_2 emission levels were determined. This data was used to determine the input related scope 3 emissions of imported ingots from different countries. The input related scope 3 emission intensities related to Türkiye's imports can be seen in figure 55.

In WoM scenario, it was assumed that Türkiye's producers would continue to import from the countries from which they currently import primary ingots the most. Each of the top eight import countries mentioned has higher CO_2 intensity levels than the global average. The average CO_2 emission intensity is 10.6 t CO_2 per tonnes of aluminium produced for these countries. For the other three scenarios, the impact of growing decarbonization policies in these import countries and the assumption that Türkiye will increase the number of import partners with relatively lower CO_2 emission intensities were considered to be the main factors that may reduce CO_2 emissions. The model can achieve a CO_2 level of 6.3 tonnes per tonnes of aluminum produced in the SPS scenario. In mitigation scenarios, 69% and 98% reductions can be achieved in input related scope 3 CO_2 intensity in LCP and FTS, respectively, compared to SPS.

A second lever for reducing input related scope 3 emissions of semi-aluminium processing is to lower the need for imported ingots by increasing the use of aluminium process scrap/ secondary aluminium as inputs. For WoM and SPS the share of process scrap is kept constant at 25%, whereas for LCP and FTS it is estimated to gradually increase to 35% and 50%, respectively.

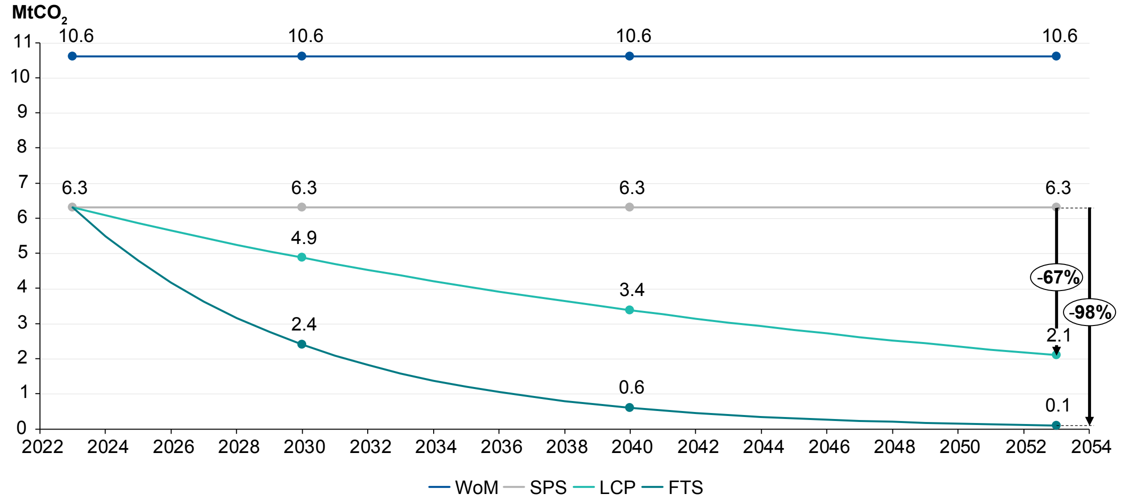
Figure 55. Input Related Scope 3 Emission Intensities for the Top Countries from Which Türkiye Imports (t CO_2/t Al)



2.4.2. Results and Insights from Input Related Scope 3 Assessment

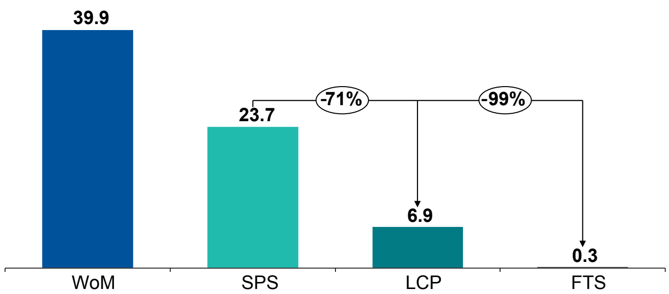
Technological advancements, efficiency gains, and import country selection all play a huge role in semi-aluminium processing input related scope 3 emissions. Changes to emission intensities of imported primary aluminium ingots in different scenarios can be seen in Figure 56.

