


Pathways to Decarbonization

A North American Aluminum Roadmap

May 2024

ICF

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I. Executive Summary

Objective

The North American Aluminum Industry Decarbonization Roadmap (Roadmap) documents the Aluminum Association's (AA) most recent work to identify potential pathways and strategic options for the North American (NA) aluminum industry to reduce its carbon emissions by 2050 and support achieving the global climate goals set by international agencies and climate institutions.

Methodology

The Roadmap is based on an Excel spreadsheet Model developed to integrate a combination of market assumptions and technology deployment scenarios to project greenhouse gas (GHG) emission reductions through 2050. The Model uses a baseline inventory year of 2021, for which the AA provided data on both production activities and carbon intensities of the production activities.

The Roadmap covers all GHG (including CO_2 and non-CO_2) emissions associated with the manufacturing of aluminum products. From a corporate perspective, the emissions covered include all three scopes. From a product perspective, the emissions covered include all emissions associated with cradle-to-gate production activities.

Emission projections are influenced by three key elements: market dynamics, carbon intensities and the adoption of impactful technologies. The Roadmap is a result of the selection of assumptions and the modeling of scenarios of these key elements.

The Model is also highly flexible and dynamic in which different scenarios can be switched to evaluate the consequences of changing assumptions and circumstances.

Key Findings

To be aligned with the emission "budget" for global heavy industries projected by the International Energy Agency (IEA) in its Net Zero by 2050 model, the NA aluminum industry needs to reduce its annual total emissions by 92% by 2050 compared to the baseline year level in 2021, at the same time aluminum product output will increase by 78%.

To achieve such a level of emission reduction, the NA industry needs to reach several major milestones that is shown in **Table ES 1** below:

Table ES 1: Emission Reduction Schedule of the Decarbonization Roadmap, Compared to the 2021 Total Emission Level

	2025	2030	2040	2050
Potential Emissions Reductions	3%	24%	63%	92%

Each of these milestones has a combination of technological and strategic options associated with it and an assumed schedule of adoption and deployment. Major options identified and their schedules of adoption and contribution of reduction are shown in **Table ES 2** below.

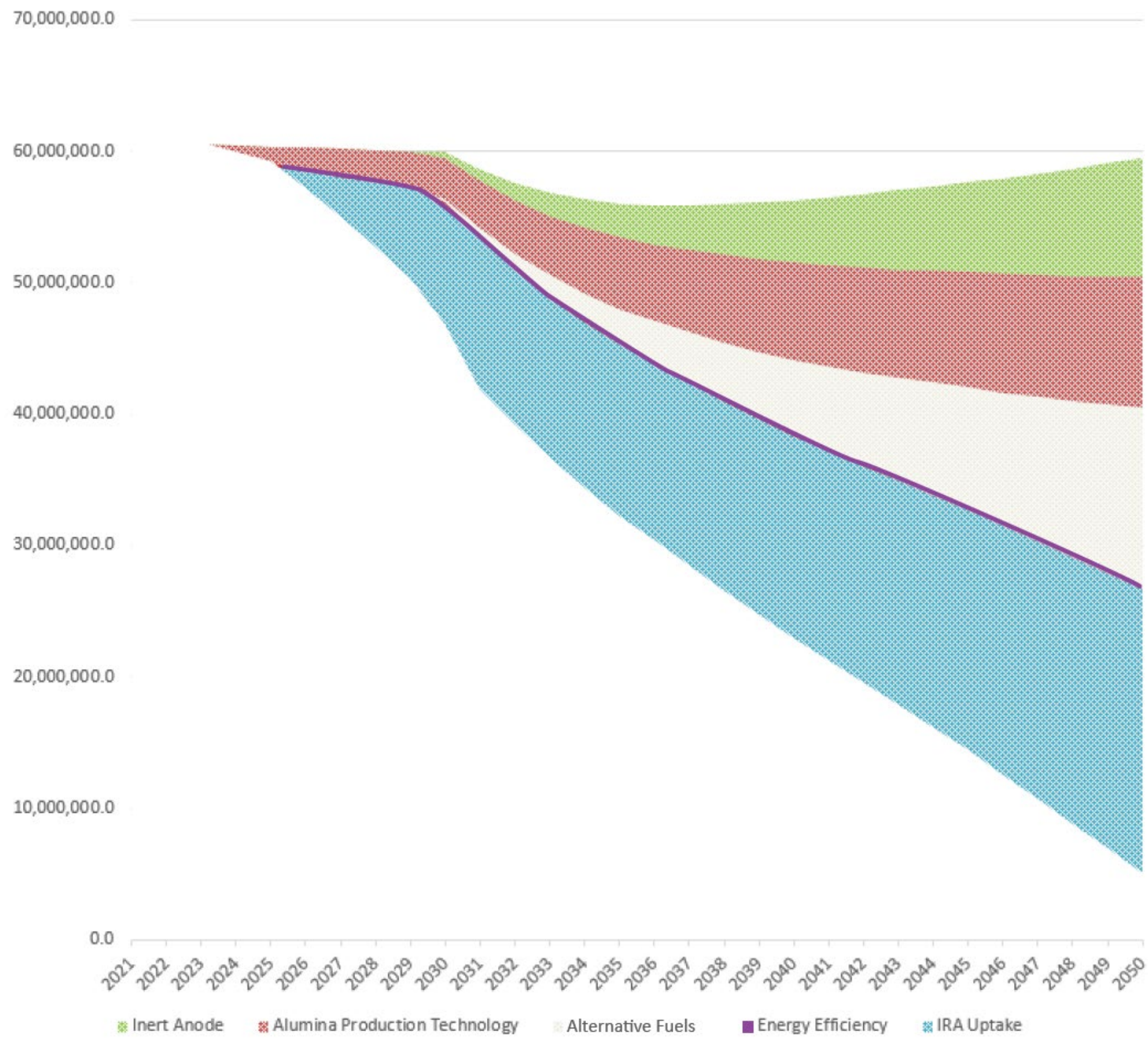
Table ES 2: Major Options for Emission Reduction, Assumed Adoption Schedule and Contribution to Reduction by 2050

Technology	Deployment Timeline	Percent Reduction Contribution by 2050
Inert Anode (or Similar)	2030-2050	15%
Alumina Production Technology	2023-2050	17%
Natural Gas Phasedown	2030-2050	23%
Electrification of furnaces	*Up to 30% of the covered furnaces would be electrified by 2050*	*30%**
Fuel switching	*50% of furnaces would be fuel switched to green hydrogen by 2050*	*53%**
Carbon capture and sequestration (CCS)	*Remaining 20% of natural gas furnaces integrate CCS technology by 2050*	*17%**
Energy Efficiency	2025-2050	0.01%
Power Grid Decarbonization High IRA Uptake	2023-2050	36%

**Indicates the percent contribution to the total reduction from natural gas phasedown by 2050*

Figure ES 1 below illustrates the total emission reduction potential (shaded area) of each of the impactful technologies. Among the options, grid decarbonization and natural gas phasedown have the largest emission reduction potential, followed by inert anode technology and cleaner alumina production.

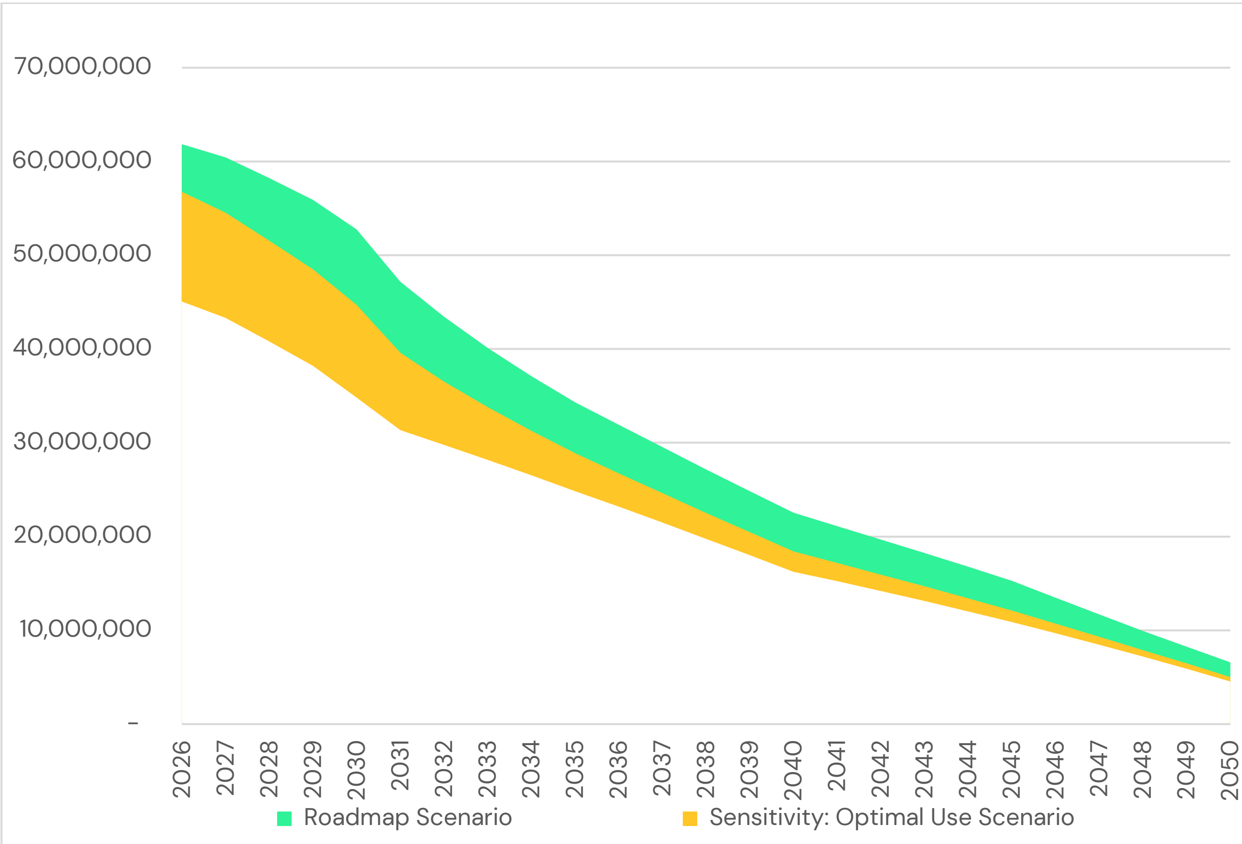
Figure ES 1: Emission Reduction Potential of Each Impactful Technology



In addition to the technologies, aluminum recycling plays a key role in emission reduction in this Roadmap through a predetermined scrap utilization scenario named Constrained Scrap Utilization. Under this scenario, the use of recycled metal to make aluminum products by NA domestic producers will be increasing from 48% today to 71% by 2050. This will help avoid the use of primary metal, which is energy and emission intensive to produce, and eliminate the associated GHG emissions by 127 million metric tons CO_2e.

More importantly, the NA market is projected to have more scrap available in the future to be further utilized to reduce emissions if the scrap supply industry could adopt better scrap sorting technologies and change its current practices. Improved scrap sorting could further help increase emission reduction more economically and effectively through a more optimistic scenario namely Optimal Scrap Utilization. Under this scenario, a total of 37 million metric tons of primary aluminum production could be **further** avoided and it will help eliminate an **additional** 160 million tons CO_2e of emissions. **Figure ES 2** shows the role of recycling in decarbonization.

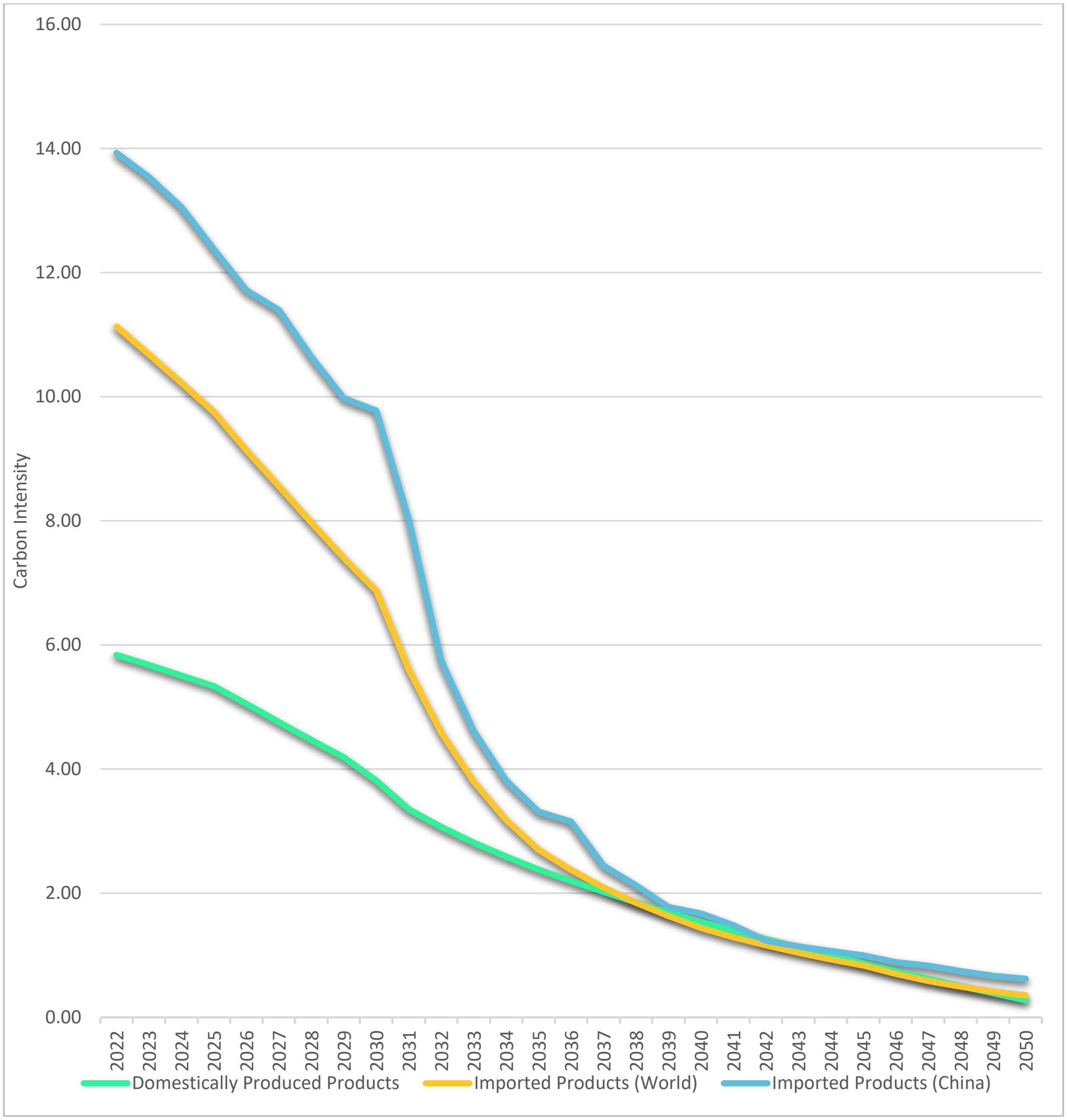
Figure ES 2: The Role of Recycling in Decarbonization



On top of mapping an emission reduction pathway for NA domestic production, emissions associated with international trade have also been thoroughly evaluated. Striking emission differences between domestically produced and imported aluminum products highlight the need for an overall emission reduction strategy that's both comprehensive and integrated for the entire NA consumer market. It also highlights the need for future trade policies to incorporate emission considerations.

Figure ES 3 shows the difference in projected emission intensities between aluminum products produced by NA domestic producers versus importing them from the rest of the world or from China. Overall, the current emission intensity of aluminum products produced in **China** is **2.5 times** of NA domestic products, and the **global** aluminum product carbon intensity is **1.9 times** of NA domestic products. These significant differences are projected to continue until well into the 2030s. Overall, the carbon intensity of NA domestic products will stay below China and the rest of the world during the entire Roadmap timeline.

Figure ES 3: Projected Carbon Intensity Differences Between Aluminum Semis Produced by NA Domestic Producers and Imported from the World or China



Key Challenges

Some of the key challenges uncovered by this Roadmap include:

- **Exogenous factors:** This refers to the emissions included in the assessment over which the NA aluminum industry has limited control. These include the national grid decarbonization, and the emissions associated with the imported alumina, primary aluminum and aluminum products. In terms of decarbonization strategies, there is value in prioritizing variables and strategies that fall within the operational boundaries of the NA aluminum industry.

- **Uncertainty around technology deployment:** Certain technologies considered for this Roadmap have been recognized by the industry as having great emissions reduction potential, however many of them are in the early stages of R&D, development or deployment, thus are associated with high uncertainty in terms of their actual emission reduction level, the scale of deployment and the anticipated deployment timeline.
- **Economic feasibility:** Assessing economic feasibility is essential for successful decarbonization of any industry, including aluminum production. The financial cost of reducing emissions by 2050 is unlikely to be met through industry investments alone. Moreover, the majority of investment needed to decarbonize the aluminum sector are likely to take place outside of aluminum facilities – in electricity generation and transition away from natural gas, among others. Although not verified by ICF or the AA, the Mission Possible Partnership's (MPP) Aluminum Transition Strategy states that a cumulative investment of approximately $1 trillion across the primary production value chain is necessary for meeting global net-zero climate goals by 2050. MPP further notes most of this investment will be needed in power supply and smelters. With North American primary aluminum accounting for about 6% of global production, an investment totaling approximately $60 billion for the region is needed to meet global net-zero climate targets in the primary production segment alone. It is important to note uncertainties associated with the projections of the future, including regulatory environment on climate change, policy development, market forces, energy supply and the role of international trade, all contribute to potential inaccuracies of integrating economic feasibility in a meaningful way to assess the next three decades in time. This report is the initial step to guide any future work that would integrate practical considerations for a realistic economic feasibility, which should be informed by a comprehensive stakeholder engagement.

Next Steps

The Roadmap only serves as a guidance and a monitoring tool for emission reductions. It is the starting point, not the end of an envisioned long and difficult journey. More work can be done to refine the Model to add more values to the Association and its members. The transition to a low carbon economy and the fight against climate change is too big of a task to be dealt with alone by any single business group, industry, community or country. This report calls for support from all stakeholders to help the NA aluminum industry to decarbonize its operations.

