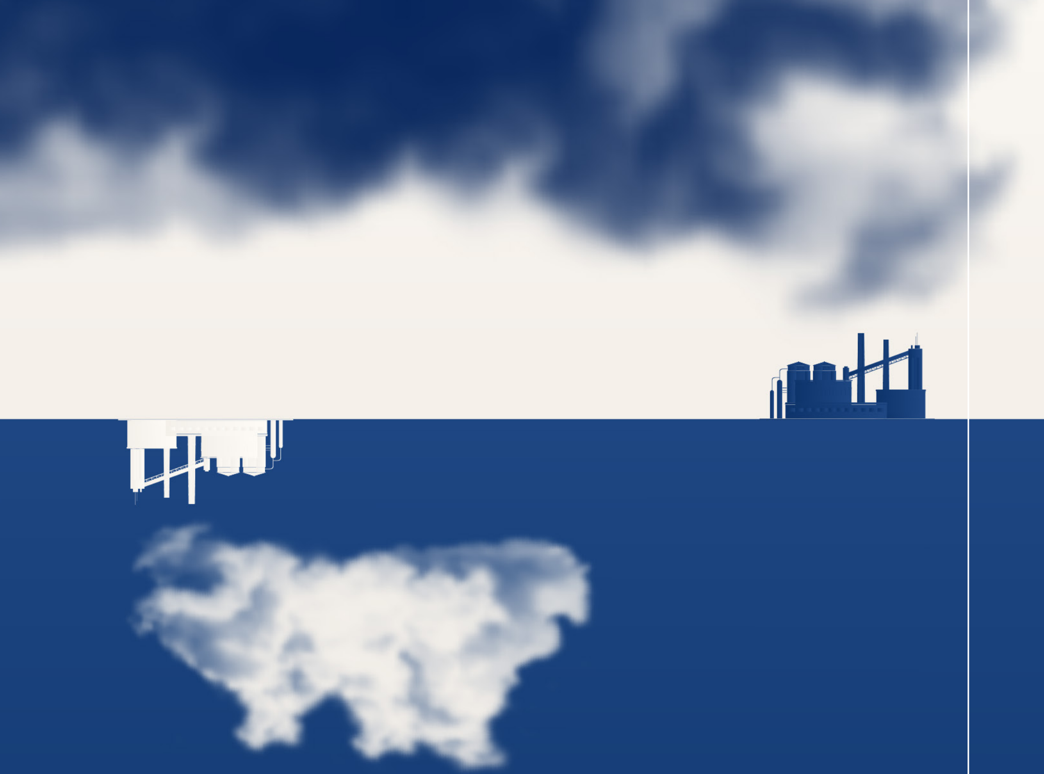
INSTITUT Montaigne



Forging a Post-Carbon Industry

Insights from Asia

OCTOBER 2024

Institut Montaigne is a leading independent think tank based in Paris. Our pragmatic research and ideas aim to help governments, industry and societies to adapt to our complex world. Institut Montaigne's publications and events focus on major economic, societal, technological, environmental and geopolitical changes. We aim to serve the public interest through instructive analysis on French and European public policies and by providing an open and safe space for rigorous policy debate.

REPORT - October 2024

Forging a Post-Carbon Industry

Insights from Asia

Institut Montaigne's reports are comprehensive analyses that result from collective reflection. They aim to put forward long-term solutions to today's most pressing public policy challenges.

Explainer
To understand the world in which we operate

Policy Paper
To provide practical recommendations

Issue Paper
To break down the key challenges facing societies

Exclusive Insights
Unique data-driven analyses and practical scenario exercises

Report
Deep-dive analyses and long-term policy solutions

Part 2

Strategies to decarbonize the Steel and Aluminum Sectors

Author

Joseph Dellatte

Dr. Joseph Dellatte joined Institut Montaigne's Asia Program in 2022 as Research Fellow for Climate, Energy, and Environment. He is also a Research Associate at Kyoto University (Japan) and a member of the Japanese Research Group on Renewable Energy Economics. He specializes in international climate policy and global climate governance, focusing on carbon pricing, industry decarbonization policy, transition finance and Asia-Europe relations on climate.

Table of contents

Introduction

In the face of the climate crisis, as the world moves rapidly toward the dangerous threshold of +2°C warming, decarbonizing industries has become an urgent priority. As the second part of the Institut Montaigne's research report on Industrial Decarbonization Policies and Strategies in Europe and Asia, this paper examines critical issues surrounding the decarbonization of two essential sectors: steel and aluminum. These industries are central to global economic activity but also contribute significantly to greenhouse gas emissions. The dual challenge of reducing emissions while maintaining industrial competitiveness forms the crux of the analysis in this report.

The first part of this report provides an extensive exploration of decarbonization policies and strategies in Europe, China, Japan, and South Korea. It addresses fundamental questions such as defining clean industrial policy and global decarbonization strategies and offers comparative insights into Europe and Asia's approaches. The focus of Part 1 is on identifying the necessary technical solutions and policy frameworks to enable a shift to greener production methods.

In this second part, the emphasis shifts to a more granular examination of the steel and aluminum sectors. Both sectors are indispensable for the post-carbon economy, with steel required for renewable energy infrastructure and aluminum crucial for lightweight transportation solutions. The report undertakes a comparative analysis of the strategies pursued by Europe, China, Japan, and South Korea to decarbonize these industries, highlighting the policy choices, technological advancements, and economic conditions shaping each region's approach.

Specifically, this section assesses technological pathways such as electrification, hydrogen-based steel production, and recycling of secondary aluminum and evaluates the financial and policy support mechanisms that will drive their deployment. With Europe on the cusp of implementing more aggressive climate policies through instruments such as the removal of free allocation from the EU Emissions Trading Scheme (ETS), the Carbon Border Adjustment Mechanism (CBAM), and the Net-Zero Industry Act, it is vital to understand the competitive dynamics between green and carbon-intensive goods and their impact on decision-making for decarbonization. Finally, this report provides recommendations tailored to the European context and is intended to ensure that the steel and aluminum industries can decarbonize without compromising their role in future economic prosperity.

Comparative Sectoral Strategies to Decarbonize Industry

1. STRATEGIES FOR DECARBONIZING THE STEEL SECTOR

The steel industry's transition is essential for meeting climate goals, and despite the inherent challenges, it is technologically achievable with the right policies in place. In fact, while "green" or "low-carbon" steel might not be entirely zero-carbon due to some very hard-to-abate emissions in the process, **options have been examined that offer significant reductions in emissions – of up to 95 percent** – while the **remaining emissions are abatable using carbon capture technologies**.

There are two types of steel. Primary steel is produced from iron ore through various processes, while secondary steel is recycled from scrap metal. Steel is produced by two main routes: the **blast furnace–basic oxygen furnace** (BF–BOF) route and the **electric arc furnace** (EAF) route. The BF–BOF route primarily uses iron ore and coke as raw materials to produce **primary steel**,[1] and the EAF route mainly recycles scrap steel[2] to **produce secondary stee**l.

Additionally, among the technologies that will be key in decarbonizing the steel sector, **direct reduced iron (DRI)**, currently fossil-based and reliant on natural gas, already contributes approximately 7 percent to global crude steel production.[3] In 2022, 71.5 percent of global crude

[1] *It is also worth noting that the BF–BOF route typically incorporates around 20 percent scrap in its production process.*

[2] *However, virgin pig iron or hot briquetted iron (HBI) are frequently utilized in the mix to achieve the desired product quality.*

[3] *Midrex Technologies, Inc., "2022 World Direct Reduction Statistics," 2023, https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2022.pdf.*

steel production, totaling 1.34 billion tons, used the BF–BOF route, while 28.2 percent came from the EAF route powered by electricity.[4]

Overall, the steel industry's decarbonization strategies involve a mix of advanced technologies and bold initiatives, often using untested methods. While these approaches hold great promise for reducing carbon emissions, they are **accompanied by significant technological and financial uncertainties**. The transition to low-carbon steel production presents significant challenges. The high cost of renewable hydrogen and the need for substantial investments in new infrastructure, including renewable energy and hydrogen supply chains, pose financial and logistic hurdles. **Producing low-carbon steel is currently estimated to be 35–100 percent more expensive** than traditional methods, but it is expected to become competitive as technologies mature and economies of scale are achieved.[5]

[4] *International Energy Agency, "Global Crude Steel Production by Process Route and Scenario (2019–2050)" October 5, 2020, https://www.iea.org/data-and-statistics/charts/global-crude-steel-production-by-process-route-and-scenario-2019-2050.*

[5] *Eurometal, "EU Steel Industry's 60 Decarbonization Projects Could Cut Emissions by a Third," June 2, 2022, https://eurometal.net/eu-steel-industrys-60-decarbonization-projects-could-cut-emissions-by-a-third/.*

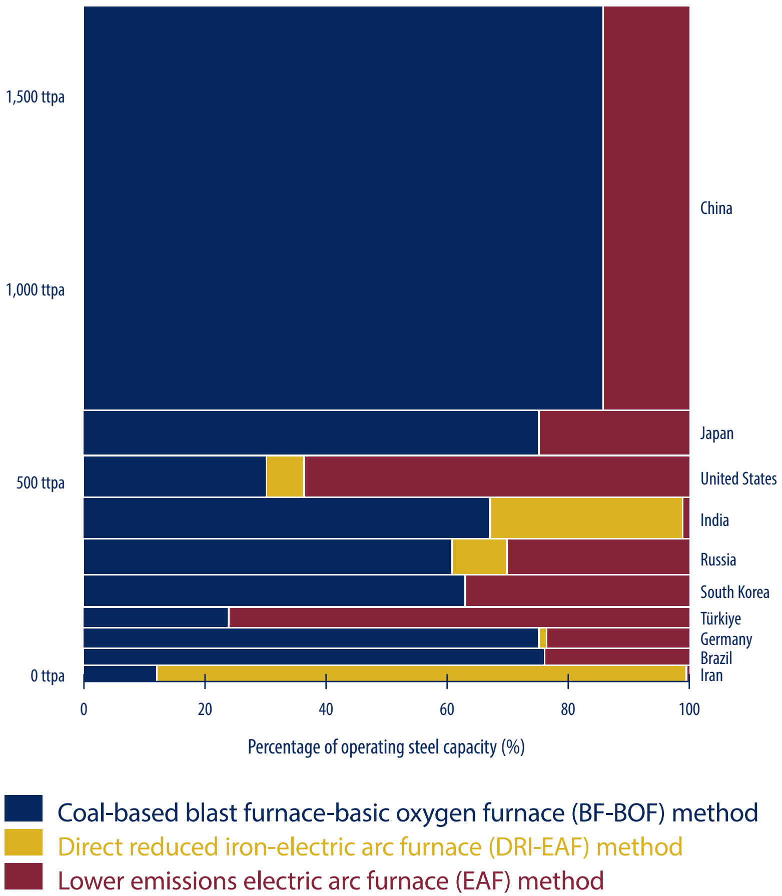
Figure 1: Proportion of operating steel capacity by technology type in the top 10 steel producers

Production of operating steel capacity by technology type in top ten steel producers.

How to reed this chart:

→ % of operating steel capacity by techologogy type.

height of bars = total operating steel capacity in thousand tonnes per year (ttpa).



Source: Global Steel Plant Tracker, Global Energy Monitor

a. China's Steel Sector Strategy

China is by far the world's largest steel producer, with massive primary steel production via coal-based blast furnaces, nearing 913 million tons per annum (mtpa) in operation and with an additional 97 mtpa under development.[6] This substantial coal-based production is incompatible with the country's carbon neutrality goals for 2060, as well as with the projected domestic steel demand, indicating significant overcapacity. Currently, China exports 6 percent of its steel, and this figure is expected to grow in the future due to weak domestic demand,[7] even if the Chinese government theoretically aims to keep primary steel in the domestic market.[8] **The steel sector represents around 15 percent of China's greenhouse gas (GHG) emissions**.[9]

Dealing with Overcapacity as the Main Answer

China's first priority in reducing emissions in its steel sector is to reduce overcapacity. The difficulties in addressing the overcapacity issue in the steel sector are largely due to the nature of China's industrial policy, as although the bodies that set policy at the national level – the National Development and Reform Commission (NDRC), Ministry of Industry and

[6] *Global Energy Monitor, "Global Steel Plant Tracker," accessed September 9, 2024, https://globalenergymonitor.org/projects/global-steel-plant-tracker/.*

[7] *Ali Hasanbeigi, Hongyou Lu, and Nan Zhou, "Net-Zero Roadmap for China's Steel Industry," Global Efficiency Intelligence & Berkeley Lab, March 2023, https://eta-publications.lbl.gov/sites/default/files/china_steel_roadmap-2mar2023.pdf.*

[8] 取消钢铁产品出口退税有何深意？影响几何？ *[What Is the Deeper Significance of Canceling Export Tax Rebates on Steel Products? What Are the Impacts?], Csteelnews, August 2, 2021, http://www.csteelnews.com/xwzx/jrrd/202108/t20210802_53075.html.*

[9] 钢铁业推进绿色低碳转型 *[Steel Industry Promotes Green and Low-Carbon Transition], Economic Daily News, July 13, 2023, http://www.news.cn/energy/20230713/8c4570a53cf-b4e129723382a14db8378/c.html.*

Information Technology (MIIT), and the Ministry of Ecology and the Environment (MEE) – aim to reduce overcapacity, the implementation of industrial policies is the responsibility of certain provinces that may be reluctant to shut down plants due to the potential negative impact on economic growth.

Consequently, until very recently, investments in coal-based blast furnace (BF) plants continued, despite policies aimed at reducing capacity and decarbonizing the sector. This schizophrenic situation of maintaining overcapacity while pursuing decarbonization goals risks creating stranded assets if polluting assets are not incrementally phased out. If China is serious about its carbon neutrality objectives, these **stranded assets could theoretically amount to up to RMB 1.92 trillion (approximately €244 billion) by 2050**.[10]

China's tentative response to the overcapacity problem is long-standing and has been driven not so much by decarbonization but by the economic risks associated with the decommissioning and proliferation of small assets. National initiatives, originating from the *1+N targets for the industry*,[11] **explicitly aim to reduce emissions by addressing overcapacity in the steel sector**. These initiatives seek to reform the steel supply to better align with China's economic needs and facilitate the shift toward low-carbon industries. However, it is important to note that in China, the definition of "low carbon" also includes the use of "coal in a cleaner manner."

[10] *"BF–BOF projects approved in 2021–2023 alone will face the risk of ending up as stranded assets worth USD 118 billion. If BF–BOF projects approved in 2017–2020 are included, the risk of stranded assets comes to USD 270 billion.": Xinyi Shen, "Steel Sector Decarbonisation in China Stalls, with Investments in Coal-Based Steel Plants since 2021 Exceeding USD 100 Billion Despite Overcapacity and Climate Goal," Centre for Research on Energy and Clean Air, March 2024, https://energyandcleanair.org/wp/wp-content/uploads/2024/03/CREA_2023H2-China-steel-analysis.pdf.*

[11] *National Development and Reform Commission, China, "Action Plan for Carbon Dioxide Peaking before 2030," October 27, 2021, https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html.*

The "Guidance Catalogue for Industrial Restructuring (2024)"[12] outlines the government's clear strategy of **concentrating the industry and promoting the development of larger production facilities** rather than multiplying smaller ones. By employing a "capacity-replacement strategy," this plan seeks to reduce the number of small production facilities. By defining what is permitted, restricted, and prohibited, the plan aims to **increase central and provincial government control over the productive apparatus to restructure it as desired**. However, despite the existence of this plan and various other central government policies, "illegal constructions," particularly in steel-dependent provinces such as Guangxi, remain persistent.[13]

In addition, between 2017 and 2023, **provincial governments in China approved numerous new iron and steelmaking projects** through capacity swap plans, which require retiring larger amounts of existing capacity and building new capacity to ensure a net reduction or stabilization in total production. These plans also aim to increase efficiency and reduce emissions per unit of production.[14] However, **many of the new projects approved are set to utilize outdated BF technology**, which relies heavily on coal, rather than adopting cleaner methods such as electric arc furnaces (EAFs).

Recent analyses indicate that no new coal-based steel or cement plants were approved in China during the first six months of 2024[15] and recently, **the central government announced a "pause" on all new steel projects**, halting the issuance of permits for future developments, **including for EAFs**.[16] The long-term stability of this decision remains uncertain, but

[12] *National Development and Reform Commission, China, 产业结构调整指导目录 (2024年本) [Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)], December 29, 2023, https://www.ndrc.gov.cn/xxgk/zcfb/fzggwl/202312/t20231229_1362999.html.*

[13] *Shen, "Steel Sector Decarbonisation in China Stalls."*

[14] *For more on this, see: Jonas Algers and Max Åhman, "Phase-In and Phase-Out Policies in the Global Steel Transition," Climate Policy (2024): 1–14. https://doi.org/10.1080/14693062.2024.2353127.*

[15] *Xinyi Shen and Belinda Schäpe, "Turning Point: China Permitted No New Coal-Based Steel Projects in H1 2024 as Policies Drive Decarbonisation," Centre for Research on Energy and Clean Air, July 2024, https://energyandcleanair.org/publication/turning-point-china-permitted-no-new-coal-based-steel-projects-in-h1-2024-as-policies-drive-decarbonisation/.*

it logically reflects the significant decline in the country's infrastructure and construction demand.

The future expansion of China's steel capacity remains uncertain. By 2025, capacity-replacement projects are expected to renew about one-third of China's steelmaking capacity, further increasing the risk of stranded assets in the sector. **Beyond decarbonization objectives, the primary factor influencing the future of the steel industry in China – and thus decarbonization and electrification – will be the sustainability of this decline in the demand for primary steel**.

The Government's Role in Guiding the Sector

Beyond dealing with overcapacity, national policies also aim to develop so-called green production chains. **The strategy at the national and provincial levels is increasingly to mitigate emissions from conventional coal-based blast furnaces that cannot be phased out quickly enough and replaced by carbon-neutral processes, primarily through carbon capture, utilization, and storage (CCUS) technologies**. This is visible in the guidance concerning steel sector restructuring provided by the NDRC,[17] MIIT,[18] and MEE.[19]

[16] *Ministry of Industry and Information Technology of the People's Republic of China,* 工业和信息化部办公厅关于暂停钢铁产能置换工作的通知 *[Notice of the General Office of the Ministry of Industry and Information Technology on Suspending Steel Capacity Replacement Work], August 20, 2024, https://www.miit.gov.cn/jgsj/ycls/wjfb/art/2024/art_beae9b1682de4457b555b42c5f839f4f.html.*

[17] 锻长板补短板 持续增强钢铁行业核心竞争力 *[Strengthening Advantages and Addressing Weaknesses to Continuously Enhance the Core Competitiveness of the Steel Industry], Csteelnews, January 31, 2024, http://www.csteelnews.com/xwzx/jrrd/202401/t20240131_84488.html.*

[18] *Ministry of Industry and Information Technology, China,* 关于政协十三届全国委员会一次会议第2236号（工交邮电类161号）提案答复的函 *[Reply to Proposal No. 2236 (Industry, Transport, and Telecommunications No. 161) of the First Session of the 13th National Committee of the Chinese People's Political Consultative Conference], September 17, 2008, https://www.miit.gov.cn/zwgk/jytafwgk/art/2020/art_9c5716cb5317439db5c637db2315be25.html.*

[19] *Ministry of Ecology and Environment, China,* 关于推进实施钢铁行业超低排放的意见 *[Opinions on Promoting the Implementation of Ultra-Low Emissions in the Steel Industry], April 28, 2019, https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/201904/t20190429_701463.html.*

Notably, the "14th Five-Year Plan for Raw Materials" (2021)[20] and the "Steel Industry Development Guidelines,"[21] two key documents for the industry's decarbonization, **do not set specific emissions reduction targets for steel up to 2025**. However, recent rules set **annual carbon intensity reduction targets in the industrial sectors for each steel route:** 1 percent for blast furnaces and 2 percent for EAF.[22]

Overall, there is considerable instability in the sector's decarbonization goals. For example, the **China Iron and Steel Association (CSA)**, a government-linked agency, initially set goals in 2021 to peak steel emissions by 2025 and reduce emissions by 30 percent by 2030. However, in 2022, the association revised these targets to a less ambitious **peak emissions timeframe between 2025 and 2030**.[23]

Provinces with high levels of steel production, such as Hebei, Jiangsu, and Shandong, all have plans to develop low-carbon steelmaking, although these plans focus more on improving current production chains than on achieving carbon neutrality.[24] There is an overall **disparate alignment**

[20] *Ministry of Industry and Information Technology, China,* 三部委关于印发"十四五"原材料工业发展规划的通知 *[Notice from Three Ministries on Issuing the '14th Five-Year' Development Plan for the Raw Materials Industry], December 29, 2021, https://wap.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_2960538d19e34c66a5eb8d01b74cbb20.html.*

[22] *State Council of the People's Republic of China,* 三部委关于促进钢铁工业高质量发展的指导意见 *[Guiding Opinions from Three Ministries on Promoting High-Quality Development of the Steel Industry], January 20, 2022, https://www.gov.cn/zhengce/zhengceku/2022-02/08/content_5672513.htm.*

[22] *State Council of the People's Republic of China,* 国家发展改革委有关负责同志就钢铁、炼油、合成氨、水泥4个行业节能降碳专项行动计划答记者问 *[National Development and Reform Commission Officials Answer Questions on the Special Action Plans for Energy Conservation and Carbon Reduction in the Steel, Refining, Synthetic Ammonia, and Cement Industries], June 8, 2024, https://www.gov.cn/zhengce/202406/content_6956537.htm.*

[23] 中共中央 国务院关于完整准确全面贯彻新发展理念 做好碳达峰碳中和工作的意见 *[Opinions from the Central Committee of the Communist Party of China and the State Council on Fully and Accurately Implementing the New Development Philosophy to Achieve Carbon Peak and Carbon Neutrality], China Central Television (CCTV), October 24, 2021, https://news.cctv.com/2021/10/24/ARTIG5kMA9zECwP9oaEim2hN211024.shtml.*

[24] *Environmental Defense Fund, "China's Policies and Actions on Carbon Peaking and Carbon Neutrality," 2023, http://www.prcee.org/yjcg/yjbg/202403/W020240313623895148361.pdf.*

between national and local objectives. Most provincial governments prioritize maximizing employment, income, and growth over closing steel mills and reducing emissions.

One of the central government's goals is to create national champions in major industries, especially steel. This involves consolidating state-owned enterprises (SOEs) and absorbing some private entities to enhance control and benefit from economies of scale. The goal is to **place 60 percent of steel production in the hands of the top 10 producers, up from the current 40 percent**. This means **concentrating more of this production in the hands of SOEs**, since 60 percent of current production is privately owned.[25]

Interestingly, most major players in China's steel industry have more ambitious goals than those officially implemented by the central government. Echoing this, at COP28, Li Jiang, a member of China's State Council, announced that **all state-owned steel enterprises must have a carbon emissions limitation plan**, answering to the government's willingness to address this issue and illustrating the strategy of taking back control over the production engine.

[25] *Shen, "Steel Sector Decarbonisation in China Stalls."*

Table 1: Top Chinese Steelmakers by Production Volume[26]

Company	Production Volume (million tons)	Ownership
China Baowu Steel Group	131.84	SOE
HBIS Group	43.76	SOE
Ansteel Group	55.65	SOE
Jiangsu Group	41.45	Private
Shougang Group	33.83	SOE
Shandong Iron and Steel Group	30.0	SOE
Beijing Jianlong Heavy Industry Group	28.67	Private
Tianjin Iron and Steel Group	27.0	SOE
Hunan Valin Steel Co., Ltd	26.48	Private
Xinyu Iron and Steel Co., Ltd	23.91	Private

A Cooperative and Technology-Agnostic R&D Approach

MIIT's "Guidance on Promoting High-Quality Development of the Steel Industry"[27] provided key guidance defining industrial policy concerning steel in China and established the **Low-Carbon Metallurgy Innovation Alliance**. This alliance is designed to enhance collaborative efforts to develop low-carbon technologies across the steel industry **by uniting R&D efforts from various stakeholders, including industry, academia, and government entities**. The alliance aims to foster innovation, facilitate the exchange of knowledge, standardize new low-carbon processes,

[26] *Table by the author, based on World Steel Association, "2023: World Steel in Figures," May 18, 2023, https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2023.pdf.*

[27] *State Council of the People's Republic of China, "Guiding Opinions on Promoting High-Quality Development of the Steel Industry."*

and accelerate the implementation of these technologies in industrial applications. This collaborative approach is intended to streamline the transition to greener steel production methods by **adopting a technology-agnostic approach, notably using hydrogen, CCUS, and EAFs**.

China's approach to decarbonization in its industrial policy, particularly in the steel sector, could be characterized more as **catch-up R&D than pioneering primary R&D**. However, this perspective is both accurate and misleading. Private steelmaking companies in China are encouraged to innovate not only with respect to decarbonization but also to improve efficiency and capture market share. In contrast, SOEs have been incentivized to scale up production to meet the substantial domestic demand for steel – at least until the recent real estate crisis. SOEs are, however, also encouraged to promote innovation in the steel sector, and the government encourages increasing the **intensity of industry R&D to about 1.5 percent of the total output value**.[28]

China is already demonstrating hydrogen-based steel production and has been operating a full-scale "hydrogen-ready" DRI since early 2024.[29] It also has several R&D initiatives focused on the steel sector. Nevertheless, the country closely monitors global competitors and market trends to absorb new technological innovations from abroad, particularly those suitable for the Chinese steel industry.

Chinese guidelines for the steel sector **promote almost any technology with the potential to decarbonize**, reduce emissions, or improve energy efficiency. There are **no significant restrictions on which directions to**

[28] *Ministry of Industry and Information Technology, China,* 三部门关于促进钢铁工业高质量发展的指导意见 *[Guiding Opinions from Three Departments on Promoting High-Quality Development of the Steel Industry], February 7, 2022, https://www.miit.gov.cn/jgsj/ycls/gt/art/2022/art_368e1aae99704e9281a618dc73c046f7.html.*

[29] *Danieli Group, "New Energiron DRI Plant Starts Production at Baowu," January 17, 2024, https://www.danieli.com/en/news-media/news/new-energiron-dri-plant-starts-production-baowu_37_867.htm.*

pursue as long as they contribute to a more integrated, energy-efficient, and carbon-neutral sector by 2060 – 10 years later than other major competitor nations. This approach allows the Chinese steel sector to rapidly adopt technology when the timing is optimal, **seeking to gain a second-mover advantage**. Overcapacity in the sector also aids decarbonization efforts, as it may facilitate reducing absolute emissions through potential decommissioning while allowing for a more gradual decrease in energy intensity.

The Example of Baowu

Baowu, the leading player in China's steel industry, is at the forefront of initiatives aimed at decarbonization, positioning itself as the industry leader in this area within China. It also demonstrates the **integrated innovation approach that is emerging in the Chinese industrial decarbonization strategy**, which focuses on big SOE actors such as Baowu.

The company has developed a comprehensive **carbon neutrality technology roadmap**,[30] which encompasses nearly all available decarbonization technologies. This roadmap includes **electrification using clean energy, hydrogen reduction processes, and CCUS**. In its decarbonization plan, Baowu also advocates for **standards for low-carbon steel to support the significant investments it plans to undertake**.[31] The company stresses that the technological mix necessary to achieve decarbonization,

[30] *Baowu Group, 专题解读｜碳中和冶金路线图和零碳工厂 [Thematic Interpretation | Carbon Neutrality Metallurgy Roadmap and Zero-Carbon Factory], December 2, 2021, https://www.baowugroup.com/glcmia/detail/246785.*

[31] *A recent proposal for a standard on low-carbon steel was recently published by the China Iron and Steel Association with inputs from BAOWU.*

involving electrification, CCUS, and hydrogen, **requires coordinated action across the entire steel value chain**. To this end, Baowu has launched a **Low Carbon Alliance**[32] under the guidance and support of MIIT to integrate these efforts into its value chain.

Baowu therefore partners with numerous companies, leveraging a broad range of technologies including energy storage, which is crucial for producing the renewable hydrogen necessary for steel manufacturing through the H2-DRI process.[33] Baowu's 12-point strategy progresses **from small prototypes to larger ones and moves to the demonstration phase before advancing to commercialization and integration into the company's value chain**. To fund these initiatives, Baowu has established a RMB 54.8 billion (approximately €7 billion) fund targeting clean energy and green technology projects, aimed at achieving its carbon neutrality goals by 2050. This plan is supported by the **Industry Innovation Fund** established by the Chinese government. Additionally, Baowu's strategy targets **cross-sectoral cooperation with diverse industries such as petrochemicals and energy production**, encompassing both hydrogen and renewable electricity. This holistic approach underscores the centrality of R&D on decarbonization strategies by SOEs such as Baowu in China's broader industrial decarbonization strategy.

[32] *Baowu Group, "Conference: To Reshape the Key Role of the Steel Industry in the Sustainable Development of Mankind," 2021, https://www.baowugroup.com/glcmia/dtcxlt2022/en.*

[33] *Rio Tinto, "China Baowu and Rio Tinto Extend Climate Partnership to Decarbonise the Steel Value Chain," June 12, 2023, https://www.riotinto.com/en/news/releases/2023/china-baowu-and-rio-tinto-extend-climate-partnership-to-decarbonise-the-steel-value-chain.*

Responding to the EU Carbon Border Adjustment Mechanism

The government announced that **the Chinese national emissions trading scheme (ETS) would be extended to the industrial sector, including steel, from 2025**.[34] This would mark a new milestone, and this move aligns with the evolving international market, especially in light of the EU's CBAM.

However, the intensity-based nature of the Chinese ETS is unlikely to change before 2030, and the actual trading of allowances from the steel sector under the Chinese ETS may not happen for some years. Even if adjustments are made, the actual emissions reductions required from the sector remain undetermined and are unlikely to be burdensome compared to those of direct competitors, at least before 2030. This implies that the **Chinese steel sector will have more flexibility to observe and adapt to winning technologies during the transition period and gain the sought-after second-mover advantage**.

China's future steel production trends are difficult to predict. However, many reports analyzing China's steel sector converge on the view that the **production peak is imminent**, followed by a continuous decline until stabilization around 2050. The Rocky Mountain Institute[35] predicts around 621 million tons of steel production in China by 2050, with **a shift toward secondary steel production using EAF technology**. However, it is **likely that China's steel sector will ultimately be a mix of electrification, clean hydrogen reduction, and extensive use of CCUS for the newest coal-based assets that will not be decommissioned**.