Figure 56. Input Related Scope 3 Emission Intensity by Year (t CO_2 / t Al)



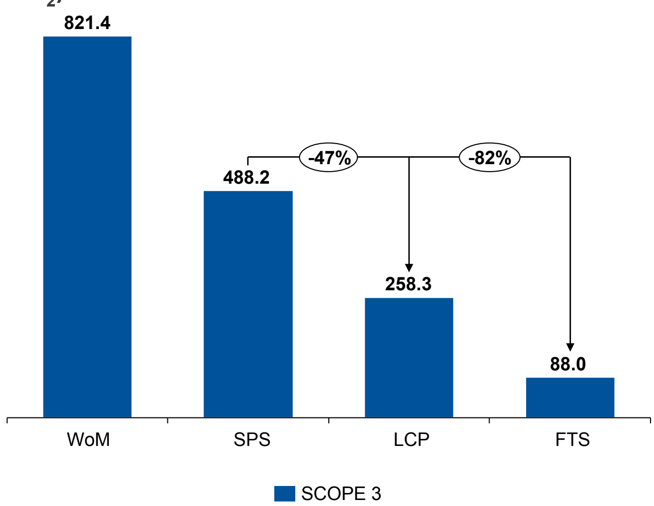
Changes in emission intensities result in significant differences between input related scope 3 emissions in different scenarios, especially in later years. In 2053, input related scope 3 CO_2 emissions are 39.9, 23.7, 6.9, and 0.3 Mt for WoM, SPS, LCP, and FTS, respectively. The graph 57 shows that LCP scenario reduces the input related scope 3 emissions by 71%, while the FTS reduces the input related scope 3 emissions by about 99% in 2053.

Figure 57. Input Related Scope 3 Emissions by Scenario in 2053 (Mt CO_2)



These changes add up to the total CO_2 budget between 2023 and 2053, and the cumulative nature of the CO_2 budget illustrates the substantial amounts of CO_2 emission reductions for the different scenarios. The total CO_2 budget in WoM scenario, which is 821.4 million tonnes of CO_2, can be reduced to 488.2 million tonnes in SPS. The total budget is reduced to 258.3 million tonnes in LCP scenario, a difference of 47% compared with SPS. In FTS, the total carbon budget is 88 million tonnes, which corresponds to a reduction of 82% compared to SPS.

Figure 58. Total CO_2 Budget Over 2023-2053 (Mt CO_2)



2.5. Investments Necessary to Achieve Decarbonization of Türkiye's Aluminium Industry

Türkiye's aluminium sector needs to deploy new technologies to achieve national decarbonization targets for the transition to a low-carbon economy. Investments are evaluated based on the technologies selected for the different aluminium sector transition pathways in each scenario.

Achieving the emission reduction targets of Türkiye's aluminium sector requires a major technological transformation and there is a significant investment need associated with this transformation. Total investment cost (NPV) for the transition of Türkiye's aluminium industry could reach 1.7-2.2 billion dollars in LCP and FTS scenarios respectively. Since primary aluminium has lower share of capacity, semi-aluminium processing represents the largest share (88.9%) of the investment requirement.

Türkiye's aluminium industry decarbonization trajectories highlight the need for development of financing mechanisms and plans. Therefore, measures to boost the mobilization of additional funds should be prioritized starting in the early years to enable the aluminium industry to accomplish the necessary technological transformation in the medium to long term. Policymakers and financial institutions need to collaborate and develop financing mechanisms so Türkiye's aluminium industry can access scaled-up capital flows to foster decarbonization investments.

2.5.1. Scenario Based Investment Cost Projections

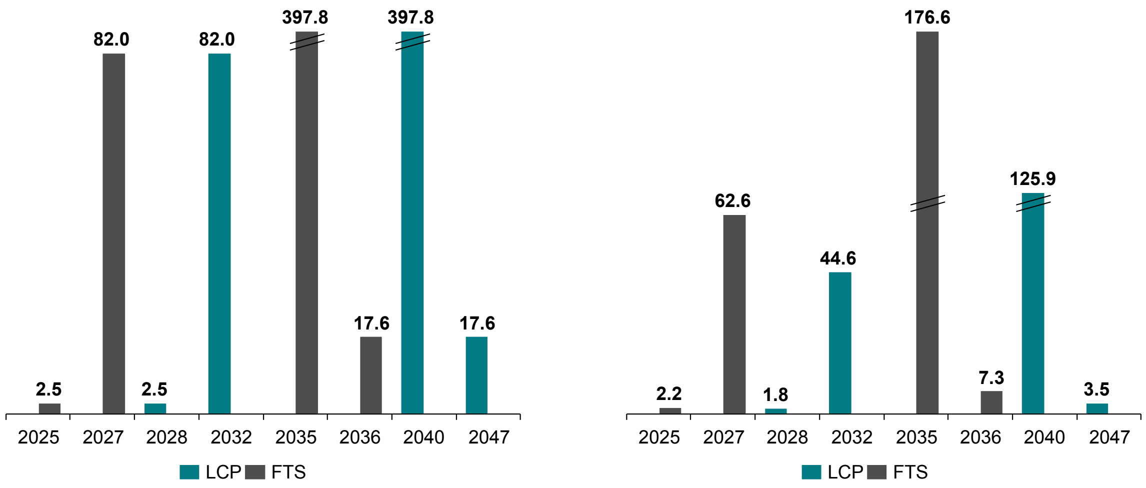
Primary Aluminium Investment Cost

Various technology combinations are used in various mitigation scenarios for primary aluminium production. The objective of the optimization model, which uses input and technology-based data sets, is to minimize cost under various scenarios. So, different cost and investment needs for different mitigation scenarios are estimated.