II. Introduction

The objective of the North American Aluminum Industry Decarbonization Roadmap (Roadmap) is to identify potential pathways and strategic options for the industry and its stakeholders to decarbonize the manufacturing of aluminum products so that by 2050, the greenhouse gas (GHG) emission profile of the industry will be aligned with the UNFCCC Paris Agreement's preferred climate change control target (limiting temperature increase to 1.5°C). In addition, the Roadmap is intended to illustrate several key aspects of the North American (NA) aluminum market including current demand and supply in the region, the emission profiles associated with "domestically" produced versus imported products, projected growth in demand and supply, and the difference in projected emission reduction pathways for domestically produced versus imported products. The outputs of this assessment effort include this public facing Decarbonization Roadmap report and a Microsoft Excel-based model developed by ICF and delivered to the Aluminum Association (AA) for internal use to benchmark and monitor emission reductions over time, along with simulating other scenarios and sensitivities embedded in the model.

In the context of this Roadmap report, the NA industry refers to the producers of aluminum metal and aluminum semi-fabricated products in Canada and the United States. Per the AA's assessment, the industry in the two countries is considered highly integrated in both operations and logistics (including ownership considerations), but most importantly represent a single value chain in which one country's focus of production activities is highly dependent on the other country. Canada is mainly a producer and supplier of primary aluminum metal and supplies roughly 60% of the total primary metal demand in the United States. Meanwhile, the United States is a main producer of secondary metal and semi-fabricated products. Other than serving U.S. demand, a significant proportion of the output in the United States is shipped back to Canada to supply the majority of the industrial and consumer demands in the country. For simplicity, the term "domestic" in this Roadmap report refers to both countries combined.

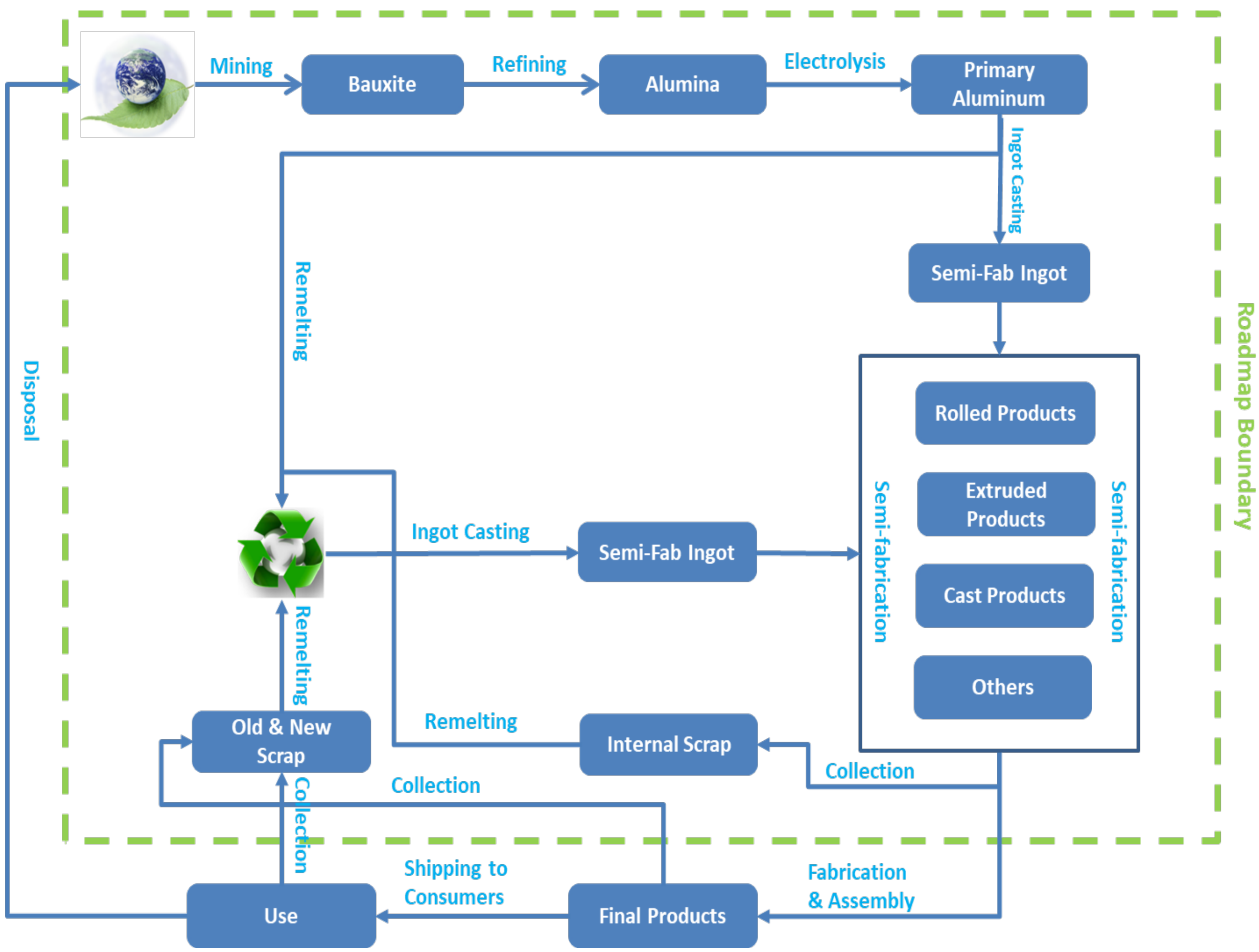
Aluminum metal in this report refers to raw metal used as a feedstock material for making aluminum products. The metal is either ore-based – known as primary metal, or scrap-based – known as secondary or recycled metal. Semi-fabricated aluminum products (semis) refer to alloyed aluminum that is processed into unique shapes and profiles through a variety of metal working techniques such as casting, extrusion, forging and rolling. Semis are usually further processed by downstream end-users into industrial and consumer products such as automobiles, airplanes, building components, electrical conductors, kitchen utensils and home appliances, and the like.

The GHG emissions covered by this Roadmap include emissions associated with producing both the raw metal and the semi-fabricated products within the boundaries illustrated in **Figure 1**, and for the activities illustrated in **Figure 2** in the next section.

From a corporate emissions perspective, the Roadmap covers all emissions of scope 1, 2 and the upstream (supply chain) of scope 3. From a product emissions perspective, it covers all cradle-to-gate emissions associated with the production of semis including energy use, transportation, process chemical reactions, etc.

On the other hand, the Roadmap does not cover emissions associated with the manufacturing activities by the downstream end-users, nor does it cover the use-phase and the disposal (if any) of the products. Detailed illustration of the Roadmap system boundary is shown in **Figure 1** below.

Figure 1: Decarbonization Roadmap System Boundary



The project was commissioned by the AA to respond to an increasing demand from stakeholders for a science-based target approach to reduce GHG emissions associated with aluminum products, and the potential challenges, opportunities and strategic options available to the aluminum industry and its value chain stakeholders. Similar work has been done in the aluminum industry. Both the International Aluminium Institute (IAI) and the Mission Possible Partnership (MPP) have done work to map the global industry's pathways to net-zero emissions that are in alignment with a 1.5 degrees Celsius pathway by 2050.[1] The Aluminium Stewardship Initiative (ASI) has published ASI entity-level GHG pathways method and tool documents. At the regional level, European Aluminium (EA) has published a Science-Based Decarbonization Pathways for the European Aluminium Industry.

The IAI work was based on a set of scenario data of Net Zero by 2050, provided by the International Energy Agency (IEA) for aluminum. The IEA's aluminum data is considered as the net-zero aligned carbon "budget" for the global aluminum industry. Under the IEA's Net Zero by 2050 scenario, global heavy industries are "budgeted" to have a total direct emission of 0.5 gigatons CO_2e in 2050.[2] The MPP work utilized data from IAI to develop an Aluminum Transition Strategy for the global primary metal production operations. The Aluminum Transition Strategy identifies electrical power decarbonization, technology deployment to reduce direct process emissions and increasing the use of recycled aluminum as some of the key components to achieve a net-zero emission profile by 2050. In addition, the MPP work estimated that a total of $1 trillion investment is needed during the next 30 years for the global primary aluminum industry and its stakeholders to achieve a transformation to net-zero emission productions.

This Roadmap is building on the same basis as the IAI and MPP work with a focus on the NA market. This Roadmap aligns with the IAI global decarbonization model in terms of goals, scopes and boundaries, methodologies, classifications of emissions, and production activities and product groups. In addition, projections on future demand for aluminum in the NA market were provided by the AA and it aligns with IAI's global growth projections.

The Roadmap is unique as it incorporates the flow of aluminum products and their emission profiles through international trade between North America and the rest of the world (RoW). The traded aluminum products covered in the Roadmap not only include semis, which can be identified by the relevant international trade codes such as the Harmonized Tariff Schedule (HTS), but also include aluminum that is embedded in other products and goods that are represented by different trade codes. This unique feature of the Roadmap allows for the NA aluminum industry and its stakeholders to effectively compare emissions

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[1] Making-1.5-Aligned-Aluminium-possible.pdf (missionpossiblepartnership.org)

[2] Net Zero by 2050: A Roadmap for the Global Energy Sector, International Energy Agency. Available at: Net Zero by 2050 – Analysis - IEA

associated with domestically made and imported aluminum products, thus integrating trade considerations that can be part of a decarbonization strategy.

Lastly, this Roadmap only focuses on identifying technological options for emission reductions. It does not evaluate economic costs and economic feasibility of the identified emission reduction options. Assessing economic feasibility is essential for successful decarbonization of any industry, including aluminum production. The financial cost of reducing emissions by 2050 is unlikely to be met through industry investments alone. Moreover, the majority of investment needed to decarbonize the aluminum sector are likely to take place outside of aluminum facilities – in electricity generation and transition away from natural gas, among others. Although not verified by ICF or the AA, the MPP's Aluminum Transition Strategy states that a cumulative investment of approximately $1 trillion across the primary production value chain is necessary for meeting global net-zero climate goals by 2050. MPP further notes most of this investment will be needed in power supply and smelters. With NA primary aluminum accounting for about 6% of global production, an investment totaling approximately $60 billion for the region is needed to meet global net-zero climate targets in the primary production segment alone.

It is important to note uncertainties associated with the projections of the future, including regulatory environment on climate change, policy development, market forces, energy supply and the role of international trade, all contribute to potential inaccuracies of integrating economic feasibility in a meaningful way to assess the next three decades in time. This report is the initial step to guide any future work that would integrate practical considerations for realistic economic feasibility, which should be informed by a comprehensive stakeholder engagement.

At the present, this Roadmap and the Model it was stemmed from are meant to be informative tools that can be used:

- To identify emission reduction options and trade-offs, and project overall emission intensities of aluminum products for the coming decades;
- As a base for communication purposes, including policy evaluation, stakeholder engagement and discussing further refinements to decarbonization strategies;
- To benchmark the industry's progress in reducing emissions over time, integrating up-to-date market and other data, including from the AA's upcoming online sustainability data collection platform.

The Model behind the Roadmap was developed using a dynamic, Excel-based tool that inventories current emissions for NA aluminum manufacturing activities and integrates specific factors that impact the overall emissions. The Model utilizes a baseline year (2021) based on actual market and emissions data and projects future scenarios to illustrate different pathways for emissions reductions into 2050. The emission projection scenarios are based on specified assumptions developed for future years that are both documented in the Model and described in this report. The assessments of market dynamics, technological feasibility and possible implementation schedule of selected decarbonization measures are all based on provision of data from AA and feedback from the Stakeholder Consultation Sessions in which members of AA and sister organizations participated. As the industry progresses, the Model tool will continue to support assessments and track progress toward emission reductions.

This report describes the development process and the results of the Decarbonization Roadmap for the NA industry. Key components of the Model used to generate emission scenarios and reduction pathways and the selection of major assumptions for the Roadmap scenario are described in Section III. Results of the Decarbonization Roadmap are shown in Section IV. The conclusions and recommendations are given in Section V. The Appendix provides additional information for the Model's capabilities and boundaries.

III. Elements of the Model and Key Assumption Selections for the Roadmap Scenario

Elements of the Model, including structure and underlying data and assumptions, are the results of decisions made in consultation with AA and its members, or a reflection of a proxy assumption (informed by literature review or industry input) to bridge specific data gaps. **Table 1** shows the dates on which technical consultation sessions were held to inform and discuss interactively with industry stakeholders about assumptions in the Model, and a combination of key assumptions selected to generate results and conclusions for the report. Members were engaged throughout the development of the model tool to discuss Roadmap elements and to reflect current industry priorities and considerations.

Table 1: Stakeholder Engagement Sessions on Technical Topics

Stakeholder Meeting Date	Technical Session Topics
April 18, 2023	Development of 2021 baseline and market projection assumptions
August 30, 2023	Market dynamics assumptions (prioritization to meet the demand) and baseline carbon intensity for domestic productions
September 14, 2023	Building carbon intensity projections for impactful technologies
January 29, 2024	North American decarbonization scenario and results

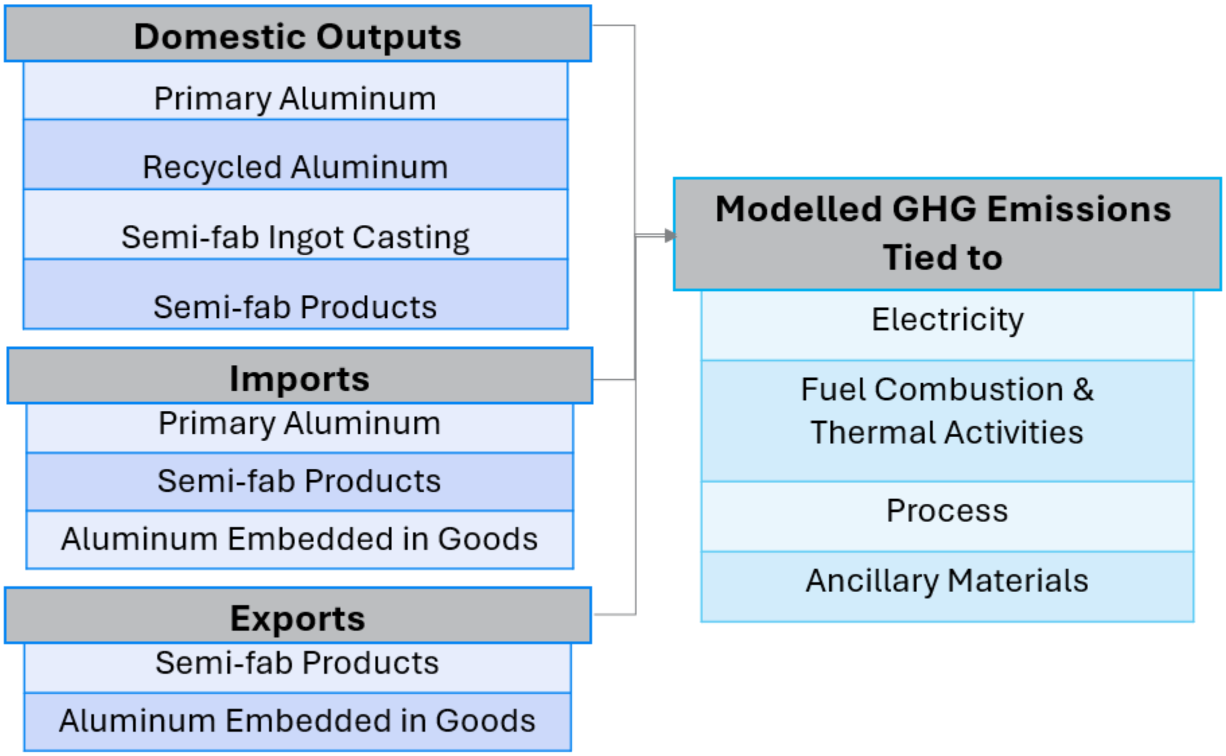
Three technical focus areas were identified as key elements of emission projections:

1) Market dynamics
2) Carbon intensity (CI) values
3) Adoption of impactful technologies

Initial inputs and assumptions were developed based on the data provided by AA, and additional industry research and results were presented to stakeholders at technical consultation sessions to get feedback and revise assumptions as needed. Each technical consultation session focused on different components of the model to get direct input and feedback. The model was built and revised simultaneously along with the technical consultation session schedules and was finalized in January 2024.

Member input was critical to help identify key areas for adjustments, and members helped refine data and prioritize emission reduction options. For example, an initial assumption was made for the CI tied to Canadian electricity (used for aluminum smelting) to be zero under the assumption that hydropower generation was assumed to have negligible emissions. Stakeholder feedback helped identify a more accurate CI value to assign to hydropower electricity generation which accounts for the methane emissions from dam infrastructure. Such feedback was critical for building a more accurate model that accounts for the complete direct and indirect emissions within the project scope and boundaries. **Figure 2** shows the major breakdown categories in which emissions are separately quantified and modeled.

Figure 2: Emission Boundaries and Classifications



The collaborative development process resulted in a range of selections and user inputs impacting the projected CI values and market dynamics for the Decarbonization Roadmap. Below is a summary of the major components for the three technical focal areas. Additional descriptions of the Model inputs are presented in Appendix 1: Additional Model and Assumptions.

i. Market Dynamics

Market dynamics help determine the volumes of future production and trade activities and thus fundamentally affect future emissions. The market dynamics considerations encompassed different scenario projections in terms of demand and supply in the region. Demand refers to the apparent demand for aluminum products by consumers in the two countries. Aluminum products are denoted in the form of semis to be consistent with the scope and boundary of the project. Supply refers to the supply of both products (semis) for downstream end-users, and the supply of raw materials used as feedstock to make the products. Volumes of demand for various products are used to determine volumes of supply through a backward tracking exercise, thus quantitatively identifying all relevant production activities and operations along the entire supply chain and calculated emissions associated with them.

Data Sources

The data used to build the market dynamics scenarios was provided by AA. Aluminum products (i.e., semis) are supplied by both NA domestic producers and importers. While the supply of products by domestic producers is straightforward from a statistical data point of view, the supply of products by importers is more complex. This is because international trade data can only capture a proportion of the actual traded volume. The complexity exists with the international trade codes. The aluminum-related Harmonized Tariff Schedule (HTS) codes can only identify products that are classified as aluminum. However, they cannot identify aluminum that is embedded in other goods and products since those are represented by non-aluminum HTS codes. These aluminum-containing goods and products include vehicles, machines, renewable energy devices, home appliances, building components, aircraft and the like.