[34] 六五环境日｜钢铁行业绿色低碳转型成效明显 – 专访中国钢铁工业协会有关负责人 *[65th World Environment Day | Steel Industry's Green and Low-Carbon Transition Shows Significant Results – An Interview with Officials from the China Iron and Steel Industry Association], China Environment News, June 5, 2024, http://www.cenews.com.cn/news.html?aid=1136558.*

[35] *Rocky Mountain Institute,* 加速工业深度脱碳： 中国水泥行业碳中和之路 *[Accelerating Deep Industrial Decarbonization: The Path to Carbon Neutrality for China's Cement Industry], August 31, 2022, https://rmi.org.cn/insights/*加速工业深度脱碳：_中国水泥行业碳中和之路 - 落基山研究所.

Notably, most industry stakeholders view steel as a crucial factor in China's economic development and believe that while the steel sector should be controlled, any constraints placed on it must not interfere with China's pursuit of its development priorities. Therefore, there is a strong emphasis on guiding the sector toward CCUS, thus enabling carbon-intensive facilities to be kept in operation as long as possible.

Table 2: Chinese Policies for Decarbonizing the Steel Sector

Legislation	Date	Issuer	Link
Guidance Catalogue for Industrial Restructuring[36]	2024	National Development and Reform Commission (NDRC)	https://www.ndrc.gov.cn/xxgk/zcfb/fzggwl/202312/t20231229_1362999.html
The 14th Five-Year Plan for Raw Materials[37]	2021	Ministry of Industry and Information Technology (MIIT)	https://wap.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_2960538d19e34c66a5eb8d01b74cbb20.html
Steel Industry Development Guidelines[38]	2022	MIIT	https://www.gov.cn/zhengce/zhengceku/2022-02/08/content_5672513.htm
Guidance on Promoting High-Quality Development of the Steel Industry[39]	2022	MIIT	https://www.gov.cn/zhengce/zhengceku/2022-02/08/content_5672513.htm
Chinese national Emissions Trading System (ETS)[40]	2021	Ministry of Environment and Ecology (MEE)	https://www.cenews.com.cn/news.html?aid=1136558
Implementation Plan for Carbon Peaking in the Industrial Sector[41]	2022	MIIT/NDRC	https://www.gov.cn/zhengce/zhengceku/2022-08/01/5703910/files/f7edf770241a404c9bc608c051f13b45.pdf

[36] *National Development and Reform Commission of the People's Republic of China, "Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)."*

[37] *Ministry of Industry and Information Technology, China, "Notice from Three Ministries on Issuing the '14th Five-Year' Development Plan for the Raw Materials Industry."*

[38] *State Council of the People's Republic of China, "Guiding Opinions from Three Ministries on Promoting High-Quality Development of the Steel Industry."*

[39] *State Council of the People's Republic of China, "Guiding Opinions from Three Ministries on Promoting High-Quality Development of the Steel Industry."*

[40] 钢铁行业绿色低碳转型成效明显 *[Significant Results in the Steel Industry's Green and Low-Carbon Transition], China Environment News, June 5, 2024, https://www.cenews.com.cn/news.html?aid=1136558.*

[41] *State Council of the People's Republic of China,* 工业领域碳达峰实施方案 *[Implementation Plan for Carbon Peaking in the Industrial Sector], August 2022, https://www.gov.cn/zhengce/zhengceku/2022-08/01/5703910/files/f7edf770241a404c9bc608c051f13b45.pdf.*

Legislation	Date	Issuer	Link
Guidelines for the steel sector[42]	2021	MIIT	https://www.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_4ac49eddca6f43d68ed17465109b6001.html
Clean electricity consumption mandate[43]	2024	NDRC	https://www.ndrc.gov.cn/xxgk/zcfb/tz/202402/t20240202_1363856.html
Hydrogen Industry Development Mid-Long Term Plan (2021–2035)[44]	2022	NDRC	https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123
Hydrogen Metallurgy Action Plan[45]	2022	NDRC	https://www.ndrc.gov.cn/xwdt/ztzl/cjgyjjpwzz/bmgzqk/202205/t20220520_1324965.html?code=&state=123

b. Japan's Steel Sector Strategy

Japan is the third-largest steel producer globally, and **the sector represents about 14 percent of total Japanese GHG emissions.**[46] The country has adopted a multifaceted strategy to decarbonize its steel industry as part of its broader goal of achieving carbon neutrality by 2050.

[42] *Ministry of Industry and Information Technology of the People's Republic of China, "十四五"工业绿色发展规划 [14th Five-Year Plan for Green Industrial Development], December 3, 2021, https://www.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_4ac49eddca6f43d68ed17465109b6001.html.*

[43] *National Development and Reform Commission, China, 关于加强绿色电力证书与节能降碳政策衔接大力促进非化石能源消费的通知 [Notice on Strengthening the Coordination of Green Power Certificates and Energy Conservation and Carbon Reduction Policies to Vigorously Promote Non-Fossil Energy Consumption], February 2, 2024, https://www.ndrc.gov.cn/xxgk/zcfb/tz/202402/t20240202_1363856.html.*

[44] *National Development and Reform Commission, China, 氢能产业发展中长期规划（2021-2035年）[Medium- and Long-Term Plan for Hydrogen Energy Industry Development (2021–2035)], March 23, 2022, https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123.*

[45] *National Development and Reform Commission, China, 工业和信息化部 国家发展和改革委员会 生态环境部关于促进钢铁工业高质量发展的指导意见 [Guiding Opinions from the Ministry of Industry and Information Technology, National Development and Reform Commission, and Ministry of Ecology and Environment on Promoting High-Quality Development of the Steel Industry], May 20, 2022, https://www.ndrc.gov.cn/xwdt/ztzl/cjgyjjpwzz/bmgzqk/202205/t20220520_1324965.html?code=&state=123.*

[46] *Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap Formulated for Transition Finance toward Decarbonization in the Iron and Steel Sectors," October 27, 2021, https://www.meti.go.jp/english/press/2021/1027_002.html.*

The challenges faced by Japan are significant due to its **high dependence on primary steel production**, the **limited availability of scrap metal necessary for EAF production**, and the real **difficulty of either producing clean hydrogen locally or importing it cheaply**.

The extent of these challenges calls into question the capacity of Japan to remain a major primary steel producer in a post-carbon world. Aware of these difficult challenges, the Japanese government, through various policies and funding mechanisms, has laid out comprehensive strategies to overcome these hurdles.

The Basis of the Strategy

Japan's steel strategy supports four directions to decarbonize and lower GHG emissions in the steel industry.

The strategy **focuses heavily on hydrogen as a decarbonization vector**. The ***Green Growth Strategy***,[47] launched in December 2020, **emphasizes the development of hydrogen reduction steelmaking technologies**. Japan is also pushing for **electrification – particularly improving EAF processes to remove impurity**, the adoption of **DRI–EAF processes**, and a mix between CCUS and hydrogen called **carbon recycling BFs** – to complement its hydrogen strategy.

CCUS technologies play a pivotal role in Japan's current strategy to decarbonize the steel industry. The government has committed to supporting the development of these technologies to capture and utilize CO_2 emissions from steel production processes. The ***Roadmap for Carbon Recycling Technologies***,[48] launched in July 2021, outlines the **plan**

[47] *Ministry of Economy, Trade and Industry, Japan, "Green Growth Strategy through Achieving Carbon Neutrality in 2050," June 18, 2021, https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/pdf/ggs_full_en1013.pdf.*

to commercialize CO_2 utilization technologies by 2030 and expand them further by 2040.

In terms of the timeline for the steel sector, this implies the following:

- The ***Technology Roadmap for Iron and Steel*** plans to begin **implementing CO_2 capture in regular blast furnaces before 2030**.[49]
- The implementation of **carbon-neutral processes such as clean hydrogen DRI is not envisioned before 2040**.
- Overall, major stakeholders in the Japanese steel industry **do not expect new processes to be introduced before 2040**, aligning with the timeline for replacing most Japanese blast furnaces.

The Regulatory and Financial Framework

The Japanese government has introduced several **financial instruments and regulatory measures** to support the steel industry's transition. The **Green Innovation Fund**, with an allocation of **JPY 2 trillion (approximately €12 billion)**, is supporting projects to decarbonize the steel industry for a total of **JPY 193.5 billion (approximately €1.15 billion) until 2030:**[50]

- JPY 14 billion (approximately €88 million) for on-site hydrogen direct reduction
- JPY 121 billion (approximately €762 million) for low-carbon tech

[48] *Ministry of Economy, Trade and Industry, Japan, "Roadmap for Carbon Recycling Technologies," July 2021, https://www.meti.go.jp/english/press/2021/pdf/0726_003a.pdf.*

[49] *Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap for 'Transition Finance' in Iron and Steel Sector," October 2021, https://www.meti.go.jp/policy/energy_environment/global_warming/transition/transition_finance_technology_roadmap_iron_and_steel_eng.pdf.*

[50] *Ministry of Economy, Trade and Industry, Japan, グリーンイノベーション基金事業 [Green Innovation Fund Project], October 15, 2021, https://www.meti.go.jp/policy/energy_environment/global_warming/gifund/pdf/gif_09_randd.pdf.*

using CO_2 contained in external hydrogen and blast furnace exhaust gas

- JPY 34.5 billion (approximately €217.4 million) for hydrogen direct injection (in classic blast furnaces, not carbon neutral) + additional 10 percent subsidy rate
- JPY 23.6 billion (approximately €148.7 million) to improve EAF by removing impurities

The ***GX Transition Bonds***, part of the ***Green Transformation (GX) strategy***, offer additional financial support for green projects, backed by a total public–private investment of JPY 150 trillion (approximately €945 billion) over the next decade.[51] Moreover, the Development Bank of Japan's **GRIT Strategy** aims to invest JPY 5.5 trillion (approximately €34.7 billion) in green and innovative initiatives by 2026, including projects in the steel sector.[52]

A Cooperative R&D and Demonstration Approach

Japan's policy emphasizes collaboration across industry, academia, and government to foster innovation in low-carbon steel production. This strategy aims to unify efforts to **develop and standardize new low-carbon processes** and to enhance research, facilitate knowledge exchange, and accelerate the adoption of low-carbon steel technologies.

Against this backdrop, COURSE50 and Super COURSE50, the flagship projects developed by NEDO and the main Japanese steel companies (NipponSteel, JFE Steel, and KobeSteel), include efforts to separate and

[51] *Ministry of Economy, Trade and Industry, Japan, 知っておきたい経済の基礎知識～GXって何？ [Essential Economic Knowledge You Should Know – What Is GX?], January 17, 2023, https://journal.meti.go.jp/p/25136/.*

[52] *Development Bank of Japan, "Response to the TCFD Recommendations," 2022, https://www.dbj.jp/en/pdf/CSR_disclo/2022/tcfd.pdf.*

recover CO_2 from blast furnaces, reduce emissions by 20 percent through CO_2 recycling and mineralization technologies, and use hydrogen injection in blast furnaces.[53] These projects, which represent the most concrete actions to decrease emissions in the steel sector in Japan to date, **do not aim for carbon neutrality but rather to enable emissions reduction during the transition period using currently available technologies** (i.e., fossil-fuel-based blast furnaces).

Table 3: Summary: Japanese Policies

Legislation	Date	Issuer	Link
Green Growth Strategy[54]	2020	Ministry of Economy, Trade and Industry (METI)	https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/pdf/ggs_full_en1013.pdf
Roadmap for Carbon Recycling Technologies[55]	2021	METI	https://www.meti.go.jp/english/press/2021/pdf/0726_003a.pdf
Technology Roadmap for Iron and Steel[56]	2021	METI	https://www.meti.go.jp/policy/energy_environment/global_warming/transition/transition_finance_technology_roadmap_iron_and_steel_eng.pdf
Comprehensive Roadmap for Hydrogen Reduction Steelmaking[57]	2023	METI	https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf

[53] *Nippon Steel, 日本製鉄株式会社 説明資料 [Nippon Steel Corporation Presentation Materials], 2022, https://www.meti.go.jp/shingikai/sankoshin/green_innovation/energy_structure/pdf/010_06_00.pdf.*

[54] *Ministry of Economy, Trade and Industry, Japan, "Green Growth Strategy through Achieving Carbon Neutrality in 2050."*

[55] *Ministry of Economy, Trade and Industry, Japan, "Roadmap for Carbon Recycling Technologies."*

[56] *Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap for 'Transition Finance' in Iron and Steel Sector."*

[57] *Ministry of Economy, Trade and Industry, Japan, "Basic Hydrogen Strategy," June 6, 2023, https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf.*

c. South Korea's Steel Sector Strategy

South Korea is a major player in the global steel industry, with large companies such as POSCO and Hyundai Steel contributing to its status as the **world's sixth-largest steel producer**. The steel sector in South Korea is responsible for about **13 percent of the nation's GHG emissions**.[58]

South Korea's steel sector is also highly trade-oriented, producing approximately 70 million tons of steel annually, with 30 million tons destined for export. Of these exports, around 10 percent are shipped to the EU, 10 percent to the US, 10 percent to China, and 20 percent to ASEAN countries, with the remainder distributed globally.[59] This broad export strategy exposes the sector to diverse market demands, from "green-friendly" customers in the EU to those prioritizing high-quality steel at competitive prices. This reality complicates the decarbonization strategy of South Korean players.

As is the case for Japan, South Korean stakeholders may face difficult choices and **potentially a complete shift in their production model in the post-carbon economy**. Despite this reality, the South Korean government is still betting heavily on its steel sector and aims to become the third-largest steel producer in the future.[60]

The Basis of the Strategy

Similar to Japan and Europe, one of the primary challenges for South Korea in decarbonizing its steel sector is the high cost associated with transitioning to low-carbon technologies. The development and implementation

[60] *Government of South Korea, 철강산업 발전전략 [Steel Industry Development Strategy], February 2023, https://www.korea.kr/docViewer/skin/doc.html?fn=6edabc4005c40af9225651251ae2d12a&rs=/docViewer/result/2023.02/17/6edabc4005c40af9225651251ae2d12a.*

of hydrogen-based steelmaking and wider adoption of electrification are the South Korean government's primary strategy. In addition, CCUS is also part of the South Korean government's agenda.

In terms of the timeline, this has the following implications:

- The main industry players target large-scale deployment of CCUS from 2040 and of most other emissions reduction technologies from 2035.
- In the "Scenario Plan for 2050 Carbon Neutrality," the government plans to **fully replace blast furnaces and converters with hydrogen reduction steelmaking by 2050**.
- The government also aims to **replace crude steel production with steel scrap electricity processes "when possible."**[61]

However, despite these targets, the extent of government involvement in the deployment of these decarbonization technologies remains to be determined. From a technological perspective, South Korea faces limitations similar to those faced by its Asian counterparts. First, the country has **limited access to scrap** metal, which is necessary for EAF production. Moreover, South Korea currently has a **low capacity for producing clean hydrogen domestically** and thus relies heavily on imports, complicating the transition to hydrogen-based steelmaking.[62]

The Support Framework

To support the financial needs of the steel industry during its transition, the South Korean government has essentially established an R&D funding

[61] *Government of South Korea, 2050 탄소중립 시나리오안 [2050 Carbon Neutrality Scenario Proposal], October 18, 2021, https://tips.energy.or.kr/uplolad/carbon/첨부1_2050 탄소중립 시나리오안-최종.pdf.*

[62] *Which triggers investment from big Korean steelmakers abroad: POSCO is investing in a full-scale hydrogen electrolyzer in Oman. See Global Energy Monitor, "POSCO Oman Green Steel Project." accessed September 9, 2024, https://www.gem.wiki/POSCO_Oman_green_steel_project.*

mechanism through the ***Carbon Neutral Industrial Core Technology Development Project*** (October 2022). This project, which selected 100 core domestic carbon-neutral technologies to invest in, is highly technology-agnostic and remains modest in scope, dedicating **KRW 209 billion (€140 million) to the steel sector**.[63]

In response to the EU's CBAM, the South Korean government has partnered with the country's three main steel companies – POSCO Holdings Inc., Hyundai Steel Co., and Dongkuk Steel Mill Co. – to promote investment and technology development aimed at achieving low-carbon steelmaking. This partnership has led to the establishment of a dedicated **KRW 1.5 trillion (around €1 billion) fund to advance decarbonized steel production**.[64]

The South Korean government has also introduced various support mechanisms, including **low-interest loans, subsidies, and tax rebates**. However, these supports are primarily directed toward R&D, with no capital expenditure (CAPEX) or OPEX subsidies in the pipeline. The government is, however, **considering the introduction of contracts for difference tailored for green hydrogen projects**, which could provide a stable revenue stream and encourage private investment.

Companies are also forming coalitions to support R&D in decarbonizing the steel sector. In February 2021, a **Low Carbon Process Research Group**[65] was launched following a joint declaration by five of the largest

[63] *2050 Carbon Neutrality Commission, South Korea,* 철강산업 탄소규제 국내대응 작업반출범 *[Launch of Domestic Task Force for Carbon Regulation in the Steel Industry], January 11, 2023, https://www.2050cnc.go.kr/base/board/read?boardManagementNo=43&boardNo=1238&page=1&searchCategory=&searchType=&searchWord=&menuLevel=2&menuNo=16.*

[64] *Igasnet,* 저탄소·고부가 철강으로 글로벌 수출 *3*강 정조준 *[Aiming for Top 3 in Global Exports With Low-Carbon, High-Value-Added Steel], March 22, 2023, http://m.igasnet.com/news/articleView.html?idxno=19960.*

[65] *ETNews,* 현대제철, 친환경 강재 등 *R&D* 투자 *2000*억원대 진입...사상 최대 *[Hyundai Steel's R&D Investment in Eco-Friendly Steel Surpasses 200 Billion Won... Reaches Record High], March 2023, https://www.etnews.com/20230303000154.*

domestic steel companies – KG Steel, SeAH Steel Holdings, POSCO, Dongkuk Steel, and SIMPAC – to achieve carbon neutrality.

Table 4: Summary: Korean Policies for Decarbonizing the Steel Sector

Legislation	Date	Issuer	Link
Scenario Plan for 2050 Carbon Neutrality[66]	2021	Government of South Korea	https://tips.energy.or.kr/uplolad/carbon/첨부1_2050 탄소중립 시나리오안-최종.pdf
Korean Emissions Trading Scheme[67]	2015	Government of South Korea	https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-47.pdf
New Industrial Growth Strategy through Revitalization of Circular Economy[68]	2023	Ministry of Economy and Finance	https://www.moef.go.kr/com/cmm/fms/FileDown.do;jsessionid=0.node20?atch-FileId=ATCH_000000000023349&fileSn=6
Hydrogen Economy Roadmap[69]	2019	MOTIE	https://www.motie.go.kr/common/download.do?fid=bbs&bbs_cd_n=72&bbs_seq_n=210222&file_seq_n=1
Green New Deal[70]	2020	The Government of the Republic of Korea	https://content.gihub.org/dev/media/1192/korea_korean-new-deal.pdf
Carbon Neutral Strategy 2050[71]	2020	The Government of the Republic of Korea	https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf

[66] *Joint Interagency, South Korea, 2050 탄소중립 시나리오안 [2050 Carbon Neutrality Scenario Draft], 2021, https://tips.energy.or.kr/uplolad/carbon/첨부1_2050 탄소중립 시나리오안-최종.pdf.*

[67] *International Carbon Action Partnership, "Korea Emissions Trading Scheme," 2015, https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-47.pdf.*

[68] *Ministry of Economy and Finance, South Korea, 순환경제 활성화를 통한 산업 신성장 전략 [Industrial Growth Strategy Through Circular Economy Revitalization], June 21, 2023, https://www.moef.go.kr/com/cmm/fms/FileDown.do;jsessionid=0.node20?atchFileId=ATCH_000000000023349&fileSn=6.*

[69] *Ministry of Trade, Industry and Energy, "Hydrogen Economy Roadmap of Korea," 2019, https://faolex.fao.org/docs/pdf/kor209756.pdf.*

[70] *Government of the Republic of Korea, "Korean New Deal: National Strategy for a Great Transformation," July 2020, https://content.gihub.org/dev/media/1192/korea_korean-new-deal.pdf.*

[71] *Government of the Republic of Korea, "2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society," December 2020, https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf.*

d. The European Steel Strategy

The European Union is a leading player in global steel production, and the sector is critical to its economy, providing around 330,000 direct jobs and 2.5 million indirect jobs. The EU steel industry is also responsible for **approximately 5 percent of the EU's CO_2 emissions**, making its decarbonization essential for achieving the EU's broader climate goals of reducing GHG emissions by 55 percent by 2030 and achieving climate neutrality by 2050.[72]

The decarbonization of the steel industry in Europe is a complex issue that involves both the European Union and its Member States. While the **EU sets overarching climate goals and provides funding mechanisms, Member States have their own specific strategies and priorities**. Overall, the EU and its Member States committed approximately **€10.5 billion for steel sector decarbonization projects** from January 2023 to March 2024. This funding structure includes a mix of direct grants, soft loans, and, increasingly, OPEX compensation.

This can lead to a somewhat disorganized policy landscape, with varying approaches and timelines for achieving decarbonization targets, potentially complicating the overall coordination and effectiveness of Europe's efforts to reduce CO_2 emissions in the steel sector. A significant factor contributing to this challenge is the **uneven financial capacity of Member States to invest in the decarbonization of their industrial sectors**.

[72] *Joint Research Centre, European Commission, "EU Climate Targets: How to Decarbonise the Steel Industry," June 15, 2022, https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-climate-targets-how-decarbonise-steel-industry-2022-06-15_en.*

The European Strategy

The EU's strategy for decarbonizing its steel industry hinges on reforming the ETS free allocation system. This reform will gradually increase the carbon price burden on the industry, thereby creating stronger incentives for stringent decarbonization efforts starting in 2028. Additionally, the implementation of the EU CBAM will enable the European steel sector to remain competitive in the European market compared to non-EU competitors. The carbon levy is intended to offset the cost differences imposed by the carbon price, reducing the risk associated with low-carbon steel production in Europe. While this measure will affect the sector's competitiveness outside the European market, it is considered neutral for the European steel sector, as the EU is a net importer of steel.[73]

The European strategy focuses on the deployment of breakthrough technologies such as hydrogen-based steelmaking, advanced electrification through EAFs, and, to a lesser extent, carbon capture and storage.

Hydrogen-based direct reduced iron (H2-DRI) is particularly emphasized, with projects across Europe aiming to replace conventional blast furnaces with hydrogen alternatives. The first H2-DRI in the world was produced at the Hybit Plant in Sweden.[74] The REPowerEU plan optimistically anticipates that around 30 percent of the EU's primary steel production will be decarbonized using renewable hydrogen by 2030.[75]

[73] *In 2023, the EU imported 26 million tons of finished steel products and exported 16.3 million tons of finished steel products. See: European Steel Association (EUROFER), "European Steel in Figures 2024," 2024, pp. 37, 43, https://www.eurofer.eu/assets/publications/brochures-booklets-and-fact-sheets/european-steel-in-figures-2024/European-Steel-In-Figures-2024-v2.pdf.*

[74] *HYBRIT, "HYBRIT: SSAB, LKAB and Vattenfall First in the World with Hydrogen-Reduced Sponge Iron," June 21, 2021, https://www.hybritdevelopment.se/en/hybrit-ssab-lkab-and-vattenfall-first-in-the-world-with-hydrogen-reduced-sponge-iron.*

[75] *Julian Somers, Joint Research Centre, "Technologies to Decarbonise the EU Steel Industry," 2022, https://op.europa.eu/en/publication-detail/-/publication/fd3b326a-8aed-11ec-8c40-01aa75ed71a1/language-en.*

CCUS is another strategy that is being considered, but there have been only a few projects of this type so far.[76] CCUS involves capturing CO2 emissions directly from steel plants and either reusing them in industrial processes or storing them underground. Projects such as the Dunkirk CCS initiative in France and similar endeavors in Belgium and Austria highlight this approach. The success of CCUS depends heavily on the development of robust infrastructure and the implementation of supportive regulatory frameworks that are still in their early stages, posing significant implementation challenges. The newly adopted Net-Zero Industrial Act is intended to accelerate this work.

The EU Level

Both the EU and individual Member States provide financial support for decarbonizing the steel sector. The EU primarily funds R&D and the initial deployment of innovative technologies through Horizon Europe, the EU Research Fund for Coal and Steel (RFCS), and the Innovation Fund. In contrast, substantial CAPEX support, particularly for building new facilities and scaling up green technologies, comes from national government subsidies.

The **European Steel Technology Platform (ESTEP)**, as part of the broader EU industrial policy strategy, facilitates collaboration among stakeholders to develop and implement innovative low-carbon technologies in steel production. ESTEP's activities include promoting hydrogen-based steelmaking and carbon capture technologies and supporting **over 100 decarbonization projects** that could collectively reduce emissions by 30 percent by 2030. This project aims to bring breakthrough technologies to the **large-scale demonstration stage by 2030**.[77]

[76] *There are three relatively minor projects in Europe to use CCUS in the steel sector: the Steelanol CCU project in Ghent, a CCS pilot in Dunkirk, France, and another pilot at Voestalpine in Linz, Austria. The vast majority of recent projects focus on hydrogen.*

[77] *European Steel Technology Platform (ESTEP), "Clean Steel Partnership," accessed September 3, 2024, https://www.estep.eu/clean-steel-partnership.*

The **EU Research Fund for Coal and Steel (RFCS)** is a central funding mechanism designed to foster innovation and research in Europe's coal and steel sectors, leveraging the legacy assets of the former European Coal and Steel Community.[78] It supports projects aimed at improving environmental sustainability, energy efficiency, and industrial safety, with a strong focus on reducing CO_2 emissions in steel production and enhancing the recyclability of materials.

Additionally, the **Clean Steel Partnership**, launched under the Horizon Europe program and the RFCS, is funded by a combination of EU and private sector contributions. The EU has committed **€700 million to this initiative for the period 2021–2027**, which is matched by an **expected €1 billion from the private steel sector**. This partnership aims to develop breakthrough technologies to drastically reduce CO_2 emissions from steel production.

Finally, the **EU's Innovation Fund**, financed by the EU ETS, also plays a role in providing CAPEX for the demonstration of low-CO_2 plants. The Innovation Fund covers up to 60 percent of total project costs.[79] In 2024, the fund opened a €4 billion call for proposals, targeting various industrial sectors, including steel. This funding supports large-scale projects (with CAPEX over €100 million) and medium-scale projects (CAPEX between €20 million and €100 million), among others. Overall, in line with its commitment to advancing innovative technologies in the steel sector, the EU Innovation Fund provided over €399 million in funding between 2021 and 2024 (for four projects, the largest of which are in Sweden).[80]

[78] *European Commission, "Research Fund for Coal and Steel (RFCS)," accessed September 11, 2024, https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/research-fund-coal-and-steel-rfcs_en.*

[79] *European Commission. "Innovation Fund Projects," accessed September 9, 2024, https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/innovation-fund-projects_en.*

[80] *European Commission, "Innovation Fund – Portfolio of the Signed Projects," accessed September 9, 2024, https://dashboard.tech.ec.europa.eu/qs_digit_dashboard_mt/public/sense/app/6e4815c8-1f4c-4664-b9ca-8454f77d758d/sheet/bac47ac8-b5c7-4cd1-87ad-9f8d6d238eae/state/analysis.*

The Member State Level

The EU Member States each have their own specific strategies and funding mechanisms, representing the **largest proportion of the aid given to industries**. This can lead to a somewhat disorganized policy landscape with varying approaches, financial means, and timelines for achieving decarbonization targets, potentially complicating the overall coordination and effectiveness of Europe's efforts to reduce CO_2 emissions in the steel sector.

France has its own strategy for decarbonizing its steel industry and aims to cut **overall industrial emissions by 35 percent by 2030 compared to 1990 levels**.[81] Initially, this plan was supported by an investment of €5.5 billion under the France 2030 plan. However, in October 2023, the government revised this allocation, reducing the decarbonization fund by €1 billion, bringing the total to €4.5 billion.[82] Despite this reduction, **€4 billion remains earmarked for high-quality decarbonization projects and €1 billion for deploying low-carbon technologies. The strategy emphasizes carbon capture and storage (CCS), the production of low-carbon hydrogen, and the increased use of biomass**. Notably, ArcelorMittal's projects in Fos-sur-Mer and Dunkirk are central to this plan, with combined investments of €1.7 billion aimed at implementing EAF and H2-DRI technologies.[83]

[81] *Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, « Le gouvernement dévoile son plan d'action pour décarboner l'industrie », February 8, 2022, https://www.economie.gouv.fr/plan-action-gouvernement-pour-decarboner-industrie.*

[82] *Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, "Maîtriser la dépense pour investir dans l'avenir," September 27, 2023, https://www.budget.gouv.fr/files/files/plf/plf-2024/dossier-presse-projet-de-loi-de-finances-2024.pdf.*

[83] *ArcelorMittal, "€1.7 Billion Decarbonisation Investment to Transform Our French Steelmaking Operations," accessed September 3, 2024, https://corporate.arcelormittal.com/climate-action/decarbonisation-investment-plans/france-arcelormittal-accelerates-its-decarbonisation-with-a-1-7-billion-investment-programme-in-france-supported-by-the-french-government.*

Germany, one of Europe's largest steel producers, also plans to decarbonize its steel industry despite growing issues in this sector in the country. Germany's strategy **focuses on the use of hydrogen to replace coal in steel production**, supported by significant government funding and public–private partnerships. The German government has launched a **€50 billion funding program to support energy-intensive industries** such as steel with the aim of ensuring they can transition to climate-neutral production.[84] The country **will also subsidize OPEX using innovative carbon contracts for difference (CCfD) that will most likely support low-carbon steel production**. Notable projects include Thyssenkrupp's green steel initiative, which has attracted a €2 billion subsidy package from the German government and received EU approval.[85] Additionally, Salzgitter Flachstahl has been granted over €1 billion for decarbonization activities.[86]

The German subsidy efforts alone will not be sufficient to replace the country's entire BF–BOF capacity. While companies such as ThyssenKrupp and Salzgitter have already begun construction, ArcelorMittal remains undecided on whether to proceed with its investment, despite the available funding. The initial strategy involved launching operations with natural gas and gradually transitioning to hydrogen as it becomes available at scale. However, the economic feasibility of this "on-ramp" was

[84] *Germany Trade & Invest (GTAI), "Germany Targets Billions for Steel Sector Decarbonization," June 16, 2023, https://www.gtai.de/en/invest/industries/energy/germany-targets-billions-for-steel-sector-decarbonization-1011840.*

[85] *European Commission. "State Aid: Commission Approves German €550 Million Direct Grant and Conditional Payment Mechanism of up to €1.45 Billion to support ThyssenKrupp Steel Europe in Decarbonising its Steel Production and Accelerating Renewable Hydrogen Uptake," July 20, 2023, https://ec.europa.eu/commission/presscorner/detail/en/IP_23_3928; Thyssenkrupp, "Thyssenkrupp Steel to Receive Federal and State Government Funding Totaling around Two Billion Euros," July 26, 2023, https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/thyssenkrupp-steel-to-receive-federal-and-state-government-funding-totaling-around-two-billion-euros.html.*

[86] *Federal Ministry for Economic Affairs and Climate Action (BMWK), "Habeck and Weil Hand over Funding Notice Worth Nearly One Billion Euros," April 18, 2023, https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2023/04/230418-habeck-and-weil-hand-over-funding-notice-worth-nearly-one-billion-euros.html.*

compromised by the surge in natural gas prices resulting from Russia's war on Ukraine, making the shift to hydrogen less attractive in the near term.[87]

Other major steel-producing countries in the EU such as Italy, Spain, and the Netherlands are also making strides toward decarbonization. Italy, for example, is focusing on direct reduction pilot plants powered by hydrogen. Spain is investing in various projects including the use of green electricity and circular economy principles to minimize the carbon footprint of steel production. The Netherlands, home to Tata Steel's IJmuiden plant, is exploring innovative ironmaking technologies such as HIsarna, which aims to significantly reduce CO_2 emissions.