Investment requirements are directly related to technological transformation. Scenario-based costs are driven by the deployment of technologies and their respective CAPEX and OPEX figures. No technological transformation is envisaged in WoM or SPS.

In the mitigation scenarios, the cost of technological transformation is distributed according to the years in which technology is introduced. While both mitigation scenarios envisage the same technological transformation, the investment years are earlier in the more aggressive FTS, which is detailed in the previous sections. As seen in the graph below, the total nominal investment cost required for mitigation scenarios is ~500 million dollars. In LCP scenario, the first technology investment is expected to be introduced in 2028, while FTS scenario attracts the first investment three years earlier, in 2025. The technology requiring the highest investment cost is inert anode, which is commissioned in 2035 and 2040 in LCP and FTS, respectively, with a requirement of ~400 million dollars.

Figure 59. Investment Cost by Scenario (Million Dollars) & NPV Investment Costs (Million Dollars)



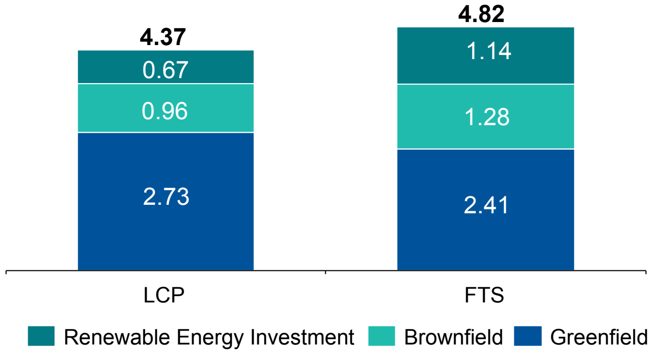
Based on the NPV of the total investment calculated using a discount rate of 7%, in the 2023-2053 period the NPV of total investment costs is 176 million dollars for LCP and 249 million dollars for FTS.

Semi-Aluminium Processing Investment Cost

Different scenarios of aluminum processing have different furnace distributions in production, different CCS introduction years and different renewable energy ratios. The optimization model's goal is to reduce costs in a variety of situations using input and technology-based data sets. Consequently, cost and investment requirements for various mitigation scenarios are estimated. The deployment of technologies, as well as CAPEX and OPEX costs, are what determine scenario-based costs. In LCP and FTS, investments are required due to capacity switching and capacity expansion.

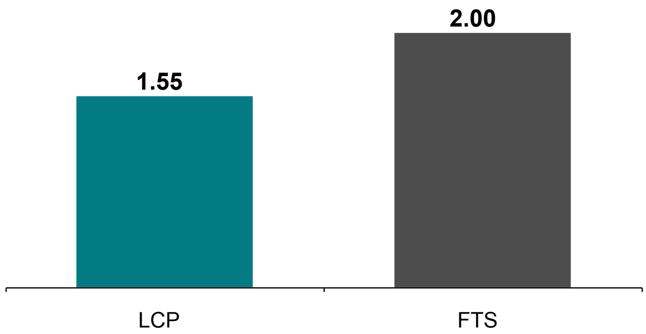
In LCP scenario there is a 0.96 billion dollars brownfield cost due to the technological transformation of the furnaces that are currently in use. There is an additional 2.73 billion dollars greenfield cost for the construction of new furnaces. As it is assumed the share of renewable energy in energy consumption will reach 50% by 2053, there is a renewable energy investment cost of 0.67 billion dollars. Thus, the total cost for LCP scenario is 4.37 billion dollars. Due to more rapid and aggressive technological transformation and higher renewable energy share the brownfield cost and renewable investment cost are significantly higher in FTS. 1.28 billion dollars of brownfield costs, 2.41 billion dollars of greenfield costs and 1.14 billion dollars of renewable energy costs adds up to a total investment cost of 4.82 billion dollars.

Figure 60. Total Investment Requirement Between 2023-2053 (Billion Dollars)



Based on the NPV of the total investment calculated using a discount rate of 7%, in the 2023-2053 period, the NPV of total investment costs is 1.55 billion dollars for LCP and 2 billion dollars for FTS.