The volume of aluminum embedded in traded goods has not been traditionally well understood by the aluminum industry given the hundreds of categories of goods that could contain aluminum, and the content of the metal could vary significantly among them. Nevertheless, this project has managed to utilize research data provided by the University of Michigan to determine an annual approximation based on historical trade data for North America and the rest of the world during the past 60 years. The University of Michigan's research was funded by the REMADE Institute, which was established and funded by the U.S. Department of Energy (DOE) to develop recycling and remanufacturing technologies. The AA was a research partner of the REMADE project, and it helped the University of Michigan build the material flow analysis (MFA) model which generates estimated annual volume of aluminum embedded in trade goods. This critical data contribution from the REMADE project is greatly appreciated.

In addition to data for aluminum embedded in traded goods, data on the availability of end-of-life (EOL) scrap for the past, present and future in the NA region is also provided by the University of Michigan. EOL scrap availability is a critical component for modeling the supply of raw materials, and data for such availability can only be estimated through MFA research, which is a result of the aforementioned REMADE project. AA has high confidence in the quality of such data due to its involvement in research projects.

Key Assumptions on Market Dynamics for the Model Development

In building the market dynamics of the Model, actual statistical data for the baseline year of 2021 was used to project the future, allowing for different assumptions to be incorporated. Several critical assumptions were made:

1) **Forms of semis in demand**. The relative shares of various forms of semis (i.e., flat-rolled, extruded, cast, forged and other) as a percentage of the total in the baseline year are assumed to stay constant (from 2021 proportions) for future years.
2) **Growth in demand**. Consumer demand for semis is assumed to be growing at an annual rate of 1% - 2% from 2021 to 2050. A 1% growth translates to an accumulative growth of 33% by 2050, and a 2% growth translates to an accumulative growth of 78% by 2050.
3) **Total domestic apparent demand in baseline year**. Net consumer demand for semis in Canada and the U.S. was determined to be approximately 13.8 million metric tons (MT) in 2021.
4) **International trade**. The international trade scenarios in the Model specifically refer to the imports and exports of both semis and aluminum embedded in goods. It is worth to note that international trade also includes the import (export from NA to the RoW is negligible) of alumina and primary aluminum metal but they are treated by the Model as part of the domestic emission profile because they are used as a feedstock for domestic semis production. International trade of semis and aluminum embedded in goods is assumed to be in three scenarios, with one considered to be realistic, and two others to be unrealistic to evaluate the theoretical potential impact of trade on emissions:
   - **Realistic scenario**: trade business as usual (BAU), in which the shares of imports and exports as the percentage of the total demand of semis will not change from 2021 to 2050 (i.e., trade will grow at the same growth rates as demand growth).
   - **Unrealistic scenario one**: no trade of semis and BAU trade of aluminum embedded in goods.
   - **Unrealistic scenario two**: no trade of either.

On top of the above, several other critical assumptions are made regarding the supply of raw metal for semis production. The production of primary/virgin raw materials usually has the highest impact on the overall emissions. On the other hand, using secondary raw materials can greatly reduce emissions. For aluminum products, raw materials can be supplied by both primary metal and recycled metal. The two metal sources lead to significant emission differences. Considerations in the availability of both metals and the practical barriers on utilizing them lead to the following key assumptions:

1) **Domestic primary aluminum capacity**. Domestic primary aluminum production capacity and output are assumed to be in three scenarios:

- o No change
- o Balanced in closing old and building new capacity
- o Increasing capacity

2) **Utilization of available scrap**. Utilization of available scrap is assumed to be in two scenarios:
   - o **Constraint scrap utilization** due to contamination and mixed alloy in the current scrap supply chain.
   - o **Optimal scrap utilization** assumes scrap can be supplied with well-sorted and highly clean quality.
3) **Import of primary metal**. As mentioned, imported primary aluminum is considered as part of the domestic emission profile. The quantity of importing it from other countries is assumed to be a function of the scrap utilization scenarios:
   - o Under the constraint scrap utilization scenario, the quantity of imported primary metal remains unchanged from 2021 to 2050;
   - o Under the optimal scrap utilization scenario, the import of primary metal is assumed to be zero between 2022 and 2050.
4) **Scrap exports and imports.** Based on the balance of the above three, any extra amount of unutilized scrap is assumed to be exported (and it was the reality for the baseline year 2021), with the priority of export assigned to EOL scrap since new scrap is clean and sorted, and thus is more likely to be used by domestic producers. Import of scrap from the rest of world is assumed to be difficult given that global scrap availability is limited and that scrap will be a highly chased raw material by manufacturers in all countries in the future.

It is important to note that in a production process, the quantity of raw metal input to make the semis is larger than the quantity of output of the semis, with the extra metal input being scrapped and subsequently recycled internally to be used as the feedstock for the next round of production (as seen in **Figure 1**). This is common for products made of all materials because the generation of scrap during an industrial process is unavoidable. On the other hand, the quantity of scrap generation is stable depending on the yields of different manufacturing processes. Scrap generated during the semi-fabrication processes in the aluminum industry is known as internal scrap or run-around scrap, and it is mostly recycled internally by the companies.

The AA's annual statistical data does not contain this proportion of the metal. For such reasons, the internal scrap is quantitatively treated in the Model as a fixed proportion to the production activities, and the amount of metal is assumed to be repeatedly mixed and remelted with new metals (primary or new and old scrap) to count for the emissions associated with it. As a result, this proportion of internal scrap metal is hidden in the Model from the balance sheet of market dynamics, through an embedded assumption that influences the total volume of semi-fab ingot casting.

Market Dynamics Assumptions Selected for the Decarbonization Roadmap

The results and conclusions in this report are based on the selection of a combination of key assumptions on market dynamics. AA and members of the technical consultation sessions have established the following model selection for market projections to help build a reasonable future scenario as the base for emission reduction projections for the NA industry: a high growth rate of domestic semis demand, constrained scrap utilization, trade BAU and no change in domestic primary aluminum production capacity.

1) **High growth rate in domestic semis demand.** This assumes a high growth rate of 2% year-over-year for domestic demand of semis. This will result in a total of 78% growth from the 2021 baseline year by 2050.
2) **Constrained scrap utilization.** This assumes that there is a constrained utilization of scrap as raw material feedstock. While the historical accumulation of aluminum in the in-use stocks (e.g., buildings, vehicles, durable goods, etc.) in society in the NA region and the increased demand in the future will result in increased scrap available over time, the constraints are due to sorting and contamination issues in the scrap recovery process that limit the use of all available scrap in domestic supply for semis production. In the current supply chain, a significant portion of scrap metal is either too contaminated or not well sorted to meet quality standards to be all used by domestic producers. As a result, additional primary aluminum needs to be imported to "sweeten" the scrap, and a proportion of surplus scrap needs to be exported. The constrained scrap utilization scenario maintains primary aluminum imports (for the domestic production of semis) static through time (2022-2050) to be equal to the quantity of the baseline year 2021.
3) **No change in domestic primary aluminum production capacity.** This assumes no change for domestic primary aluminum capacity and output from the 2021 baseline level.
4) **Trade BAU.** This assumes the same level of growth in trade on aluminum products (semis) as the growth of demand (2% annual), and shares of both traded semis and traded aluminum in embedded goods remain the same as the 2021 baseline year. In 2021, a total of 3,812,443 metric tons equivalent of aluminum semis was net imported into NA (of which 18% was semis, 82% was aluminum embedded in goods). The trade BAU assumption also maintains the same ratios for the different forms of aluminum products (e.g., flat-rolled, extruded, cast or others) imported as semis or as aluminum embedded in goods to meet domestic demand.

5) **Supply of semis from domestic producers and importers**. Based on the above parameter selections, 73% of apparent demand will be met by domestic production and the remaining 27% will be met by net imports including semis and aluminum embedded in goods. This ratio is maintained through 2021 – 2050.

The selection of these scenario parameters is based upon industry knowledge and input gathered from AA and its members throughout the development of the Model and intended to reflect a relatively realistic emission reduction pathway based on current and future industry considerations. **Table 2** below illustrates the results generated for the market dynamics selection, per aluminum outputs, calculated for the Roadmap.

Table 2: Demand/Supply Totals for Roadmap Scenario (MT)

Year	2025	2030	2035	2040	2045	2050
Total Semis Demand	15,237,352	16,823,268	18,574,247	20,507,469	22,641,903	24,998,491
Imports of Semis	1,795,064	1,981,896	2,188,173	2,415,920	2,667,371	2,944,993
Imports of Goods	5,211,744	5,754,186	6,353,086	7,014,321	7,744,377	8,550,418
Export of Semis	(1,063,487)	(1,174,176)	(1,296,385)	(1,431,313)	(1,580,286)	(1,744,763)
Export of Goods	(1,816,609)	(2,005,683)	(2,214,437)	(2,444,917)	(2,699,386)	(2,980,340)
Domestic Production of Semis	11,110,640	12,267,045	13,543,809	14,953,459	16,509,827	18,228,183
New Scrap	1,741,503	1,922,760	2,122,882	2,343,833	2,587,781	2,857,120
EOL Scrap	6,010,063	6,651,518	7,386,440	8,078,586	8,690,127	9,241,490
Domestic Primary Metal Production	4,044,577	4,044,577	4,044,577	4,044,577	4,044,577	4,044,577
Imported Primary Metal	1,274,616	1,274,616	1,274,616	1,274,616	1,274,616	1,274,616
Import/Export of Scrap	(1,960,118)	(1,626,426)	(1,284,706)	(788,152)	(87,274)	810,382

ii. Carbon Intensity Values

CI Values for the Baseline Year

The baseline year (2021) CI values associated with the production activities, processes and raw material inputs are of great importance for future emission projections. These values are the starting point for the industry to decarbonize its productions. Identifying accurate data that is representative of the current average emission levels of the NA industry would help the industry efficiently and effectively decarbonize. To identify hotspots and emission reduction strategies and pathways, the CI values are classified into four major categories by emission sources:

- Emissions associated with electricity consumption
- Emissions associated with fuel combustion and thermal energy
- Direct process emissions
- Emissions associated with ancillary materials

Table 3 shows the key CI values associated with the products or production activities in NA during the baseline year, breaking down by emission sources. **Table 4** shows the accumulative emissions associated with aluminum products produced by NA domestic producers. It is important to point out that the NA industry's emissions of 60 million metric tons of CO_2 equivalent (CO_2e) in 2021 is only about 5% of the 1.1 billion metric tons CO_2e of the total emissions by the global aluminum industry.

Table 3: CI of NA Domestic Production in 2021, MT CO_2e/MT Output

Production Activities	Electricity	Fuel Combustion & Thermal	Process Emissions	Ancillary Materials	Total
Primary Aluminum	3.474	2.387	1.770	0.835	8.466
Recycled Aluminum	0.075	0.392	0.000	0.059	0.526
Semi-fab Ingot Casting	0.120	0.337	0.000	0.063	0.520
Semi-fabrication	0.407	0.269	0.000	0.024	0.700

Table 4: Total Emissions Associated with NA Domestic Production in 2021, MT CO_2e

Production Activities	Electricity	Fuel Combustion & Thermal	Process Emissions	Ancillary Materials	Total
Domestic Primary Aluminum	12,378,168	9,535,050	7,158,780	3,377,165	32,449,163
Imported Primary Aluminum	7,730,662	3,117,076	2,511,567	1,052,833	14,412,138
Recycled Aluminum	364,528	1,905,266	0	286,762	2,556,556
Semi-fab Ingot Casting	641,151	1,797,895	0	336,604	2,775,651
Semi-fabrication*	4,175,892	2,763,153	0	246,345	7,185,389
Total	25,290,401	19,118,440	9,670,347	5,299,709	59,378,897

**Includes Semi-fabrication sheets, foil, extrusion, foundry (casting) products and an aggregated "others" category*

The broken-down CI values are further traced to connect with energy consumptions and energy sources, as well as chemical reactions associated with each individual production processes. The entire value chain, from the mining of bauxite to the production of semis, is quantified in the CIs. This breakdown allows for better portrayal of emission hotspots and targeted reductions in the decarbonization strategies assessed.

Among the current hotspot sources of emissions for the NA industry, from both the CI and total emissions perspective, electricity is the largest emission source, followed by fuel combustion (including fuel for furnaces, vehicles and machines) and thermal energy (such as steam). Direct process emissions, which are emissions associated with the release of CO_2 or other greenhouse gases through chemical reactions during a production process, are the third largest emission source. Within the production activities, the hotspot is the production of primary aluminum, which includes:

- Electricity consumption during the electrolysis process.
- Direct emissions during the electrolysis process that are associated with the consumption of carbon anode and the Anode Effect. The consumption of carbon anode leads to the emission of CO_2, and the Anode Effect leads to the emission of perfluorocarbon (PFC) gases, which have high global warming potential values.
- Emissions associated with the production of alumina, which requires high pressure and high temperature steam to operate digestors and calciners.

In addition, emissions associated with natural gas combustion in the metal remelting or heating furnaces during recycling, ingot casting and semi-fabrication processes are also identified as a key emission reduction target by the NA industry, as the majority of aluminum companies in the region are devoted to these production activities. Data for domestic production for the 2021 baseline year is based on the North American Semi-Fabricated Aluminum Product LCA published by the AA in 2022. Data for primary aluminum production in other regions and countries is provided by Sphera based on its GaBi database. Data for "global" recycling and semi-fabrication is based on estimated values by the IAI and MPP models.

CI Values for Future Years – Simulating Emission Reduction Pathways

Domestic production CI values for future years are simulated based on preselected low carbon production strategies and technologies and their potential or "necessary" deployment schedules. A potential deployment schedule reflects the view of the AA and its members about practical possibilities. A "necessary" deployment schedule, on the other hand, reflects the theoretical need for the technologies to be deployed at a certain time in order for the industry to achieve its emissions reduction goal by 2050. In other words, if such technologies could not be deployed, the industry would have been unaligned with the global climate target.

Future CI values for imported semis (including aluminum embedded in goods converted to semis) are simulated based on the IAI and MPP models. Such simulations are influenced by the source countries or regions of export. For the Roadmap Model, two sets of source scenarios are assumed:

- Semis produced and exported by the RoW
- Semis produced and exported by China

Although the NA market has its traditional trade partners in the past, the future of trade is highly unknown and it could be influenced by a variety of factors such as geopolitical relationships among countries, tariff schedules among counties, regional trade arrangements, changes on World Trade Organization (WTO) rules and the like. For these reasons, the RoW scenario is selected and represents a global average. In addition, the scenario of China is added as a sensitivity analysis for the following reasons:

- China represents more than 50% of the global aluminum outputs. It is the largest exporter of both aluminum semis and aluminum embedded in traded goods.
- Although the NA market imports semis from a variety of countries, China is often considered the ultimate producer of the majority of these semis because many countries import them from China and then export them to the NA market. Net imported semis was 5% of the apparent demand in the NA market in 2021.

- China is also considered to be the major source of production for aluminum embedded in goods that have been imported into the NA market. In 2021, net import of aluminum embedded in goods, when converted to semis for scope consistency with this project, was 22% of the apparent demand in the NA market.

Lastly, future CI values for semis exported (including aluminum embedded in goods converted to semis for scope consistency) by NA producers is calculated by using the simulated total emissions of domestic production during a year (including emissions associated with imported primary aluminum) divided by the output of total semis in the same year.

iii. Impactful Technologies

As it is identified in the previous section, emission hotspots for the NA industry include electricity consumption, direct process emissions during the electrolysis process, the production of alumina, and the consumption of natural gas during recycling, ingot casting and semi-fabrication operations. Among these emission hotspots, some of them are "endogenous" in nature, which means they can be controlled at a certain level by the domestic aluminum producers, while others are "exogenous" factors:

- **Endogenous factors:**
    - Direct process emissions associated with the electrolysis process when alternative technology is made available.
    - Emissions associated with captive power generation by a small group of primary aluminum smelters if fuel switching for power generation is possible.
    - Emissions associated with the domestic production of alumina if fuel switching is possible through the availability of cleaner alternative fuels and the related delivery infrastructure.
    - Emissions associated with fuel combustion in furnaces if fuel switching is possible through the availability of cleaner alternative fuels and the related delivery infrastructure.
    - Indirect emissions associated with differences in production efficiency, reflected in energy consumption per unit of output and product yield.
- **Exogenous factors:**
    - Emissions associated with energy supply including the supply of electricity and natural gas by the existing energy infrastructure when cleaner alternatives are not available or accessible.
    - Emissions associated with the supply of ancillary materials, although this part of the emissions are minor and almost negligible.
    - Emissions associated with imported primary aluminum and alumina. The NA industry currently does not have enough production capacity to meet the demand for primary aluminum and alumina. These raw materials need to be

imported from a group of traditional trade partners. The extra demand of alumina and primary aluminum by NA producers has been stably imported during the past three decades from a group of traditional trade partners including countries in South America, Oceania (Australia and New Zealand) and Middle East.

To reduce emissions, new technologies and production strategies must be adopted and widely deployed across the industry during the next three decades. This is particularly important for emissions related to endogenous factors. On the other hand, emissions associated with exogenous factors must also be reduced to be able to achieve a net zero target as reductions in endogenous factors alone could not meet the most stringent targets by themselves. From this perspective, addressing climate change and reducing emissions is an "all-hands-on-deck" task for the entire value chain and for all stakeholders.

The assessment of technological feasibility focuses on the availability of the technologies and the potential ability to be deployed industry-wide over time. Economic feasibility is only considered in the context of assuming realistic timelines for implementation of each identified technology through hearing from stakeholders on key challenges.

Even when considering technological implementation, multiple assumptions need to be built as reliable data still needs to be developed to properly document the (direct and indirect) emissions tied to the technologies, assuming they are implemented at scale. Thus, due to high uncertainty, the Decarbonization Roadmap acknowledges the criticality of economic feasibility for technology adoption and deployment but does not conduct an economic assessment to estimate the costs of transition to a net zero emission economy for the aluminum industry. Readers are encouraged to read the MPP report which provided estimations for investment needed for the various decarbonization technologies to be deployed throughout the global primary aluminum production facilities.