Key Challenges

Europe holds a dominant position in the global engineering market for steel manufacturing equipment, with the top three companies – SMS Group,[88] Danieli,[89] and Primetals[90] – headquartered within the EU. Danieli has developed its own DRI technology, while SMS Group and Primetals serve as the primary licensees of the Midrex technology, which is being explored in the United States. **This gives the European steel industry a significant advantage in the production and deployment of advanced DRI solutions**.

The transition to carbon neutrality in the European steel sector **hinges on the availability of cost-competitive fossil-free energy carriers**

[87] *For more on the current situation in Germany's steel sector, see: Federal Ministry for Economic Affairs and Climate Action, "Drucksache 20/11678," 2024, https://table.media/wp-content/uploads/2024/07/04153753/2024-07-02-Antwort-BuRe-KA-Gruener-Stahl-Drs.-20-11678-2-1.pdf.*

[88] *SMS Group, corporate website, accessed September 9, 2024, https://www.sms-group.com.*

[89] *Danieli, corporate website, accessed September 9, 2024, https://www.danieli.com/en/.*

[90] *Primetals Technologies, corporate website, accessed September 9, 2024, https://www.primetals.com.*

– especially electricity and clean hydrogen steelmaking – and **related infrastructure, including for CO_2 transport and storage**, as well as **carbon recycling mechanisms**. However, the **choice of decarbonization** vectors is also subject to local conditions regarding the availability of renewable and low-carbon resources.

The EU has enacted ambitious climate policies with short-, middle-, and long-term instruments for decarbonization. Under current legislation and industry projections, **the continued operation of BF–BOF plants in Europe will become virtually impossible shortly after the end of the free allocations in the EU ETS** (2038 by some projections). This has still led to a marked increase in the pace of decarbonization initiatives, highlighted by significant recent investments. Despite this progress, **there remains no viable business case for large-scale investments in green steel without substantial state support**. The financial hurdles in decarbonizing the steel industry are significant, requiring major public funding to drive the transition to low-carbon production methods.

Against this backdrop, in the steel sector, **two main challenges to the low-carbon transition** remain. The first is the **price gap**, as the cost of green steel production is around **30–100 percent more expensive** than that of traditional fossil-based steel. The second challenge is **the dependence on regional markets for energy sources for low-carbon steel**, such as hydrogen and electricity, rather than on the global market, meaning that EU steel producers need to contend with regional prices rather than global ones, as well as with local conditions regarding resource availability.

To achieve its target of cutting GHG emissions by 55 percent by 2030 and carbon neutrality by 2050, the current EU projects **need to be expanded to an industrial scale. Within the EU, the capacity investment needs** for low-carbon projects in the steel sector are estimated by sector representatives to reach the following amounts:[91]

- **€31 billion for capital expenditures (CAPEX) by 2030**.
- **€54 billion for operating expenditures (OPEX) by 2050**.

This level of investment is not currently being met by European industries or public authorities.

Table 5: Summary: EU Policies for Decarbonizing the Steel Sector

EU Policy/Directive	Specific Targets/Requirements	Description
Fit-for-55 Package, 2021[92]	Reduce emissions by 55% by 2030 compared to 1990 levels.	Emphasis on **using hydrogen in steel production** and **implementing CCS technologies**.
EU Emissions Trading System (ETS)[93] **and CBAM**[94]**, 2023**	Gradual reduction in the cap on emissions allowances by 2.2% annually. Total end of free allocation by 2034. Introduction of Carbon Border Adjustment Mechanism (CBAM).	Reduces emissions allowances over time and prevents carbon leakage by adjusting the price of carbon at the border for imported steel
Energy Efficiency Directive (EED)[95]**, 2023**	Improve energy efficiency by 32.5% by 2030. + further increase its energy efficiency ambition by at least 11.7% in 2030 compared to the level of efforts under the 2020 EU Reference Scenario.	Targets improvements in energy efficiency. (no precise target by sector). Most industries are obliged to implement a system of energy management. No precise target by sector
Renewable Energy Directive (RED III)[96]**, 2023**	Increase the share of renewable energy in the EU's energy mix to 42.5% by 2030 in all sectors.	Annual increase in the share of renewable energy in each sector by 1.6% until 2030.
Circular Economy Action Plan[97]**, 2020**	The plan aims to increase the recycling rate from 33% in 2020 to over 50% by 2050.	Promotes sustainable product design, increases recycling rates, and reduces waste.

[91] *European Steel Association (EUROFER), "Low-CO2 Emissions Projects," May 23, 2022, https://www.eurofer.eu/issues/climate-and-energy/maps-of-key-low-carbon-steel-projects.*

EU Policy/Directive	Specific Targets/Requirements	Description
Ecodesign for Sustainable Products Regulation (ESPR)[98], 2024	Expands the Ecodesign Directive (2009/125/EC) to cover nearly all products, focusing on sustainability and circular economy principles.	ESPR aims to improve product design to enhance durability, recyclability, and energy efficiency while reducing overall environmental impact throughout the product life cycle. Targets industries, including steel, to decarbonize production and use more recycled materials.
Industrial Emissions Directive (IED)[99], 2022	Reduce industrial emissions through the application of Best Available Techniques (BAT).	Ensures industries use BAT to minimize emissions: CCUS, Scrap, DRI, EAF, heat recovery.

[92] *European Commission, "Delivering the European Green Deal," accessed September 9, 2024, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.*

[93] *European Commission, "EU Emissions Trading System (EU ETS)," accessed September 9, 2024, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.*

[94] *European Commission, "Carbon Border Adjustment Mechanism," accessed September 9, 2024, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.*

[95] *European Commission, "Energy Efficiency Directive," accessed September 9, 2024, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en.*

[96] *European Union, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023," October 18, 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202302413.*

[97] *European Commission, "Circular Economy Action Plan," accessed September 9, 2024, https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.*

[98] *European Commission, "Ecodesign for Sustainable Products Regulation," accessed September 9, 2024, https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en.*

[99] *European Commission, "Industrial and Livestock Rearing Emissions Directive (IED 2.0)," accessed September 9, 2024, https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/industrial-and-livestock-rearing-emissions-directive-ied-20_en.*

e. Electrifying the Steel Sector

The EAF process for producing **secondary steel** involves melting scrap steel with an electric arc, significantly reducing reliance on primary steel-making methods and therefore lowering CO_2 emissions. This process is particularly suitable for developed economies with **abundant scrap steel supplies**. This process alone is capable of reducing carbon dioxide emissions by nearly 90 percent per ton of crude steel produced. To be carbon neutral, this process requires access to abundant clean electricity.

Despite its benefits, scaling the EAF process globally faces several challenges. One major hurdle is the **variation in scrap steel quality**, which can contain impurities that affect the steel's properties, posing challenges for industries requiring high-grade materials such as the automotive and aerospace sectors. Additionally, the **availability and quality of scrap steel vary significantly across regions**, impacting the feasibility of widespread adoption. Enhancing the efficiency and output quality of EAF steel requires advanced sorting and pretreatment technologies to remove impurities, increasing both operational complexity and costs. The global steel industry is investing in R&D to overcome these obstacles. Some innovations, such as using plastic waste as a foaming agent in EAFs, have shown promise in improving sustainability and reducing costs.[100]

f. Electrification in China

It has become fashionable to describe China as the world's first "electrostate" – a country leading the global electrification revolution. A significant part of China's strategy to decarbonize the steel industry is outlined in the "Implementation Plan for Carbon Peaking in the Industrial Sector"[101]

[100] *World Steel Association, "Climate Change and the Production of Iron and Steel," 2021, https://worldsteel.org/wp-content/uploads/Climate-change-production-of-iron-and-steel-2021.pdf.*

[101] *State Council of the People's Republic of China, "Implementation Plan for Carbon Peaking in the Industrial Sector."*

and the MIIT "Guidelines for the Steel Sector."[102] These documents **focus heavily on the development of EAFs to reduce emissions.** This could be one of the low-hanging fruit of China's industrial decarbonization.

The steel sector is currently predominantly based on primary steel production and **lacks effective recycling policies**. EAFs are seen as a straightforward way to reduce emissions in the short term while maintaining sufficient production levels. The initial target is to produce up to 15 percent of steel from EAFs by 2025.

To achieve this 15 percent EAF production target by 2025, China would need to produce 143 mtpa using EAF technology. As of January 2024, China has 151 mtpa of EAF capacity in operation, indicating that **the necessary infrastructure is already in place, provided that EAF capacity utilization rates are optimized.**[103] Furthermore, the MIIT guidelines for 2030 have fluctuated over time. Initially, in 2020, the goal was for 20 percent of Chinese steel to come from EAFs by 2030.[104] This target was scaled back in the MIIT 2022 decarbonization plan due to concerns that increasing EAF capacity amid overcapacity would necessitate significant reductions in BF operations, a potentially disruptive strategy for many provinces that are still investing in these traditional carbon-intensive furnaces.

A major limitation in the electrification of the Chinese steel industry is the **difficulty of accessing steel scrap in China**, although this supply is expected to increase.[105] This leads to some **EAFs being fed not with**

[102] *Ministry of Industry and Information Technology, China, "14th Five-Year Plan for Green Industrial Development."*

[103] *Global Energy Monitor, "In China, a Small Boost to Low-Emissions Steelmaking Can Mean Big Cuts to Its Carbon Footprint," China Steel Brief, March 2024, https://globalenergymonitor.org/wp-content/uploads/2024/03/GEM-China-steel-brief-March-2024.pdf.*

[104] *State Council of the People's Republic of China, "Guiding Opinions from Three Ministries on Promoting High-Quality Development of the Steel Industry."*

[105] *There are hardly any sophisticated models projecting steel availability/supply. However, some sources expect an increase to 320 million tons by 2025, 390 million tons by 2030, and up to 500 million tons by 2050. See: Global Energy Monitor, "Global Steel Plant Tracker."*

recycled steel scrap but with pig iron from traditional coal-based BFs due to the current scrap shortage and massive availability of pig iron.[106] Another significant challenge is the **availability of low-carbon electricity**. Despite China's gigantic renewable electricity generation capacity, it has not yet met the growing demand from the grid, leading **many current EAFs to be powered by coal-based electricity.**

Main National Strategy to Enhance the Use of Electric Arc Furnaces

The success of the Chinese electrification strategy relies on a **complete overhaul of the country's recycling capacity**. The "14th Five-Year Plan on Raw Materials"[107] and the "Steel Industry Development Guidelines"[108] **prioritize electrification in the short term**, encouraging provinces to support the transition to EAFs connected to low-carbon energy sources and implement policies to improve access to steel scrap.

Traditional industrial policy instruments, such as fiscal incentives and the creation of a price index for scrap iron and steel, are used to guide the market. These documents set specific targets, such as achieving a **30 percent ratio of scrap steel utilization in steelmaking by the end of the 14th Five-Year-Plan period** and **reaching 200 million tons of annual processing capacity for scrap iron and steel**. The national government also implemented a **clean electricity consumption mandate** that may have an effect on the current usage of clean electricity by EAF in China.[109]

[106] *This is the current reality of Chinese EAFs, which are the most carbon-intensive in the world, with 2.1 tn. CO_2 / tn. steel compared to a global average of 1.3 tn. CO_2 / tn. steel.*

[107] *Ministry of Industry and Information Technology, China, "14th Five-Year Plan for the Development of the Raw Materials Industry."*

[108] *State Council of the People's Republic of China, "Guiding Opinions from Three Ministries on Promoting High-Quality Development of the Steel Industry."*

[109] *National Development and Reform Commission, China, "Notice on Strengthening the Coordination of Green Power Certificates and Energy Conservation and Carbon Reduction Policies to Vigorously Promote Non-Fossil Energy Consumption."*

Currently, however, most experts and Chinese industrialists interviewed for this study emphasize that EAFs powered by renewable energy are still less competitive than coal-based processes. Therefore, **without substantial subsidies, a reform of the electricity market, and the implementation of a significant carbon price, this competitiveness issue is unlikely to change**, even if additional EAF capacity is built. Furthermore, current R&D support for improving EAFs and scrap quality is not at the forefront of the Chinese steel sector strategy.[110] Indeed, most funding and guidance is going toward other technologies, particularly CCUS and hydrogen reduction processes.

g. Electrification in Japan

The Japanese government has laid out an extensive strategy to promote electrification within the steel sector. The **Technology Roadmap for Iron and Steel**[111] plans to expand EAF and improve the technology to **large-scale EAF and low-impurity EAF steel from 2030**.

Key Challenges

One of the primary hurdles in shifting to EAF technology in Japan is the **low level of utilization of high-quality steel scrap** in the country. This scarcity is compounded by the high demand for scrap from other sectors and the export of scrap metal. To **address the scrap availability issue**, the government is considering implementing new policies including **stricter regulations on scrap exports and incentives for recycling**

[110] *While EAF is a mature technology, research could still be valuable in improving scrap sorting and feedstock monitoring—potentially through AI technology. This would enhance the quality of secondary steelmaking, minimizing the reliance on virgin pig iron or HBI to achieve the desired steel grades.*

[111] *Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap for 'Transition Finance' in Iron and Steel Sector," October 2021, https://www.meti.go.jp/english/press/2021/pdf/1027_002a.pdf.*

within Japan. Also under consideration is financing the development of advanced sorting and processing technologies to improve the quality and availability of scrap for EAF use.

The **high cost of electricity in Japan**, coupled with the **need for substantial investment in grid infrastructure**, complicates the electrification strategy. Although EAFs are less carbon-intensive, they require significant amounts of electricity, making their operation economically challenging without substantial support and subsidies. The government is, therefore, considering policies to **reduce electricity costs for steel producers**, such as **subsidies for renewable energy use** and investments in grid infrastructure to support the increased demand from electrified steel production.

Additionally, the quality of steel produced by current EAF technologies does not meet the demands of the Japanese economy, particularly in car and machine manufacturing, which requires higher-quality steel. Therefore, **switching completely to EAFs in the near future is not considered desirable by most industry stakeholders**, who are calling for further development of technologies to remove impurities from scrap steel.

Policy Framework and Strategies

The Japanese government's Green Growth Strategy, launched in December 2020, includes **support for the development and adoption of EAF technology**.[112] The government aims to promote the transition to EAFs by providing **financial incentives, investing in R&D, and supporting the necessary infrastructure developments**. Through the

[112] *Ministry of Economy, Trade and Industry, Japan, "Green Growth Strategy through Achieving Carbon Neutrality in 2050."*

Green Innovation Fund, the Japanese government has allocated JPY 23.6 billion (approximately €149 million) to support the electrification of the steel sector.[113] Additionally, the **GX Transition Bonds**,[114] designed to attract private investment in green projects, are also supposed to provide additional financial support for electrification (under the renewable energy use portfolio of JPY 31 trillion, or approximately €195.51 billion).

The Japanese strategy places a **strong emphasis on R&D**. The Green Innovation Fund supports various projects aimed at **improving the performance of EAFs** (which are currently 30 percent less efficient than BFs). For instance, significant investments are being made to **tackle the challenges associated with removing impurities in scrap steel**, which is crucial for producing high-quality steel through the EAF route and establishing large-scale EAFs, as **the technology roadmap sees emerging from 2040**.

The Japanese government is also implementing various **regulatory measures** to support the transition to electrified steel production. These include **setting ambitious targets for scrap utilization** and creating **market mechanisms to ensure the availability of low-carbon electricity, especially where EAFs are located**.[115]

h. Electrification in South Korea

South Korea is also actively pursuing policies to increase the use of EAFs as part of its broader decarbonization strategy for the steel industry. The country's main vehicle to decarbonize industry – the **Carbon Neutral**

[113] Ministry of Economy, Trade and Industry, Japan, "Green Innovation Fund Project."

[114] Ministry of Economy, Trade and Industry, Japan, "Japan Climate Transition Bond Framework," November 2023, https://www.meti.go.jp/policy/energy_environment/global_warming/transition/climate_transition_bond_framework_eng.pdf.

[115] Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap Formulated for Transition Finance toward Decarbonization in the Iron and Steel Sectors."

Industrial Core Technology Development Project – promotes electrification, with an emphasis on EAFs in the steel sector.

A major obstacle is the **demand for primary steel from key customers** in the electronics and car manufacturing sectors. South Korea's industrial requirements necessitate a continuous supply of primary steel, which is traditionally produced using blast furnaces. This dependence on primary steel complicates the transition to EAFs.

Moreover, South Korea – a key importer of scrap metals, notably from Japan – still faces **limitations in accessing sufficient quantities of scrap steel**, which is crucial for the effective operation of EAFs. Therefore, the government has set objectives of building a **steel scrap ecosystem** and **enabling access to the resource**, which is currently behind in the country.[116]

Scrap Steel Strategy

Access to scrap steel has thus become a central strategy for a country as heavily involved in steelmaking as South Korea. The South Korean government has, therefore, established a **strategy of ensuring a balanced supply and demand of steel resources, with the aim of securing a circular steel economy**.[117] This involves conducting a detailed statistical investigation across all stages of the steel value chain, including the occurrence, demand, and distribution of steel by grade and region.

In the first half of 2023, the government launched the **"Iron Resources Coexistence Forum"** to foster collaboration between steel manufacturing companies and steel scrap companies. To secure a stable scrap supply, efforts will be made to **obtain scrap volumes from key international sources, particularly the US and Japan, while reviewing measures to**

[116] *Government of South Korea, "Steel Industry Development Strategy."*

[117] *Ministry of Economy and Finance, South Korea, "Industrial Growth Strategy Through Circular Economy Revitalization."*

prevent the outflow of domestic scrap. In this sense, the economic battle for scrap metal will only become more acute when decarbonization goals are implemented more stringently.

The high initial investment required for transitioning from traditional BFs to EAFs presents another significant challenge. The capital expenditure needed for this shift is substantial, and the **existing funding mechanisms in South Korea are not sufficient to cover these costs entirely**. Additionally, the energy supply and infrastructure required to support EAF technology present further complications. EAFs demand a stable and substantial supply of electricity, ideally sourced from renewable energy. However, South Korea's current renewable energy infrastructure may not be adequate to meet this increased demand, and the nuclear sector itself is considered key for future development.

To address these challenges, the government is investing in R&D to improve the efficiency of EAF technology and is **providing KRW 24.1 billion (approximately €16.2 million)** toward this end for the period 2024–2025.[118] **This includes efforts to enhance the efficiency of EAFs and to integrate them with imported DRI steel**. By importing DRI steel, South Korea can supplement the scrap steel supply needed for EAF operations, facilitating the transition to greener steel production methods.

Companies are also betting on improving and expanding their use of EAFs. Dongkuk Steel is planning to complete an R&D project on hyper-electric furnaces by 2028.[119] POSCO is betting on the establishment of renewable electric furnaces based on bridge technology by 2030 and expects to close down all its coal processes by 2050.[120]

[118] *Ministry of Economy and Finance, South Korea, "Industrial Growth Strategy Through Circular Economy Revitalization."*

[119] *An advanced type of EAF, see: Dongkuk Steel, "Steel for Green," 2022, https://m.dongkuk.com/upload/pdf/2022_steel_for_green_en.pdf.*

[120] *POSCO, "POSCO's Initiative for a Clean Earth," accessed October 1, 2024, https://www.posco.co.kr/homepage/docs/eng7/jsp/climate/s91c6000010a.jsp.*

i. Electrifying the European Steel Sector

The advancement of EAF technology in Europe marks a stride toward decarbonizing the steel industry. Electrification in Europe presents a viable solution to some of the challenges of deploying hydrogen reduction steelmaking, given the high costs associated with producing or importing clean hydrogen. If the main strategy to decarbonize the steel industry in Europe is still targeting hydrogen reduction, **the future of European steel in a post-carbon world may rely heavily on EAF technology**, potentially supported by a model of importing primary steel or reduced iron.

The Political Economy of EAF in Europe

At the European level, support and strategies for electrifying the steel sector and industry in general are relatively weak. Overall, industries' electrification strategies **mostly depend on national policies**, which play a crucial role in supporting EAF adoption. For instance, Germany has pledged €1.3 billion to help decarbonize steel production by building EAFs at ArcelorMittal's factories in Bremen and Eisenhüttenstadt.[121] This funding is part of a larger €2.5 billion investment package aimed at reducing carbon emissions by 60 percent by 2030.[122]

The growing market demand for low-carbon steel, driven by consumer preferences and corporate sustainability goals, supports the economic

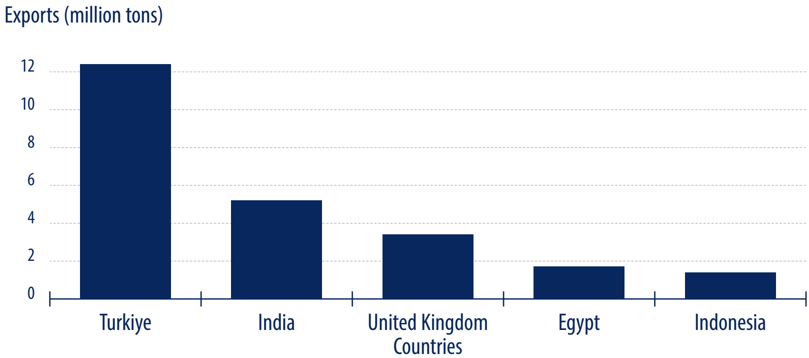
[121] *Federal Ministry for Economic Affairs and Climate Action (BMWK), "Habeck übergibt Förderbescheid über rund 1,3 Milliarden Euro an ArcelorMittal" [Habeck Delivers Grant of Around 1.3 Billion Euros to ArcelorMittal], May 30, 2024, https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2024/05/20240530-foerderbescheid-1.3-mrd-euro-arcelormittal.html.*

[122] *Jack McGovan, "German Govt Pledges €1.3 Bln in Funding to Help Decarbonise Steel Production," Clean Energy Wire, February 6, 2024, https://www.cleanenergywire.org/news/german-govt-pledges-eu13-bln-funding-help-decarbonise-steel-production.*

viability of EAF technology and, therefore, the demand for scrap. Despite the high electricity costs associated with its operation, countries with abundant renewable energy sources, such as Spain and the Nordic nations, find EAF technology particularly viable.[123]

In contrast to most of its Asian counterparts, Europe benefits from a robust recycling infrastructure, **ensuring a steady supply of steel scrap, which is essential for EAF operations**. However, over the past decade, the **EU's scrap exports have surged significantly, primarily to Türkiye**.[124] Some have raised concerns that the current **CBAM regulation does not include pre-consumer scrap**, potentially creating a loophole that could allow CBAM requirements to be easily circumvented.[125]

Figure 2: EU steel scrap exports by destination



[123] Halina Yermolenko, "European Investment in the EAF Continues to Grow," July 6, 2023, GMK Center, https://gmk.center/en/news/european-investment-in-the-eaf-continues-to-grow/.

[124] In 2021, the EU exported 13.1 million tons of ferrous scrap to Türkiye, making it the largest destination for EU scrap, accounting for nearly 48 percent of all EU ferrous metal exports. This trend continued into 2023, with Türkiye remaining the primary destination, receiving 12.2 million tons of recyclable raw materials from the EU. See: Eurostat, "Exports in Recyclable Raw Materials Increased in 2023," May 22, 2024, https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240522-1.

[125] Sandbag – Smarter Climate Policy, "A Scrap Game: Impacts of the EU Carbon Border Adjustment Mechanism," June 3, 2024, https://sandbag.be/2024/06/03/a-scrap-game-cbam-impacts/.

To address the environmental concerns associated with scrap exports, **the EU is revising its Waste Shipment Regulation**. The updated regulation, which was adopted in April 2024 and will take full effect by May 2027, introduces stricter controls on the export of waste, particularly to non-OECD countries. These countries must now demonstrate their capability to manage the waste sustainably before they are permitted to receive it. This regulatory overhaul aims to **bolster the circular economy within the EU by ensuring that waste is recycled and reused within the union**, thus supporting the EAF sector and reducing the environmental impact of waste exports.[126]

The Future Role of EAF in Europe

EAF technology currently accounts for 44 percent of Europe's steel production, especially in countries with strong recycling systems and access to affordable electricity.[127] Italy and Spain, where projects focus on integrating clean electricity into the steelmaking process, are notable leaders in this field. For instance, ArcelorMittal's initiatives in Sestao, Spain, aim to utilize green electricity and H-DRI to produce low-carbon steel.[128] The integration of renewable energy into the steel production process offers a promising pathway to sustainability, but it also requires substantial investment and poses risks related to energy supply stability and cost.

[126] *European Commission, "New Regulation on Waste Shipments Enters into Force," May 20, 2024, https://environment.ec.europa.eu/news/new-regulation-waste-shipments-enters-force-2024-05-20_en.*

[127] *Annalisa Villa, "Europe to Press on with Low-Emission Steel Production Projects in 2024," S&P Global, December 12, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/121123-europe-to-press-on-with-low-emission-steel-production-projects-in-2024.*

[128] *ArcelorMittal, "ArcelorMittal Sestao to Become the World's First Full-Scale Zero Carbon-Emissions Steel Plant," July 2021, https://flateurope.arcelormittal.com/flatnews/2021-news/news_july_2021/sestao-zero-carbon-emissions.*

Looking ahead, EAFs could play an even more significant role, particularly if primary steelmaking or ironmaking is transferred outside of Europe due to the high costs associated with hydrogen production. Hydrogen-based steelmaking, while promising, is currently expensive. **If Europe shifts primary steelmaking abroad, EAF technology, relying on recycled steel scrap or imported reduced iron, could become the predominant method within the continent**.

j. Producing Primary Steel Using Clean Hydrogen

Decarbonizing the primary steel production process is a complex challenge. The production of iron, which is the precursor to steel, is particularly carbon-intensive. There are two primary reasons for this: first, the process requires enormous amounts of heat, and second, carbon is used as a feedstock to facilitate the chemical reaction necessary to reduce iron ore into pure iron. This ironmaking process alone accounts for 3 to 4 gigatons of GHG emissions annually and is a major source of other pollutants.

One classic approach to decreasing steel emissions involves using natural gas in a process called direct reduced iron (DRI), which takes place in a **shaft furnace**. Unlike traditional BFs using coal, DRI requires less heat and does not melt the iron. Instead, it purifies iron ore, and **where natural gas is used, it can be replaced with hydrogen produced from clean electricity**. This hydrogen can eliminate the vast majority of GHG emissions associated with iron production. This decarbonizing strategy is the most widely considered by the steel industry worldwide.

Traditional steel production methods, which use a BF followed by a BOF, produce, on average, 2.44 tons of CO_2 equivalents per ton of steel, with massive variations between countries and methods used.[129] In contrast, **using clean hydrogen DRI associated with an EAF powered by clean electricity can reduce emissions by up to 97 percent**.[130]

The fundamental chemical reaction in steel production involves breaking the bonds between iron and oxygen atoms in iron ore (iron oxide). In traditional methods, carbon from coal serves as the bonding agent, producing CO_2 as a byproduct. However, in the hydrogen reduction process, **hydrogen replaces carbon, and the byproduct is water vapor instead of CO_2.**[131]

Different Types of DRI Tech

Different DRI technologies have varying requirements regarding the quality of iron ore, which is a critical element for decarbonizing the steel industry:[132]

- **H2 shaft furnaces require high-grade iron ore (ore with more than 67–68 percent of iron) to function efficiently**. These furnaces operate by using hydrogen to directly reduce iron ore at **high temperatures**, resulting in lower carbon emissions. However, the need for high-grade iron ore is a significant limitation.[133] Recent advancements aim to allow these furnaces to use lower-grade ore by enhancing the reduction process and incorporating robust purification systems to handle impurities.