Figure 61. NPV of Investment Between 2023-2053 (Billion Dollars)



3 The Roadmap for Progressive Decarbonization of Türkiye's Aluminium Sector

3. The Roadmap for Progressive Decarbonization of Türkiye's Aluminium Sector

Policy recommendations that together make up the decarbonization roadmap are refined from the outputs/insights gathered through desk research, workshops, and meetings conducted throughout the project, as well as sectoral know-how of experts and, most importantly, modelling outputs. Within an overarching methodology, policy recommendations are grouped under **Input and Technology** and **Policy and Market** high level policy themes, and under these two policy themes **12 main policy areas** have been generated. Following an overview of the policy roadmap, this section details the scope and justification for including these policy areas in the plan. Under each policy sub-section, Türkiye's current standing and announced strategies are also covered.

A) Input and Technology

1. Input Optimization
2. Technologies Reducing the Direct Carbon Output
3. Carbon Capture, Utilization, and Storage Technologies
4. Green Energy
5. Process Improvement
6. Inclusive Employment and Upskilling/Reskilling of Labour Force

B) Policy and Market

1. ETS
2. Trade Models
3. National Policy Documents
4. Green Transformation Finance
5. Cooperation
6. Circular Economy

3.1. Input and Technology

Decarbonization policy areas related to input and technology are detailed below. **Specific technologies** that have been prioritized by the model are distinguished with the **color green.**[53] Some of the technologies given below are not prioritized by the model results, however they are included in the policy roadmap because they are considered in the Technology Roadmap developed by the Scientific and Technological Research Council of Türkiye (TUBITAK).

- **Phase 1** (2023-2025)
- **Phase 2** (2026-2038)
- **Phase 3** (2039-2053)

[53] Technologies with less than 1% share in production capacity by model outcomes are not "prioritized" by this project's methodology.

	Application Time/Interval		
A.1) Input Optimization	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Take necessary actions to increase the utilization of recycled scrap in secondary aluminum production, which has significantly lower emissions compared to primary aluminum production.	●	●	
Develop technologies for manufacturing of metallurgical quality alumina from non-bauxite sources (such as alunite, clay) and for the enrichment and utilization of existing bauxite ores.	●	●	
Monitor Türkiye's scrap aluminium imports and develop strategies to support scrap aluminium supply in line with international dynamics.	●	●	
To control and reduce imported ingot embedded emissions in semi-aluminium processing, import primary aluminium from countries and suppliers with low emissions, and encourage suppliers to report and reduce their emissions.	●	●	●

	Application Time/Interval		
A.2) Technologies Reducing Direct Carbon Output	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Replace the boilers used in the digestion process in alumina refining with less emissive boilers (such as boilers working with electricity and Concentrated Solar Thermal-CST) and make feasibility and investment plans for their implementation.		●	●
Fuel switch, which is the only option to fully decarbonize the alumina calcination process, from fossil fuels to electricity or green H_2.	●	●	
Closely monitor the developments in inert anode cell technology, which is expected to be commercialized in the 2030s at the earliest and carry out the necessary feasibility studies.			●
Develop and integrate heat recovery systems for alternative use of waste heat generated in end-to-end aluminium production process.	●	●	
Prioritize use of lower emission furnaces in semi-aluminium processing and encourage companies to make investments in reverberatory furnaces with high energy and metal efficiencies and induction furnaces with electricity.	●	●	

	Application Time/Interval		
A.3) Carbon Capture, Utilization, and Storage Technologies	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
To increase Türkiye's Carbon Capture, Utilization and Storage capability; strengthen the financial (e.g. use of green financing instruments), legal (e.g. establish a regulatory framework using a clear taxonomy) and technical infrastructure (e.g. physical and human capital to carry out R&D and related entrepreneurial activities).	●	●	●
Evaluate integrating CCS technology in the electrolysis cells to reduce the emissions considerably.			●

	Application Time/Interval		
A.4) Green Energy	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Strengthen the national grid infrastructure to provide the renewable energy needed for aluminum production and provide incentives to the private sector to transition from fossil fuel to green H_2.	●	●	
Identify available and appropriate technologies to make green H_2 commercially available and cost-effective for the aluminium sector and conduct medium to long term supply planning at the national level.	●	●	●
Evaluate the use of low-emission small modular nuclear reactors (SMR) in primary production and semi-aluminium smelting processing.	●	●	●

	Application Time/Interval		
A.5) Process Improvement	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Install digital monitoring systems integrated with energy management systems and implement modern, innovative maintenance approaches in aluminum plants to increase energy efficiency, maximize production and reduce GHG emissions.	●		
Use advanced automation in electrolysis cells and smelting units for instant monitoring of parameters.	●	●	
Develop processes and methods to increase energy efficiency in secondary aluminium production from gathering the scrap through separation, including smelting.	●	●	●