Decarbonization Technology Selection

The Model tool included embedded assumptions for CI projections specific to the penetration timeline and scale for each impactful technology. The dynamic Model capabilities allow users to adjust these assumptions to project the impact of specific technology deployment in reducing emissions. To develop the Decarbonization Roadmap, the AA established the following model selections for each of the impactful technologies and the underlying assumptions for integrating their adoption and deployment:

1) **Inert anode (or similar technology) deployment.** New inert anode or similar technology can drastically reduce direct process emissions from primary aluminum production with new systems that emit oxygen during the smelting process instead of CO_2. The potential and feasibility of these systems and materials are still being

evaluated. However, the industry has voiced that adoption and deployment could start occurring in the early 2030s. This is also reflected in the IAI and MPP models. Types of anode materials being assessed for or under development are ceramic anodes, cermet anodes, metal (alloy) anodes and various coatings.[3] The deployment of this technology is assumed to be able to eliminate all direct process emissions associated with the electrolysis activity. For the inert anode penetration, the Model assumes an associated CI of 0.31MT CO_2/MT primary aluminum output, based on an estimate stemmed from the MPP model, and including anode fabrication, anode production energy, process CO_2 and Non-CO_2 GHG emissions.

The Roadmap models a linear penetration rate for inert anode deployment beginning in 2030 through 2050, based on currently available information about the technology's capacity to scale. It also includes a sensitivity analysis case for an earlier implementation timeline beginning in 2028 through 2040. The sensitivity analysis is included to assess the impact of a faster adoption if market conditions are permitted.

2) **Natural gas phasedown.** Fossil fuel-based natural gas is used to fire furnaces to heat up or remelt metal during aluminum ingot casting, recycling and semi-fabrication processes. The amount of natural gas consumption by NA domestic producers is large. Fuel switching to alternatives, such as hydrogen or low-carbon electricity, or adding carbon capture and sequestration (CCS) technology can significantly reduce emissions. Major natural gas phasedown options include the electrification of furnaces from 2030 to 2050, fuel switching to green hydrogen (or alternative non-CO_2 emitting fuels) from 2030 to 2050 in addition to carbon capture technology being implemented in scrubber chambers.
    a. **The electrification of furnaces** assumes a conservative conversion of 1:1 in *delivered energy* consumption from natural gas to electricity. Member feedback on this assumption emphasized that the electrification of furnaces may be limited due to scale constraints and other operational considerations. For instance, some companies have indicated that the current cost of running induction furnaces is several times higher than natural gas furnaces. The Roadmap scenario assumes up to 30% of the covered furnaces would be electrified by 2050.
    b. **Fuel switching** may encompass all alternative fuels, including lower CI biofuels and hydrogen. The Roadmap scenario models fuel switching assuming it is 100% green hydrogen implementation for simplicity as current industry research indicates that hydrogen would be a *relatively* simple replacement in existing

[3] Inert anode technology for aluminium smelters | Climate Technology Centre & Network | Tue, 11/08/2016 (ctc-n.org)

natural gas systems. The replacement of natural gas with green hydrogen is assumed to result in negligible upstream emissions and the Roadmap assumes that 50% of furnaces can be fuel switched to green hydrogen by 2050.

c. **CCS** technologies are still being evaluated for feasibility, costs and net impact. Based upon a literature review and members' feedback, the Roadmap acknowledges that the specifics for actual application of CCS technologies may impact reduction potential. The Roadmap assumes that there will be a 70% in emission reductions for furnaces where CCS technologies are deployed, where literature indicates a potential up to 90% in emissions reductions. The Roadmap scenario assumes that the remaining 20% of natural gas furnaces (after 30% of them are electrified and 50% of them are switched to green hydrogen) integrate this technology by 2050.

3) **Grid decarbonization.** While the electricity supply for aluminum facilities in Canada is based on 100% hydropower (which is still tied to a very low emission profile accounting for methane emissions in dam infrastructure), most aluminum companies in the U.S. are still relying on emission intensive electricity from the grid. The Roadmap uses energy data from the U.S. Energy Information Administration (EIA) to consider the emissions reduction impacts from grid decarbonization for U.S. operations over time. The Roadmap models the electricity-related emission reductions achieved from a grid decarbonization following the EIA's Inflation Reduction Act (IRA) High Uptake scenario, which shows the upper bounds of the impact of the IRA provisions resulting in a cleaner electric grid compared to the reference case. This U.S. electricity generation scenario is considered an optimistic trend toward a cleaner grid through 2050. The Roadmap uses the IRA High Uptake grid scenario to account for the likely increased clean energy adoption resulting from significant federal investments in the U.S. in clean energy technologies.[4]

Table 5: IRA High Uptake Scenario Carbon Intensity Factors of the U.S. Power Grid ($MTCO_2e/MWh$)

U.S. Power Grid	2021	2025	2030	2035	2040	2045	2050
High IRA Uptake	0.43	0.38	0.21	0.18	0.17	0.17	0.16

4) **Alumina production technology.** The Roadmap scenario incorporates an alumina decarbonization pathway based on the IAI 1.5 Degree Scenario and assumes that emission reductions will come from a combination of the following technologies: electric calcination, mechanical vapor recompression and green hydrogen for calcination heat.

[4] AEO2023 Issues in Focus: Inflation Reduction Act Cases in the AEO2023 (eia.gov)

a. **Electric calcination.** The conventional calcination process uses coal or natural gas combustion to provide the high temperature heat (steam) required; clean calcination could reduce or eliminate these emissions by using renewable energy, for example through electrification or green hydrogen for the heating process. Electric calcination pilots are being implemented globally, including the Australian Alcoa Renewable Powered Electric Calcination Pilot, to better understand the technological and economic feasibility of this approach.[5]

b. **Mechanical vapor recompression.** Similarly to electric calcination, the use of renewable energy in the form of mechanical vapor recompression to electrify steam production in the alumina refining process would further reduce or eliminate alumina (refining)-related emissions.

As these mechanisms are still in early stages of feasibility testing and deployment, the Roadmap adopts IAI's projected CI values and its emissions breakdowns for alumina refining based on IAI's assumed integration schedule of these technologies. In addition, during the technical consulting process, some companies mentioned that the actual emissions profiles of NA alumina refining facilities are much lower than the global average. As more data becomes available from the deployment of these technologies, the associated CI and timeline for deployment used in the Roadmap should be refined.

Table 6: Carbon Intensity Projection for Alumina Production Technology Deployment ($MTCO_2e$/MT Primary Aluminum Output)

	2018	2030	2035	2040	2045	2050
Electricity	0.263	0.209	0.152	0.100	0.064	0.027
Ancillary	0.230	0.186	0.135	0.090	0.057	0.024
Thermal Energy	1.932	1.476	1.003	0.607	0.345	0.114

5) **Energy efficiency.** The Roadmap models an assumption of increased energy efficiency in terms of energy usage (kWh/MJ/Btu) on a per unit of output basis that will increase in small increments from 2025-2050, up to 15% cumulatively by 2050. Member feedback supported this assumption that energy efficiency improvement is expected to occur from a combination of multiple technologies and operational practices.

6) **Increased use of recycled materials.** As mentioned in the market dynamics section, a constrained scrap utilization scenario is chosen for the Roadmap based on the reality that not all scrap available can be effectively utilized by domestic

[5] Alcoa Renewable Powered Electric Calcination Pilot - Australian Renewable Energy Agency (ARENA)

producers because of scrap quality in the existing supply chain. This scenario maintains the same quantity of the imports of primary aluminum for the next three decades at the 2021 baseline level, with the imports from traditional trade partners. It leads to a gradual increase in the shares of recycled metal as a feedstock for domestic semis production (i.e., recycled content) from 48% in 2021 to 71% in 2050. Extra available scrap will be exported in future years.

While it is a constrained utilization of recycled metal, it still helps significantly reduce emissions compared to a business-as-usual case (i.e., share of recycled metal being kept at 48%). This level of recycled material utilization is **a fundamental precondition** for emission reduction by the NA industry. Otherwise, achieving net-zero emissions by 2050 will be much harder and much more complex.

In addition to this minimum level of scrap utilization, the Roadmap also added a sensitivity analysis scenario to further illustrate the potential for emission reduction through increased use of scrap. This will be discussed in the Results section.

Additional Considerations Not Modeled in the Decarbonization Roadmap

Additional technologies and operational practices are considered significant and potentially impactful for emissions reductions. However, they were not modeled in the Decarbonization Roadmap, mainly due to the uncertainties associated with technology readiness, potential for scale, schedule for adoption and deployment, and the availability and reliability of data for making projections.

Additional technologies. The dynamic Model capabilities allow the user to model additional percentage emission reductions based on an aggregated assumption of additional technology integration. Additional potential technology pathways considered for the Model were discussed during the stakeholder technical consultation sessions and were ultimately not included. These additional pathways include the utilization of small modular reactor (SMR) power generation technology, plasma technology, process optimization and digitization, emissions offsets and certifications, and advanced electrolysis techniques. The Roadmap scenario described in this report assumes low expectations for these inputs to change significantly to impact the CI projected for future years through 2050. The feasibility of these technologies and emissions mitigation opportunities can be assessed and considered for future updates to the Roadmap and the Model tool.

IV. Results

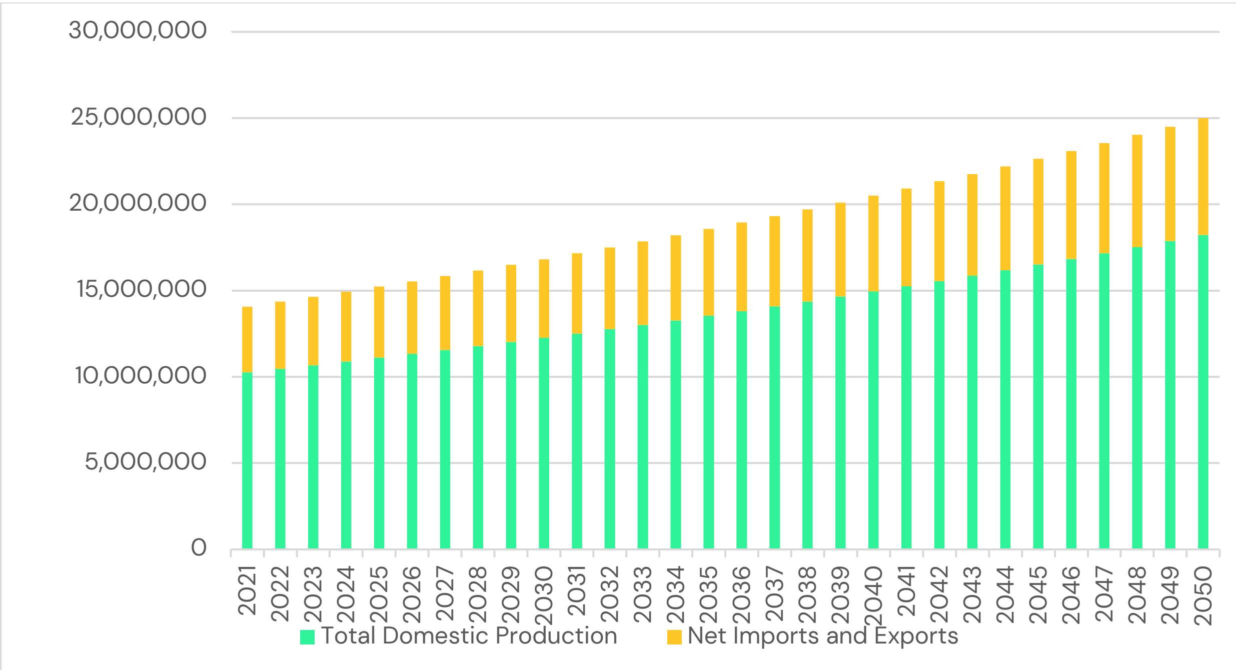
This section describes the results of the modeled carbon intensities and total emissions projections for the Decarbonization Roadmap scenario, including the expected reductions estimated for the various technology and energy integration discussed in Section III. As discussed in Section II, the Decarbonization Roadmap scenario and related results use information gathered through the Model development process and insights from AA members to build estimates and illustrate feasible pathways and emissions trends. The Roadmap's accuracy is dependent on available data and assumptions. As described in the previous section, the underlying assumptions and data will evolve as technology alternatives progress and additional information becomes available.

__**Growth in Production**__

Figure 3 shows the result of growth projection from both domestic producers and net imports for the Decarbonization Roadmap. Overall, 73% of the apparent demand for semis will be produced by domestic producers and 27% will be net imported. The shares are assumed to be constant, and the accumulative growth for both is 78% by 2050. Such a growth projection is aligned with the global projection by IAI. However, the relative shares of production between domestic and foreign producers in the future will be largely dependent on change in market situations and trade policies. The impact of trade on emissions will be discussed in the following sections.

It is especially important to note that of the 27% of net imported aluminum products in 2021, only 5%, or 675,864 metric tons, was "visible," i.e., the net imports could be identified by HTS codes and the data was captured in statistical reports. The other 22%, or 3,136,579 metric tons, was invisible and not captured by statistical data due to the aluminum that is embedded in other goods and products. This is the first time such data has been revealed to the aluminum industry through high-quality research. The total quantity and the scale of invisible aluminum imported into the NA market is massive and it needs to be noticed by the industry and by all stakeholders to effectively address emissions associated with trade.

Figure 3: Growth Projection for Domestic Production and Net Imports Based on Trade BAU Assumption (MT)



Decarbonization Roadmap for NA Domestic Production

The GHG emission reductions are illustrated in **Figure 4** against an assumed BAU scenario. This BAU scenario assumes no changes in the CIs from the 2021 baseline year for domestic activities and imported primary aluminum. The BAU scenario shows that emissions will continue to increase through 2050 if no significant investments are made for decarbonization. **Table 7** shows the emission reduction schedule. Overall, total annual emissions associated with NA domestic production need to be reduced by 92% compared to the 2021 baseline year emission level, with a near-term reduction of 24% by 2030, and a longer-term reduction of 63% by 2040. The most critical timeframe for the NA industry to reduce its emissions on a massive scale is 2030-2040.

At the same time, output from the NA domestic industry will increase 20%, 46% and 78% by 2030, 2040 and 2050, respectively. In terms of absolute emission quantities, the 2021 baseline level is approximately 60 million metric tons of CO_2e. By 2050, it will be roughly 5 million metric tons of CO_2e, illustrating the scale and challenge of emissions reduction.

Table 7: Emission Reduction Schedule of the Decarbonization Roadmap, Compared to the 2021 Total Emission Level

	2025	2030	2040	2050
Potential Emissions Reductions	3%	24%	63%	92%

While the scale of decarbonization facing the NA aluminum industry is significant, potential opportunities do exist to enable the industry to achieve a net-zero emission profile by 2050. **Figure 4** also shows the emissions reduction potential of each impactful technology discussed previously in Section III. The largest amount of emissions reduction is from the grid decarbonization which contributes to around 36% of total emission reductions compared to a BAU scenario in 2050.

Figure 5 illustrates the same emissions reduction schedule, broken down by sources of emissions (per the CI breakdowns) through the assumed implementation of the same impactful technologies.

It is worth noting that the emissions associated with the import of primary aluminum are treated as an exogenous factor in the NA Domestic Roadmap. Emissions of imported primary aluminum are projected to be reduced over time based on a global schedule, but the scale of reductions is not depicted in both **Figure 4** and **Figure 5** in the shaded area, which only shows the domestic emission reduction profile including power grid decarbonization and technology adoption and deployment.

Figure 4: Illustration of Emission Reduction Schedule for Domestic Activities Against a Business-as-Usual Scenario