[129] *For more on emissions disparities between China, Europe, Japan, and South Korea, see: Ruochong Xu et al., "Plant-by-Plant Decarbonization Strategies for the Global Steel Industry," Nature Climate Change 13 (2023): 1067–1074, https://www.nature.com/articles/s41558-023-01808-z.*

[130] *Jessica Terry, Chathurika Gamage, Nick Yavorsky, and Rachel Wilmoth, "Unlocking the First Wave of Breakthrough Steel Investments in the United States," RMI, 2023, https://rmi.org/insight/unlocking-first-wave-of-breakthrough-steel-investments-in-the-united-states/.*

[131] *Josué Rodríguez Diez, Silvia Tomé-Torquemada, Asier Vicente, Jon Reyes, and G. Alonso Orcajo, "Decarbonization Pathways, Strategies, and Use Cases to Achieve Net-Zero CO2 Emissions in the Steelmaking Industry," Energies 16, no. 21 (2023): 7360, https://doi.org/10.3390/en16217360.*

[132] *Soroush Basirat, "Green Steel Pathways for the New Hydrogen-Powered DRI-EAF Projects," Energy Post, April 4, 2024, http://web.archive.org/web/20240520054028/https://energypost.eu/green-steel-pathways-for-the-new-hydrogen-powered-dri-eaf-projects/.*

[133] *Technically, it is not the DRI plants that struggle with lower-grade ores, but rather the EAFs in the second stage of the process.*

- **Midrex** is the leading technology for shaft DRI production and can operate using natural gas, with the ability to gradually integrate hydrogen as it becomes more cost-effective. This flexibility allows for a smoother transition from natural gas to hydrogen, making it a viable option for regions currently reliant on natural gas.
- **Energiron** technology is an inherently hydrogen-ready tech, meaning it can start using hydrogen as a reducing gas without significant equipment modifications. This technology can handle a variety of iron ore grades, although optimal performance is achieved with higher-grade ores. Energiron's capability to adapt to different reducing gases positions it as a crucial technology for the steel industry's transition to lower carbon emissions.

- The **HyREX** process, **developed by POSCO in South Korea**,[134] represents a flexible and innovative approach to DRI steel production capable of handling lower-grade iron ore fines directly in a fluidized bed reactor. Unlike traditional DRI processes that require high-grade iron ore pellets and utilize shaft furnaces, **HyREX bypasses the pelletization step**, reducing both costs and carbon emissions.[135] By integrating hydrogen reduction with electric melting, HyREX efficiently removes impurities, producing high-quality steel.[136] However, its **significant energy requirements due to the endothermic hydrogen reduction reaction** present a challenge, making the process heavily reliant on consistent and affordable renewable energy sources to maintain reaction temperatures and ensure economic sustainability.

[134] *POSCO, "Great Conversion to Low-Carbon Eco-Friendly Steelmaking Process (HyREX)," June 2, 2022, https://newsroom.posco.com/en/special-project-for-great-conversion-to-low-carbon-eco-friendly-steelmaking-process-%E2%91%A0-hyrex/.*

[135] *For more information see: Agora Industry, "Low-Carbon Technologies for the Global Steel Transformation," April 11, 2024, https://www.agora-industry.org/publications/low-carbon-technologies-for-the-global-steel-transformation.*

[136] *Primetals Technologies, "HyREX demonstration plant from POSCO and Primetals Technologies," August 31, 2022, https://magazine.primetals.com/2022/08/31/hyrex-demonstration-plant-from-posco-and-primetals-technologies/.*

Globally, around 400 integrated steel mills rely on blast furnaces.[137] Each will face a decision within the next 20 years about whether to reinvest in coal-based steelmaking or pivot to cleaner alternatives. For primary steel, the shift to DRI processes using clean hydrogen is crucial, offering a cleaner method and avoiding reinvestment in outdated carbon-intensive technology. Currently, some industrial steel companies, especially in Europe, are **transitioning from BFs to "hydrogen-ready" shaft furnaces**. However, the term "hydrogen ready" should be approached with caution, as these furnaces, **in the absence of a massive supply of clean hydrogen, will run initially on natural gas**, with a vague timeline for transitioning to hydrogen.

k. China and Hydrogen Steelmaking

China's industry decarbonization strategy, like that of other countries, aims to develop hydrogen use for steel production. China is a leader in electrolyzer production and plans to leverage its significant advancements in renewable energy to produce hydrogen, some of which will be used in the steel industry.

However, the Chinese policy on hydrogen use in the steel sector is somewhat flexible. **China aims to develop shaft furnaces for DRI and combine hydrogen with natural gas in traditional BFs by 2030**. In China, where a large, relatively young fleet of BFs exists, this technology is being prioritized for the near-to-medium term. This approach reduces emissions but is not carbon neutral, helping to limit the number of stranded assets.

In many parts of the world, the availability of hydrogen has limited the development of clean H2-DRI plants. However, China stands out by having

[137] *SteelWatch, "Sunsetting Coal in Steel Production," June 2023, https://steelwatch.org/wp-content/uploads/2023/06/FINAL-SteelWatch_SunsettingCoalInSteel_June2023-sunday-25th-june.pdf.*

built a substantial share of electrolyzers powered by renewable energy. Despite being the world's largest consumer and producer of hydrogen, **Chinese hydrogen facilities operate at less than 10 percent capacity on average**. Therefore, hydrogen availability is not the primary limitation for Chinese H2-DRI production. Instead, the industry's main challenge lies in inadequate energy resources.

In recent years, China has experienced insufficient power supply and abrupt power cuts, known as the "power shortage," leading to unstable energy supplies for industrial users and consequences for hydrogen-based DRI deployment and EAF production.[138] However, the extensive deployment of renewable energy in the country suggests the potential for a swift and substantial supply of clean hydrogen. This is particularly important for enhancing flexibility within the electricity grid. Consequently, this development could significantly incentivize the shift toward hydrogen-based steelmaking in China.

Support

In 2022, China released its first *Hydrogen Industry Development Mid-Long Term Plan* (2021–2035).[139] This plan clarifies that hydrogen will be part of China's energy supply systems and emphasizes the coordinated development of the hydrogen supply chain, including production, storage, transportation, and utilization, especially in transportation and industrial sectors such as steel.

[138] *Rachel Parkes, "Hydrogen Electrolyser Factories Are Only Operating at 10% Capacity on Average: BNEF," Hydrogen Insight, February 1, 2024, https://www.hydrogeninsight.com/electrolysers/hydrogen-electrolyser-factories-are-only-operating-at-10-capacity-on-average-bnef/2-1-1591720.*

[139] *National Development and Reform Commission, China, "Medium- and Long-Term Plan for Hydrogen Energy Industry Development (2021–2035)."*

China's policies consider H2-DRI technology a way to decarbonize its steelmaking industry, viewing it as a **pivotal long-term strategy**. The MIIT/NDRC "Implementation Plan for Carbon Peaking in the Industrial Sector" includes references to hydrogen shaft furnaces and mentions the need to improve technology currently controlled by Chinese companies.[140] The MIIT "Guidance on Promoting High-Quality Development of the Steel Industry" (2022) even advocates establishing a ***Low-Carbon Metallurgy Innovation Alliance*** and formulates a ***Hydrogen Metallurgy Action Plan***. The "Guidance Catalogue for Industrial Restructuring" (NDRC-2024),[141] defining the industries that are part of China's energy transition, encourages the use of green hydrogen, including for metallurgy. These texts aim to target industrial policy support for H2-DRI in China by promoting provinces to go in this direction.

Central to this initiative is the Hydrogen Metallurgy Action Plan,[142] which positions **hydrogen as crucial in transitioning toward low-carbon steel production**. The plan emphasizes technological innovation, focusing on developing and optimizing hydrogen-based steelmaking processes to replace coal with hydrogen as a reducing agent. Additionally, it highlights the need to **establish the necessary infrastructure for hydrogen production, storage, and transportation** to facilitate large-scale adoption in the steel industry. The plan also recommends **implementing pilot projects to test and refine hydrogen metallurgy techniques, followed by scaling successful models for broader industry adoption**. To support hydrogen, the Action Plan promotes crafting supportive policies and regulations that facilitate investments and operations in hydrogen steel production. These could include **subsidies, tax**

[140] *State Council of the People's Republic of China, "Implementation Plan for Carbon Peaking in the Industrial Sector."*

[141] *National Development and Reform Commission, China, "Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)."*

[142] *National Development and Reform Commission, "Guiding Opinions from the Ministry of Industry and Information Technology, National Development and Reform Commission, and Ministry of Ecology and Environment on Promoting High-Quality Development of the Steel Industry," May 20, 2022.*

incentives, and specific mandates or guidelines for the adoption of hydrogen technologies. Among the financial incentives, the plan proposes financial mechanisms to offset the initial high costs associated with adopting hydrogen technologies in steel production.

Hydrogen Steelmaking Projects in China

China **already has a few DRI demonstration projects**, mostly utilizing hydrogen-rich gases from industrial processes. Notable examples include the Hebei Iron and Steel Group (HBIS), self-described as the world's first hydrogen metallurgy demonstration project, which partnered with Tenova in 2020 to develop a DRI plant with a capacity of 0.6 million tons per year using coke-oven gas containing 70 percent hydrogen.[143] This first demonstration project, using a technology that is not currently carbon neutral, is followed by plans for a second-stage plant of the same capacity using green hydrogen. Additionally, Baowu Steel is investing RMB 1.89 billion (approximately €240.6 million) to build a DRI facility at its Zhanjiang steel plant, with a capacity of 1 million tons per year.

The Hydrogen Strategy

These initiatives indicate that **China's steel sector is currently far from deploying truly clean H2-DRI systems,** which are being developed in Europe or considered in Japan and South Korea. These technological options are viewed as mid-term to long-term future solutions and as not well-suited to the present Chinese context beyond the demonstration stage. As in other countries, this does not prevent Chinese steelmakers, particularly private ones like Delong Steel, from investing in other parts

[143] *HBIS Group, "HBIS Practice and Action Plans for Low-Carbon Development," accessed October 1, 2024, https://worldsteel.org/wp-content/uploads/HBIS-practice-and-action-plans-for-low-carbon-development.pdf.*

of the world that are potentially rich in renewables, such as the UAE, to produce H2-DRI steel.[144]

Although existing policies aim to support their development, it is evident that without more stringent decarbonization targets and policies such as carbon pricing, these technologies would not be practical or impactful in the current Chinese steel market. However, this **aligns with the Chinese industrial strategy of gaining the second-mover advantage: waiting for trials to be established in other countries, learning from their processes, and then rapidly scaling up development**. This strategy allows China to benefit from the lessons learned elsewhere and implement large-scale advancements more efficiently.

I. Japan and Hydrogen Steelmaking

Japan's strategy for decarbonizing its steel sector relies on developing and implementing **hydrogen reduction technologies in the long term (from 2040)** and **using hydrogen in traditional BFs in the medium term (from 2030)**.

The country still faces several significant challenges in implementing hydrogen-related technologies. One of the primary challenges is the **high cost associated with the production and utilization of green hydrogen**, which makes H2-DRI less economically viable compared to carbon-intensive steelmaking methods, especially in the absence of a robust carbon price globally. The **high capital expenditure (CAPEX) and operating expenditure (OPEX)** associated with hydrogen infrastructure also pose substantial financial barriers.

[144] *SteelOrbis, "UAE-Based ESA Joins Forces with China's Delong Steel to Build Low-Carbon Raw Materials Facility," June 4, 2024, https://www.steelorbis.com/steel-news/latest-news/uae-based-esa-joins-forces-with-chinas-delong-steel-to-build-low-carbon-raw-materials-facility-1343264.htm.*

Furthermore, the transition to H2-DRI requires a significant increase in renewable energy capacity to produce green hydrogen. Japan's limited domestic renewable energy resources and high electricity costs exacerbate this challenge. The technological maturity of hydrogen reduction steelmaking is another hurdle, as in Japan, the **technology is still in the development and demonstration phase**. Achieving the necessary technological advancements and scaling up production processes to commercial levels will take time and require continuous innovation. Additionally, **accessing high-grade iron ore is considered challenging for Japanese companies**, necessitating the development of technologies to utilize lower-grade ores effectively and of other strategies to have access to high-grade iron ore.

Support Framework

The Ministry of Economy, Trade, and Industry has set ambitious targets and committed significant resources to fostering hydrogen steelmaking. The **Technology Roadmap for Iron and Steel** plans to develop hydrogen reduction based on **blending hydrogen and gas from 2030 and to implement clean hydrogen DRI from 2040**.[145] Additionally, Japan's plan involves developing large-scale electrolysis and hydrogen storage technologies to ensure a consistent supply of clean hydrogen. METI's **comprehensive roadmap for hydrogen reduction steelmaking**[146] includes incremental targets and support mechanisms such as **subsidies, tax incentives, and public procurement policies**, all designed to reduce the cost gap between green and carbon-intensive steel production.

Central to this strategy is the Green Innovation Fund, which includes support for different solutions for blending hydrogen into blast furnaces of up to JPY 14 billion (approximately €88 million) and JPY 121 billion

[145] *Ministry of Economy, Trade and Industry, Japan, "Technology Roadmap for 'Transition Finance' in Iron and Steel Sector."*

[146] *Ministry of Economy, Trade and Industry, Japan, "Basic Hydrogen Strategy."*

(approximately €762 million). The same fund entails JPY 34.5 billion (approximately €217.4 million) for H2-DRI and JPY 23.6 billion (approximately €148.7 million) for EAF using DRI steel.[147] This fund **supports R&D projects, demonstration plants, and the eventual commercialization of H2-DRI technology**.

Furthermore, the GX policy package enables **tax rebates and subsidies for CAPEX to encourage investments in green hydrogen technologies for the steel industry**. OPEX support in the form of CCfDs is being introduced more widely for clean hydrogen production. The **GX Transition Bonds**,[148] funded by the fossil fuel levy and business contributions, **provide approximately JPY 193.5 billion (approximately €1.2 billion) for H2-DRI**.[149]

Hydrogen Steelmaking Projects in Japan

The most notable initiative under this hydrogen strategy is the Super COURSE50 project.[150] Involving major steel companies such as Nippon Steel, JFE Steel, and Kobe Steel, this government-supported project aims to halve CO_2 emissions by **integrating hydrogen into the traditional coal-based steel production process**. The initiative involves injecting hydrogen generated on-site into BFs, with the goal of achieving commercialization by 2030. In contrast to their European counterparts, **Japanese**

147 Ministry of Economy, Trade and Industry, Japan, "Green Innovation Fund Project."

148 Ministry of Economy, Trade and Industry, Japan, "Japan Climate Transition Bond Framework."

149 Ministry of Economy, Trade and Industry, Japan, 成長志向型カーボンプライシング構想 *[Growth-Oriented Carbon Pricing Initiative], May 14, 2024, https://www.meti.go.jp/policy/energy_environment/global_warming/GX-league/gx-league.html.*

150 Government of Japan, "The Road to Net Zero with Green Steel," March 1, 2024, https://www.japan.go.jp/kizuna/2024/03/net_zero_with_green_steel.html.

companies don't currently have concrete hydrogen-ready DRI shaft furnaces in the investment pipeline (not before 2040).

Japan has, however, **a first H2-DRI demonstration project, announced in 2024**. Tenova (an Italian company) has been awarded a contract to build an Experimental Direct Reduction Plant at Nippon Steel Corporation's Hasaki R&D Center.[151] This project, supported by NEDO, aims to develop and test technology for reducing low-grade iron ore using hydrogen as the primary reducing agent. The plant will utilize ENERGIRON technology and is supported by the Green Innovation Fund.

m. South Korea and Hydrogen Steelmaking

South Korea's strategy for decarbonizing its steel sector centers massively on the development and implementation of hydrogen-based DRI technology. The key component of this strategy is the **HyREX** process developed by POSCO, a H-DRI technology that **does not require high grades of iron ore**. The main characteristic of this strategy is its prolonged development time, given that it is **hampered by technical challenges** and a government that is more complacent toward decarbonization.

The South Korean government and industry players, notably POSCO and Hyundai Steel, are investing in R&D on H2-DRI technology. The strategic transition agenda involves replacing traditional BFs with H2-DRI plants by 2050, with the intermediate goal of **producing 1 million tons of steel using HyREX technology by 2030**.

[151] *Green Steel World, "Tenova to Provide the First Hydrogen Experimental DRI Plant in Japan," March 19, 2024, https://greensteelworld.com/tenova-to-provide-the-first-hydrogen-experimental-dri-plant-in-japan.*

Policies Supporting Hydrogen Steelmaking

The South Korean government has rolled out several policies to support the development and adoption of H2-DRI technology. In parallel, it has also adopted policies supporting hydrogen production and imports and **clean energy procurement to incentivize steel companies to buy clean energy**.[152] Overall, the main policies supporting hydrogen steelmaking are as follows:

- **The Hydrogen Economy Roadmap:**[153] Launched in 2019, this roadmap aims to develop a comprehensive hydrogen ecosystem encompassing production, storage, transportation, and utilization. It primarily focuses on blue and gray hydrogen but lays the groundwork for future green hydrogen integration.
- **The Green New Deal:**[154] Part of the broader Korean New Deal, the Green New Deal allocates KRW 73.4 trillion (approximately €49.4 billion) – of which KRW 42.7 trillion (approximately €28.7 billion) is from the Treasury – to investments in green finance to support business investments in the green transition, including hydrogen technology and decarbonizing the industrial sector using hydrogen.
- **Carbon Neutral Strategy 2050:**[155] This strategy emphasizes the **development and commercialization of hydrogen reduction steelmaking**. It supports R&D investments and aims to facilitate the transition from traditional blast furnaces to hydrogen-based DRI plants.

[152] *Government of South Korea, "Steel Industry Development Strategy."*

[153] *Netherlands Enterprise Agency (RVO), "Hydrogen Economy Plan in Korea," 2019, https://www.rvo.nl/sites/default/files/2019/03/Hydrogen-economy-plan-in-Korea.pdf.*

[154] *Government of South Korea, "Korean New Deal: National Strategy for a Great Transformation."*

[155] *Government of South Korea, "2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society."*

The KRW 1.5 trillion (around €1 billion) fund to advance decarbonized steel production includes promoting the **commercialization of HyREX technology** and reaching the mid-term goal of producing 1 million tons of hydrogen per year by 2030. In the long run, the plan is to **phase out all 11 BFs and replace them with 14 HyREX facilities between 2040 and 2050**, marking a significant step toward sustainable steel production.[156]

Challenges in Implementing Hydrogen DRI in South Korea

Nevertheless, the transition to H2-DRI in Korea faces multiple challenges, primarily involving access to cheap clean hydrogen, which brings with it many other sub-challenges:

1. **High production costs:** 3.7 million tons of hydrogen are required per year to support an annual production capacity of 38 million tons of steel. In terms of government funding, South Korea has failed to catch up with other major developed nations, which have allocated annual funding of up to four times higher than South Korea's KRW 26.9 billion (approximately €18.1 million) for the 2023–2025 period.[157]
2. **Hydrogen supply and infrastructure:** South Korea has limited domestic production of green hydrogen, which is essential for the DRI process. Most hydrogen used in the interim will be **blue hydrogen imported from countries such as Oman**. Ensuring a stable and large-scale supply of green hydrogen remains a significant bottleneck. The government has initiated discussions with Australian companies to secure hydrogen supplies and is investing in R&D for hydrogen transport technologies. It is **also considering the adoption of CCfDs to stimulate domestic hydrogen production**.

[156] *IGasnet, "Aiming for Top 3 in Global Exports With Low-Carbon, High-Value-Added Steel."*

[157] *Government of South Korea, "Steel Industry Development Strategy."*

Major companies such as POSCO are exploring the use of small modular reactor (SMR) nuclear technology in the long term to enable the self-production of hydrogen.

3. **Electricity demand:** The H2-DRI process requires a substantial amount of electricity. Given that only a small percentage of Korea's electricity comes from renewable sources, there is an added challenge of securing enough clean energy to power the DRI plants. Replacing coal BF–BOF facilities with H2-DRI facilities with an annual production capacity of 38 million tons of steel increases electricity demand proportionally (3,700 MWh/year). Moreover, such facilities would **need to purchase the entirety of their electricity demand within the existing grid system**, bearing in mind that only 12.7 percent of Korea's power generation comes from renewables.[158]

While POSCO has developed the HyREX process, this technology is still in its infancy. Full deployment of hydrogen-based steelmaking is targeted for the long term, post-2040, indicating a need for further technological advancements and scaling efforts. These challenges suggest a significant dependence on hydrogen produced abroad, with all the associated challenges of sourcing and shipping it at a reasonable price. Like Japan, South Korea faces difficult choices regarding the future of its steel industry.

Pilot Projects from South Korean Steel Companies

POSCO plans to **produce 300,000 tons of hydrogen steel by 2027–28 from its Pohang site**,[159] **using blue hydrogen from Oman and later clean hydrogen it will produce in Oman**.[160]

[158] *Government of South Korea, "Steel Industry Development Strategy."*

[159] *Global Energy Monitor, "POSCO Oman Green Steel Project."*

[160] *Global Energy Monitor, "POSCO Oman Green Steel Project."*

Hyundai Steel is focusing on electrification and hydrogen-based steelmaking processes.[161]

POSCO is also planning a significant investment to support its hydrogen-based steelmaking initiatives. The company aims to **invest between KRW 30 and 40 trillion (approximately €20.2–27 billion) by 2050** in the development of hydrogen reduction steel technology and related infrastructure.[162] This investment is part of POSCO's broader goal of establishing a hydrogen production capacity of 5 million tons and achieving KRW 30 trillion (approximately €20.2 billion) in hydrogen sales by 2050.[163]

Hyundai Steel, on the other hand, has announced its "Hy-Cube" project, a CO_2-neutral steel production system based on hydrogen and EAF technologies.[164] While specific investment figures for Hyundai Steel were not disclosed, the company is focusing on beginning to convert its production processes to hydrogen-based systems by 2030, indicating substantial financial commitments toward this transition.[165]

[161] *POSCO, "POSCO's Net Zero Carbon 2050 Declaration Background and Achievement Goals," January 21, 2022, https://newsroom.posco.com/en/poscos-carbon-neutrality-2050-declaration-background-and-achievement-goals/.*

[162] *POSCO, "POSCO to Establish Hydrogen Production Capacity of 5 Million Tons," December 18, 2020, https://newsroom.posco.com/en/posco-to-establish-hydrogen-production-capacity-of-5-million-tons/.*

[163] *Hydrogen Central, "POSCO Group to Invest US$40bn in Australia by 2040, Including Hydrogen for Steel-Making," December 2, 2022, https://hydrogen-central.com/posco-group-invest-us40bn-australia-2040-including-hydrogen-steel-making/.*

[164] 철강 3사, 전기로·수소환원제철로 탄소중립 속도 *[Three Steel Companies Accelerate Carbon Neutrality Through Electric Arc Furnaces and Hydrogen Reduction Steelmaking], Hankyung, June 5, 2023, https://plus.hankyung.com/apps/newsinside.view?aid=202305307059i.*

[165] *Green Steel World, "Hyundai Steel to Build 'Hy-Cube', a CO2-Neutral Steel Production System," May 30, 2022, https://greensteelworld.com/hyundai-steel-to-build-hy-cube-a-co2-neutral-steel-production-system.*

n. The Impact of Technology Uncertainty

Beyond these pilot projects, technological uncertainty remains a significant issue for South Korea. POSCO is considering both CCUS for its existing BFs and the HyREX process as future technologies to drive its decarbonization efforts. However, from interviews conducted for this study, it appears that **the company is undecided about whether to pursue its flagship HyREX technology to the large-scale commercialization stage**.

The challenge with HyREX, despite its complexity, is in fact its reliance on hydrogen. Unlike most shaft furnaces used by POSCO's European competitors, which can operate with natural gas until a secure supply of clean hydrogen is available, HyREX requires hydrogen from the outset. While the HyREX process promises to simplify operations over time by eliminating the need for high-grade iron ore, it cannot use natural gas as an interim solution. Given the significant difficulty and expense involved in sourcing affordable hydrogen, **POSCO is also considering the shaft furnace option**. The company plans to make a decision about the future of this technology within the next two years.

Europe and Hydrogen Steelmaking

Europe's approach to decarbonizing its steel sector relies heavily on integrating hydrogen as a critical vector for reducing carbon emissions. This strategy involves **significant investments in hydrogen production and infrastructure**, policy instruments aimed at supporting industrial transition, and collaborative efforts across the continent. The European strategy is characterized by a policy framework designed to **promote the use of green hydrogen in steel production, thus reducing the sector's carbon footprint**.

Main Challenges

The primary issue in Europe concerning the decarbonization of the steel sector using hydrogen is obtaining **access to sufficient amounts of cheap clean hydrogen quickly enough to meet decarbonization targets**. The European Union ETS provides a timeline for decarbonization, with the sector needing to be carbon neutral by 2050 and facing significant carbon pricing from 2028 onwards (with gradual phasing out of free allocation until the complete phase-out in 2034). This creates a **pressing need for a continuous and affordable green hydrogen supply, which is currently limited to certain regions**.

There are three main general barriers complicating this strategy:

- **Access to green hydrogen:** To use hydrogen in Europe for producing primary steel, industries need 24/7 access to hydrogen. This requires a stable and affordable supply of green energy, which is currently constrained to regions such as Scandinavia and Spain.
  - For instance, the H2 Green Steel project in Sweden aims to produce steel with a **current price premium of around 20–25 percent over carbon-intensive steel**, covered by buyers willing to pay more for green labeling.[166]
- **Investor base and off-takers:** Developing hydrogen-based steel production is **capital intensive and requires a strong investor base** and committed off-takers. Currently, this is not fully established in Europe, slowing down the transition process.
- **"Hydrogen-ready" shaft furnaces:** Many of the current projects in Europe are "hydrogen-ready" shaft furnaces capable of using either clean or non-clean hydrogen. **In the absence of sufficient clean hydrogen, these furnaces will use natural gas initially**. This interim solution is due to the lack of readily available green hydrogen,

[166] *H2 Green Steel, "Powering a New, Clean Industrial Revolution," accessed September 10, 2024, https://www.h2greensteel.com.*

highlighting a significant challenge in achieving immediate decarbonization. This means that the critical factor will be gaining **access to cheap and clean hydrogen in the fastest possible manner.**

Investments and Projects in Hydrogen Steelmaking in Europe

Significant investments are being made to support hydrogen steelmaking in Europe, and companies are demonstrating and even deploying the first plants. Overall, the European steel sector is poised to receive an estimated **€20 billion in investments over the next decade to develop and scale up hydrogen-based steel production technologies**.[167]

H2 Green Steel, a Swedish initiative focused on decarbonizing steel production using hydrogen, is probably the most famous hydrogen reduction project in Europe. The company has raised substantial funds for its projects, securing around €6.5 billion in total financing. This includes a **€250 million grant from the EU Innovation Fund**. Additionally, the Swedish National Debt Office has provided a green credit guarantee for €1.2 billion, and the European Investment Bank (EIB) has committed €314 million as part of the senior debt funding,[168] contributing to an overall figure of €4.2 billion in senior debt from a group of over 20 lenders.[169]

[167] *European Commission, "Commission Outlines European Hydrogen Bank to Boost Renewable Hydrogen," March 16, 2023, https://energy.ec.europa.eu/news/commission-outlines-european-hydrogen-bank-boost-renewable-hydrogen-2023-03-16_en.*

[168] *European Investment Bank (EIB), "Sweden: EIB and NIB to Provide €371 Million with InvestEU Backing for H2 Green Steel's Large-Scale Production of Steel with Minimal Carbon Footprint," January 22, 2024, https://www.eib.org/en/press/all/2024-015-eib-and-nib-to-provide-eur371-million-with-investeu-backing-for-h2-green-steel-s-large-scale-production-of-steel-with-minimal-carbon-footprint.*

Beyond this newcomer initiative, the big actors in the European steel sector are also acting on hydrogen steelmaking.

ArcelorMittal targets investing approximately €1.7 billion to decarbonize its steel production processes by incorporating hydrogen technology. This includes various projects in France, Spain, Belgium, and Germany. Specifically, for France, the investment for the Dunkirk site has increased to €1.8 billion, with the support of the French government.[170] This project involves building a DRI unit and two EAFs, aimed at transforming iron ore using hydrogen instead of coal. These facilities are expected to be operational by 2027. The company has secured and should receive significant state aid to support these initiatives: €850 million from the European Commission for its Dunkirk project in France;[171] €280 million for its Ghent facility in Belgium to develop a low-carbon steel pilot project;[172] and €460 million for H2-DRI in Gijón, Spain.[173] In Germany, ArcelorMittal is still deliberating on which

[169] *H2 Green Steel, "Leading European Financial Institutions Support H2 Green Steel's €3.5 Billion Debt Financing," October 24, 2022, https://www.h2greensteel.com/latestnews/leading-european-financial-institutions-support-h2-green-steels-35-billion-debt-financing.*

[170] *Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, "France 2030: Signature du contrat d'aide soutenant la décarbonation du site d'ArcelorMittal à Dunkerque," January 15, 2024, https://presse.economie.gouv.fr/france-2030-signature-du-contrat-daide-soutenant-la-decarbonation-du-site-darcelormittal-a-dunkerque/.*

[171] *Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, "France 2030: Signature du contrat d'aide soutenant la décarbonation du site d'ArcelorMittal à Dunkerque."*

[172] *European Commission, "State aid: Commission Approves €280 Million Belgian Measure to Support ArcelorMittal Decarbonise Its Steel Production," June 22, 2023, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3404.*

[173] *CDE Almeria, "European Commission Approves €460m Aid to ArcelorMittal Spain to Support Decarbonisation of Its Steel Production," February 21, 2023, https://www.cde.ual.es/en/european-commission-approves-e460m-aid-to-arcelormittal-spain-to-support-decarbonisation-of-its-steel-production/.*

site to prioritize, with investments in Bremen and Eisenhüttenstadt remaining uncertain despite having secured substantial financial support.

Thyssenkrupp plans to invest up to €10 billion in transitioning to hydrogen-based steel production by 2030.[174] Currently, the company is making a substantial investment of over **€2 billion to transition to hydrogen-based steel production**. This investment will fund the construction of Germany's largest direct reduction plant for low-CO_2 steel at the Duisburg site. The project is part of Thyssenkrupp's broader tkH2Steel transformation initiative, which aims to replace coal-based blast furnaces with hydrogen direct reduction plants. This project is supported by public funding, with the German government committing up to €2bn and the state of North-Rhine Westphalia providing €700 million to support the initiative.[175] Furthermore, Thyssenkrupp has partnered with RWE to ensure a reliable supply of green hydrogen for its steel production, highlighting the importance of having access to this resource.