A.6) Inclusive Employment and Upskilling/Reskilling of Labour Force	Application Time/Interval		
	Phase 1 (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Identify and invest in new qualifications, skills and trainings, differentiated for sub-sectors and regions, needed to promote the green transformation of the aluminium sector.	●	●	●
Ensure equal opportunities for all in the aluminum sector employment	●	●	●
Prepare and implement training programs to meet the workforce needs that will arise with the green transformation of the sector by carrying out studies to harmonize the education curriculum and higher education programs with the new skills framework.	●	●	●

3.2. Policy & Market

Decarbonization policy areas related to policy and the market are detailed below.

B.1) Emissions Trading System	Application Time/Interval		
	Phase 1 (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Establish an ETS in Türkiye in line with EU legislation and establish necessary mechanisms to incentivize green transformation for those operating in strategic sectors.	●	●	
Allocate free allowances for facilities emitting below the sector average, especially for emission-intensive sectors with high carbon leakage risk.	●	●	
To understand the economic costs of achieving mitigation targets and to determine the emission limits (within the scope of ETS/carbon pricing), prepare marginal abatement costs (MAC) for low carbon technologies and implementations in the aluminium sector.	●		

B.2) Trade Models	Application Time/Interval		
	Phase 1 (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Carry out studies to ensure that the practices in Türkiye meet the required qualifications and are recognized by the EU, in line with the principles of emission measurement and reporting under EU CBAM.	●		
Analyse actual / expected market shifts after EU CBAM and adopt measures to protect Türkiye's competitiveness.	●	●	●
Identify trade policy steps related to the implementation of EU CBAM to ensure the continuation of Türkiye's exports to EU countries.	●		

	Application Time/Interval		
B.3) National Policy Documents	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Carry out feasibility studies and identify priority areas for research and development (R&D) and innovation aspects that need to be evaluated at the national level with a comprehensive perspective.	●	●	●
Identify where national legislation differs from EU legislation and ensure coordination to secure full harmonization that protects the right to free movement of goods.	●	●	
Develop a clear and long-term plan, aligned with national energy and climate strategies, to achieve sustainable energy transition in the aluminium sector.	●		

	Application Time/Interval		
B.4) Green Transformation Finance	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Increase and expand the scope of current public incentives to increase energy efficiency in aluminum production facilities.	●		
Increase and expand the scope of current public incentives and support mechanisms for the deployment of low-emission technologies.	●	●	●
Mobilize private capital for the deployment of low-emission technologies.		●	