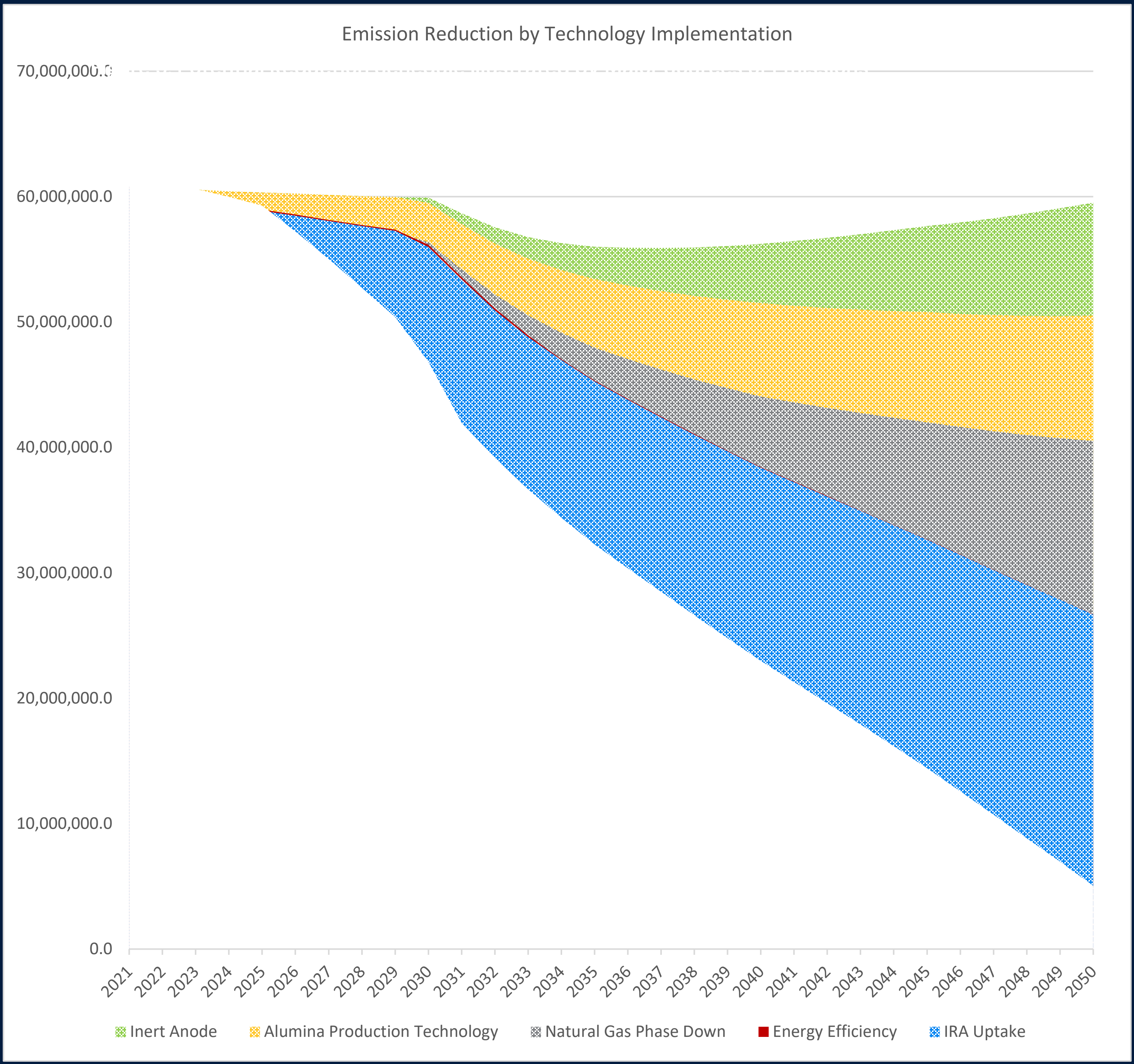
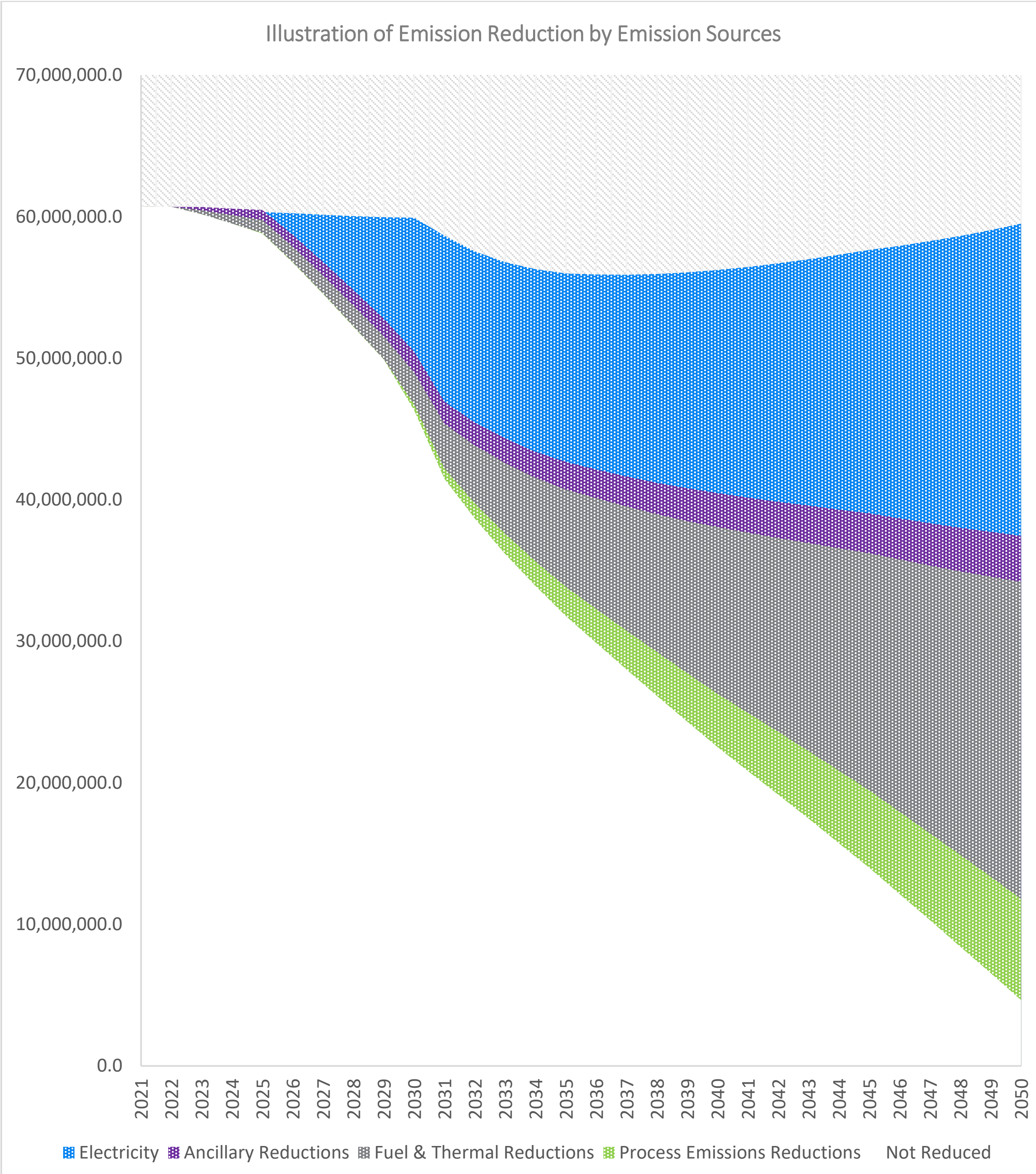


Figure 5: Potential Reduction Schedule Illustrated by Major Sources of Emissions



Attention needs to be paid to the differences of **Figure 4** and **Figure 5**. Differences in classifications leads to their looking different. One is from a technology perspective and the other is from the emission source perspective. Certain categories of the two are overlapping while other categories are segregated, with the total shaded areas of the two figures being equal.

As demonstrated in **Figure 5**, the reductions associated with electricity emissions have a significant impact throughout the Roadmap timeline. As observed, before 2035 the emissions reductions tied to electricity generation represent the main potential reductions with more than 60% of the reductions by 2031. After 2035, the emissions reductions tied to fuel and thermal sources start to be a significant contributor to the overall emission reductions, reaching 41% of the total in 2050 (against 40% of total reductions from electricity).

Figure 6 shows a breakdown of residual emissions by production activities over time. In the baseline year, the largest source of emissions is associated with both domestic primary aluminum production and the import of primary aluminum from traditional trade partners. The rest is associated with recycling, semi-fabrication ingot casting and semi-fabrication. With the progress of time, these relative shares change along with the deployment of technologies and the power grid decarbonization. **Figure 7** illustrates the evolution of the relative shares of emission sources over time as emissions decrease.

Figure 6: Residual Emissions from Domestic Production by Production Activities Over Time

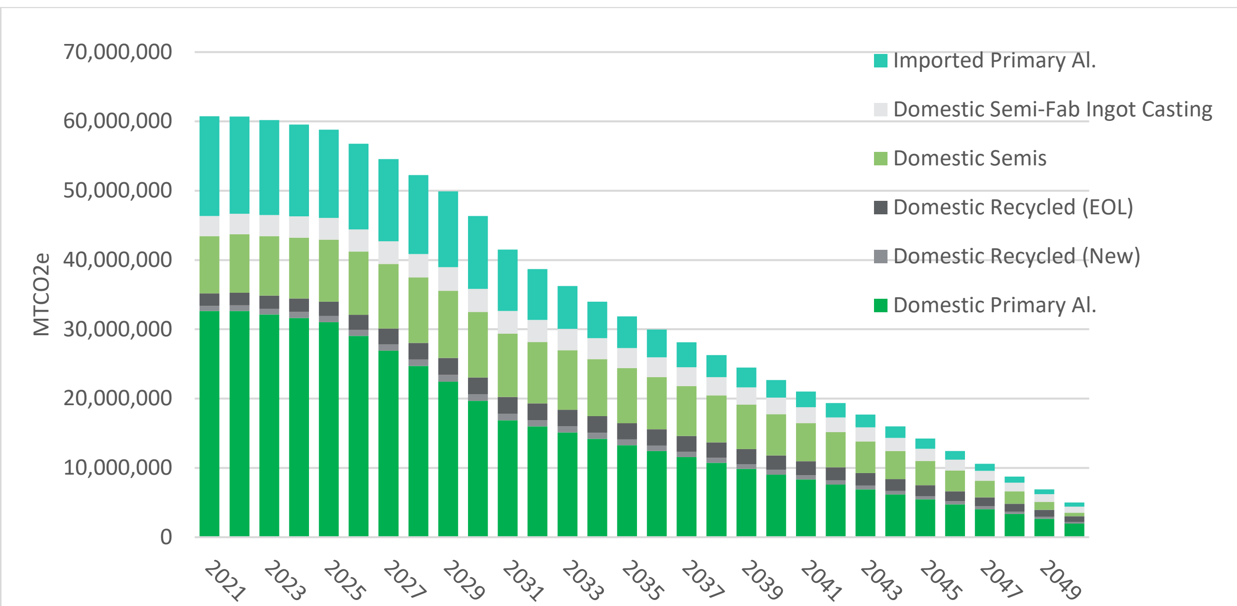
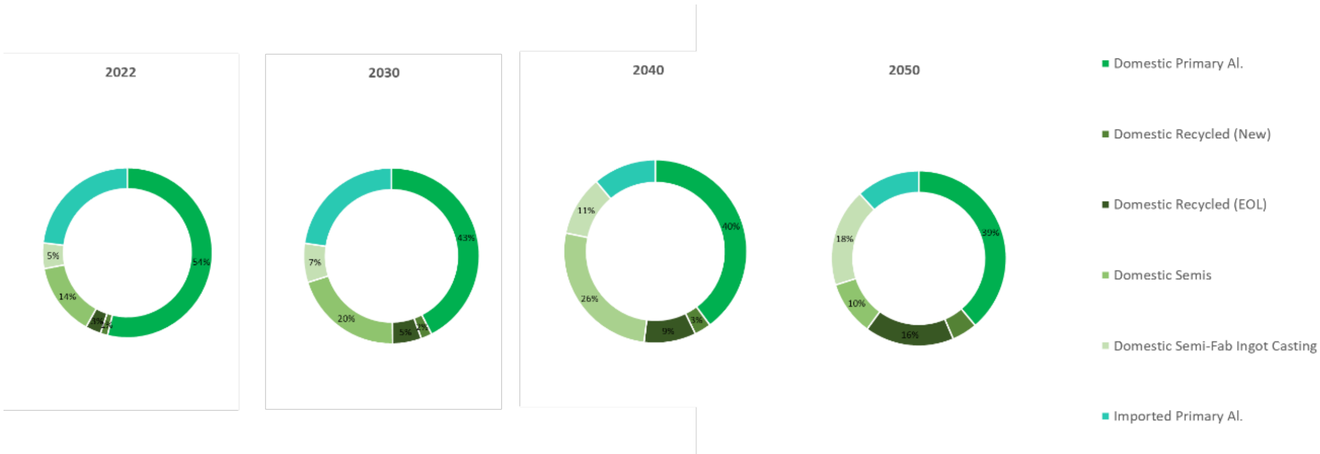
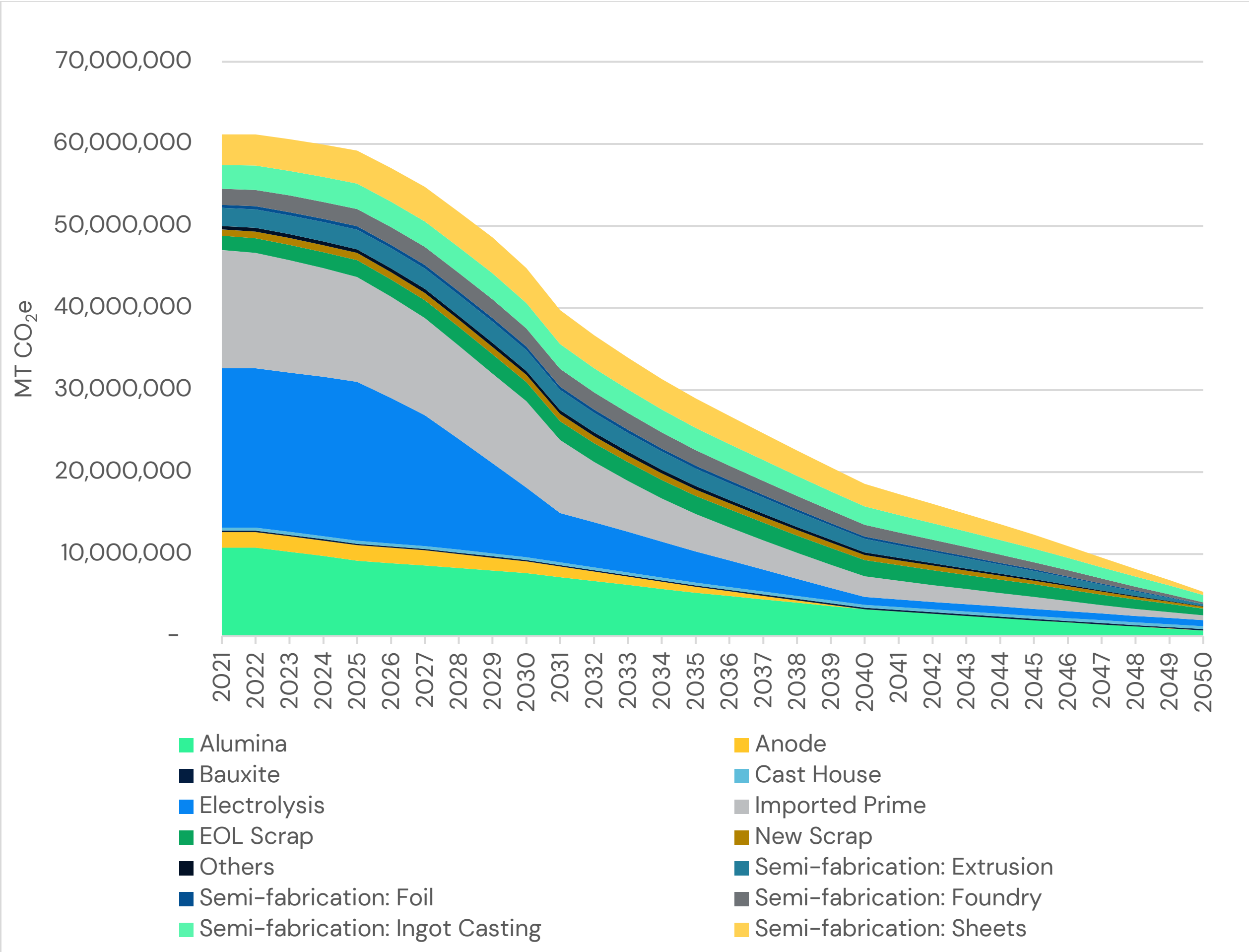


Figure 7: Evolution in the Shares of Residual Emissions from Domestic Production by Production Activities



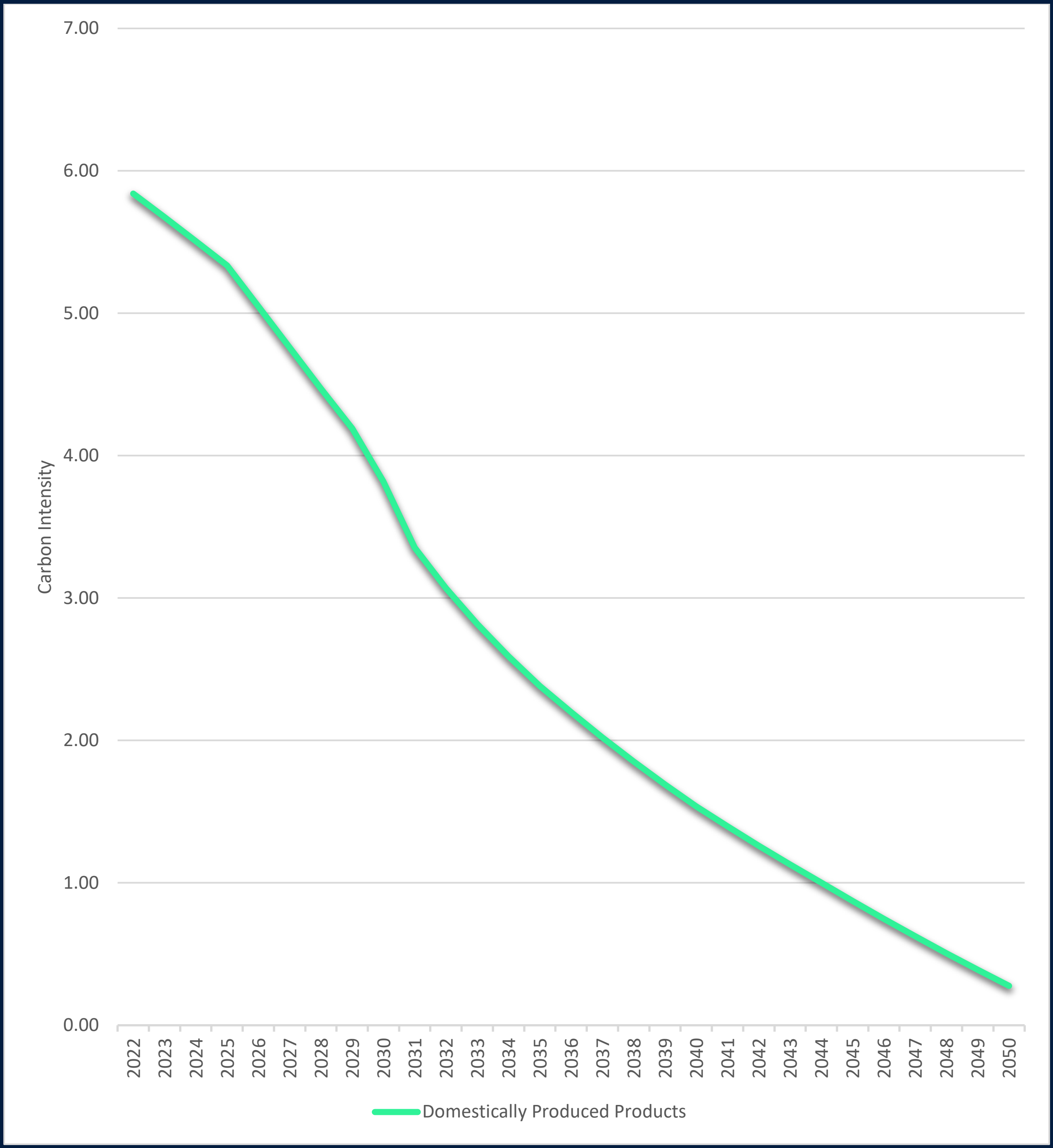
It is also worth looking deeper into the details about the sources of residual emissions and their reductions over time. **Figure 8** offers detailed breakdown by key production processes. As observed, emission reductions associated with electrolysis and alumina as well as the imported primary aluminum are among the most critical processes and activities to achieve the Decarbonization Roadmap target.