[174] *Kevin Knitterscheidt, "CO2-freie Produktion bis 2050: ThyssenKrupp will Hochöfen dichtmachen" [CO2-Free Production by 2050: ThyssenKrupp Plans to Shut Down Blast Furnaces], Handelsblatt, January 21, 2019, https://www.handelsblatt.com/unternehmen/industrie/stahlherstellung-co2-freie-produktion-bis-2050-thyssen-krupp-will-hochoefen-dichtmachen/23879546.html.*

[175] *Federal Ministry for Economic Affairs and Climate Action (BMWK), "La Commission européenne autorise plus grand projet de décarbonation à ce jour en Allemagne," July 20, 2023, https://www.bmwk.de/Redaktion/FR/Pressemitteilungen/2023/07/20230720-la-commission-europeenne-autorise-le-plus-grand-projet-de-decarbonation-a-ce-jour-en-allemagne.html.*

Table 5: Summary of Clean Steel Projects around the world

	European Projects	Asian Projects	American Projects
Carbon Direct Avoidance (CDA)	**40**	**17**	**4**
*BF-BOF to EAF	7	1	1
*Electrochemical process	0	0	1
*Electrowinning	1	0	0
*NG-DRI to H-DRI	16	8	1
*H-DRI	16	8	1
Smart Carbon Usage (SCU)	**3**	**1**	**0**
BF-BOF to HIsarna	1	0	0
Biogenic syngas DRI	1	0	0
Biomass for BF	1	1	0
Carbon Capture and Storage (CCS)	**6**	**2**	**3**
CCUS for BF-BOF	4	2	2
ESR	2	0	0
MOE	0	0	1
Total	**49**	**20**	**7**

o. The Fundamental Challenges in Designing an Efficient Steel Decarbonization Policy

The immediate goal for a relevant industry decarbonization policy is to demonstrate that carbon-neutral steel is a viable commercial option. This involves building new facilities and converting existing ones to showcase the feasibility of these technologies. However, different strategies may coexist, depending on the location, the structure of the local economy, and, of course, politics.

One critical dimension to consider is the constant evolution in technology, which may significantly change the equation of decarbonizing the steel sector. **Technology uncertainty must therefore be at the heart of policies supporting low-carbon steel deployment**, keeping the doors open to any new type of technological development that may change the game.

Switching from BFs to DRI processes, adaptable to hydrogen, is seen as the most practical step toward achieving cleaner steel production. However, this strategy **requires massive, stable, and affordable access to clean hydrogen**, which is not easily accessible in many regions of the world. Furthermore, the steel industry in a post-carbon world faces challenges such as the **need for high-grade iron ore – with lower levels of impurity – for the DRI ironmaking process** and significant investment in new infrastructure.

High-grade iron ore, typically with iron content above 67 percent, is essential for efficient DRI processes. Unfortunately, such high-grade deposits are limited and geographically concentrated, primarily in regions such as Brazil, Australia, Canada, and Scandinavia. Mining companies face long lead times in developing these resources, and the beneficiation processes needed to upgrade lower-grade ores, which include magnetic separation and flotation, can be both costly and technologically demanding.[176]

Beyond the process itself, decarbonizing the steel sector presents a significant technical challenge due primarily to two key engineering issues. First, there is a need to produce sufficient clean hydrogen, which involves **advancing electrolyzer technology**, particularly in terms of load management, and ensuring its efficient delivery to DRI steel manufacturing plants. Second, **mining companies must find ways to upgrade traditional lower-grade iron ore to reduce impurities** and make it suitable for the DRI process. **Resolving these difficult challenges could potentially lead to a shift in the traditional geographic locations of the steel industry**.

[176] *Institute for Energy Economics and Financial Analysis, "More High-Grade Iron Ore Needed to Accelerate Steel Decarbonisation," June 28, 2022, https://ieefa.org/articles/more-high-grade-iron-ore-needed-accelerate-steel-decarbonisation.*

Importing Intermediary Steel Products
vs. Importing Carbon-Neutral Iron

These two defining challenges raise difficult questions for some traditional steel-producing regions about the future viability of primary steel production in a post-carbon economy. **It may indeed be more economically viable for some of these regions, some of them in Europe, to import intermediate steel products or reduced iron rather than continue local production**, given the difficulties they may face in sourcing cheap and stable clean hydrogen.

The International Energy Agency projects that by 2050, around 59 percent of primary steel production will need to come from DRI–EAF processes to meet net-zero emissions targets.[177] One of the key advantages of the DRI–EAF route is that it **does not require full integration, as its intermediate product – sponge iron or HBI – can be easily stored and transported**. This contrasts with the BF–BOF route, which demands full integration at a single site, as its intermediate product is hot liquid metal. Therefore, **importing intermediary green steel products to locations less endowed with renewables will be part of the strategy**.

Another potential solution could enable a fundamental shift in production methods. Traditionally, steel production relies on **integrated mills that combine ironmaking and steelmaking. In a decarbonized model, separating these processes may be advantageous**. Green hydrogen DRI technology can be used in regions combining abundant renewable energy – making hydrogen production more economical – and easy access to high-grade iron ore. **The iron produced can then be exported to global steelmaking facilities with EAFs**, which are more flexible and electricity-powered, enabling parts of the supply chain to be

[177] *International Energy Agency (IEA), "Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking," October 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.*

kept in traditional steelmaking regions or – for various economic security reasons – where customers and skills are located.

This dissociation optimizes resource use and opens up new opportunities to transform the global steel supply chain. With the ironmaking and steelmaking processes being dissociated, regions with abundant renewable energy resources, such as Australia and the Middle East, are well positioned to become key players in the ironmaking production of green steel, leveraging H2-DRI technologies that can then be shipped to regions with only EAFs.[178]

The DRI–EAF route could also **open the door for new economic players to enter the steel value chain**. Mining companies, for example, might begin constructing DRI plants at their mine sites. Unlike traditional steelmakers, these companies are not constrained by the incumbent innovators' dilemma, which allows them to adapt more easily to new technologies. Building DRI plants would represent a natural extension of their existing operations, allowing them to continue serving the same customers with minimal disruption. Furthermore, mining companies typically have more experience operating in high-risk investment environments and tend to maintain strong relationships with local governments. This expertise, combined with the support of technology providers or EPC contractors, could make it easier for mining companies to establish DRI plants in regions where steelmakers lack an existing presence.

How to Make the Right Decision?

What is the best discriminating factor for countries to design their decarbonization strategy? **Cost, of course, must play a role**. The cost structure of low-carbon steel is significantly driven by the production of clean

[178] *Rachel Wilmoth, Chathurika Gamage, Lachlan Wright, and Sascha Flesch, "Green Iron Corridors: A New Way to Transform the Steel Business," RMI, April 23, 2024, https://rmi.org/green-iron-corridors-a-new-way-to-transform-the-steel-business/.*

hydrogen, which is highly energy-intensive, **requiring about 3 MWh of electricity to produce enough hydrogen to convert 1 ton of iron ore into DRI**. Consequently, **energy costs account for approximately 45 percent of inputs for hydrogen-based DRI–EAF processes**, compared to traditional BF–BOF methods, where raw materials constitute around 60–70 percent of costs and energy around 20–30 percent.[179]

This **shift alters regional cost competitiveness, with regions such as the US, Canada, Brazil, Australia, and China likely benefiting due to better access to renewable energy, while Japan, South Korea, and Europe (e.g., Germany) might lose their competitive edge**.[180] Within Europe, the migration of steel plant locations is highly probable.

Capital expenditures for low-carbon steel plants are high, driven by advanced technologies and renewable infrastructure needs. **The timing of new capital expenditures in the steel industry is closely linked to the age of the existing capital stock**. A significant number of BF–BOF plants are approaching the end of their technical lifespans, necessitating reinvestment in the near future. These elements will play a significant role in choosing the right strategy.

The transition to low-carbon steel additionally relies on government support, subsidies, and carbon pricing, with current clean hydrogen production costs expected to decrease as technology advances and economies of scale are achieved. **(Geo)politics should also play its part**, with

[179] *Sarah Macnaughton, Paul Butterworth, and Zsombor Garzo, "Green Transition Will Disrupt Steel Trade Flows," CRU Group, June 29, 2022, https://sustainability.crugroup.com/article/green-transition-will-disrupt-steel-trade-flows; World Steel Association, "Energy Use in the Steel Industry," https://worldsteel.org/wp-content/uploads/Fact-sheet-Energy-use-in-the-steel-industry.pdf.*

[180] *For more on the "renewables pull" effect, see: Sasha Samadi, Andreas Fischer, and Stefan Lechtenböhmer, "The Renewables Pull Effect: How Regional Differences in Renewable Energy Costs Could Influence Where Industrial Production Is Located in the Future," Energy Research & Social Science 104 (October 2023): 103257, https://doi.org/10.1016/j.erss.2023.103257; Philipp C. Verpoort, Lukas Gast, Anke Hofmann, and Falko Ueckerdt, "Impact of Global Heterogeneity of Renewable Energy Supply on Heavy Industrial Production and Green Value Chains," Nature Energy 9 (2024):491–503, https://doi.org/10.1038/s41560-024-01492-z.*

countries deciding how strategic their steel industry is and how much they want to maintain significant output within their own territories.

Thus, **both strategies can be suitable**, depending on the location, the industrial structure of the region, and, of course, politics. A region with high demand for primary steel but limited access to high-grade iron ore and lacking clean hydrogen production potential might favor the dissociation strategy to maintain its primary steelmaking industry. Conversely, a similar region with lower demand for primary steel might benefit more from the first strategy, importing intermediate carbon-neutral steel goods.

Technology Uncertainty as a Key Barrier

While hydrogen reduction processes are likely to be crucial for decarbonizing the steel sector, other potential breakthroughs are emerging. Innovative methods such as reducing iron directly with electricity are being explored. One such example is the molten oxide electrolysis (MOE) process, which produces steel by electrolytically reducing iron ore in a molten oxide electrolyte at high temperatures. Unlike H2-DRI steelmaking, which relies on hydrogen as a reductant, MOE uses an electric current to reduce iron ore into pure iron, releasing oxygen gas as a byproduct.[181] Although MOE faces challenges such as high energy consumption and the need for durable materials, it offers a potential cost advantage by eliminating the hydrogen intermediary.

This long-term option underscores the fact that technological breakthroughs toward cheaper, more efficient processes are always possible. Therefore, industrial decarbonization policies must not only support the development of current decarbonization technologies but also facilitate

[181] *Boston Metal, "Innovative Metals Processing," accessed September 10, 2024, https://www.bostonmetal.com.*

access for potential new entrants. **This means that technology agnosticism and openness are essential in designing support policies, as long as they meet emissions reduction requirements**.

p. Key Comparative Insights

Given the vast **diversity and regional disparities within the steel industry, along with the fluctuating global demand for steel, applying a universal policy for the sector's decarbonization is highly challenging**. The industry produces approximately 1.3 billion tons of steel annually using basic oxygen steelmaking, a method that relies heavily on carbon. **Transitioning this process to a low-carbon alternative within the next decade appears to be unfeasible**. Nonetheless, the steel sector is committed to reducing its GHG emissions. A mere 10 percent reduction in Scope 1 emissions could lead to a global decrease of 200 million tons in GHG emissions, equivalent to the annual emissions of France.

Until the hydrogen steelmaking process can be implemented on a large scale, it is imperative for governments to support the decarbonization efforts of these carbon-intensive industries. As the **market for green steel is still in the development stages** across regions such as South Korea, Japan, and Europe, **policy measures should motivate early adopters among steel customers to opt for green premium steel**, thus aiding in the reduction of Scope 3 emissions. Moreover, policies must facilitate transition support mechanisms, as by themselves, **companies risk not being able to afford to finance substantial emissions reductions in their current operations on a large scale**.

State support is also crucial in overcoming two key challenges in the transition to green hydrogen in steel production:

- **State intervention can help industries move up the learning curve**, much like Germany's feed-in tariffs (FIT) for solar PV stimulated early demand and brought down costs.

- There is a "chicken-and-egg" problem with hydrogen infrastructure in Europe. While studies indicate large future demand for hydrogen, current demand remains limited, making it difficult to justify the massive investments needed for hydrogen infrastructure. **Supporting both H2-DRI plants and hydrogen supply can help bridge this critical phase of uncertainty**, enabling industries to scale up. Once the core infrastructure has been established, other sectors, especially those requiring high-temperature heating, such as adjacent metal manufacturing clusters, will find it easier to transition to green hydrogen, further advancing decarbonization efforts.

China's Steel Future

China's strategy for decarbonizing its steel sector is marked by a pragmatic and phased approach, characterized by its agnosticism toward specific technologies and incremental implementation. This strategy is designed to **balance immediate reductions in emissions with long-term technological development and adoption**.

A primary element of China's strategy is reducing steel production capacity. This measure was originally aimed neither at reducing emissions nor at improving the carbon intensity per unit of steel produced but at lowering the total output from the steel sector. This aligns with the reduced domestic demand for steel, particularly from the infrastructure sector. The strategy is gradual and helps in managing the economic impacts, especially in provinces that are heavily dependent on steel manufacturing. By slowing down production, which reduces emissions, China buys time to develop and mature alternative steel production processes.

It has become fashionable to describe **China as the world's first "electrostate" – a country leading the global electrification revolution**. Against this backdrop, the **deployment of more EAF capacity and better utilization of current EAFs** are integral components of China's steel decarbonization strategy. This approach represents **low-hanging fruit in reducing the steel industry's carbon footprint**. However, questions remain about whether China will enforce a mandate to prioritize EAFs over traditional BFs and whether the country can promptly develop its steel scrap strategy to facilitate the rapid electrification of its steel sector.

China's extensive renewable energy capacity generates a significant amount of electricity, often exceeding grid demand. A key strategy involves directing this surplus green electricity toward EAFs, thus preventing waste and promoting sustainable practices. Nonetheless, to remain competitive, EAFs require a consistent electricity supply, even when green electricity is unavailable, necessitating reliance on conventional brown electricity. The Chinese government and companies recognize this challenge and the need to develop strategic policies to support the accelerated development of EAFs, which is currently lacking.

Beyond electrification, leading private sector companies such as Delong Steel and large SOEs such as Baowu are taking the lead. In particular, the **DRI hydrogen process**, combined with the extensive renewable energy infrastructure being developed in China, represents a genuine pathway for greener steel production in the country **in the mid to long term**.

A significant portion of China's strategy relies on carbon capture utilization (CCU) and carbon capture and storage (CCS) – a solution that is even further away from realization than H2-DRI in the country. For CCU, this depends on the development of industrial ecosystems where captured CO_2 can be utilized. Regions with significant chemicals industries, which can utilize CO_2 in their processes, are particularly strategic. Locating CO_2 sources, such as large BFs, near these industrial users is critical to Chinese strategy. For CCS, this option will be employed in regions with suitable geological formations for CO_2 storage. However, for these two options to be economically viable, **China will need to go beyond mere subsidies and establish a robust carbon pricing mechanism and stimulate demand for low-carbon steel**.

Therefore, creating a market for carbon-neutral steel, both domestically and internationally, is critical for China. Domestically, the country is already considering mandates and standards, but these are still only at a very nascent stage and are not targeting carbon-neutral steel at this point. **International demand triggered by instruments such as the European Union's CBAM could provide early incentives for low-carbon steel projects**.

However, until very recently – before the recent moratorium – substantial investment continued to flow into new, more efficient blast furnaces – through the capacity swap policy – which are not carbon-neutral, and the **risk of stranded assets in the country is real**.

The phased and technology-agnostic strategy allows China to observe and adopt successful examples from elsewhere before committing to large-scale deployment. While decreasing domestic steel demand may offer temporary reductions in emissions and new coal-based capacity installed, genuine decarbonization of the sector will require significant time and investment. The goal of fully decarbonizing the industrial sector by 2060 (or maybe earlier) will thus depend on the gradual implementation of diverse technological solutions, the need to consume clean energy by-products (clean electricity, clean hydrogen), and the creation of economic frameworks to support them.

Unlike Japan, South Korea, and Europe, **the redefinition of the steel sector in a post-carbon world does not alter China's ambition to remain the world's largest producer of primary steel – despite falling domestic demand**. The country aims to retain the entire value chain within its borders and to expand its market share in the future carbon-neutral steel market. This strategy leverages China's renewable energy advantage and partnerships that ensure access to affordable iron ore.

Japan's Choices

The Japanese steel industry faces the slow pace of development of low-carbon technology in the country and the need to secure vast amounts of green hydrogen in a country with low capacity to produce it.

The economic feasibility of this transition demands substantial investments from both the private and public sectors, highlighting the need for a coordinated approach to fund the production of low-carbon steel and compensate society adequately.

In view of the current challenges to the decarbonization of the steel industry, **several major elements need to be considered** to ensure the realization of a carbon-neutral society by 2050:

- **Ensuring the economic viability** of the low-carbon transition, given that its costs are enormous and **require large-scale investments from the private and public sectors**, including in areas such as **OPEX**, in order to **fund the production of low-carbon steel** and find appropriate compensation for society.
- **Securing green infrastructure for low-carbon ammonia and green hydrogen at reasonable costs**.
- **Developing CCUS through intersectoral cooperation** with the support of national governments.
- Securing large amounts of green hydrogen through the **construction of green infrastructure**.
- **Adapting hydrogen strategies depending on the geographic location** and the availability of green hydrogen locally, as countries such as Japan will have to rely both on small-scale production and imports.

The steel sector in Japan is at a critical crossroads where political decisions will shape its future sustainability. **The Japanese government must decide whether to provide sufficient subsidies to keep primary steelmaking operations within the country**. This decision is crucial, as it will impact the industry's ability to balance the promotion of decarbonization with the growing demand for green steel, which is expected to outstrip supply between 2030 and 2035. Furthermore, most Japanese blast furnaces will reach their replacement period by 2040. If the cost of accessing clean hydrogen is not low enough at that time, these furnaces may not be replaced by DRI systems. Instead, EAFs could become the preferred choice, leading to the relocation of primary steel production to regions with more favorable economic conditions for steel manufacturing or iron reduction.

Korea's Dilemma

The South Korean government has set targets for decarbonization, yet the policy framework and financial incentives are still evolving. The carbon pricing mechanism under the Korean ETS has not provided a strong and stable enough signal to drive significant investment in green technologies in the steel sector. Furthermore, the balance between supporting industry competitiveness and imposing stringent environmental regulations remains a delicate issue in the country, and without a higher carbon price, the adoption of most decarbonization technologies by the sector seems highly improbable.

A potential game changer for the South Korean government's steel decarbonization strategy and overall carbon pricing policy is Europe's CBAM. With up to **10 percent of its steel exports exposed to this policy**, the government and major steel producers have been **compelled to take action, despite the challenges posed by the diverse needs of their consumers**. The main answer has been to reform the SK ETS, trying to make it compliant with the CBAM regulation incrementally.

Furthermore, the adoption of the EU CBAM and a potential extension of a CBAM-like mechanism to the US steel market represent a substantial challenge for South Korea. Indeed, if the Global Agreement on Sustainable Steel and Aluminum (GASSA) extends the CBAM to include the US, the impact on South Korea's steel exports would be significantly greater. This possibility is prompting a shift in South Korea's climate policies.

South Korea's steel sector faces significant challenges in a post-carbon world due to the critical position it holds in the global steel industry. Producing 70 million tons of steel annually, with 30 million tons exported, South Korea's economy is deeply trade-dependent. Approximately 80 percent of South Korea's steel trade is directed toward regions that are unlikely to support a rise in prices due to higher CO_2 costs, such as ASEAN countries and China. This trade dependence means that it is difficult for South Korean actors to afford to significantly increase steel prices, even with rising CO_2 costs. Consequently, **the transition to a low-carbon steel sector will likely be slow**, despite the pressing need for decarbonization.

Finally, beyond external pressure and weak domestic stringent incentives to decarbonize the steel sector, the challenges of accessing the clean electricity and clean hydrogen needed to decarbonize the steel sector in the country are formidable. **Importing hydrogen may not be economically viable**, pushing South Korea to consider alternative strategies. One approach being explored is the reduction of iron in regions like the Middle East or Australia for further processing in EAFs in South Korea. However, this would **completely change the nature of the South Korean steel sector and would be likely to change its position in the global market**. Despite the significant export demand and looming challenges, South Korea aims to become the third-largest producer of steel by 2030, demonstrating its commitment to maintaining a competitive edge in the global steel industry while navigating the complexities of decarbonization.

Europe Must Make the Right Choices

Manufacturing Low-Carbon Steel in Europe with Hydrogen Requires More Pragmatic Hydrogen Regulation

The future of the steel industry in Europe in a net-zero world is poised to undergo a significant transformation driven by technological innovation and stringent environmental regulations. This is likely to lead to the adoption of technologies such as hydrogen-based steelmaking and CCUS in the medium term. With the probable exception of some Scandinavian projects, most current H2-DRI projects being deployed are likely to face the issue of being "hydrogen ready" while not having access to sufficient clean hydrogen, and therefore need to run on natural gas – or non-clean hydrogen – for the time being. This strategy has become more expensive and unstable since Russia's invasion of Ukraine.

To genuinely meet the decarbonization target in the steel sector, increased investment in renewable energy sources and nuclear energy will be crucial to power decarbonization technologies sustainably. The sector considers **the key barrier for large-scale hydrogen reduction steelmaking projects in the EU to be the strict definition of Renewable Fuels of Non-Biological Origin**.[182] Two critical elements under this definition are as follows:

1. **Prohibition for state aid in electricity production:** Projects receiving state aid for electricity production are not considered green. Additionally, if a project is not covered by the EU ETS after 2028, it is not considered green.
2. **Subsidies and carbon intensity:**
   a. Instead of a strictly renewable energy approach, **there is a need**

[182] *European Union, "Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023," 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.157.01.0011.01.ENG&toc=OJ%3AL%3A2023%3A157%3ATOC.*

to shift to a carbon intensity approach that enables all types of clean hydrogen to be used for decarbonization.

b. This means **enabling self-production** using any kind of carbon-neutral technology.

The Heart of the Challenge in Europe for a Post-Carbon Steel Industry

The steel industry and governments will need to **find solutions to several challenges linked to the energy transition**:

- They will need to secure energy reliability, as the amount of electricity needed for these low-carbon projects is expected to **reach 165 TW/h by 2030, compared to 75 TW/h currently**, of which **90 TW/h is for the production of green hydrogen via electrolysis**. This would create **unprecedented demand** in Europe that the steel sector may have difficulty meeting, as it only generates around 35 TW/h.
- They must **address challenges concerning infrastructure** and **energy use for the deployment of CCUS** technologies.
- They will need to **improve scrap availability across entire supply chains**, bearing in mind that the **EU exports 20 billion tons of scrap every year**.

Additionally, keeping constant **updates and assessments on carbon rules** and prospective rules for greenhouse gas emissions will be crucial to **monitoring the development of CCU technologies**, especially since the adoption of the Net-Zero Industrial Act. Public authorities need to use the regulatory framework to find a balance between the technical feasibility of low-carbon technologies and the barriers created during the transition period. This should include **enhanced support for CCU projects, easing of administrative delays to supporting CCS projects**, and attempting to **address the lack of suitable infrastructure**, even for supported technologies such as hydrogen, as the rules that are intended to suit the greenest hydrogen create additional costs for its development during the transition period.

Prioritize Clean Hydrogen for Industrial Sectors

There is a **need to develop and prioritize hydrogen as a decarbonization vector for industrial sectors** such as steel and chemicals, as the **highest bids for hydrogen use will be in these sectors**. From the industries' perspective, **hydrogen will serve as a means to internalize the external costs of CO_2** – meaning they would rather invest in hydrogen than in carbon allowances. This should push decision-makers to agree on common sense principles as part of the EU hydrogen strategy adopted in July 2020 in order to put hydrogen pilot projects into practice. From the market's perspective, **hydrogen pricing is likely to remain very high**, which will reinforce the difficulty of gaining access to the resource and **should, therefore, incentivize stakeholders to establish a strong regulatory framework**.

The Impact of the Carbon Border Adjustment Mechanism

The introduction of the CBAM and the gradual removal of free allocation from the EU ETS are set to have a profound impact on the European steel sector, presenting both opportunities and significant challenges. The CBAM mechanism is designed to encourage foreign producers to reduce emissions by imposing a cost equivalent to the EU carbon price on imports, thus promoting global decarbonization efforts.

However, the transition is fraught with economic and operational hurdles. From the sector's perspective, the additional carbon costs for the steel industry are projected to be nearly €14 billion by 2030, which will significantly affect competitiveness unless adequately managed.[183] High initial costs and the complexity of compliance for importers pose significant challenges. Afraid of the potential impact of free allocation removal not matching the effectiveness of the CBAM, the sector stresses the need for a phased approach, maintaining some free allocations under the EU ETS until the CBAM proves effective. It is true that the CBAM poses remarkable challenges in terms of carbon accounting and verification that will not be easy to monitor, while steel companies covered by the EU ETS will face the burden of free allocation removal very quickly.

On the positive side, if well implemented, the CBAM will have substantial benefits for the European steel sector. By imposing equivalent carbon costs on imports, the CBAM helps ensure that European producers, who face some of the world's highest environmental standards and associated costs, are not undercut by cheaper carbon-intensive steel from non-EU countries.[184] It has also encouraged other countries, such as Japan and China, to consider implementing carbon pricing or accelerating their existing plans. This can help maintain some steelmaking capacity within Europe while driving forward the industry's decarbonization goals globally thanks to the power of the EU market.[185] If all this is true, **this paper has also shown that the sector dynamics among Europe's trading partners are not solely reliant on the European market, triggering**

[183] *European Steel Association (EUROFER), "Prohibitive Energy and Carbon Prices Risk Undermining EU Steel Industry Decarbonisation: EU Leaders Must Act, Warns EUROFER," December 16, 2021, https://www.eurofer.eu/press-releases/prohibitive-energy-and-carbon-prices-risk-undermining-eu-steel-industry-decarbonisation-eu-leaders-must-act-warns-eurofer.*

[184] *Nuomin Han, "How will the EU's CBAM Impact Global Iron & Steel?" Wood Mackenzie, March 27, 2024, https://www.woodmac.com/news/opinion/how-will-the-eus-cbam-impact-global-iron--steel/.*

[185] *Jing Shuai et al., "The Impact of the EU's Carbon Border Adjustment Mechanism on the Global Iron and Steel Trade and Emission Reduction," Environmental Science and Pollution Research 31 (2024): 21524–21544, https://doi.org/10.1007/s11356-024-32528-2.*

questions that are particularly difficult to answer for countries such as South Korea, Japan, and even China that also have to answer to market demand from countries that do not place the same priority on low-carbon steel.

On the negative side, resource shuffling presents a significant risk to the effectiveness of the CBAM in the steel sector. Steel producers outside the EU could selectively export their cleanest, least carbon-intensive products to Europe while continuing to produce more carbon-intensive steel for other markets. This circumvents the full decarbonization of their operations, undermining the CBAM's goal of reducing global emissions. Such practices could create a false impression of progress in addressing carbon leakage while limiting actual reductions in emissions across the steel industry. This distortion could also lead to unfair competition for EU steelmakers, who must comply with stricter decarbonization requirements across their entire production process.

To mitigate this, **adopting a country- and sector-based average calculation method for carbon intensity within the CBAM would be beneficial**. This approach simplifies the verification process by using sectoral averages, addressing the complexity of accounting for each exporter individually. Importantly, it reduces the risk of resource shuffling by ensuring that the entire steel industry in exporting countries is incentivized to decarbonize, rather than selectively exporting cleaner products to the EU. This method upholds the environmental goals of the CBAM by ensuring a more equitable and effective mechanism for reducing global carbon leakage and maintains a level playing field between EU and non-EU producers.

Choosing Where to Place Our Dependency

However, despite the potential benefits of the CBAM for the European steel sector, keeping ironmaking in Europe still presents substantial challenges, including the high costs associated with producing or importing green hydrogen and the need for extensive infrastructure development. The steel industry will need to adapt by enhancing energy efficiency and shifting toward circular economy practices, such as recycling scrap steel to minimize waste and emissions. Against this backdrop, **Europe could transition to a secondary steel production model, focusing on EAFs that melt recycled steel and imported DRI, rather than relying heavily on hydrogen to reduce iron domestically**.

While this transition poses its own set of challenges, including the need for a stable supply of high-quality scrap and upgrading EAF technology, it offers a viable pathway to achieving a sustainable and competitive steel industry in a net-zero future. This model leverages the existing scrap metal market and requires regulations enhancing scrap use, improving EAF efficiency, and mandating the use of clean energy. This model will probably be suitable for most current European steelmaking regions, particularly those far from cheap access to clean energy.

For its post-carbon steel sector, **Europe will ultimately need to decide where to place its dependency**. It could maintain reliance **at the iron ore stage**, as it does today, which is generally seen as less risky due to the wide availability of mining countries. Alternatively, **it could shift dependency to the pellet – in the form of hot briquetted iron (HBI) – post-DRI stage**, which poses a higher risk of supply disruption, as suppliers in this stage are less easily replaceable in the event of a crisis.

q. Summary of Recommendations for the Steel Sector in Europe

Recommendation A

Implement a country – and sector-based average calculation method for carbon intensity within the CBAM. Even as a temporary measure, this approach would simplify verification and reduce the risk of circumvention, such as exporting only the cleanest production to Europe while neglecting to decarbonize the sector as a whole.

Recommendation B

Renewable Fuels of Non-Biological Origin Directive (RFNBO): The EU's strict definition of RFNBO represents a significant barrier to large-scale hydrogen reduction steelmaking projects. The key regulatory hurdles include the following:

- **Prohibition for state aid in electricity production for clean hydrogen:** Projects receiving state aid for electricity production are not considered green.
- **Subsidies and carbon intensity:** A shift toward a carbon intensity approach is needed to enable the use of all types of clean hydrogen in the transition phase, including nuclear-based hydrogen.

Recommendation C

Prioritize clean hydrogen for industrial sectors such as steel:

- The development and prioritization of hydrogen as a decarbonization vector for the industry are vital. The EU hydrogen strategy aims to facilitate hydrogen pilot projects. However, high hydrogen pricing and difficulties of access necessitate a strong regulatory framework to support this transition.
- **At this stage, priority must be given to the steel sector – and to (petro)chemicals – in clean hydrogen supply**. This will enable it to launch market demand and decarbonize this sector faster than is possible in other sectors.

Recommendation D

Enhancing energy efficiency and circular economy practices: Adapting to the post-carbon economy requires the steel industry to enhance energy efficiency and shift toward circular economy practices. This includes the following aspects:

- **EAFs:** Transitioning to secondary steel production models that focus on EAFs, which melt recycled steel and imported DRI, rather than relying heavily on hydrogen to reduce iron domestically.
- **Recycling scrap steel:** Reverse the recent trend of increasing scrap exports.
- In the era of the CBAM, **steel scrap is a carbon asset, and Europe must adopt more stringent regulations to keep steel scrap in Europe** and recycle it on the continent.