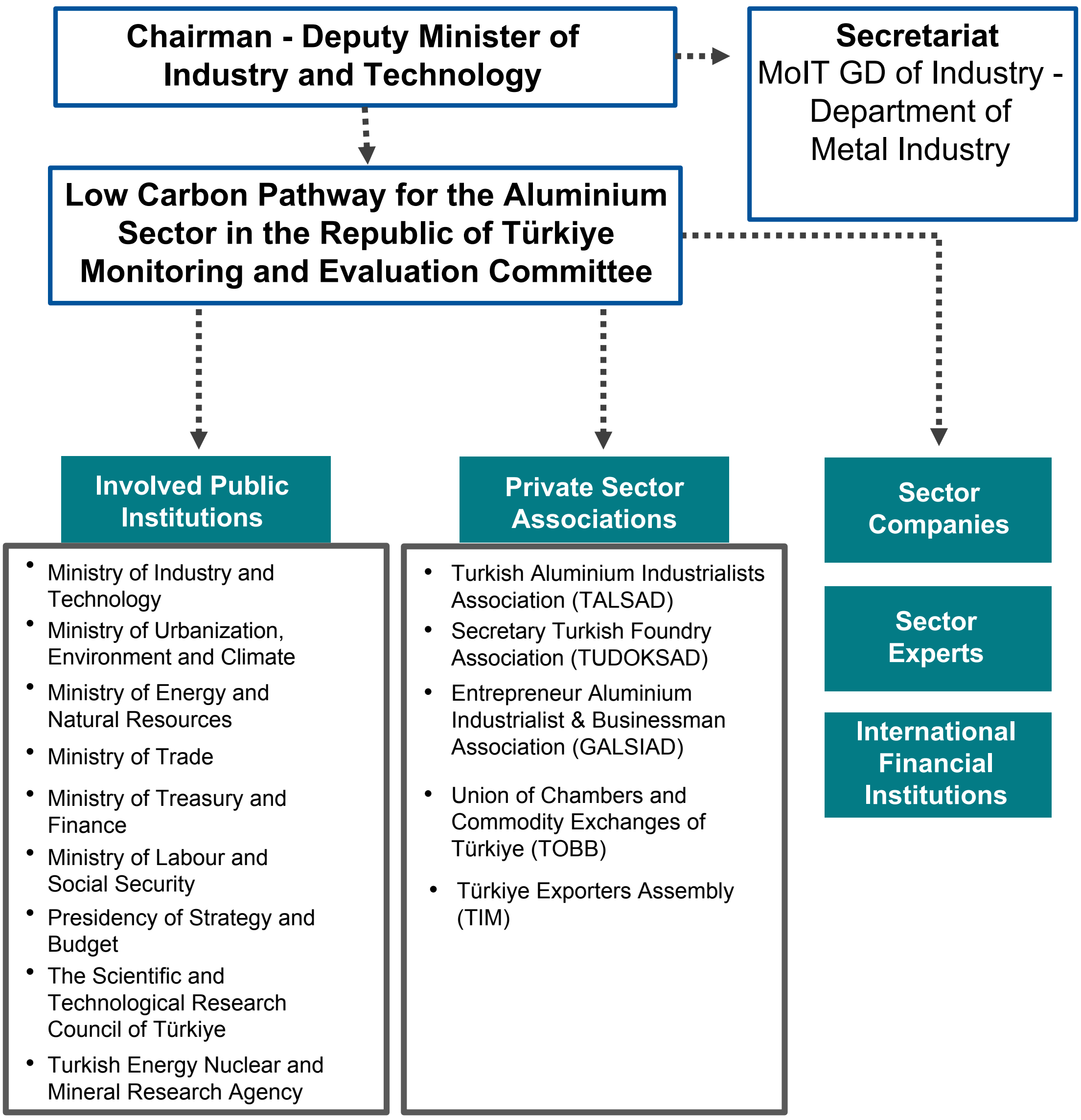
	Application Time/Interval		
B.5) Cooperation	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Create funding opportunities to carry out projects on energy and material efficiency and disseminate the outcomes of optimization studies to increase energy and material efficiency in all processes.	●	●	●
Increase collaboration and interaction for the voluntary adoption of internationally recognized standards by companies and encourage companies' involvement in international sectoral organizations (e.g. International Aluminium Institute, European Aluminium Association, European Aluminium Stewardship Initiative, etc.).	●	●	●
Ensure active participation and feedback from private sector stakeholders in the design of national emission reduction policies.	●		
Establish a database for monitoring the progress of aluminium industry on the low carbon pathway by involving ecosystem stakeholders such as ministries, chambers of commerce, engineering chambers, universities and NGOs.	●	●	●

	Application Time/Interval		
B.6) Circular Economy	**Phase 1** (2023-2025)	**Phase 2** (2026-2038)	**Phase 3** (2039-2053)
Use green technologies for metal recovery from slag and recycle residual waste.	●	●	
Carry out studies to recycle precious metals in the red mud produced in alumina production.	●	●	
Support the development projects of high quality, value-added, long-lasting and recyclable aluminium products to contribute to the decarbonization of end-user sectors using aluminium inputs and conducting studies to recover aluminum scrap from end-user sectors.		●	●
Develop methods and practices related to by-product and waste management in aluminium plants.	●	●	●

Monitoring and Evaluation Mechanism

Along with stakeholder mapping, monitoring the implementation of policy recommendations and their impact on the national aluminium sector is also of crucial importance. Therefore, to ensure that the high standards set for the delivery of the established roadmap are consistently met, a monitoring and evaluation mechanism that tracks and assesses the implementation process and results on a regular basis is a must. To this end, **a Monitoring and Evaluation Committee is proposed.**

Structure of the M&E Committee



4 Conclusion

4. Conclusion

Aluminium is a strategic manufacturing sector not only for Türkiye, but globally, touching many sectors downstream both in manufacturing and in services. While Türkiye's aluminium sector is mostly built on aluminium fabrication processes and semi-aluminium processing (as opposed to the larger primary aluminium production share of some industry leaders, such as China and Russia), the sector is responsible for considerable CO_2 emissions, nevertheless.

The aluminium industry is a strategic sector in Türkiye as it offers products for many areas, from automotive to white goods, defense to construction. As the EU is by far the industry's largest export partner, EU CBAM may have significant impacts on the competitiveness of aluminium producers in Türkiye unless the necessary measures and actions are taken to ensure decarbonization efforts. In addition, Nationally Determined Contributions under the Paris Agreement also call for decarbonization measures in the sector. In this context, this project aims to lay out a low carbon pathway for the aluminium sector in Türkiye, in line with the country's international commitments and decarbonization goals.