Figure 8: Breakdown of Emission Reductions by Key Processes or Activities



Finally, it is worth showing the NA Domestic Industry Decarbonization Roadmap in emission intensities. Such intensities can be calculated using the annual emission projections of domestic production divided by the total output of semis in each year. **Figure 9** shows the calculated CIs of the Roadmap. The CI for the baseline year 2021 is 5.91 MT CO_2e/MT semis. The CIs for 2030, 2040 and 2050 are projected to be 3.82, 1.54 and 0.28 MT CO_2e/MT semis, respectively.

Figure 9: North American Semis Carbon Intensity Projection, in MT CO_2e/MT of Semis



The Role of Key Technologies

Inert anode technology. The Roadmap models a linear penetration rate for inert anode deployment beginning in 2030 through 2050, impacting emissions associated with the production of carbon anode and the subsequent direct process emissions of the electrolysis process during primary aluminum production. Under this scenario, a total of **100 million tons** of CO_2e emissions can be reduced compared to the BAU scenario through 2050 (total area of the shaded green area in **Figure 4**).

As the timeline for widescale deployment is still uncertain, a sensitivity case for a slightly early and much faster deployment timeline (2028 through 2040) is illustrated in **Figure 10**. The reductions potential for both deployment scenarios is significant; however, the technology needs to be matured and significant capital investment is required since all existing smelters need to be retrofitted and any newly built smelters need to be built with this technology. Otherwise, the industry would need to rely on other options such as CCS to achieve the alignment with the global emission profile projected by the IAI and MPP models.

Figure 10: Emission (MT CO_2e) Reductions Tied to Inert Anode Deployment for the Roadmap and a Sensitivity Scenario, Compared to the BAU Scenario

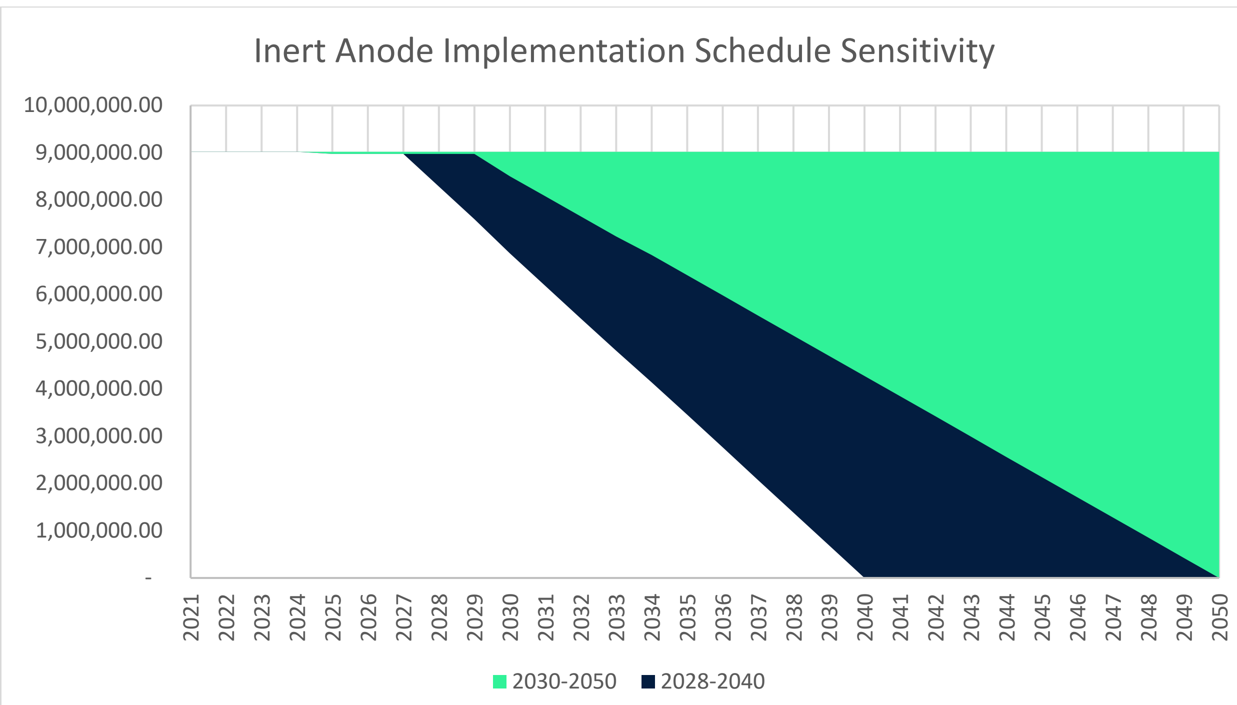


Table 8 shows the impact of an earlier deployment of the inert anode technology. Cumulatively, this represents 53 million metric tons of emissions savings through an earlier

and more rapid pace of deployment compared to a later and slower pace of deployment over the timeline of the assessment.

Table 8: Emissions Difference (MT CO_2e) Between the Two Different Schedules for Inert Anode Technology Deployment

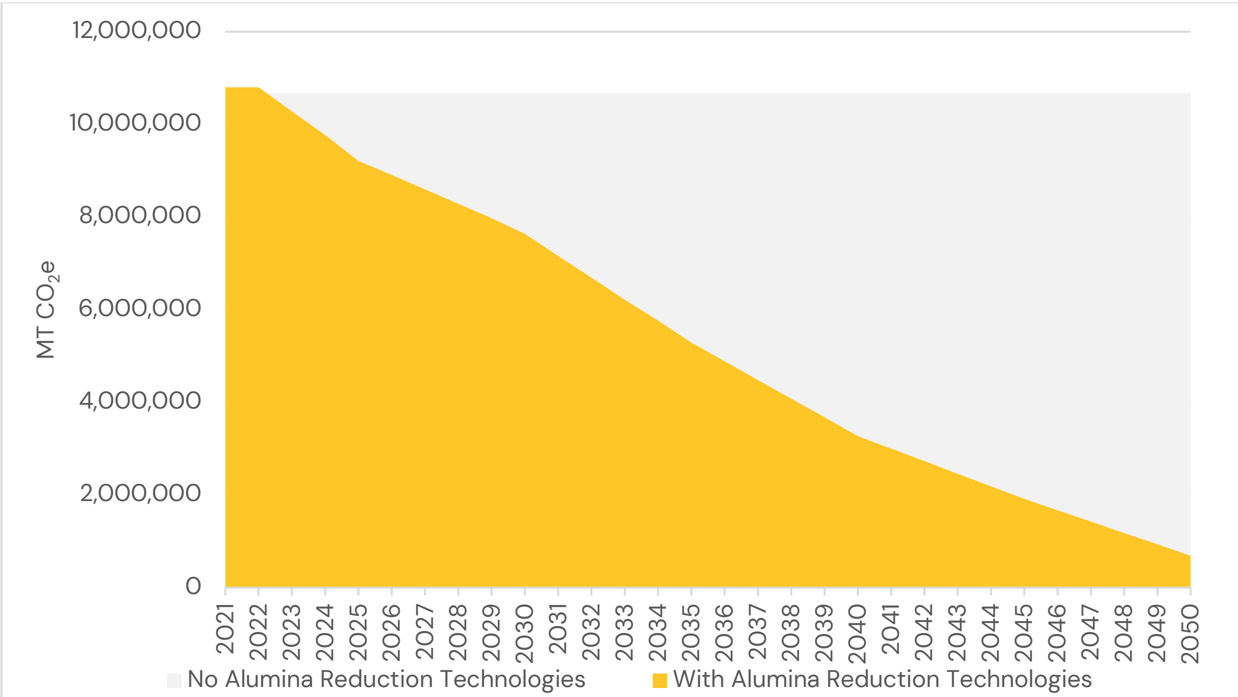
	2025	2030	2035	2040	2045	2050
Emissions Savings Achieved from Earlier Deployment Schedule	0	(1,635,387)	(2,958,563)	(4,273,480)	(2,136,740)	0

While the NA aluminum industry is working to test, mature and scale up for the adoption of the technology, significant up-front investment is needed during the next three decades for the technology to be incorporated into both existing and new smelters. Demand for capital could be on the scale of billions of dollars. This report calls for policy makers to consider smart policy incentives and investors to make funds available to help with the industry's transition.

Alumina production technology. As previously discussed, the Roadmap used the IAI CI values to project emission reductions associated with alumina refinery activities over the timeline considered. **Figure 11** below illustrates the resulting reductions, against BAU, achieved through the implementation of a combination of technologies for the production of all the alumina needed as feedstock for domestic primary aluminum production. In total, around **157 million tons** of CO_2e emissions can potentially be reduced during the next three decades.

It is important to emphasize again that a significant proportion of the alumina needed by the NA primary aluminum producers has been imported because domestic production capacity is very limited. This situation complicates the Roadmap because much of the emission reduction potential becomes an exogenous factor. Fortunately, the supply of alumina to NA smelters has been traditionally coming from several trade partner countries in South America and Oceania. Alumina producers in these countries are actively developing decarbonization technologies and solutions that have been reflected in the IAI and MPP models and adopted in this Roadmap.

Figure 11: Alumina Production Emission Reduction Schedule (for All Alumina Needed for Domestic Primary Aluminum Production)



Natural gas phasedown. As explained previously, the Roadmap scenario includes a linear assumption for natural gas phasedown through the implementation of three technologies from 2030 to 2050 for the three related production activities: recycled metal production, semi-fab ingot casting and semi-fabrication. The technologies include furnace electrification through induction technology, switching fuel and CCS. Electrification is assumed to cover up to 30% of the furnaces, fuel switching is assumed to cover 50% of the furnaces and the remaining 20% of furnaces is assumed to be covered by CCS.

Both electrification and fuel switching have been assumed a conservative 1:1 energy conversion for each unit of delivered energy (i.e., MJ of delivered hydrogen or electricity is assumed to heat or melt the same amount of metal as 1 MJ of delivered natural gas does). A CCS device is assumed to be added to the remaining natural gas furnaces with a capability to sequestrate 70% or more of the CO_2 emissions from combustion. Overall, the potentials for the three identified technologies to reduce emissions related to the combustion of natural gas in furnaces are roughly the same as the shares of their assumed deployment: 30%, 50% and 20%, for electrification, green hydrogen and CCS, respectively. In total, **around 225 million tons** of CO_2e emissions can potentially be reduced during the next three decades. **Figure 12** through **Figure 14** below illustrate the emission reduction potentials of the three technologies.

Figure 12: Reductions Achieved from 30% of Furnaces Electrified by 2050

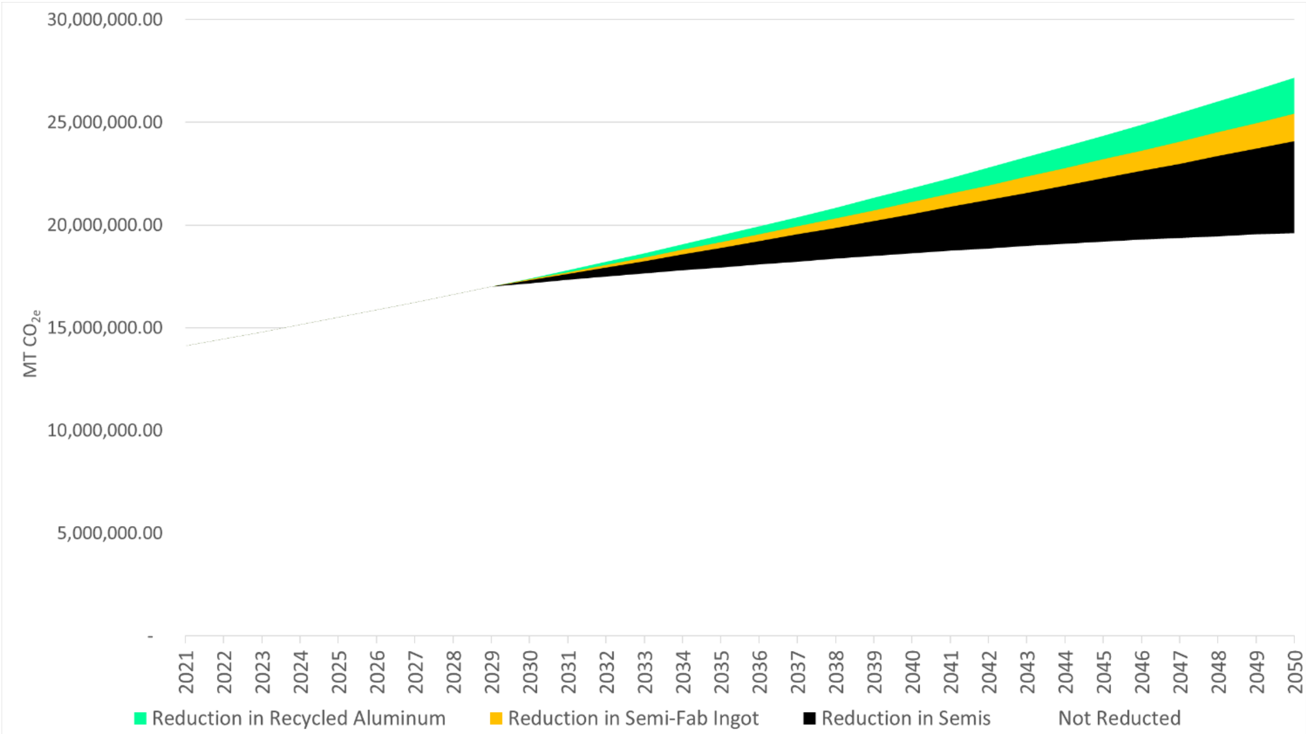


Figure 13: Reductions Achieved from 30% of Furnace Electrification and 50% of Furnace Switching to Green Hydrogen by 2050

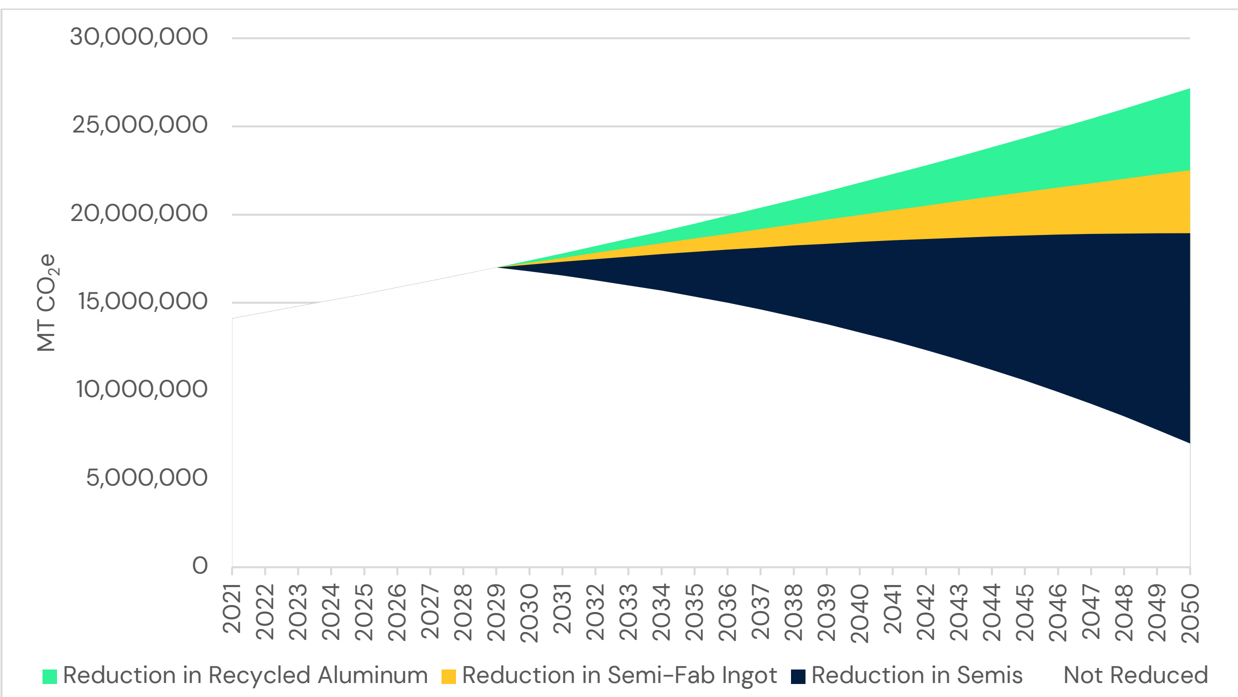
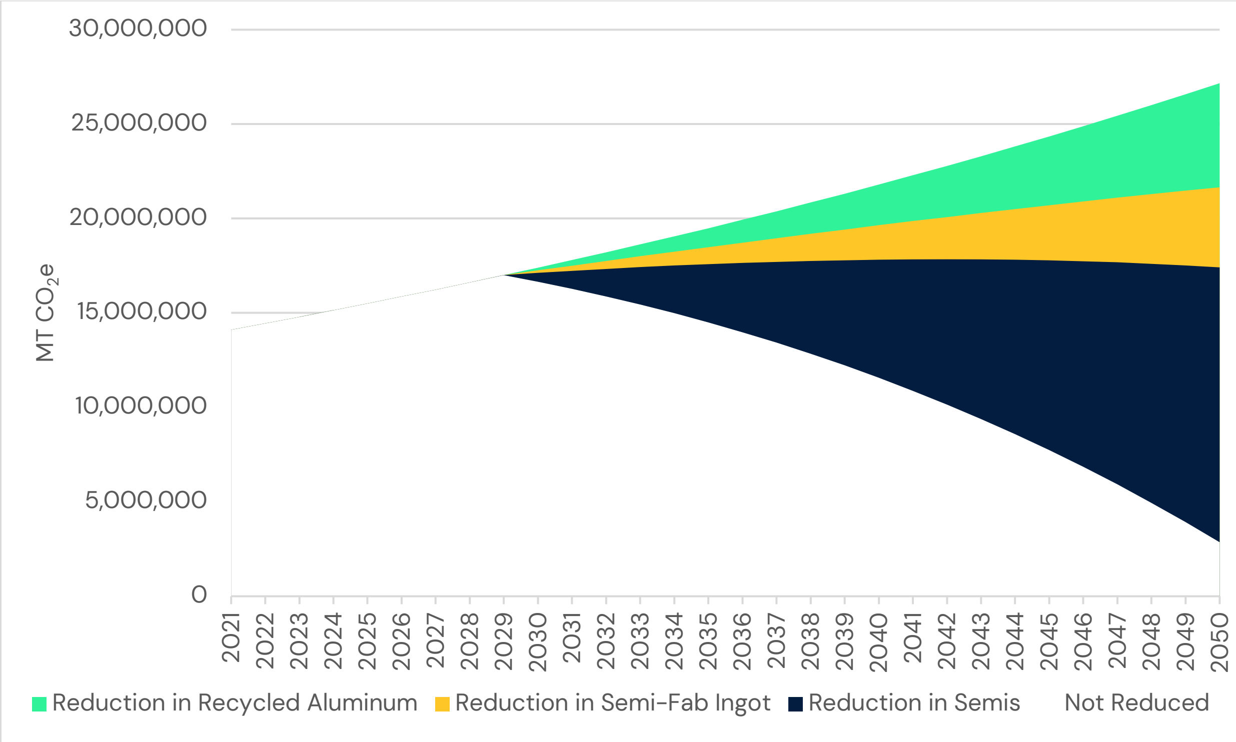


Figure 14: Reductions Achieved from 30% of Furnace Electrification, 50% of Fuel Switching to Green Hydrogen and CCS Covering the Remaining 20% by 2050



Although these technologies have great potential to reduce emissions, the availability and affordability are among the most critical preconditions for the NA aluminum industry to adopt them. For instance, green hydrogen combustion technology can help reduce emissions to a negligible level. Yet, there are very high uncertainties on when green hydrogen can be made available and delivered to those industrial facilities in both Canada and the United States, in large scale, abundant quantity and affordable costs. The answers to these questions largely rely on the energy industry and the infrastructure providers.