2. STRATEGIES FOR DECARBONIZING THE ALUMINUM SECTOR

a. The Current State of the Aluminum Sector

Aluminum is derived from bauxite ore, which is found abundantly in regions such as Australia, China, Brazil, and Guinea. The extraction and refining of bauxite into alumina and subsequently into aluminum require substantial amounts of electricity, contributing heavily to the sector's carbon footprint.

The aluminum industry is a significant contributor to global greenhouse gas emissions due to its energy-intensive production processes. In total, emissions from the aluminum sector represent roughly 1.1 billion tons of CO_2-eq.[186] This represents **about 2 percent of global GHG emissions**. The emissions are primarily due to the energy-intensive nature of aluminum production in regions that rely on coal-fired power plants.

Globally, the production of aluminum is concentrated in a few key regions. China is by far the largest producer, producing 60 percent of global aluminum output, followed by the Gulf region, Russia, and Canada. Europe[187] has relatively low production levels (3.7 Mt in 2024), importing most of its primary aluminum. Japan, for instance, relies on primary aluminum imports and increased use of secondary aluminum (recycled). In 2024, global primary aluminum production was approximately 65 million tons, with China alone accounting for over 37 million tons.[188]

[186] *International Aluminium, "Greenhouse Gas Emissions – Aluminium Sector," January 25, 2023 (accessed September 10, 2024), https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/.*

[187] *Including Iceland and Norway.*

[188] *International Aluminium, "Primary Aluminium Production," August 20, 2024 (accessed September 10, 2024), https://international-aluminium.org/statistics/primary-aluminium-production/.*

b. Aluminum Production and Process

The production of aluminum involves **two main processes: smelting and melting**.

Smelting is the process of extracting aluminum from alumina[189] (aluminum oxide). This process is highly energy-intensive and is the primary source of emissions in aluminum production. Smelting is carried out using the Hall–Héroult process, which involves electrolysis.

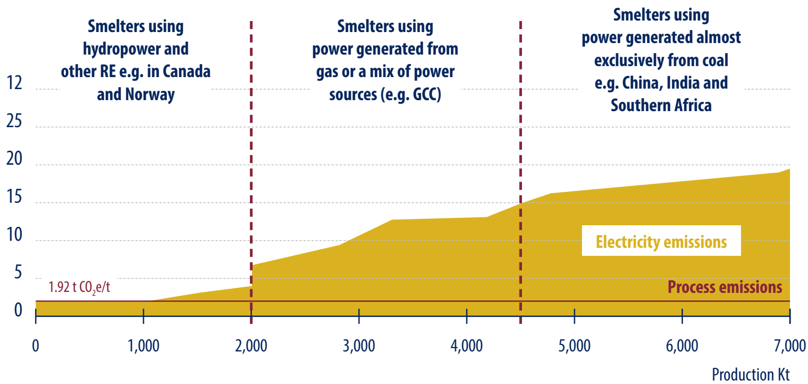
The aluminum smelting process involves the following steps:

1. **Electrolysis:** Alumina is dissolved in molten cryolite (a sodium aluminum fluoride mineral) in a large electrolytic cell. The cell contains a carbon anode and a carbon cathode.
2. **Baking process:** This involves heating **carbon anode** blocks to high temperatures to achieve the necessary properties and typically involves using fossil fuels such as natural gas, heavy fuel oil, or coal tar pitch, resulting in significant CO_2 emissions.
3. **Carbon anodes:** When an electric current is passed through the cell, the **carbon anode reacts with the oxygen in the alumina, forming carbon dioxide (CO_2)**. This is where the majority of emissions come from.
4. **Liquid aluminum:** The aluminum is reduced (separated from the oxygen) and collects at the bottom of the cell in a molten state. It is then siphoned off and cast into ingots, billets, or other forms for further processing.

[189] *Alumina is produced from bauxite through the Bayer process, which involves crushing the bauxite, mixing it with sodium hydroxide to dissolve the alumina, and then precipitating and calcining the resulting alumina hydrate to obtain pure alumina.*

The smelting process is responsible for the bulk of aluminum production emissions due to the consumption of carbon anodes, the significant electricity required, and the fuel used in the heating process. The carbon intensity of the electricity used greatly affects the overall emissions of the process. For example, China relies heavily on coal-fired power plants, making its aluminum production more carbon-intensive (14.7 tons of CO_2 per ton of aluminum) compared to Europe (less than 7 tons of CO_2 per ton of aluminum, around 2 tons in France), which benefits from a cleaner energy mix.

Figure 3: Aluminum intensity across regions (CRU)



The melting process, also known as secondary production or recycling, involves re-melting aluminum scrap/or primary aluminum to produce new aluminum products. This process is significantly less energy-intensive and contributes **only about 1 percent of the sector's GHG emissions**.

The aluminum melting process involves the following steps:

1. **Collection and sorting:** Aluminum scrap is collected and sorted based on its alloy composition and cleanliness. This can include beverage cans, automotive parts, and construction materials.
2. **Shredding and cleaning:** The scrap is shredded and cleaned to remove contaminants and impurities.
3. **Re-melting:** The cleaned scrap is melted in a furnace. Unlike smelting, this process does not require electrolysis or carbon anodes, resulting in significantly lower energy use and emissions.
4. **Alloying and casting:** The molten aluminum is alloyed with other elements as needed and cast into ingots, billets, or other forms for further manufacturing.

Recycling aluminum saves up to 95 percent of the energy required for primary production and can significantly reduce the industry's overall carbon footprint. Secondary aluminum production is crucial for achieving a high degree of circularity in the aluminum sector.

The location of aluminum production significantly impacts its carbon footprint due to the varying carbon intensity of electricity grids. Primary aluminum production has largely vanished from many developed countries, including Japan, the US, and most European nations,[190] especially following the recent energy crisis.

[190] *However, France continues to maintain a primary aluminum industry, leveraging its nuclear power to sustain production.*

c. Decarbonizing Primary Aluminum Processes

Decarbonizing primary aluminum production – smelting – involves several key technologies and approaches developed by industries and supported by governments:

1. **Clean electricity:** Transitioning to clean electricity sources for the electrolysis process (and the heating process) drastically reduces the carbon footprint since **roughly two-thirds of the emissions in the aluminum sector come from electricity**.[191] Regions with abundant renewable energy resources, such as hydropower, wind, or solar, are better positioned to produce low-carbon aluminum.
2. **CCUS:** Implementing CCUS technologies can capture CO_2 emissions from aluminum production and either store it underground or utilize it in other industrial processes (e.g., to produce e-methanol). This is a strategy that has been studied for primary aluminum production, especially in the absence of innovation to replace carbon anodes in the primary aluminum process.[192] However, due to the relatively low direct emissions from smelting processes compared to other energy-intensive sectors such as steel and cement, the **aluminum industry is currently less suited to lead the development of carbon capture technologies**.
3. **Inert anodes:** Replacing carbon anodes with inert anodes in the electrolysis process is essential for achieving total carbon abatement in the aluminum industry. Traditional carbon anodes release carbon dioxide when they react with oxygen during electrolysis. In contrast,

[191] *IAI data reveals an average 9.3 t of CO2/t of Al for electricity, to compare to a total (Scopes 1, 2, and 3) of 15.1 tn CO2 / tn. Al. See: International Aluminium Institute, "Greenhouse Gas Emissions Intensity – Primary Aluminium," November 29, 2023 (accessed September 10, 2024), https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/.*

[192] *Antonis Peppas, Chrysa Politi, Sotiris Kottaridis, and Maria Taxiarchou, "LCA Analysis Decarbonisation Potential of Aluminium Primary Production by Applying Hydrogen and CCUS Technologies," Hydrogen 4, no. 2 (2023): 338–356, https://doi.org/10.3390/hydrogen4020024.*

inert anodes eliminate this direct source of CO_2 emissions, producing only oxygen as a byproduct, thus significantly reducing greenhouse gas emissions from the smelting process.[193] This technology is currently at a relatively early stage of development and will require international cooperation in the aluminum sector to be accelerated. **The sector is unlikely to see this technology mature before the 2040s**. Companies such as Alcoa and Rio Tinto are pioneering this technology with their ELYSIS project, which aims to eliminate all direct GHG emissions from the smelting process.[194]

4. **Clean hydrogen:** Many projects are considering clean hydrogen as replacement fuel (to replace natural gas) in the baking phase of the carbon anodes (which requires a great deal of heat).[195] Some projects also consider replacing carbon anodes with clean hydrogen by utilizing **clean hydrogen as a reductant in the smelting process**.[196] This technology is still in a very early development phase, but is receiving attention in R&D projects in some countries.[197]

d. Decarbonization Strategies for Secondary Aluminum

Decarbonizing the melting process in aluminum production is also a critical step toward reducing the overall carbon footprint of the sector.

[198] *Ian Wells and Sophia Ahmed, Natural Resources Defense Council (NRDC), "The Role of Inert Anodes in Aluminum Decarbonization," August 10, 2023, https://www.nrdc.org/bio/ian-wells/role-inert-anodes-aluminum-decarbonization.*

[194] *Alcoa, "The World's First Carbon-Free Smelting Technology," accessed September 10, 2024, https://www.alcoa.com/products/elysis.*

[195] *Antonis Peppas et al., "LCA Analysis Decarbonisation Potential of Aluminium Primary Production by Applying Hydrogen and CCUS Technologies."*

[196] *Halvor Kvande, Gudrun Saevarsdottir, and Barry Welch, "Decarbonizing the Primary Aluminum Industry," Light Metal Age, March 20, 2023, https://www.lightmetalage.com/news/industry-news/smelting/decarbonizing-the-primary-aluminum-industry/.*

[197] *Antonis Peppas et al., "LCA Analysis Decarbonisation Potential of Aluminium Primary Production by Applying Hydrogen and CCUS Technologies."*

This effort is particularly significant given the high energy consumption associated with primary aluminum production. The recycling of aluminum scrap – known as secondary aluminum production – offers a less carbon-intensive alternative.

Aluminum's relatively low melting point (660.3°C) compared to other metals makes it easier and less energy-intensive to recycle, contributing to its **high recyclability**. Additionally, unlike many other metals, **aluminum retains its properties through multiple recycling processes**, making it a good candidate for high recycling.

The primary strategy for governments and companies to decarbonize the melting process is to **electrify the process using clean electricity**. The two other points are the necessity of **adopting ecodesign** and **circularity policies** and adopting innovative **aluminum resource supply chains**.

Designing aluminum products with end-of-life recycling in mind can substantially enhance the sector's circularity. This involves addressing the following aspects:

- **Product design for disassembly:** Creating products that can be easily disassembled at the end of their life cycle to facilitate recycling reduces waste and ensures that the materials can be effectively reused.
- **Material selection:** Choosing aluminum alloys that are easier to recycle and have lower environmental impacts during production and end-of-life processing enhances circularity.
- **Extended producer responsibility (EPR):** Implementing policies that make producers responsible for the entire life cycle of their products, including take-back, recycling, and final disposal encourages manufacturers to design more recyclable products.

Developing a **robust supply chain where aluminum scrap is treated as a central resource** is essential. This includes implementing the following approaches:

- **Efficient collection systems:** Establishing comprehensive systems for collecting aluminum scrap from various sources, including households, industries, and construction sites.
- **Advanced sorting technologies:** Implementing cutting-edge technologies such as automated sorting systems and AI to separate different types of aluminum alloys efficiently.
- **High-performance recycling processes:** Developing and deploying processes that can handle mixed aluminum scrap and still produce high-quality recycled aluminum. This includes techniques for **removing impurities** and ensuring the recycled aluminum meets industry standards.

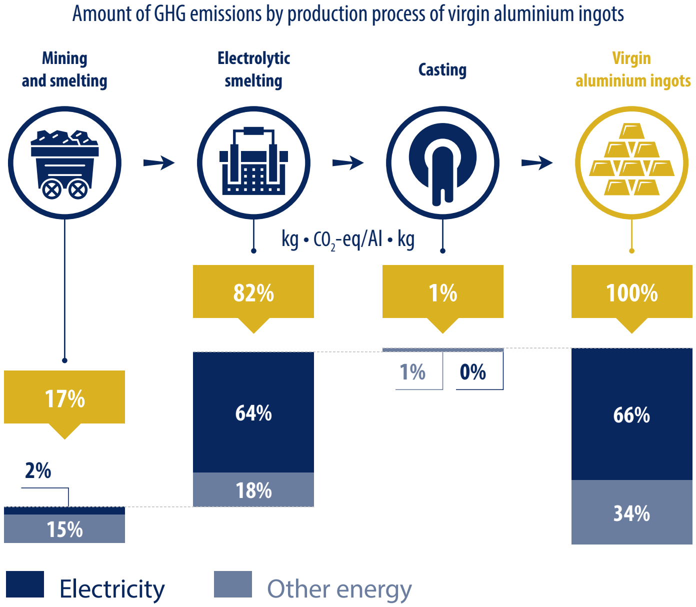
One of the primary challenges in aluminum recycling is **managing the different types of aluminum alloys used in various applications**. Each type requires a specific recycling process, and removing impurities is a critical step. Addressing these challenges involves the following aspects:

- **Alloy segregation:** Enhancing technologies for the identification and segregation of various aluminum alloys to ensure that the recycling process can be tailored to the specific needs of each type.
- **Removing impurities:** Developing advanced methods for removing impurities from recycled aluminum, such as through the use of novel filtering technologies or chemical treatments.
- **Performance enhancement:** Investing in research to improve the performance of recycled aluminum, including developing alloys that can maintain or even exceed the properties of primary aluminum despite the presence of recycled content.

e. Decarbonizing a Highly Geopolitical Sector

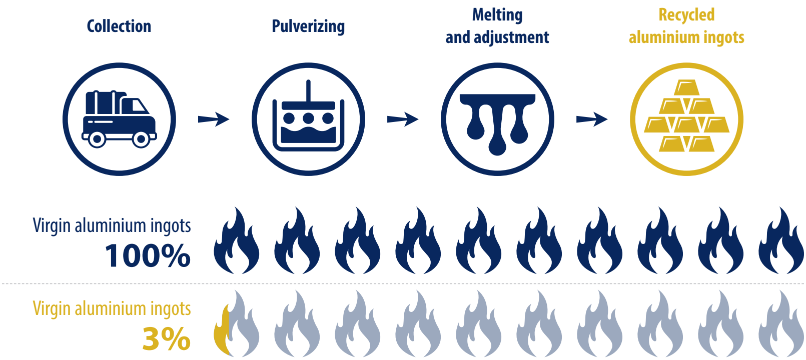
Aluminum is a critical metal for many industries of the future. The political economy of decarbonizing the aluminum sector involves navigating complex global supply chains, regional energy policies, and economic dependencies. **As clean energy technologies such as solar panels, wind turbines, and high voltage lines require substantial amounts of aluminum, the demand for decarbonized aluminum is expected to grow massively**. The sector is extremely reliant on electricity and electricity cost. Therefore, regions with access to cheap clean energy sources have a competitive advantage in producing low-carbon aluminum.

Figure 4: Emissions in the aluminum process



Source: International Aluminium Institute.

Reclycled alumimium ingots production process and amount of GHG emissions



Source: Japan Aluminium Association.

f. China's Strategy for Aluminum

China's dominance in aluminum production presents a significant challenge for global decarbonization efforts due to its heavy reliance on coal-powered electricity[198] – the sector is responsible for 4.5 percent of total Chinese GHG emissions.[199] The current utilization rate of clean electricity in the sector is particularly low, and recycling remains at a minimal level. If China aims to decarbonize this highly carbon-intensive sector, it will require massive industry restructuring toward electrification.[200]

[198] *47GW of Coal electricity capacity in China is directed toward the aluminum sector alone, this is bigger than the entire German coal fleet.*

[199] *667Mt in 2020.*

[200] *For more on the utilization rate of clean electricity and coal usage see: International Green Economy Association, 产业"双碳"范例丨中铝环保节能集团：双碳背景下的铝业降碳路径 [Industrial 'Dual Carbon' Model | Chinalco Environmental Protection and Energy Conservation Group: Aluminum Industry's Carbon Reduction Path Under the Dual Carbon Framework], 2023, http://www.igea-un.org/cms/show-6722.html.*

The country aims to decarbonize while maintaining its position as the leading aluminum producer. A range of policies have been implemented to **restrict blind expansion** of smelting capacity, **attract aluminum scrap** while restricting primary aluminum exports to support its rapidly growing cleantech industries, and **restructure its industrial base**.[201]

Additionally, **China is trying to shift its aluminum sector** away from regions that are dependent on coal-fired power plants **to provinces with abundant clean electricity**, particularly hydropower. This move could substantially reduce the global carbon footprint of the aluminum industry.

However, the Chinese strategy still faces the classic challenges of decarbonizing the country's industrial sector. Despite voluntary policies, the government struggles to maintain control over the production apparatus, which **includes both private and state-owned entities**[202] – Chinalco, a SOE, being the largest aluminum-producing company in the world.[203] This approach is a typical form of Chinese industrial policy, **aiming to enforce a "clusterization strategy"** for the sector. This strategy focuses on locating cleaner aluminum production in areas with access to large amounts of clean electricity, scrap materials, and proximity to a customer base – **a form of vertical integration** with the limitation mandated by access to massive amounts of clean electricity.[204]

[201] *15 percent export tax that China levies on exports of primary aluminum, and to which should be added incomplete rebates of value-added tax that further discourage aluminum exports: OECD, "Government Support in Industrial Sectors," OECD Trade Policy Papers, no. 270, 2023, https://doi.org/10.1787/1d28d299-en.*

[202] *50 percent of the total primary aluminum output in China is manufactured by SOEs, and SOEs represent a dominant share of the domestic market. See: European Commission, "Staff working document SWD(2024)91: Commission Staff Working Document on Significant Distortions in the Economy of the People's Republic of China for the Purposes of Trade Defence Investigations," 2024, https://ec.europa.eu/transparency/documents-register/detail?ref=SWD(2024)91&lang=en.*

[203] *7.1 million tons produced in 2022. See: Statista, "Leading Primary Aluminum Producing Companies in 2022, Based on Production Output," June 28, 2024, https://www.statista.com/statistics/280920/largest-aluminum-companies-worldwide/.*

[204] *Regions with access to sufficient bauxite will still be favored, even if they do not have easy access to abundant clean electricity. These regions will have to wait for the development of a massive clean electricity transport infrastructure before they can be decarbonized.*

Table 6: China's Main Aluminum Manufacturers[205]

Rank	Company	Production Volume (Million Metric Tons)	Ownership status
1	Aluminium Corporation of China (Chalco)	7.1	SOE
2	China Hongqiao Group Ltd.	6.5	Private
3	Shandong Nanshan Aluminium Co. Ltd.	2.6	Private
4	Xinfa Group	3.1	Private
5	Henan Mingtai Al. Industrial Co., Ltd.	1.0	Private
6	East Hope Group	1.6	Private
7	Shandong Weiqiao Pionnering Group	4.8	Private
8	Yunnan Aluminium	1.1	SOE
9	SPIC Aluminium International trading	0.9	SOE
10	Guangxi Investment Group	0.85	SOE

Staying Dominant While Decarbonizing

Despite the willingness from the central government to cap aluminum production, **aluminum is considered a critical sector in China and is central to the country's strategy to remain the center of global clean-tech production**. Due to China's insufficient domestic bauxite resources,[206] the country imports about 60 percent of its bauxite from abroad.[207] **China alone buys 83 percent of the total bauxite shipped globally**.[208]

[205] *By the author, data from the International Aluminum Institute and the China National Bureau of Statistics.*

[206] *In China, the largest bauxite deposits are found in Shanxi, Henan, the Guangxi Zhuang Autonomous Region, and Guizhou. The primary provinces for alumina production are Henan, Shandong, Guangxi, Xinjiang, Inner Mongolia, Shanxi, and Guizhou. Major electrolytic aluminum producers are located in Shandong, Xinjiang, and Inner Mongolia. Additionally, there are production plants in other provinces, such as Yunnan and Guangxi, the latter of which has recently become an attractive location due to its inexpensive renewable electricity.*

[207] *SHMET, 2023年中国铝土矿对外依存度继续攀升 [China's Bauxite Import Dependency Continues to Rise in 2023], February 5, 2024, https://www.shmet.com/news/newsDetail-2-883109.html.*

In aluminum production, electricity can account for up to 40 percent of the total production cost. Therefore, the competitiveness of **China's aluminum industry relies heavily on access to cheap electricity**.

Historically, coal – an abundant and inexpensive domestic resource – has been used to provide this cheap electricity. China produces roughly 60 percent of global aluminum,[209] most of it through processes that rely on coal-fired power plants. However, as the sector moves toward decarbonization, **the strategy is to transition to more efficient and sustainable production processes to remain competitive in the global market**. This entails the **electrification of primary aluminum production using its consequent renewable base** (particularly hydroelectricity) at **a cheap cost and the development of recycling initiatives**.

Emissions Trading Scheme Expansion

Crucial to the promotion of clean electrification of the aluminum sector in the country and globally, **China's national ETS**, which focused initially on the power sector, is scheduled to **expand to cover aluminum production.**[210] This includes **accounting for indirect emissions from electricity consumption used in aluminum smelting**.[211]

[208] *Chinese Shipping,* 中国铝土矿进口逆势增长成为干散货航运市场亮点 *[China's Bauxite Imports Defy Trends, Becoming a Highlight in the Dry Bulk Shipping Market], May 25, 2023, https://info.chineseshipping.com.cn/cninfo/News/202305/t20230525_1377288.shtml.*

[209] *International Aluminium, "Primary Aluminium Production."*

[210] *Zhao Xuan and Kelsey Cheng, "China Expands Emissions Trading Scheme to Include Aluminum Industry," Caixin Global, March 15, 2024, https://www.caixinglobal.com/2024-03-15/china-expands-emissions-trading-scheme-to-include-aluminum-industry-102175796.html.*

[211] *Ministry of Ecology and Environment, China,* 关于公开征求《企业温室气体排放核算与报告指南 铝冶炼行业》《企业温室气体排放核查技术指南 铝冶炼行业》意见的通知 *[Notice on Public Solicitation of Opinions for the 'Guidelines for Corporate Greenhouse Gas Emissions Accounting and Reporting in the Aluminum Smelting Industry' and the 'Technical Guidelines for Corporate Greenhouse Gas Emissions Verification in the Aluminum Smelting Industry], March 15, 2024), https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202403/t20240315_1068508.html.*

Although it is not possible to be sure when this expansion will happen – the first phase is currently scheduled for 2025 – new guidelines for emissions accounting in the aluminum sector were released in March 2024, simplifying the reporting process (for both direct and indirect emissions) and preparing for the expansion of the ETS to include aluminum production.[212] Given the share of China in the world's aluminum production, this expansion will have a significant impact on the decarbonization of the aluminum sector globally. Beyond the expansion, the transition from an intensity-based ETS to an auctioned-based cap-and-trade system will be the real benchmark changing the deal for the aluminum sector.

The Transition to Renewable Energy Sources

The Chinese government has recognized the carbon-intensive nature of its aluminum production, which is primarily due to its reliance on coal-fired electricity. To mitigate this, the strategy involves **shifting to renewable energy sources for aluminum smelting**. This shift is incentivized and accompanied by **mandates to consume clean electricity**. Provinces with a high degree of renewable electricity have become central to this transition, leveraging their abundant hydropower resources to support aluminum production.

Renewable Energy Targets

- China's goal is that **more than 25 percent of the energy used in aluminum electrolysis will be derived from renewable sources** by 2025[213] and that this figure will reach **30 percent by 2030**.[214] This will mostly be achieved through the relocation of primary aluminum production to provinces with high availability of hydroelectricity.[215]

[212] *Ministry of Ecology and Environment, China, "Notice on Public Solicitation of Opinions for the 'Guidelines for Corporate Greenhouse Gas Emissions Accounting and Reporting in the Aluminum Smelting Industry' and the 'Technical Guidelines for Corporate Greenhouse Gas Emissions*

Shifting between Provinces

- **Provincial competition is also being mobilized to attract the aluminum sector to regions with high availability of green electricity**. For example, Yunnan has a plan that includes moving substantial aluminum capacity from coal-dependent regions such as Shandong to Yunnan, where hydropower constitutes 75 percent of the electricity mix.[216]

Regulatory Measures and Financial Incentives

China's regulatory framework is designed to encourage recycling and reduce emissions from aluminum processes through **guidelines aimed to control the sector's expansion (how much it expands and where this expansion happens), provide strong directions for what technologies to stop using**, and offer **financial incentives for reducing emissions.**[217]

[213] *State Council of the People's Republic of China,* 国务院关于印发《*2024—2025*年节能降碳行动方案》的通知 *[Notice of the State Council on Issuing the '2024–2025 Energy Conservation and Carbon Reduction Action Plan'], May 29, 2024, https://www.gov.cn/zhengce/content/202405/content_6954322.htm.*

[214] *State Council of the People's Republic of China, "Implementation Plan for Carbon Peaking in the Industrial Sector."*

[215] *Ministry of Industry and Information Technology, China.* "十四五"原材料工业发展规划的通知 *[Notice on the '14th Five-Year Plan for the Development of the Raw Materials Industry'], December 29, 2021, https://www.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_2960538d19e34c66a5eb8d01b74cbb20.html.*

[216] *Min Zhang and Tom Daly, "Hongqiao to Move Additional 1.93 MM MTPA of Aluminium Smelting Capacity to Yunnan Province," Reuters, December 28, 2021, https://www.reuters.com/article/markets/currencies/china-hongqiao-to-move-aluminium-smelting-capacity-to-yunnan-province-idUSKBN2J706H/.*

[217] *Aluminum is not covered in the "Made in China 2025" but is included in later texts, guidelines, and roadmaps.*

The 2024 version of the "Guidance Catalogue for Industrial Restructuring"[218] restricts the expansion of new and inefficient aluminum smelting projects and promotes the adoption of advanced recycling techniques. **Small-scale and inefficient operations are being phased out** to improve overall efficiency and reduce emissions.[219] Overall, this strategy resembles those implemented for the steel industry, aiming to maintain control over the production apparatus of this extremely energy-intensive sector.

Institutions such as the Bank of China also play a role in providing transition finance to projects that focus on reducing emissions and energy consumption in aluminum refining and smelting, as well as enhancing recycling capabilities. However, the guidelines for accessing these bonds **do not mandate carbon neutrality**, and they **promote projects using both gas and electricity**. Nonetheless, they have **eligibility thresholds** below the national average emissions per ton of aluminum produced.[220]

Provincial governments also play a crucial role in **supporting the greening of the sector** – without carbon neutrality targets – by providing various measures, particularly financial ones, to help decarbonize the industry. These efforts aim to enhance energy efficiency and meet future demand for green aluminum. Such measures may include **lowering operating costs**,[221] **setting production targets**,[222] or **mandating the use of available clean electricity**.

[218] *National Development and Reform Commission, China, "Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)."*

[219] *Projects producing less than 100,000 tons per year are restricted.*

[220] *Bank of China Limited, "Transition Bonds Management Statement," January 2021 https://pic.bankofchina.com/bocappd/report/202101/P020210106328842685396.pdf.*

[221] *People's Government of Yunnan Province,* 关于印发云南省全链条重塑有色金属及新材料产业新优势行动计划的通知 *[Notice on Issuing the Yunnan Province Full-Chain Reshaping Action Plan for Gaining New Advantages in the Non-Ferrous Metals and New Materials Industries], December 16, 2021, http://www.yn.gov.cn/ztgg/lqhm/lqzc/djzc/202202/t20220223_236886.html.*

[222] *Zhengzhou Vios Foreign Investment Service Center,* 河南省人民政府办公厅关于印发河南省钢铁行业转型发展行动方案（2018-2020年）等4个方案的通知 *[Notice from the General Office of the People's Government of Henan Province on Issuing the 'Henan Province Steel Industry Transformation and Development Action Plan (2018–2020)' and Four Other Plans], December 31, 2018, https://www.waizi.org.cn/policy/52055.html.*

Industry associations play their part in implementing government policies within the aluminum sector. The **China Non-Ferrous Metals Fabrication Industry Association (CNFA)**[223] and **China Recycled Metal Association (CRMA)**[224] ensure compliance with government regulations and promote best practices in recycling and emissions reduction.

Guiding Technological Advancements

Beyond promoting the end of polluting processes, in the Chinese strategy, advancing technology is pivotal to reducing emissions. This is particularly true in the smelting process. The Chinese government has outlined various technological reforms to enhance energy efficiency and reduce emissions. The strategy aims to make progress in two directions simultaneously: **energy efficiency** and **emissions reduction**.

"The 14th Five-Year Plan (FYP) on Raw Materials" and related guidelines encourage the development of high-efficiency, low-emissions smelting technologies. This includes **promoting "advanced" aluminum electrolysis and research into "ultra-low-emission" technologies**.[225] Guidance also **provides guidelines to support R&D to improve carbon anodes, and potentially following-up on R&D conduced in Western countries to develop alternative anodes in the mid to long terms**.[226]

[223] *China Nonferrous Metals Fabrication Industry Association (CNFA), accessed September 10, 2024, https://www.cnfa.net.cn/.*

[224] *China Recycled Metal Association (CMRA), accessed September 10, 2024, http://cmra.cn/index.html.*

[225] *Ministry of Industry and Information Technology, China, "Notice on the '14th Five-Year Plan for the Development of the Raw Materials Industry.'"*

[226] *National Development and Reform Commission, China, "Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)."*

Development of Recycling (Keeping Scrap and Policy Implementation)

The Chinese national and local governments are also collaborating to **improve the aluminum sector's recycling capabilities** in order to support decarbonization efforts and maintain the country's leading position in the industry. By **attracting aluminum scrap from abroad** and recycling it, China aims to have access to a sufficient amount of the resources that are essential for its industrial sector. **Aluminum scrap is increasingly perceived as an asset that industries should aim to obtain domestically and abroad**.