This extensive work boils down to two key areas of output: 1. modelling and scenario analysis and 2. A policy roadmap. The modelling and scenario analysis work aims to identify the optimal pathway for the decarbonization of the aluminium industry in Türkiye for the 2023-2053 period. In doing so, primary aluminium and semi-aluminium processing pathways are modelled separately to accurately reflect differences and nuances in these separate processes. Scope 1, 2 and 3 emissions are modelled under four scenarios (WoM, SPS, LCP, and FTS) and the optimum scenario (LCP) then sheds light on the amount of investment to be generated and policy actions to be taken as next steps. These next steps in turn form the policy roadmap, which defines the main intervention areas and specific measures necessary for the low carbon pathway.

Overall, this project finds that CO_2 emissions from semi-aluminium processing and emissions embedded in imported raw materials are of greater significance in Türkiye than primary aluminium manufacturing. In Türkiye's aluminium sector's low carbon pathway, emission reduction in primary manufacturing will depend on radical technological upgrades such as inert anodes and process improvements, while semi-aluminium processing decarbonization will be supported mainly by optimizing input use, energy, and material efficiency. Introduction of new technologies in furnaces in semi-aluminium processing and securing necessary investment for this will be critical. A final key area of action will be close monitoring of countries from which ingots are imported, to manage embedded emissions in these products. Furthermore, finding scrap sources inside and outside the country and increasing secondary aluminium production capacities are vital.

The study estimates the total NPV cost of investments is approximately 1.7-2.2 billion dollars, and the decarbonization trajectories recommended highlight the need for development of financing mechanisms and plans. Therefore, measures for boosting the mobilization of additional funds should be prioritized in the short term to enable the aluminium industry to make the necessary technological transformation in the medium to long term. Policymakers and financial institutions need to collaborate and develop new and innovative financing mechanisms, so Türkiye's aluminium industry has access to scaled-up capital flows to foster decarbonization investments.

Implementation of this roadmap will require the continuous support and effective coordination of all stakeholders. The proposed monitoring and evaluation committee should play a leading role in following the developments affecting the aluminium sector, and the committee should upgrade the established forecasts and policy framework when needed and guide all stakeholders in implementing the policies under their control and ownership.

5 Annex

5. Annex

Annex 1: ETS and EU CBAM Effect on Projections

Türkiye's vs. EU ETS and its Potential Effects on the Aluminium Industry

Three scenarios have been developed by incorporating projections for the EU CBAM and the planned domestic ETS into projections.

For the first scenario, aluminium sector projections are made without considering any ETS or EU CBAM. Exports are not expected to be affected in any way since no additional carbon mechanism or pricing is defined in this scenario.

Figure 62. Carbon Price Projections Under EU ETS vs. TR ETS (Euro)

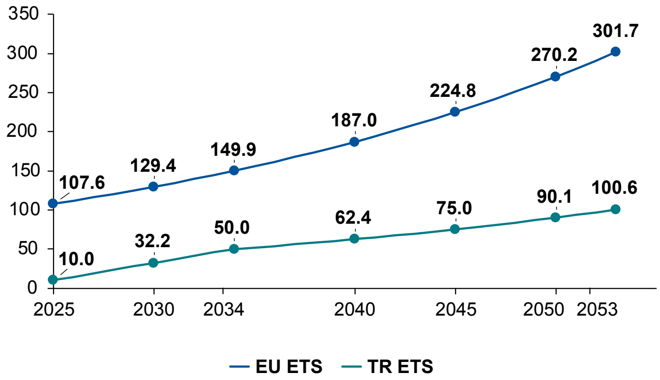
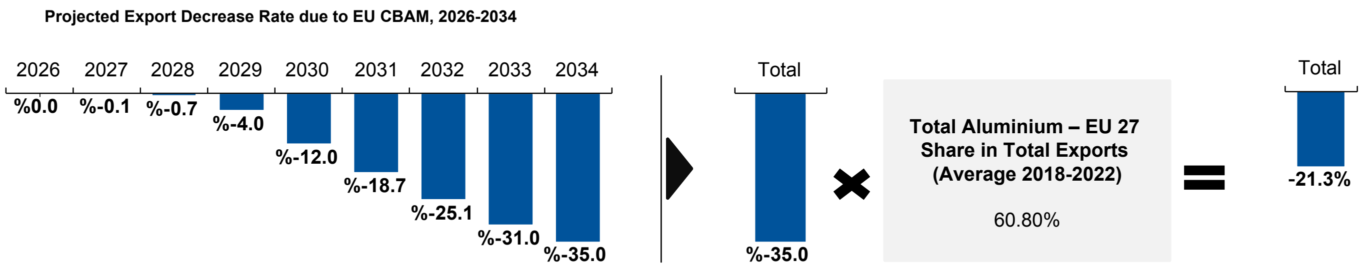