The same is true for electrification. At present, induction furnaces cannot meet the scale requirements of the aluminum industry and it is considered by industry experts to be more expensive to operate (reflected during the technical consultation sessions). In addition, carbon intensity of the electricity used to operate the induction furnaces today could be higher than natural gas furnaces depending on which power grid is supplying the electricity to the locations of the facilities. It certainly doesn't make sense for companies to switch to electrical furnaces that will result in more emissions.

Lastly, the CCS technology is still in the early experimental stage now. The applicability, scalability and affordability of the technology to sequester CO_2 emissions effectively and economically from natural gas-fired furnaces are still highly uncertain.

The Role of Trade

An important feature and component of the Decarbonization Roadmap, as emphasized in the introduction, is the integration of trade dynamics. This is critical to the overall strategies in emission reduction for the NA market since every single product traded internationally has a theoretical embodied emissions associated with it (note: this is based on emission accounting concept, not in physical form because GHG emissions are physically detached from products in most cases except for the embedded emissions associated with carbon-based products). Yet, traditional trade activities and trade policies have not incorporated emission considerations. This Roadmap reveals the impact of trade on emissions and provides a solid ground for future policy references and business strategy developments.

The Roadmap treats the traded aluminum in two separate ways. The imported (export of alumina and primary aluminum is excluded since it is negligible) alumina and primary aluminum are counted as part of the domestic production emission profile. Meanwhile, the emissions associated with the import and export of semis and aluminum embedded in finished goods are counted separately as the emission profile of trade. **Figure 16** shows the full emission profile of trade, both imports and exports, and its reduction projections under the assumption that the trade partner is the RoW and its emission reduction pathway follows the IAI model. **Figure 15** shows the net emission profile of net imports, again under the assumption that the trade partner is the RoW and its emission reduction follows the IAI model during the next three decades.

From a product volume point of view, as it was shown in **Figure 3**, only 27% of the apparent demand in the NA market has been met and will be met by net importing under the Roadmap scenario. This ratio is assumed to be constant during the timeframe of the Roadmap. Among the 27% net imported aluminum products, 5% of them will be in the form of semis and 22% will be in the form of aluminum embedded in finished goods, converted into the form of semis for scope consistency.

From the total emission point of view, the emissions associated with net imports are significantly higher than the emissions associated with domestic production, which is 2.7 times bigger in production volume. For instance, in 2021 in which actual emissions are estimated, total emissions from net imports were approximately 69 million metric tons of CO_2 equivalent compared to 60 million metric tons of CO_2 equivalent associated with domestic production. This striking difference in total emissions between domestically produced and imported aluminum products is projected to continue until 2030 when the two will be roughly equal. Given the 2.7 times difference in production volume, the negative impact of emissions in imported aluminum products deserves attention.

Figure 15: Imported Emission Projections Associated with the Net Imported Aluminum Products – RoW Scenario

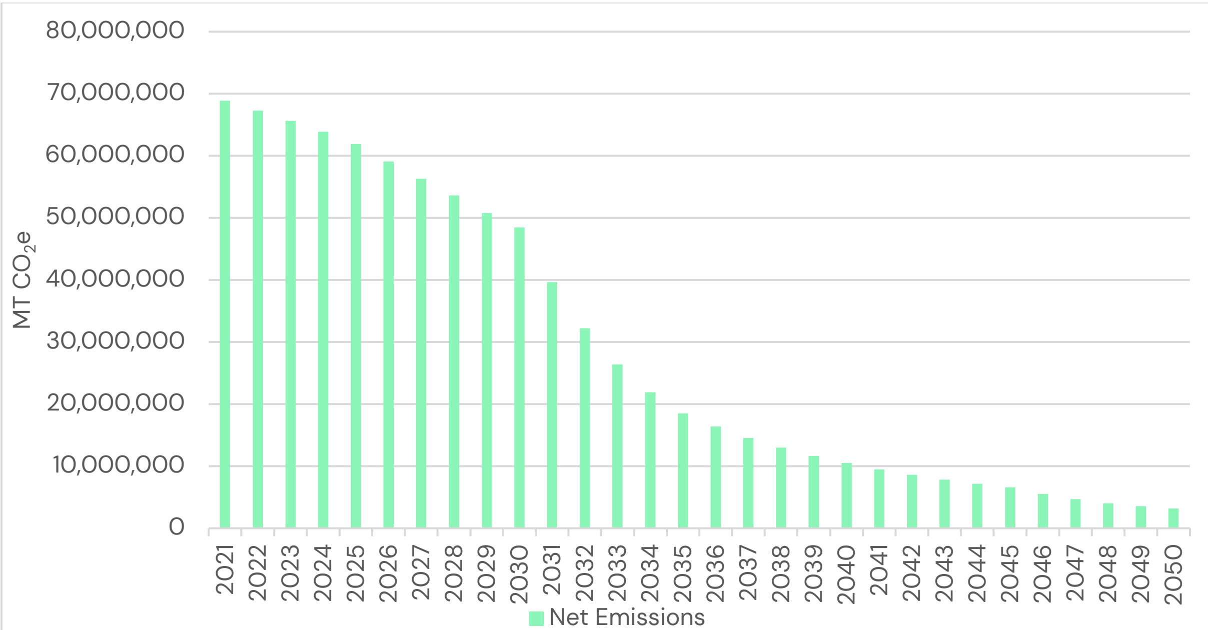
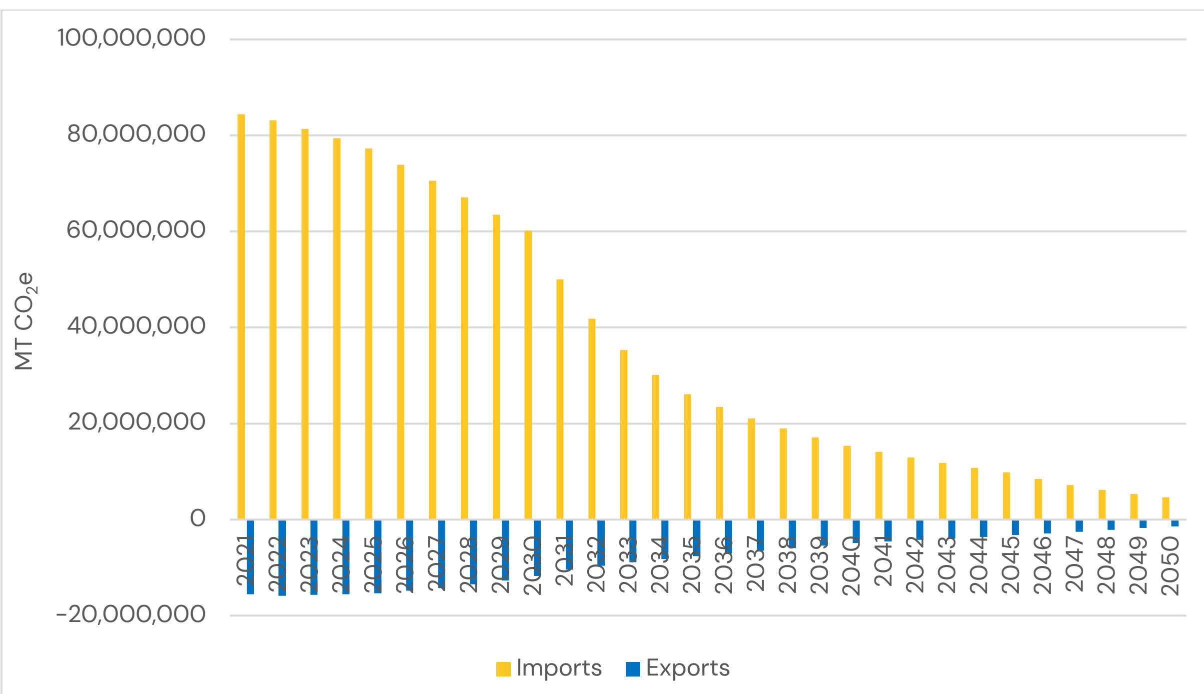
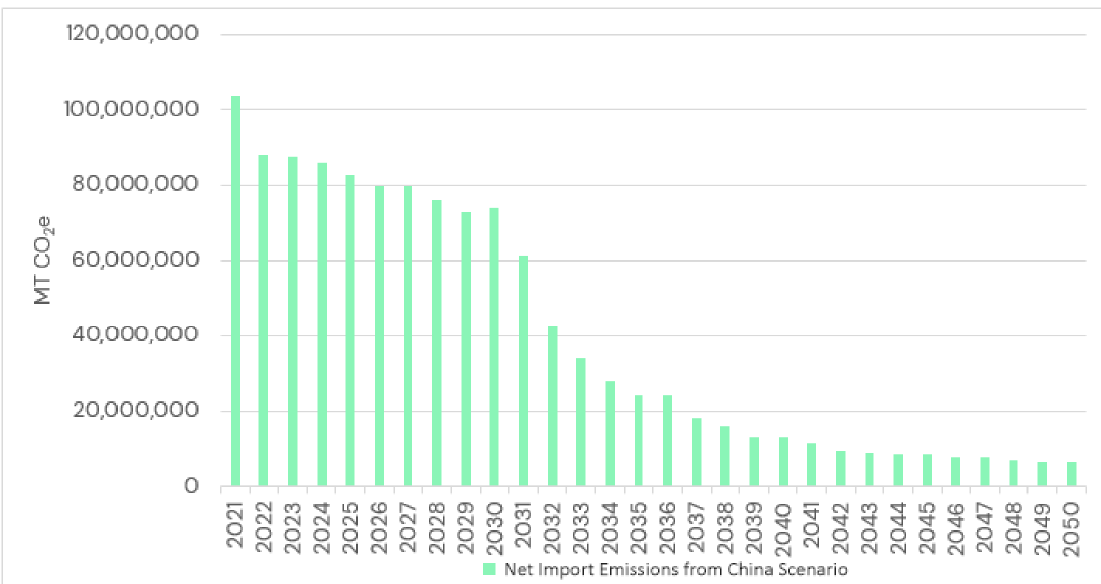


Figure 16: Trade Emission Projections – Imports and Exports with the RoW Scenario



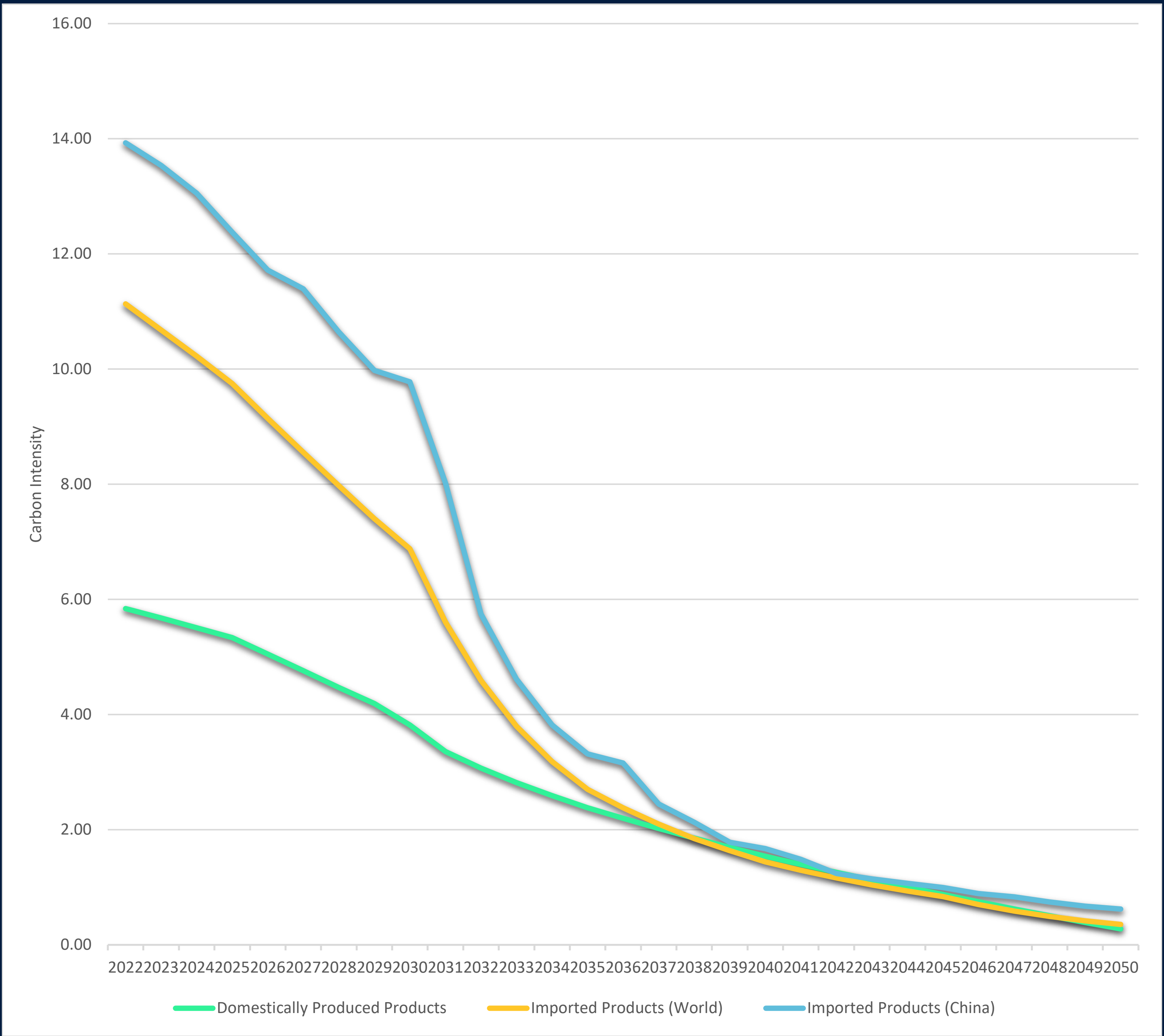
As it was explained in the CI values subsection in Section III, on top of analyzing emissions associated with trade between NA and the RoW, the Model includes a sensitivity scenario in which China would be the main source of production for products imported into the NA market. This scenario is important to further understand the impact of trade because according to the AA, the majority of imported aluminum products in the past two decades can be traced back to China as the main origin. **Figure 17** shows the emission estimates and emission reduction projections for a scenario in which the imported aluminum products would be sourced from China. These estimates and projections utilize a combination of data from both the IAI and MPP models. Sourcing aluminum products from China would cause the total emissions to be increased by 30% more than sourcing them from the RoW. In other words, importers in the NA market can contribute as much as 30% of total emission reductions every single year if they would simply avoid China as the original source of aluminum production.

Figure 17: Trade Emissions Projections – China Scenario



Comparing the emission impact of trade from an annual total emission perspective is important. However, revealing the average emission intensity associated with each unit of products imported versus domestically produced can help stakeholders make better informed decisions. **Figure 18** shows the comparison of CI for each unit of aluminum semis domestically produced versus imported from the RoW and from China. This explains why the proportionately smaller volume of net imports has significantly higher total emissions compared to domestic production (based on the assumed technology deployment and associated reductions, as previously described). For instance, in 2022, carbon intensity of NA domestically produced semis is estimated to be 5.8 MT CO_2e/MT of semis, compared to 11.1 MT CO_2e/MT semis for the RoW and 13.9 MT CO_2e/MT semis for China, and this gap remains significant until the latter part of the 2030s. Also as observed in **Figure 18**, even in the latter part of the covered timeline, as the three CI curves are closer, the CI of NA aluminum products under this Roadmap scenario is projected to stay below both the RoW and China through 2050.

Figure 18: Difference in Carbon Intensity (MT CO_2e/MT Semis) Among NA Domestically Produced Versus Imported Semis from the RoW and China, Projected to 2050



To further explain the cumulative impact of sourcing aluminum products from NA domestic producers versus importing from other countries during the next three decades, the Roadmap analyzes a non-realistic scenario of "no trade" for semis and aluminum embedded in finished goods, in which all NA apparent demand will be produced by NA domestic producers. Under this scenario, the NA industry would still need to import primary aluminum since the domestically available raw material supply (both scrap and prime) would not be enough to meet the demand.

Figure 19 illustrates the cumulative impact of the no trade scenario in comparison with the trade BAU scenario. Overall, an estimated total of **400 million metric tons** of CO_2e emissions can be avoided through 2050 if all aluminum product demand in the NA market would be sourced from NA domestic producers. **Table 9** provides the quantitative annual emission difference in selected years. Of course, this is a non-realistic scenario. At present, the domestic industry does not have adequate raw metal supply to meet the assumed growth in demand, so this pathway would require:

- Increase in domestic primary aluminum production capacity either in Canada or in the U.S. (provided that the U.S. grid will achieve low carbon intensity);
- Fully utilize the domestically available scrap materials; or
- Increase the imports of primary aluminum or scrap material from the RoW.