The government is providing support for the recycling of aluminum through the following policies:

- The MIIT/NDRC "Implementation Plan for Carbon Peaking in the Industrial Sector" sets ambitious targets for increasing the **output of recycled aluminum to 11.5 million tons by 2025**, with **recycled metals accounting for more than 24 percent of the total supply**.[227]
- **Provincial plans:** Various provinces have introduced detailed plans to support aluminum recycling. For example, **Yunnan**[228] and **Guangxi** have proposed measures to **establish zero-carbon green aluminum industrial parks** and provide **financial support** for recycling initiatives and green electricity consumption. **Henan**, for instance, is implementing not only strict capacity controls but also **production targets** for aluminum using scrap.[229]

[227] *State Council of the People's Republic of China, "Implementation Plan for Carbon Peaking in the Industrial Sector."*

[228] *People's Government of Yunnan Province,* 关于印发云南省全链条重塑有色金属及新材料产业新优势行动计划的通知 *[Notice on Issuing the Yunnan Province Full-Chain Reshaping Action Plan for Gaining New Advantages in the Non-Ferrous Metals and New Materials Industries], December 16, 2021, https://www.yn.gov.cn/ztgg/lqhm/lqzc/djzc/202202/t20220223_236886.html.*

[229] *Zhengzhou Vios Foreign Investment Service Center, "Notice from the General Office of the People's Government of Henan Province on Issuing the 'Henan Province Steel Industry Transformation and Development Action Plan (2018–2020)' and Four Other Plans."*

Impact of the Carbon Border Adjustment Mechanism

The Chinese industrial strategy actively aims to keep primary aluminum in the country and only promote the export of finished or semi-finished aluminum products.[230] However, **Europe still imports aluminum products from China**,[231] and these imports will be affected by the implementation of the EU CBAM. China has its own domestic ETS market, but it currently only covers power generators, which trade at a significant discount compared to the EU ETS. Even if the CN ETS expands to cover the aluminum sector before the implementation of the CBAM, the key differences in the price of CN ETS compared to the EU ETS, along with the intensity-based nature of the system, will still lead to a carbon adjustment. Consequently, the additional cost to move Chinese aluminum to the EU will be substantial, likely reducing Chinese primary aluminum flows to the EU.

The primary factor driving differences in direct emissions from aluminum smelters is whether they source their power from the grid or have a captive power plant. Those with captive power have significantly higher direct emissions. The carbon footprint of aluminum imports mainly comes from the electricity used in the electro-intensive smelting process. Currently, the primary fuel for many captive power plants is coal. In China, 88 percent of primary aluminum production is based on coal-fired electricity generation, while the remaining 12 percent is based on hydropower.[232]

[230] *Such as sheet, strip, plate, profiles, rod and bar, tube, wire, forgings etc.*

[231] *World Integrated Trade Solution, "Aluminium Unwrought, Alloyed Imports by Country in 2023," World Bank, 2023 (accessed September 10, 2024), https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2023/tradeflow/Imports/partner/WLD/product/760120; Siyi Liu and Mei Mei Chu, "China Aluminium Exports Covered by EU Carbon Tax down 30%," Business Live, February 5, 2024, https://www.businesslive.co.za/bd/world/asia/2024-02-05-china-aluminium-exports-covered-by-eu-carbon-tax-down-30/#google_vignette.*

[232] *Alexandra Maratou and Andrei Marcu, "The Aluminium Value Chain and Implications for CBAM Design," European Roundtable on Climate Change and Sustainable Transition (ERCST), June 2021, https://ercst.org/wp-content/uploads/2021/08/The-aluminium-value-chain-and-implications-for-CBAM-design.pdf.*

However, China's trend of relocating smelters to provinces powered by hydropower could further decrease the carbon intensity of its aluminum production, potentially mitigating the impact of the CBAM on the Chinese aluminum sector and increasing the attractiveness of **these products for the European market**. Regarding the impact of the EU CBAM on China, semi-finished or finished aluminum products are not yet covered by the EU CBAM provisions. This is where the fragility of the EU CBAM system lies concerning potential circumvention strategies by China or any other manufacturing country. **The CBAM indirectly promotes the export of semi-finished or finished aluminum products** – manufactured with aluminum that does not incur a carbon cost – to the EU market. These products would then compete with those using primary aluminum covered by the EU ETS.

Table 7: Summary: Chinese Policies for Decarbonizing the Aluminum Sector

Legislation	Date	Issuer	Link
Guidance Catalogue for Industrial Restructuring[233]	2024	NDRC	https://www.ndrc.gov.cn/xxgk/zcfb/fzggwl/202312/P020231229700886191069.pdf
The 14th Five-Year Plan (FYP) on Raw Materials[234]	2021	Ministry of Industry and Information Technology (MIIT)	https://wap.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2021/art_2960538d19e34c66a5eb-8d01b74cbb20.html
Implementation Plan for Carbon Peaking in the Industrial Sector[235]	2022	MIIT/NDRC	https://www.gov.cn/zhengce/zhengceku/2022-08/01/5703910/files/f7ed-f770241a404c9bc608c051f13b45.pdf

[233] *National Development and Reform Commission, China, "Guiding Catalogue for Industrial Structure Adjustment (2024 Edition)."*

[234] *Ministry of Industry and Information Technology of the People's Republic of China. (2021), "Notice from Three Ministries on Issuing the '14th Five-Year' Development Plan for the Raw Materials Industry."*

[235] *State Council of the People's Republic of China, "Implementation Plan for Carbon Peaking in the Industrial Sector."*

g. Japan and Aluminum Decarbonization

Japan does not produce primary aluminum domestically. It imports primary aluminum from countries with cheap access to energy and melts aluminum at home to manufacture aluminum products. The Japanese strategy to decarbonization therefore focuses on **increasing the recycling rate** of aluminum and transitioning to clean energy for aluminum melting processes. This includes the promotion of **transitioning to clean electricity, energy efficiency improvements**, and **developing more efficient carbon recycling technologies**.

Challenges and Strategies for Aluminum Decarbonization in Japan

The decarbonization of the Japanese aluminum sector hinges on the following three main challenges:

Energy Transition for Aluminum Melting

Electrification, changing fuel to **hydrogen or ammonia**, and **CCUS** are currently being considered by the Japanese sector and the government.

Shifting to electrification for aluminum melting to try to reach carbon neutrality is only viable if Japan's electricity grid is significantly decarbonized. Current efforts focus on increasing the share of renewables in the energy mix to 36–38 percent and of nuclear to 20–22 percent by 2030.[236] **This means that, considering the grid mix, the green electrification of the Japanese sector is not forecast for the near future but is instead a long-term objective for the post-2040 period**.

[236] *Agency for Natural Resources and Energy, Japan,「GX実現」に向けた日本のエネルギー政策（後編）脱炭素も経済成長も実現する方策とは [Japan's Energy Policy Towards Achieving 'GX' (Part 2): Strategies to Realize Both Decarbonization and Economic Growth], May 26, 2023, https://www.enecho.meti.go.jp/about/special/johoteikyo/gx_02.html.*

Considering the perceived difficulty of producing sufficient clean electricity in Japan, the aluminum sector is **exploring the potential for using green hydrogen and ammonia in the melting process**. This aims to replace gas (currently used in Japan to produce heat in the aluminum sector) with hydrogen or ammonia. This is based on Japan's overall strategy of importing clean hydrogen from abroad and using it for application at home. One of the industrial applications of this clean hydrogen could well be in the aluminum sector. However, supply and cost remain substantial barriers in a sector facing significant price competition from abroad.

If the strategies mentioned above are not feasible, the sector is also considering the option of continuing to use fossil fuels while capturing the resulting emissions and transporting the captured CO_2 to areas with storage capacity. However, with the current state of technology, this approach would **necessitate a substantial carbon price to cover the costs of capturing and transporting the CO_2 over long distances**. This would make aluminum production in Japan economically challenging.

Carbon Intensity of Imports

Decarbonizing Japan's aluminum imports poses a significant challenge, as it depends on the carbon policies of exporting countries.[237]

The implementation of a CBAM similar to the EU CBAM could help mitigate the carbon footprint of imported aluminum by imposing tariffs on carbon-intensive imports. **There are calls from the Japanese sector for a Japanese-style CBAM for the aluminum sector**, arguing that decarbonizing the sector without a carbon price and a CBAM in place will

[237] *The fastest growing import markets in Raw Aluminium for Japan between 2021 and 2022 were United Arab Emirates ($251M), China ($100M), and Saudi Arabia ($97.8M). See: OEC – The Observatory of Economic Complexity, "Raw Aluminium in Japan," accessed September 10, 2024, https://oec.world/en/profile/bilateral-product/raw-aluminium/reporter/jpn.*

be mostly impossible. The government has explored the possibility of **implementing carbon adjustment from the late 2020s**, but this option remains to be confirmed, as the country is highly export-exposed and there are fears of retaliation in case of a CBAM implementation.

If Japan is really going for a CBAM-like measure, this would involve disclosing emissions from aluminum electrolysis, ingot casting, anode/paste production, and the energy consumed in these processes. Over time, these disclosures could expand to cover full life cycle emissions, providing a comprehensive understanding of the carbon footprint associated with aluminum production. This is considered very challenging by Japanese actors.

Recycling Rates and Scrap Management in a Time of High Competition

The Japanese strategy also involves **reducing dependence on imported primary aluminum by increasing domestic aluminum recycling**.

Japan boasts one of the highest recycling rates globally, primarily due to its strict recycling laws such as the **End-of-Life Vehicle Recycling Law**[238] and the **Construction Material Recycling Law**.[239] Currently, Japan's downstream aluminum industry is able to recycle 76 percent of waste disposal, which accounts for **48 percent** of inputs, emitting around **97 percent** less GHG emissions compared to primary aluminum. However, the recycling rate for wrought products remains low (10 percent) due to the mixing of alloys and degradation of purity.[240]

[238] *Ministry of Economy, Trade and Industry, Japan, "Act on Recycling, etc. of End-of-Life Vehicles," July 12, 2002, https://www.meti.go.jp/policy/mono_info_service/mono/automobile/automobile_recycle/law_notice/pdf/english.pdf.*

[239] *Ministry of the Environment, Japan, "Construction Material Recycling Law," accessed October 1, 2024, https://www.env.go.jp/content/900452889.pdf.*

[240] *EN+ Group, "Green Growth in Japan: The role of Aluminium in the Low-Carbon Transition," accessed October 1, 2024, https://enplusgroup.com/upload/iblock/257/Green-Growth-in-Japan-_-ENG.pdf.*

Additionally, **around 20 percent of Japan's aluminum scrap is exported**, reducing the domestic resources available for recycling. This scrap is now considered a **domestic carbon resource**, and companies are increasingly advocating for scrap preservation action in the country in order to **create an aluminum circular supply chain that would not be disrupted by external forces**.

Indeed, given its capacity to be labeled "low carbon," aluminum scrap is becoming very valuable, and policies should support access to it. Traditional economic policy would advocate for the complete liberalization of the aluminum scrap trade to ensure that scrap is available where it is most needed. However, during the carbon neutrality transition period, intense competition between countries may arise, potentially leading to some sectors collapsing if they cannot secure access to scrap aluminum.

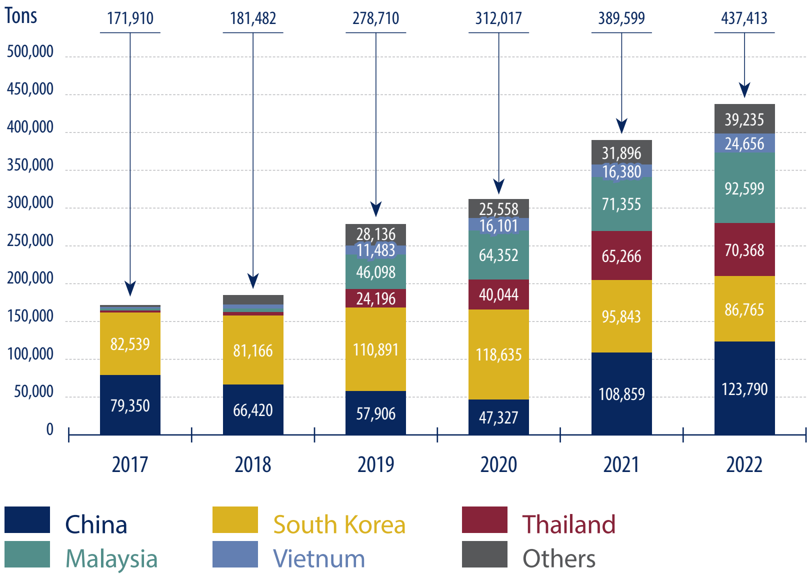
The country aims to achieve a **75 percent recycling rate for aluminum products by 2050**. To achieve this, the Japanese policy aims to promote a circular aluminum economy to expand domestic resource circulation to **retain valuable aluminum scrap** and **reduce dependence on imported primary aluminum**. The government is **considering regulations to prevent the export of scrap metal**, thus ensuring it is recycled domestically – but has yet to introduce such measures. The strategy also encompasses **developing innovative sorting technologies** to maintain alloy purity and meet **high standards for recycled aluminum applications**.[241]

[241] *Interviews with METI.*

Figure 5: Outflow of Aluminum Scrap from Japan

(Total Al Scrap export & import of Japan)

- About 20% of ingot imports flow overseas, equivalent to 4.6 M tons of CO_2 (about 40 M tons over 10 years), equivalent to over 0.4% of Japan's total CO_2 emissions.
- Domestic recycling of scrap aluminium, which is a domestic low-carbon resource, is an issue.



Source : METI.

Policy Support Needed

The aluminum sector is one of the sectors **covered by the Green Innovation Fund**, in addition to the R&D support it receives for recycling technologies, electrification, and CCUS. However, stakeholders including the Japan Aluminum Association and companies such as UACJ emphasize the need for **green procurement policies** and ecodesign mandates to stimulate demand for green aluminum. These **ecodesign mandate**s should apply to finished products (such as cars) for carbon content and enable an easy-to-recycle approach.[242]

The Japanese government aims to introduce **public procurement** to establish benchmarks for low-carbon aluminum. Nevertheless, the current green standard carbon footprint of 4 tn. CO_2 / tn. Al – following the International Aluminium Institute's (IAI) Level 1 guidelines – is still the initial standard since the early 2000.[243] This definition is still far from carbon neutrality, and the government's objective of **creating a distinct market for low-carbon aluminum has yet to materialize in legislation**.

Future Prospects in the Post-Carbon Aluminum Market

Aluminum's significance is set to grow as demand increases for its use in electric vehicles (EVs), renewable energy infrastructure, and long-distance power transmission. Japanese stakeholders understand the critical position of aluminum well. However, Japan faces significant challenges in the post-carbon aluminum market. The Green Innovation Fund promotes technologies that enhance aluminum sorting and recycling rates in the country. Nevertheless, the high costs associated with **recycling aluminum in Japan could jeopardize the sustainability of the sector without substantial protective measures – mostly because of clean energy scarcity in the country**.

[242] *According to interviews.*

[243] *Ministry of the Environment, Japan, "Act on Promotion of Procurement of Eco-Friendly Goods and Services by the State and Other Entities (Act on Promoting Green Procurement)," May 31, 2000, https://www.env.go.jp/en/laws/policy/green/.*

For Japan, which exports around 4 percent of its aluminum products to the EU,[244] the CBAM will have a modest impact at first. This does not prevent the CBAM from being perceived as an incentive to decarbonize by most of the Japanese aluminum sector.[245]

Beyond the CBAM, most of the Japanese aluminum sector believes that the **standardization of green aluminum is essential to effectively decarbonize the industry**. This is particularly crucial as Japan imports primary aluminum and processes it domestically, facing limited capacity to decarbonize internally. Standardization, especially in collaboration with the EU, **can address the disparities in carbon content and recycling practices, which are often subject to varying interpretations, particularly concerning the recycling rate of pre-consumer scrap waste**.

Table 8: Summary: Japanese Policies for Decarbonizing the Aluminum Sector

Legislation	Date	Issuer	Link
End-of-Life Vehicle Recycling Law[246]	2022	METI	https://www.meti.go.jp/policy/mono_info_service/mono/automobile/automobile_recycle/law_notice/pdf/english.pdf
Construction Material Recycling Law[247]	2003	Ministry of Land, Infrastructure and Transport	https://www.env.go.jp/content/900452889.pdf https://www.jstage.jst.go.jp/article/jares1985/17/1/17_1_12/_pdf/-char/en[248]

[244] *World Integrated Trade Solution, "Japan Profiles, Hollow, Aluminium, Alloyed Exports by Country in 2021," accessed September 10, 2024, https://wits.worldbank.org/trade/comtrade/en/country/JPN/year/2021/tradeflow/Exports/partner/ALL/product/760421.*

[245] *From interviews.*

[246] *Ministry of Economy, Trade and Industry, Japan, "Act on Recycling, etc. of End-of-Life Vehicles."*

[247] *Ministry of the Environment, Japan, "Construction Material Recycling Law."*

[248] *Shinichi Tokumoto,* 建設 リサイクル法の概要について *[Overview of the Construction Recycling Law], 2003, https://www.jstage.jst.go.jp/article/jares1985/17/1/17_1_12/_pdf/-char/en.*

h. Korea and Aluminum Decarbonization

South Korea's aluminum demand is on the rise, driven primarily by the automotive, electronics, and construction sectors. However, domestic production of primary aluminum remains limited, resulting in significant dependence on imports. Although the government is committed to decarbonization, the aluminum sector's strategy faces challenges due to this increasing demand, which may hinder progress toward reducing carbon emissions.

Challenges in Decarbonization

The main challenges for South Korea in decarbonizing its aluminum industry are similar to those faced by Japan. The aluminum production process is highly energy-intensive, and South Korea's energy mix still relies heavily on fossil fuels, leading to high carbon emissions. The current technological infrastructure for aluminum production in Korea is outdated, **relying on a coal-intensive electricity grid and gas for heat generation**. These processes are not optimized for low-carbon emissions, necessitating substantial investment in new technologies to reduce the industry's carbon footprint.

Dependence on imported aluminum further complicates efforts to control the carbon footprint of the supply chain, especially when imported aluminum is produced in countries with environmental regulations that would not follow the direction of carbon neutrality. In 2020, South Korea produced 1.5 million tons of aluminum and imported 2.7 million tons, highlighting the significant reliance on imports. The country imports primary aluminum from several countries, with significant percentages coming from India (31.1 percent), Australia (17.8 percent), and Malaysia (10.4 percent).[249]

The transition to green technologies and processes involves high costs, and there is currently **limited financial support provided by the government to bridge the gap between conventional and green technologies**.

Impact of the EU Carbon Border Adjustment Mechanism

The implementation of the EU CBAM is also expected to have repercussions on the aluminum sector in South Korea. South Korean aluminum producers, who exported €564 million worth of aluminum products to the EU in 2022 – 168 million of aluminum unwrought,[250] will need to account for the extra costs of the CBAM, which could potentially reduce their competitiveness in the European market, especially considering the carbon intensity of South Korean aluminum.

The South Korean government has expressed concerns that the CBAM may act as a trade barrier and is advocating for the EU to recognize South Korea's efforts in reducing carbon emissions, including initiatives such as the RE100 campaign, where companies commit to 100 percent renewable energy usage (through green credits).[251] This is, of course, insufficient to be exempted from carbon adjustment.

As is the case in many regions, the EU CBAM has a significant influence on the acceleration of decarbonization efforts in the South Korean aluminum

[249] *OEC – The Observatory of Economic Complexity, "Raw Aluminium in South Korea," accessed September 10, 2024, https://oec.world/en/profile/bilateral-product/raw-aluminium/reporter/kor.*

[250] *Trading Economics, "European Union Imports of Aluminum from South Korea," accessed September 10, 2024, https://tradingeconomics.com/european-union/imports/south-korea/aluminum.*

[251] *Lee, Ho-Jeong, "EU CBAM Slammed as a Tariff in Disguise," Korea JoongAng Daily, July 15, 2021, https://koreajoongangdaily.joins.com/2021/07/15/business/economy/EU-carbon-CBAM-Korean-steel/20210715175000435.html.*

sector. The government and industry stakeholders are adapting to these changes to mitigate adverse effects and leverage the benefits of a more sustainable production model. One major adaptation involves the **reform of the SK ETS**, although its **timing remains uncertain**. Additionally, the aluminum sector is seeing new announcements of investments in greening technologies from companies within the industry.

Strategic Policies and Measures

To address the decarbonization challenges in the aluminum sector, South Korea is implementing several policies and strategies. The country has a strategy **focusing on hydrogen (particularly for heating) and on clean electrification to decarbonize aluminum processes**.

However, despite this focus, the **clean electrification of the aluminum sector in South Korea is still not a priority**, and access to clean hydrogen is still far ahead. The current carbon-intensive nature of the grid, which has still failed to decarbonize, creates a very serious challenge for decreasing emissions in a highly electricity-intensive sector like aluminum. This may explain why there is currently **no target, nor a concrete strategy aiming to completely electrify and mandate clean energy consumption, for aluminum in the country**.

Overall, the **Carbon Neutral Green Growth Technology Innovation Strategy**,[252] the main vehicle for industry decarbonization support, lists **100 core technologies for decarbonizing industry** in the country but mainly focuses on steel, cement, and chemicals, **avoiding aluminum as a priority sector to decarbonize**. However, electric heating furnaces – a technology available for aluminum recycling – are among the technologies supported.

[252] *Kim & Chang, 국가 탄소중립·녹색성장 기본계획 의결 [Approval of the National Carbon Neutrality and Green Growth Basic Plan], June 20, 2023), https://www.kimchang.com/ko/insights/detail.kc?sch_section=4&idx=27411.*

This does not prevent downstream companies in the aluminum value chain (such as car companies) from taking the initiative to demand aluminum produced with renewable energy (e.g., Hyundai[253]). Many aluminum manufacturers are also aiming for electrification on their own, investing into R&D with the support of the MOE or MOTIE's subsidies to obtain new processes or know-how (e.g., Novelis Korea[254]), or investing in renewables for their aluminum process (e.g., Lotte Aluminum[255]).

Aluminum Scrap as a Carbon Asset

The **Korean Green New Deal[256]** and the **2050 Carbon Neutral Technology Strategy[257]** emphasize the need for a circular economy in the aluminum sector. Specific policies such as the **Strategy for Industrial New Growth through Invigoration of Circular Economy** support the recycling of materials, including aluminum, for instance in batteries and vehicles.[258]

One key strategy of the South Korean aluminum sector, supported by the government, is to **attract aluminum scrap**, which is less carbon-intensive compared to primary aluminum, **from abroad**.[259] South Korea is

[253] *Agreement to supply "low carbon" aluminum from Russia's Rusal (before the Russian war against Ukraine): Rusal, "RUSAL Becomes a Preferred Supplier to Hyundai Sungwoo," December 17, 2020, https://rusal.ru/en/press-center/press-releases/rusal-becomes-a-preferred-supplier-to-hyundai-sungwoo/.*

[254] *Novelis, "2022 Global Sustainability Report: Shaping a Sustainable World Together," 2022, https://www.novelis.com/wp-content/uploads/2022/12/Novelis-FY2022-Sustainability-Report.pdf.*

[255] *Lotte Aluminium, "Environment/Quality/Safety Management," accessed September 10, 2024, https://www.lotteal.co.kr/eng/manage/safeManage_envir.asp.*

[256] *Government of South Korea, "Korean New Deal: National Strategy for a Great Transformation."*

[257] *Ministry of Science and ICT, South Korea, "Establishment of the Strategy for Technology Innovation for Carbon Neutrality," 2023, https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=&bbsSeqNo=42&nttSeqNo=495.*

[258] *Ministry of Economy and Finance, South Korea, "Industrial Growth Strategy Through Circular Economy Revitalization."*

actually already the second-largest importer of aluminum scrap in the world and the largest in Asia with 0.9Mt.[260]

Following this strategy, the government is focusing on **establishing efficient recycling systems** – and conducting R&D on how to prevent quality degradation – while **incentivizing the import of high-quality scrap** to reduce the overall carbon footprint. However, **in Korea, the use of plastic waste as fuel in aluminum recycling, a process that is far from being carbon neutral, is considered "low carbon."[261]**

If these are the main regulations incentivizing the recycling in the industrial sectors in Korea, overall, the aluminum sector lacks significant incentive to change. Further investments are needed to improve the infrastructure and technology for aluminum recycling and **increase the use of scrap aluminum**. These policies do, however, consider **tax rebates as a way to support technology adoption**.

Support for R&D on Carbon Capture, Utilization, and Storage and Frontier Technologies

South Korean companies, with strong support from the government, are also investing in research and development on CCUS technologies. The government has allocated significant funding to develop and commercialize these technologies across various industrial sectors, committing up to KRW 159 billion (approximately €107 million) as part of the Korean New Deal 2.0.[262] Aluminum companies, among other sectors, are the

[259] *Vikram Rajeev, "Economic Benefits and Circular Economy Leads to Rising Popularity of Aluminum Recycling in APAC," Frost & Sullivan, August 10, 2021, https://www.frost.com/growth-opportunity-news/economic-benefits-and-circular-economy-leads-to-rising-popularity-of-aluminum-recycling-in-apac/.*

[260] *In 2022: US 29.7 percent, Thailand 11 percent, Japan 9.02 percent: The Observatory of Economic Complexity, "Scrap Aluminium in South Korea," accessed September 10, 2024, https://oec.world/en/profile/bilateral-product/scrap-aluminium/reporter/kor?yearExportSelector=exportYear1.*

[261] *Government of South Korea, "2050 Carbon Neutrality Scenario Proposal."*

key beneficiaries of these CCUS funds. They are collaborating with other industries to assess the feasibility of integrating CCUS into their processes, with a **long-term implementation target set for beyond 2040**.[263]

The industry considers continued investment in new technologies such as **inert anodes and the expanded use of hydrogen as a reductant** in aluminum production to be critical. Although these technologies could theoretically be funded by the R&D provisions of the Korean New Deal 2.0, they are **not classified as "critical technologies."**[264] Consequently, the sector has not fully embraced the incentive to develop these technologies for complete decarbonization, instead favoring the hypothetical potential of CCUS technologies over substantial R&D investment in new carbon-neutral processes. **This preference may be influenced by the perception that the future of South Korea's aluminum industry lies in recycling and importing primary aluminum from abroad**.

Other Types of Support

The government is promoting a **public–private partnership approach**, working closely with private industry to foster innovation and develop low-carbon technologies. For example, companies such as Hyundai are partnering with global suppliers to source low-carbon aluminum and investing in recycling facilities to enhance sustainability, while also receiving support from the government.[265]

[262] 관계부처 합동 *[Joint Initiative by Relevant Ministries],* 한국판 뉴딜 *2.0 -*미래를 만드는 나라 대한민국 *-* 관계 부처 합동 *[Korean New Deal 2.0: A Nation Creating the Future – Joint Initiative by Relevant Ministries], (July 14, 2021), https://outlook.stpi.narl.org.tw/pdfview/4b1141007f9b57d9017fc0093b374d74.*

[263] *From interviews.*

[264] *Joint Initiative by Relevant Ministries, "Korean New Deal 2.0: A Nation Creating the Future – Joint Initiative by Relevant Ministries."*

[265] *From interviews.*

The Ministry of Trade, Industry, and Energy has been working on establishing standards for the carbon intensity of industrial goods, including aluminum. This includes the **implementation of eco-labels** and **green certificates** to encourage the consumption of green products – **however, so far, none of these labels promotes carbon neutrality**.

Finally, the South Korean strategy is also centered around strengthening international collaboration, particularly with major economies like the United States, with which the country exchanges a great deal of industrial goods. This includes negotiating agreements to address aluminum oversupply globally and promote decarbonization technologies. Among these types of international cooperation, there are also **transnational public–private partnerships**. The South Korean aluminum sector acknowledges that it will need to create coalitions for R&D if it wants to remain competitive.

Table 9: Summary: Korean Policies
for Decarbonizing the Aluminum Sector

Legislation	Date	Issuer	Link
Korean Emissions Trading System[266]	2015	Government of the Republic of Korea	https://icapcarbonaction.com/en/ets/korea-emissions-trading-scheme
Carbon Neutral Green Growth Technology Innovation Strategy[267]	2023		https://www.kimchang.com/ko/insights/detail.kc?sch_section=4&idx=27411
Korean Green New Deal[268]	2020	Government of the Republic of Korea	https://content.gihub.org/dev/media/1192/korea_korean-new-deal.pdf

[266] *International Carbon Action Partnership, "Korea Emissions Trading Scheme," 2015, https://icapcarbonaction.com/en/ets/korea-emissions-trading-scheme.*

[267] *Kim & Chang, "Approval of the National Carbon Neutrality and Green Growth Basic Plan."*

[268] *Government of the Republic of Korea, "Korean New Deal: National Strategy for a Great Transformation."*

Legislation	Date	Issuer	Link
2050 Carbon Neutral Technology Strategy[269]	2021	Ministry of Science and ICT	https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=&bbsSeqNo=42&nttSeqNo=495&searchOpt=ALL&searchTxt=
Strategy for Industrial New Growth through Invigoration of Circular Economy[270]	2023	Ministry of Economy and Finance	https://www.moef.go.kr/com/cmm/fms/FileDown.do;jsessionid=0.node20?atchFileId=ATCH_000000000023349&fileSn=6
Korean New Deal 2.0[271]	2021	Government of the Republic of Korea	https://outlook.stpi.narl.org.tw/pdfview/4b1141007f9b57d9017fc0093b374d74

i. The European Strategy for Aluminum

Current Status

In Europe, primary aluminum production is concentrated in countries such as Germany, France, Iceland, and Norway, where energy-intensive smelters operate. However, high electricity costs and regulatory challenges have led to a decline in production capacity, with **Europe losing 30 percent of its capacity since 2008.**[272]

[269] *Ministry of Science and ICT, South Korea, "Establishment of the Strategy for Technology Innovation for Carbon Neutrality."*

[270] *Ministry of Economy and Finance, Republic of Korea, "Industrial Growth Strategy Through Circular Economy Revitalization."*

[271] *Joint Initiative by Relevant Ministries, "Korean New Deal 2.0: A Nation Creating the Future – Joint Initiative by Relevant Ministries."*

[272] *European Aluminium, "Net-Zero by 2050: Science-Based Decarbonisation Pathways for the European Aluminium Industry," November 2023, https://european-aluminium.eu/wp-content/uploads/2023/11/23-11-14-Net-Zero-by-2050-Science-based-Decarbonisation-Pathways-for-the-European-Aluminium-Industry_FULL-REPORT.pdf.*

The broader aluminum value chain in Europe, including recycling and semi-fabrication, remains robust, supported by over 600 plants across 30 countries.[273] **The EU imports approximately 9.4 million tons of aluminum,** which is **more than three times its primary production (2.2 million tons)**, reflecting its dependence on external sources to meet demand. Despite the fact that aluminum scrap is widely considered a carbon resources by experts and industry in the era of the CBAM, **European exports, particularly of aluminum scrap, have also been significant, with over 1.5 million tons exported in 2021**.[274]

The sector's GHG emissions are a concern, although European production is more carbon-efficient compared to global averages. The industry has reduced its carbon intensity significantly and aims for carbon neutrality by 2050. **Primary production in Europe emits around 6.8 kg of CO_2 per kg of aluminum, compared to the global average of 16.1 kg**.