Figure 63. Projected Export Decrease Rate[55]



For the other scenarios, the domestic ETS is assumed to be operational in 2025 and EU carbon prices are assumed to average 100 euros in 2023 and rise to 150 euros in 2034, when the EU CBAM will be fully operational, and to ~300 euros by 2053. In the second (TR ETS<EU ETS) scenario, carbon prices in Türkiye are projected to start at 10 dollars in 2025 and reach 50 dollars in 2034, after which they increase at the same pace as EU carbon prices. In the third scenario (TR ETS=EU ETS) Türkiye's carbon prices are assumed to be the same as EU carbon prices starting from 2025.

In the TR ETS<EU ETS scenario, aluminium sector exports are assumed to be negatively affected by 35% in 2034, based on the EBRD study.[54] For the prior years, the rate is calculated based on the assumption that the sector's exports would be negatively affected by the phasing out of free allocations and positively affected by Türkiye's carbon price being approximately equal to the European carbon price. The rate at which aluminium sector exports would be affected is calculated based on the share of exports to the EU. In the third scenario, it is assumed that exports would not be affected in any way as prices would be equal, but this scenario would increase costs in domestic production due to higher a ETS price.

[54]BRD & Climate Focus (2022). Potential Impacts of the Carbon Border Adjustment Mechanism on the Turkish Economy.

[55]ibid

Annex 2: Types of Furnaces Used in Semi-Aluminium Processing

Reverberatory Furnace: This type of furnace is commonly used for melting ingots and scrap aluminium. It is a stationary furnace that typically uses natural gas as an energy source. The furnace is lined with refractory materials to protect the furnace walls from the heat of the flames. Reverberatory furnaces are divided into five technology levels.

1. **Conventional Reverberatory Furnaces:** These are the simplest reverberatory furnaces, and they are frequently used to melt low-grade aluminium scrap. They have a single burner and little control over the temperature of the environment. Conventional reverberatory furnaces have low efficiency, high energy use, and high emissions.

2. **Improved Reverberatory Furnaces:** These furnaces are designed to enhance energy efficiency and reduce emissions compared to conventional models. They typically have multiple burners and advanced combustion control systems that allow for better temperature control and heat recovery. Some improved reverberatory furnaces also incorporate preheating zones to reduce fuel consumption.

3. **Advanced Reverberatory Furnaces:** With even greater levels of energy efficiency and environmental performance, these furnaces represent the most recent advancements in reverberatory furnace design. Advanced models might have features like automated controls, waste heat recovery systems, and advanced combustion systems. They are employed in specialized applications where precise temperature control and high efficiency are essential.

4. **Highly Advanced Reverberatory Furnaces:** The best available technology in reverberatory furnaces with the lowest emissions and energy consumption. These furnaces reduce emissions and energy consumption by using oxygen-enriched air to combust fuel, which results in higher temperatures and more efficient combustion. This combustion method also reduces emissions of other pollutants like nitrogen oxides (NO_x) and particulate matter.

5. **Electric Reverberatory:** These furnaces use electricity as the main input and so produce only scope 2 emissions. Electric reverberatory furnaces are typically employed for melting and refining aluminium scrap. The electric heating elements in the furnace generate the necessary heat to melt the aluminium, while the reverberatory design allows for effective heat transfer and mixing of the molten metal.

Rotary Furnace: Due to their capacity to melt a range of scrap, rotary furnaces are also referred to as multi-purpose melting furnaces. The furnace design allows high heat transfer, rotational motion, and flux, making it suitable for melting many different scraps, including slag. The furnace works by rotating the charge through the furnace, which is in direct contact with a gas burner, or a refractory wall directly heated by the burner.

Crucible Furnace: Crucible furnaces, also known as pit furnaces, are of small capacity and are typically used for melting small quantities. These furnaces can be operated with pure scrap, ingots, or molten aluminium. The aluminium is placed or poured into a ceramic crucible contained in a circular furnace which is fired by a burner. The energy is applied indirectly to the metal by heating the crucible. Installation costs are low and no technical expertise is required.

Induction Furnace: This type of furnace uses electromagnetic induction to melt aluminium scrap. The furnace is made up of a coil of copper wire that generates an electromagnetic field when an electric current is passed through it. The electromagnetic field heats the scrap aluminium, melting it for reuse. The main advantages of this furnace type are the ability to change alloys quickly, temperature control, low oxidation, and high liquid quality. The disadvantages are size limitations, high investment requirements, and operating cost.