Nevertheless, such a quantitative analysis can provide insights and perspectives, and can be used to evaluate policy considerations and the potential impact of trade in GHG emissions.

Figure 19: Emission Reduction Potential Between Roadmap Scenario (Trade BAU) and Theoretical No Trade Scenario (No Trade of Semis and Al Embedded in Goods)

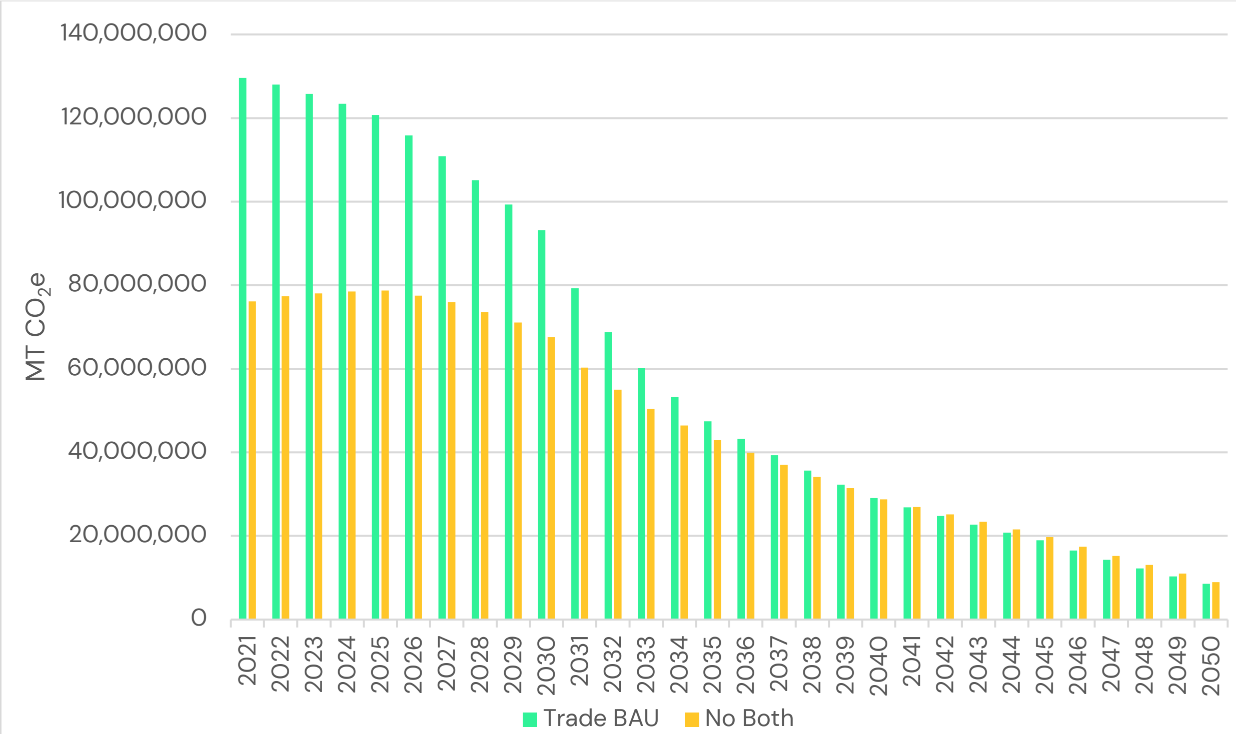


Table 9: Trade BAU Emissions Difference (No Trade of Semis and Al Embedded in Goods) in MT CO_2e

	2025	2030	2035	2040	2045	2050
Emissions Difference	42,024,730	25,668,700	4,572,937	330,148	-791,671	-349,246

The Role of Recycling

Recycled aluminum only has about 5% of the energy demand and GHG emissions compared to producing primary aluminum from ore (bauxite). Increasing the use of recycled aluminum to make aluminum products is one of the most effective and cost-efficient ways of manufacturing to achieve an emission reduction target. However, the use of recycled material is often constrained by two factors: the availability of scrap and the quality of scrap.

From the scrap availability point of view, North America is projected to have enough scrap available (combining the end-of-life and the new scrap materials) for use to meet the raw material demand for domestic production under the Decarbonization Roadmap scenario, which assumes a trade BAU and a high growth demand (2%) for semis. However, from the scrap quality point of view, as aforementioned, not all scrap material can be utilized by domestic producers to make aluminum semis due to the presence of contamination and the high level of mix of different alloys resulting from the current scrap collection and sorting practices by scrap suppliers.

For such reasons, the constrained scrap utilization scenario applied in the Roadmap maintains the quantities of both domestically produced and imported primary aluminum at the 2021 baseline level, with imports coming from traditional trade partners. Under this scenario, since the output of semis is increasing year over year, the use of recycled materials as feedstock to produce semis is projected to increase gradually, from a share of 48% in 2021 to 71% in 2050. This is equal to saying that the average recycled content of semis produced domestically will grow from 48% to 71% during the timeline of the Roadmap. Under this scenario, emission differences can be compared with a recycled content BAU situation to evaluate the emission reduction impact of the role of recycling.

To further explore the role of recycling on emission reductions, the Model also includes an "optimal scrap utilization scenario" in which the share of recycled materials as feedstock for NA domestically produced semis would jump from 48% in 2021 to 61% in 2022 through stopping the imports of primary aluminum from other countries. The share would then increase gradually from 61% in 2022 to 78% in 2050. This scenario has the effect of theoretically reducing around 37 million metric tons of imported primary aluminum in the covered timeline and replacing it with the equivalent amount of recycled aluminum.

According to the AA, such a scenario is not considered realistic at present due to scrap sorting issues in the supply chain. This scenario is only intended to further illustrate the potential role of recycling in the context of decarbonization.

Figure 20 and **Table 10** show the projected emission difference between recycled content BAU (48%) and the two assumed scenarios. For the Roadmap scenario, which is using the constrained scrap utilization scenario, a total of **127 million metric tons of CO_2e** is potentially reduced from 2021 to 2050 compared to a theoretical recycled content BAU. If looking at the optimal scrap utilization scenario, this results in a total of **287 million metric tons CO_2e of emissions** that can be potentially avoided during the same period compared to the same theoretical recycled content BAU scenario.

Figure 20: Emissions Reductions Achieved (MT CO_2e) from Increased Use of Recycled Materials, Against a Theoretical Scrap Utilization BAU

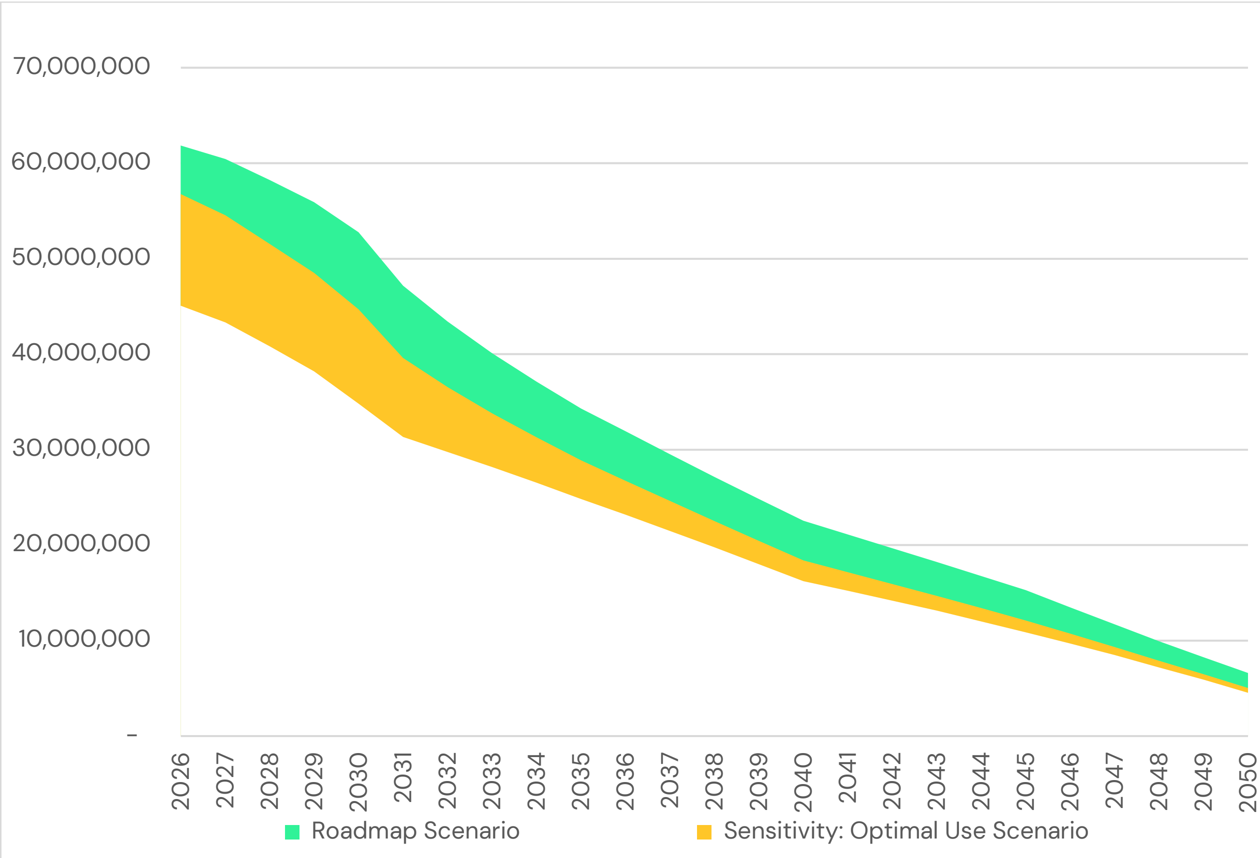


Table 10: Difference in Emissions Between the Recycled Content BAU and the Roadmap Scenario

	2025	2030	2035	2040	2045	2050
Difference in Emissions RC BAU vs. Roadmap Scenarios (MT CO_2e)	4,178,003	8,061,609	5,415,864	4,140,797	3,160,735	1,576,712

Between the Roadmap scenario of constrained scrap utilization and a more aggressive but theoretical optimal scrap utilization scenario, there is a cumulative emission difference of **160 million metric tons of CO_2e**. This emission difference is so significant that it is comparable to the emission reduction potential of some of the impactful technologies during the three decades of timeline.

In addition to the quality issues of scrap recycling, the loss of a significant proportion of post-consumer packaging scrap to landfill in North America, particularly in the United States, is another area for scrap sub-utilization.[6] This loss of scrap to landfill is currently not integrated in the Model. However, it is worth mentioning that the industry is aware that the loss of packaging materials, especially used beverage cans (UBCs), represents both a loss of critical materials and a loss of additional emission reduction opportunities.

[6] Aluminum Can Advantage: Sustainability Key Performance Indicators, AA 2021: https://www.aluminum.org/canadvantage .

V. Conclusions and Recommendations

Thanks to some of the unique properties of aluminum, including high strength in alloy forms, lightweight, durability and recyclability, this material is used in countless applications. With the increasing demand for aluminum products, this industry has the potential to achieve significant GHG emission reductions and be a key player in the North American (NA) transition toward more sustainable solutions and a lower carbon economy. The production of aluminum is associated with high energy-intensive activities and emissions, which also weighs into the need to accelerate the implementation of emissions reduction strategies in order to meet its climate and emissions reduction targets.

This Decarbonization Roadmap is an exercise to identify strategic options and pathways for the NA aluminum industry to reduce its emissions and strive to achieve a net-zero emission profile by 2050. As revealed in this report, the industry faces tough challenges of reducing annual total emissions by 92% by 2050 compared to the baseline year level in 2021, while at the same time increasing total aluminum product output by 78% compared to 2021.

As also highlighted in this report, many key opportunities exist to reduce emissions. Technological options identified by this study include power grid decarbonization, inert anode, cleaner alumina refining, natural gas phasedown through electrification, fuel switching and CCS, among others. Improved scrap sorting could further help increase emission reduction more economically and effectively. With a combination of all of these, the NA industry would be able to meet its emission reduction targets and fulfill its climate obligations.

On top of mapping an emission reduction pathway for NA domestic production, emissions associated with international trade have also been thoroughly evaluated. Emission profile differences observed between domestically produced and imported aluminum products highlight the need for emission reduction strategies that are comprehensive and integrated for the entire NA consumer market, and to consider trade dynamics as a potential part of GHG emission reduction strategies.

While the Decarbonization Roadmap Report and its associated Model will be primarily used by the Aluminum Association (AA) and its members to develop strategies and plans to reduce GHG emissions associated with the manufacturing of aluminum products, and to monitor progress in the next three decades, the study does call for support from policy makers, investors, researchers, up- and down-stream stakeholders, and the like to support the industry in achieving its GHG emission reduction goals.

For policy makers, this Roadmap emphasizes the need for policy developments and executive actions that support the industry in its decarbonization targets, including access to cleaner and affordable energy, support in research and development of emission reduction technologies, and incentives for the adoption and deployment of such technologies and strategies discussed in this report.

For investors, the Roadmap calls for the availability of capital to help the aluminum industry achieve its emissions reduction goals, especially through technological options that are still in the R&D stage and therefore require time to mature and deploy.

For all other stakeholders, this Roadmap emphasizes the impact of different actions (trade, geographic sourcing of raw materials and products, recycling practices and more) on GHG emissions, and encourages them to engage in the conversation and in intentional choices that can make a difference both today and in the future to support the transition toward a cleaner economy.

For the AA, possible future work may include continuous updating of the Model tool as new data and new information become available; continuous monitoring of industry progress; market sector analysis; economic feasibility research; and more. It is understood that the AA is developing an online sustainability data collection platform. Such a platform will certainly help the industry monitor progress and develop additional emission reduction strategies.

Appendix 1: Additional Model Characteristics and Assumptions

Table 11: Excel Model Contents

Excel Tab	Contents
Results	Dashboard of emissions results including summary tables and graph
Emissions Projections	GHG emissions calculations following the scenario inputs selection
Baseline CI	Breakdown of the CI values obtained from the AA, establishing the 2021 baseline CI for this model
2021 Baseline	Market data and resulting GHG emissions for the baseline year of 2021
CI Projections	Details of the CI projections by aluminum output and activity based on assumptions made
Raw Emissions Results	Table indexing the emissions results for further processing or visualization
Assumptions	List of detailed assumptions taken to quantify the greenhouse gas emissions in each one of the tabs included in this spreadsheet

Table 12: BAU CI for Imported Products (Tonnes CO_2e/Tonnes of Specified Aluminum Output)

	Electricity	Fuel Combustion & Thermal	Process Emissions	Ancillary Materials	Totals
Imported Primary Aluminum	6.065	2.446	1.970	0.826	11.307
Imported Semis and Finished Goods - World	7.400	2.284	1.411	0.432	11.526
Imported Semis and Finished Goods - China	10.323	2.393	1.504	0.485	14.705

Table 13: 1.5 Degrees CI for Imported Products (Tonnes CO_2e/Tonnes of Specified Aluminum Output)

	2021	2025	2030	2035	2040	2045	2050
Imported Primary Aluminum – Trade Partners	11.31	10.02	8.25	3.57	1.99	1.16	0.46
Imported Semis and Finished Goods – World	11.51	9.75	6.88	2.70	1.44	0.84	0.35

Table 14: 1.5 Degrees CI for Other Process Inputs for Domestic Production (Tonnes CO_2e/Tonnes of Specified Aluminum Output)

	2025	2030	2035	2040	2045	2050
Primary Aluminum	4.360	3.570	2.122	0.675	0.418	0.160
Recycled Aluminum	0.406	0.351	0.268	0.186	0.133	0.080
Semi-fab Ingot Casting	0.350	0.288	0.255	0.221	0.148	0.075
Semi-fabrication	0.257	0.211	0.187	0.163	0.109	0.055

Table 15: 2021 Baseline Year Market Ratios

Product	Ratio
Net Imports	
Ratio of Net Imported Semis	5%
Ratio of Net Imported Aluminum Embedded in Goods	22%
NA Domestic Semi Productions	
Ratio of Sheet	43%
Ratio of Foil	4%
Ratio of Extrusion	26%
Ratio of Foundry (Casting)	22%
Ratio of Others	5%
NA Domestic Primary Production	
Canada Primary	77.6%
U.S. Primary	22.4%

Table 16: Supply/Demand Scenario Selections

Scenario Options	Selection Inputs	Data for Selection
Total Semis Demand	1% Growth	1% growth annually applied to apparent demand of semis
	2% Growth	2% growth annually applied to apparent demand of semis
Trade Scenario	Trade BAU	Maintains the same trade ratios as the 2021 baseline
	No Trade of Semis and BAU Trade of Goods	Assumes no imports or exports of semis and maintains the same trade ratios as the 2021 baseline
	No Trade of Both	Assumes no imports or exports
Domestic Primary Production	No Change in Capacity	Assumes static domestic primary production capacity

	Add Capacity	Assumes new smelters come online and increase primary production by 500 thousand metric tonnes annually beginning in 2035 and an additional 500 thousand metric tonnes annually beginning in 2038
	Add New and Close Old	Assumes new smelters come online and existing smelters retire, cumulatively resulting in an average increased capacity of 1% annually beginning in 2035 through 2039, and a 2% increase from 2021 levels from 2040 through 2050
Scrap Utilization Scenario	Optimal Scrap	Assumes zero import/export of primary aluminum
	Scrap Use Constraint	Assumes 1,275Mt of imported primary aluminum

Table 17: Major User Inputs and Default Assumptions That Can Be Edited in the Model

User Input	Default Assumption
EOL Scrap Collection Rate (End of Life Scrap Supply)	80%
Scrap Collection for New Scrap Generated	100%
Total Primary and Recycled Material Remelted Through Independent Semi-Fab Ingot Casting by Semi-Fabricators	60%
Penetration Rate of Inert Anode Technology (Start Year)	2030
Penetration Rate of Inert Anode Technology (Completion Year)	2050
Conversion Factor of Aluminum Embedded in Goods to Semis (Assuming 15% Scrap Rate during Product Assembly and Finishing)	1.176
Energy Conversion Ratio from Natural Gas Furnace to Electric Furnace	1
Energy Conversion Ratio from Natural Gas Furnace to Green Hydrogen	1
User Input to Decarbonization through Other Technological Pathways	1% annually beginning 2025