The GHG emissions intensity of aluminum production in Europe shows **considerable variation among Member States**, primarily due to differences in the **carbon footprint of their electricity grids**. On average, the emissions intensity of aluminum production in France is around 4–5 tons of CO_2 per ton of aluminum, which is significantly lower than the European average of about 6.8 tons of CO_2 per ton. This is thanks to its predominantly nuclear and renewable energy mix, which drastically reduces carbon emissions from electricity used in aluminum smelting. Norway also demonstrates lower emissions intensity in aluminum production (similar to France in carbon intensity) due to its extensive use of

[273] *European Aluminium, "Aluminium Industry: A Strong, Sustainable & Complete European Value Chain," accessed September 10, 2024, https://european-aluminium.eu/about-aluminium/aluminium-industry/.*

[274] *"According to figures from the European statistics authority Eurostat, exports to third countries totaled 1.1 million tons in 2021, 18 per cent more than in 2020, when around 950,000 tons of aluminum scrap left the EU." Christoph Schmidt, "EU Countries Export Record Million Tonnes of Aluminium Scrap in 2021," April 13, 2022, EUWID Recycling and Waste Management, https://www.euwid-recycling.com/news/business/eu-countries-export-a-record-one-million-tonnes-of-aluminium-scrap-in-2021-200422/.*

hydroelectric power. In contrast, countries like Germany and Italy, which rely more on fossil fuels for electricity generation, have higher emissions intensities, often exceeding 8 tons of CO_2 per ton of aluminum.[275]

These disparities underline the **importance of the energy mix in determining the environmental impact of aluminum production**. As Europe strives to reduce its carbon footprint, increasing the share of renewable and nuclear energy in electricity grids across Member States will significantly lower the emissions intensity of aluminum production sector-wide.

The main European strategy for decarbonizing aluminum is connected to the removal of free allocation on the EU ETS and the parallel implementation of the CBAM. Beyond the CBAM, the EU and Member States are also supporting decarbonization technologies in the sector.

The EU supports R&D and the demonstration of low-carbon technologies through various funding mechanisms such as **Horizon Europe** and the **Innovation Fund**, and of course **funding mechanisms at the Member State level are also part of the equation**. These programs theoretically support projects that aim to reduce emissions in aluminum production using **clean hydrogen, clean electrification, CCUS**, and **inert anode**. However, as one can see, clean electrification is currently the main strategy in Europe, with growing attention given to CCUS and – at least on paper – to hydrogen usage.

[275] *International Energy Agency, "Aluminium," accessed September 10, 2024, https://www.iea.org/energy-system/industry/aluminium.*

Table 10: EU level policy related to Aluminum Sector decarbonization

EU Policy/Directive	Specific Targets /Requirements	Description	Link
Fit-for-55 Package, 2021[276]	Reduce emissions by 55% by 2030 compared to 1990 levels.	Focus on **increasing recycling rates**, using **renewable electricity**, and developing **hydrogen** and **CCUS** technologies.	Fit-For-55 Package
EU Emissions Trading System (ETS)[277] **and CBAM**[278]**, 2023**	Gradual reduction in the cap on emissions allowances by 2.2% annually. Introduction of Carbon Border Adjustment Mechanism (CBAM).	Reduces emissions allowances over time and prevents carbon leakage by adjusting the price of carbon at the border for imported aluminum.	EU ETS CBAM
Energy Efficiency Directive (EED)[279]**, 2023**	Improve energy efficiency by 32.5% by 2030. + further increase its energy efficiency ambition by at least 11.7% in 2030 compared to the level of efforts under the 2020 EU Reference Scenario.	Targets improvements in energy efficiency. (no precise target by sector). Most industries are obliged to implement a system of energy management.	Energy Efficiency Directive Revised Version[280]
Renewable Energy Directive (RED III)[281]**, 2023**	Increase the share of renewable energy in the EU's energy mix to 42.5% by 2030 in all sectors.	Annual increase in the share of renewable energy in each sector by 1.6% until 2030.	RED III
Circular Economy Action Plan[282]**, 2020**	The plan aims to increase the recycling rate from 33% in 2020 to over 50% by 2050.	Targets higher recycling rates for aluminum, encouraging innovation in recycling technologies.	Circular Economy Action Plan
Industrial Emissions Directive (IED)[283]**, 2022**	Reduce industrial emissions through the application of Best Available Techniques (BAT)	Applies to all sectors, ensuring the application of Best Available Techniques (BAT) to reduce emissions.	IED

276 *European Commission, "Delivering the European Green Deal."*

277 *European Commission, "EU Emissions Trading System (EU ETS)."*

278 *European Commission, "Carbon Border Adjustment Mechanism."*

279 *European Commission, "EU Energy Policy," accessed October 1, 2024 https://energy.ec.europa.eu/index_en.*

Clean Electricity Use, Electrification, and Clean Hydrogen

In the Clean Energy for All Europeans Package, the **Renewable Energy Directive (RED III)**[284] mandates higher shares of renewable energy, ensuring that a significant portion of the electricity used in aluminum production comes from clean sources **(+1.6 percent annually until 2030)**. RED III aims to achieve at least a 42.5 percent share of renewable energy in the EU's energy mix by 2030, which supports the decarbonization of energy-intensive industries such as aluminum production.

The revised **Energy Efficiency Directive** significantly enhances the EU's efforts toward energy efficiency, setting ambitious targets and new regulations specifically impacting the aluminum sector.[285] The directive **mandates a 11.7 percent reduction in final energy consumption by 2030 compared to 2020**[286] levels. For the industrial sector, including aluminum production, the directive **expands energy audit obligations** to all companies consuming energy above a certain threshold, including SMEs. Large industrial consumers must implement energy management systems to optimize energy efficiency.

[280] *European Union, "Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency," September 20, 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2023_231_R_0001&qid=1695186598766.*

[281] *European Union, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023."*

[282] *European Commission, "Circular Economy Action Plan."*

[283] *European Commission, "Industrial and Livestock Rearing Emissions Directive (IED 2.0)."*

[284] *European Union, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023."*

[285] *European Commission, "European Green Deal: Energy Efficiency Directive Adopted, Helping Make the EU 'Fit for 55,'" July 25, 2023, https://energy.ec.europa.eu/news/european-green-deal-energy-efficiency-directive-adopted-helping-make-eu-fit-55-2023-07-25_en.*

[286] *European Union, "Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency."*

The aluminum sector, being energy-intensive, will also be affected by stricter regulations on energy performance and increased **annual energy savings targets, rising to 1.9 percent by 2030**. This includes a focus on decarbonizing heating and cooling systems, integrating renewable energy, and prioritizing energy efficiency improvements for vulnerable customers and those in social housing.

When it comes to hydrogen use in the aluminum sector, some industry actors actually emphasize their willingness to research and demonstrate projects. But, in practice, support is still lacking. The IPCEI Hy2Tech and Hy2Use initiatives encompass a range of projects designed to leverage hydrogen for decarbonizing diverse industrial sectors. Despite the potential for the aluminum sector to gain insights from demonstration projects in other industries such as steel, **there is currently no dedicated project funding for R&D or demonstration of hydrogen usage specifically within the aluminum sector**.

The EU's support for clean electrification in industrial sectors remains relatively limited. Currently, **there are no common targets for achieving a specific level of clean electricity consumption tailored to the aluminum sector**. This policy gap results in a lack of data on the future demand for clean electricity in this industry at the European level. Consequently, this could lead to a shortfall in the future supply of clean electricity, which is critical for the successful decarbonization of the aluminum sector.

At the Member State level, on the other hand, most support is going toward clean electrification. This support comes through a combination of regulatory mandates, financial incentives, and investments in renewable energy and innovative technologies, as described earlier in this paper. Each country has tailored its approach to address the specific needs and challenges of these sectors (e.g., hydropower in Scandinavia, nuclear in France).

Table 11: Examples of member states policies to decarbonize the aluminum industry

Country	Policy Name	Key Actions
Germany	Renewable Energy Sources Act (EEG)[287] and National Action Plan on Energy Efficiency (NAPE)[288].	• Subsidies for renewable energy.. • Energy efficiency programs targeting aluminum production. • R&D in low-carbon electrolysis.
France	France 2030[289].	• Use of low-carbon nuclear energy. • Carbon tax incentives. • Modernization grants for aluminum smelters.
Italy	Renewable energy targets[290] and energy efficiency incentives[291].	• Investment in renewable energy for industrial use. • Incentives for improving energy efficiency in aluminum plants. • Promotion of aluminum recycling.
Spain	National Integrated Energy and Climate Plan[292], public–private partnerships.	• Increasing renewable energy supply to aluminum sector. • Implementation of decarbonization plans. • Fostering public-private partnerships for clean technology in aluminum production.

[287] *Federal Government of Germany, "We're Tripling the Speed of the Expansion of Renewable Energies," December 23, 2022, https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/amendment-of-the-renewables-act-2060448.*

[288] *Federal Ministry for Economic Affairs and Energy, Germany, "National Action Plan on Energy Efficiency," December 2014, https://www.bmwk.de/Redaktion/DE/Downloads/M-O/nape-national-action-plan-on-energy-efficiency.pdf?__blob=publicationFile&v=1.0*

[289] *Agence de Transition Écologique (ADEME), France, "Plan de transition sectoriel de l'industrie de l'aluminium en France" [Sectoral Transition Plan for the Aluminum Industry in France], March 22, 2023, https://presse.ademe.fr/2023/03/lademe-publie-le-plan-de-transition-sectoriel-de-lindustrie-de-laluminium-en-france.html.*

[290] *Government of Italy, "Integrated National Energy and Climate Plan," December 2019, https://energy.ec.europa.eu/system/files/2020-02/it_final_necp_main_en_0.pdf.*

[291] *International Energy Agency, "Italy 2023: Energy Policy Review," 2023, https://iea.blob.core.windows.net/assets/71b328b3-3e5b-4c04-8a22-3ead575b3a9a/Italy_2023_EnergyPolicyReview.pdf.*

[292] *European Commission, "Spain's National Energy and Climate Plan," January 20, 2020, https://energy.ec.europa.eu/system/files/2020-06/es_final_necp_main_en_0.pdf.*

Country	Policy Name	Key Actions
Sweden	Hydropower and wind energy usage[293], innovation funding, and national sustainability goals. Sweden's Integrated National Energy and Climate Plan[294].	• Extensive use of renewable hydropower. • Funding for clean aluminum technology research. • Aligning aluminum sector with national carbon neutrality goals.
Poland	Energy Policy of Poland until 2040:[295] • Coal reduction initiatives. • EU funding for energy transition[296].	• Transitioning aluminum sector from coal-based electricity to renewables. • Leveraging EU funds for sector modernization (Modernisation fund). • Adopting advanced clean technologies.
Netherlands	Sustainable Industry Program[297].	• Increase in renewable energy usage. • Focus on energy efficiency and electrification in industrial processes.
Belgium	Federal and regional renewable energy strategies[298] and industry-specific decarbonization initiatives	• Expansion of renewable energy capacity. • Energy efficiency programs. • Subsidies for clean industrial technology adoption.

[293] *Swedish Energy Agency, "An Overview of Energy in Sweden 2022," September 22, 2022, https://www.energimyndigheten.se/en/news/2022/an-overview-of-energy-in-sweden-2022-now-available/.*

[294] *Ministry of Infrastructure, Sweden, "Sweden's Integrated National Energy and Climate Plan," European Commission, January 16, 2020, https://energy.ec.europa.eu/system/files/2020-03/se_final_necp_main_en_0.pdf.*

[295] *Ministry of Climate and Environment, Poland, "Energy Policy of Poland until 2040," February 2, 2021, https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040.*

[296] *European Investment Bank, "Poland Received €5.1 Billion from EIB Group in 2023 to Bolster Economy," March 25, 2024, https://www.eib.org/en/press/all/2024-128-poland-received-eur5-1-billion-from-eib-group-in-2023-to-bolster-economy.*

[297] *Business.gov.nl., "Environment and Energy Subsidies," accessed September 10, 2024, https://business.gov.nl/finance-and-taxes/subsidies/environment-and-energy/.*

[298] *National Energy and Climate Plan, "Belgium's National Energy and Climate Plan 2021–2030," 2023, https://www.nationalenergyclimateplan.be/en.*

Frontier Carbon Neutrality Technologies for Aluminum in Europe

Inert Anode Development

Inert anodes represent a significant technological advancement in the decarbonization of the aluminum sector, and R&D in this technology is supported by the EU, individual Member States, and private initiatives. Initiatives such as the *Sustainable Aluminum Finance Framework*[299] (developed in collaboration with industry stakeholders and financial institutions), facilitate financing for low-carbon technologies, including inert anodes, by helping banks assess and align their portfolios with climate goals (e.g., Citi, ING, Société Générale, and Standard Chartered).

One example of support for inert anode technology in Europe is the collaboration between **TRIMET Aluminium SE and Arctus Aluminium**, which receives support from regional governments such as the German state of North-Rhine Westphalia. This project focuses on scaling up inert anode technology to reduce CO_2 emissions during aluminum production.[300] However, these projects are currently at the R&D level, and none has reached the demonstration level yet.

[299] *E. Marchán and T. White, "Clean Energy 101: Why and How to Fund the Decarbonization of Aluminum," RMI, December 5, 2023, https://rmi.org/clean-energy-101-why-and-how-to-fund-the-decarbonization-of-aluminum/.*

[300] *Trimet, "CO_2-Free Aluminum Production," accessed September 10, 2024, https://www.trimet.eu/en/trimet/sustainability/environmental-and-climate-protection/production-of-inert-metallic-anodes; "Trimet Takes the Next Step towards CO2-Free Aluminium Production," Aluminium Journal, July 15, 2024, https://www.aluminium-journal.com/trimet-takes-the-next-step-towards-co2-free-aluminium-production.*

Carbon Capture in the Aluminum Sector

CCUS is theoretically supported for all industrial sectors in Europe, including the aluminum sector. However, the aluminum sector has received **less attention than the cement or steel sectors for CCUS**. The aluminum sector is not considered a priority in the current EU carbon management strategy.[301]

In the aluminum sector, the C4Capture project, spearheaded by TRIMET, FIVES, Rio Tinto, and Aluminium Dunkerque, is focused on developing a new carbon capture technology specifically designed for the primary aluminum production sector. It receives funding from ADEME in France.

Another example is the 3D Project-DMX Demonstration in Dunkirk, which aims to demonstrate an innovative CO_2 capture technology[302] that can be adapted for various industries, including aluminum. The project is supported by the European Union's Horizon 2020 Research and Innovation program, which has allocated €14.8 million in subsidies toward the total project budget of €19.3 million. This project is part of a broader decarbonization initiative involving a €1.7 billion investment in the Fos-sur-Mer and Dunkirk sites through ADEME into electrification, H2-DRI, and CCUS.[303] The initiative brings together a consortium of eleven stakeholders from six European countries, including ArcelorMittal, Axens, TotalEnergies, and IFP Energies Nouvelles (IFPEN).[304]

[301] *European Commission, "Questions and Answers on the EU Industrial Carbon Management Strategy," February 6, 2024, https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_586.*

[302] *The "3D" project aims to capture CO2 using an innovative Amine DMX™ solvent process, which is more energy-efficient and cost-effective than traditional methods.*

[303] *ArcelorMittal, "€1.7 Billion Decarbonisation Investment to Transform our French Steelmaking Operations."*

The few other projects aimed at realizing carbon capture for aluminum in Europe are at Europe's periphery, such as the Alcoa project in Iceland.[305] Norsk Hydro, a leading aluminum producer, is exploring carbon capture technologies at its aluminum production facilities in Norway.[306]

Recycling of Aluminum

The **Circular Economy Action Plan**[307] is central to enhancing the circular economy within the EU by increasing recycling rates and reducing waste. The plan aims to increase the overall recycling rate from 33 percent in 2020 to over 50 percent by 2050. For the aluminum sector, this plan includes **specific measures and support** for improving recycling technologies and practices:

- **enhancement of collection and sorting systems;**
- **ecodesign requirements and producer responsibility programs;**
- **development of advanced recycling technologies;**
  - **high-efficiency melting furnaces;**
  - **innovative separation techniques.**

In the European Union, the overall recycling rate for aluminum, including packaging, automotive, and construction applications, is already at 51 percent.[308] The aluminum sector is aiming for a **full circularity target by 2030**.[309]

[304] *ArcelorMittal, "The 3D Project (DMXTM Demonstration in Dunkirk)," accessed September 10, 2024, https://corporate.arcelormittal.com/climate-action/decarbonisation-technologies/the-3d-project-dmx-demonstration-in-dunkirk; 3D DMX Demonstration Dunkirk, "About Us," accessed September 10, 2024, https://3d-ccus.com/.*

[305] *Alcoa, "SustanaTM: Alcoa's Low Carbon Aluminum Solutions," accessed September 10, 2024, https://www.alcoa.com/products/sustana.*

[306] *Hydro, "Developing Carbon Capture and Storage Technology for Aluminium Smelters," May 15, 2024, https://www.hydro.com/en/global/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminium-production/developing-carbon-capture-and-storage-technology-for-aluminium-smelters/.*

[307] *European Commission, "Circular Economy Action Plan."*

[308] *Taylor, B. "Europe's Aluminum Producers Recycling at Higher Rate," Recycling Today, February 1, 2022, https://www.recyclingtoday.com/news/european-aluminium-recycling-sustainability-progress-2025-goals/.*

Europe actually **faces an issue similar to that confronted by Japan** when it comes to aluminum scrap. Recycling aluminum scrap is of interest as a way to save emissions – and generate carbon assets – but **a large quantity of European aluminum scrap is exported to be recycled abroad**. The EU regulates the trade of aluminum scrap to ensure sustainable recycling practices through the **EU Waste Shipment Regulation**.[310] These regulations encourage the retention and recycling of aluminum scrap within the EU, lowering the need for primary aluminum production and associated emissions.

Table 11: Aluminum Decarbonization Projects:

Company	Country	Technology	Status	Continent
Hydro	Norway, Sundal	Bioenergy, biomethane	Demo	Europe
Inner Magnolia Company	China	Electrolytic	R&D	Asia
Aluminium Coorporation	China	Electrolytic	Scalling up in Progress	Asia
China Hongqiao Group	China	Green Aluminium	Scalling Up in Progress	Asia
KU LEUVEN	Belgium	Green Aluminium	R&D	Europe
ALu Green	Norway	Green Aluminium (9 Projects in total)	Scaling Up	Europe
Hydro	Spain, Navarra	Green Hydrogen	Demo	Europe
Hydro	Norway	Hal Zero	R&D	Europe
Statkraft	Norway	Hydro Power	Scalling up in Progress	Europe
Hydro	Norway	Plasma Technology	Demo	Europe
Hydro	England	Recycling	Scaling up in Progress	Europe
Aughinish R&D	England	Recycling	Demo	Europe
Hydro, SINTEF, NTNU	Norway	Recycling	Demo	Europe

[309] *European Aluminium, "Our Technical Advocacy: Standards & Life Cycle Assessment," accessed September 10, 2024, https://european-aluminium.eu/our-work/standards-life-cycle-assessment/.*

[310] *European Commission, "New Regulation on Waste Shipments Enters into Force."*

Company	Country	Technology	Status	Continent
Metal Packaging Europe	Europe	Recycling	Scalling up in Progress	Europe
Hydro	Spain	Recycling	Scalling up in Progress	Europe
Mingtai Aluminium INdustry	China	Recycling	R&D	Asia
Hydro, PARAT	Brazil	Recycling	Scaling up	South America
Hydro	Germany, Dormagen	Scrap Sorting Plant	Scalling up in Progress	Europe
GreenGo Energy, Hydro	Sweden	Solar Project	Demo	Europe
Hydro Rein and Opplysningsvesenets	Norway	Solar Project	R&D	Europe
Hydro	Sweden	Solar Project	Scaling up in Progress	Europe
Hydro Rein and Green Go Energy	Denmark	Solar Projects	Demo	Europe
Hydro, Eviny, Zephyr	Norway	Wind Project	Demo	Europe
Vedanta Aluminium	India	Wind, Solar and storage solutions	Scalling up in Progress	Asia

Source: author and International Aluminum Institute.

j. The Key Challenges Emerging from the EU CBAM in the Aluminum Sector

The European Union's CBAM is anticipated to significantly impact the aluminum sector, both within the EU and globally. For aluminum, Norway, the UAE, and Iceland were the largest suppliers to the EU in 2023.[311] Goods from these countries, covered by the EU ETS, will not be subject to the CBAM, and aluminum flows from these sources are likely to remain largely unaffected. Other key suppliers not covered by the EU ETS include Russia, Türkiye, China, the UAE, and India. Among these, India and China have the highest emissions intensity by a significant margin.

[311] *World Integrated Trade Solution, "European Union Aluminium Unwrought, Alloyed Imports by Country in 2023," accessed September 10, 2024, https://wits.worldbank.org/trade/comtrade/en/country/EUN/year/2023/tradeflow/Imports/partner/ALL/product/760120.*

The **CBAM covers unwrought aluminum**, including primary forms such as ingots, billets, and slabs. Additionally, it applies to **aluminum plates, sheets, and strips**, which are commonly used in the construction, automotive, and packaging industries. The mechanism also includes **aluminum bars, rods, and profiles,** which are extruded products used in various construction and manufacturing applications, as well as **aluminum wire and aluminum tubes and pipes** used in the electrical, transportation, and construction sectors.[312]

However, measuring greenhouse gas emissions from aluminum products is a formidable challenge due to the **numerous factors influencing these emissions**. The complexity stems from the diverse **fuel mix used in alumina production**, the differing **CO_2 emissions factors of electricity grids, and the variable sources of alumina across regions**. Additionally, the share and type of **captive power employed and the extent of energy-efficient technologies adopted** vary significantly. The aluminum **product mix**, the **age of manufacturing facilities, and the stringency of environmental regulations** further complicate emissions assessments. Moreover, the cost and quality of inputs, along with the intricate **boundary definitions for the aluminum industry**, add layers of difficulty in accurately measuring and standardizing emissions. Despite these complexities, **more than 81 percent of emissions are attributed to the carbon intensity of the electricity used** in aluminum manufacturing. Therefore, the CBAM focuses on addressing these specific emissions to enhance accuracy and effectiveness in emissions measurement.

[312] *European Commission, "Guidance Document on CBAM Implementation for Importers of Goods Into the EU," December 13, 2023, https://taxation-customs.ec.europa.eu/system/files/2023-11/CBAM%20Guidance_EU%20231121%20for%20web_0.pdf.*

The Question of Covering Indirect Emissions from the Electrolysis Process

A significant issue arises during the transitional phase of the CBAM. Because of the formidable complexity of monitoring emissions in the aluminum value chain, only direct emissions are going to be covered by the EU CBAM in the transitional phase (until 2026, at first). This exclusion is significant because indirect emissions from electricity consumption, especially during the electrolysis process, account for the majority of aluminum sector emissions (9.3 tn. CO_2 / ton of aluminum, 62 percent of total emissions).

European aluminum producers purchasing their electricity from the grid face indirect carbon costs due to the pass-through of carbon prices paid by the electricity producers covered by the EU ETS. To offset this, Member States can provide state aid to compensate for these indirect costs, but this compensation is complex and uncertain, potentially leading to over- or under-compensation.[313]

Therefore, during the transitional phase, there is a misalignment that suggests that the CBAM may overlook a substantial portion of the carbon footprint of aluminum production, resulting in only partial decarbonization efforts. The European Commission has indicated that **indirect emissions will eventually be included for all sectors covered by the CBAM, including aluminum**. This extension is expected to be phased in after the transitional period, starting from January 1, 2026. By that time, importers will need to report both direct and indirect emissions and purchase CBAM certificates accordingly.[314] However, **indirect emissions are going to be calculated based on default value**, which will be **less precise than what European manufacturers are going to face**.[315]

[313] *Juliette de Valence, "The Complexities of Applying the EU's CBAM to Aluminium Producers," Environmental Finance, June 3, 2024, https://www.environmental-finance.com/content/analysis/the-complexities-of-applying-the-eus-cbam-to-aluminium-producers.html.*

[314] *From interviews.*

This raises genuine concerns for the sector, especially for the remaining European aluminum smelting companies, which fear **non-EU competition shifting downstream in the value chain and resource shuffling**.

Risk Shifting Downstream in the Value Chain

The CBAM currently focuses more on primary aluminum production and less on downstream products, risking carbon leakage downstream in the value chain. This poses a challenge to the aluminum sector, as it increases input costs for EU producers of semi-finished products, who are heavily reliant on imported primary aluminum. The introduction of the CBAM raises these costs, **reducing the competitiveness of EU producers compared to non-EU competitors, potentially leading to production relocation or increased imports of finished products**.

A critical question arises: What products will be made from green European aluminum? If the CBAM aims to decarbonize European imports, manufacturing may be outsourced, negating the environmental benefits of the CBAM. This scenario could see sectors producing high volumes of low-value semi-finished products – such as flat rolled and extruded aluminum – relocating abroad, compromising the competitiveness of EU producers and reducing the EU's market share in the global aluminum industry.[316]

[315] *European Commission, "Default Values for the Transitional Period of the CBAM between 1 October 2023 and 31 December 2025," December 22, 2023, https://taxation-customs.ec.europa.eu/system/files/2023-12/Default%20values%20transitional%20period.pdf.*

[316] *Alexandra Maratou and Andrei Marcu, "The Aluminium Value Chain and Implications for CBAM Design."*

Resource Shuffling and Circumvention

A significant issue related to the CBAM is resource shuffling. This occurs when non-EU countries exploit gaps in the CBAM by **importing scrap aluminum – which is considered carbon-neutral – recycling it, and then exporting it as a carbon-neutral product**. This practice could undermine the objectives of the CBAM by allowing high-carbon materials to enter the EU market without adequate carbon pricing. Essentially, resource shuffling circumvents the intended carbon cost, leading to a misrepresentation of the actual carbon footprint and hindering the effectiveness of the CBAM in reducing global emissions. Circumvention risks also pose a challenge. Exporting countries might modify their production processes to avoid CBAM payments, such as by **converting primary aluminum into scrap or altering product specifications**. These strategies could undermine the effectiveness of the CBAM, allowing carbon-intensive products to enter the EU market without bearing the intended carbon costs.[317]

[317] *Alexandra Maratou and Andrei Marcu, "The Aluminium Value Chain and Implications for CBAM Design."*

k. Policy Recommendations for a European Industrial Strategy to Decarbonize the Aluminum Sector

Recommendation A

Extend CBAM coverage and enhance monitoring:

1. **Broaden the scope of the CBAM:** Expand the CBAM to include semi-finished and selected finished aluminum products as soon as possible. This would capture a larger share of embedded emissions and prevent carbon leakage throughout the value chain.
2. **Simplify administrative procedures:** Develop streamlined procedures and clear guidelines for calculating embodied emissions in semi-finished and finished products. This will reduce administrative burdens and compliance costs for businesses.
3. **Enhance monitoring and enforcement:** Strengthen monitoring and enforcement mechanisms to prevent circumvention of the CBAM and ensure all relevant products are subject to it. This will help maintain a level playing field within the industry.
4. **Apply an average electricity mix emissions factor:** To prevent the bypass of the CBAM by non-European producers, consider applying the average electricity mix emission factor of the exporting country to export data, even as a transitory measure. Although controversial, this approach could ensure a more accurate representation of the carbon footprint of imported aluminum products.

Recommendation B

Support for Tech Research and Deployment:

1. **Increase funding for low-carbon technologies:** Increase funding and support for the research, development, and deployment of low-carbon technologies. This includes financial incentives and regulatory support to accelerate the adoption of innovations such as **inert anodes and hydrogen-based processes**.
2. **Support the transition and competitiveness of the EU aluminum sector:** Implement complementary measures such as financial support for innovation, energy efficiency improvements, and transition assistance to help the industry adapt to the new regulatory environment.

Recommendation C

Promote Green Standardization for Aluminum:

1. **Enhance recycling standards and competitiveness:** Address the challenge of standardization to meet CO_2 emissions targets. The aluminum sector has significant potential for GHG emissions reduction through increased recycling rates. **Ensure competitive pricing for green recycled aluminum** to prevent substitution by more carbon-intensive materials like plastic in relevant applications. Establish fair standards to facilitate an equitable comparison between green recycled aluminum and its carbon-intensive counterparts.

2. **Support standardization in the downstream industry:** Promote standardization to create compatibility between green aluminum and steel and ensure fair pricing. As the Life Cycle Assessment (LCA) methodology for green cars is expected to be established between 2024 and 2026, this will drive competition in the automotive market to reduce GHG emissions. **Public procurements and government support are needed** to support the green premium market and ensure fair competition **based on standardized measurements**.

Recommendation D

Bridging the Cost Gap:

- **Facilitate capital investments:** To support capital investments in the aluminum (and steel) industries for green premium goods, government support through sizable public investments is crucial.
- **Adopt OPEX support mechanism during the transition period:** This will help **alter demand uncertainty** and encourage the adoption of green premium goods in the market.

Appendix 1
Korean policy toward industry decarbonization

Korean policy towards industry decarbonization

Text	Industry Decarbonization measures
The 2030 Basic Roadmap for Achieving the National Greenhouse Gas (GHG) the Reduction Target (2030 Roadmap (June 2018)[318]	Specific GHG reduction plans for 8 sectors and 30 sub-sectors by 2030.
	Framework for the operation of **K-ETS from 2018 to 2020**.
	In the industrial sector to **reduce emissions by 56.4 MTCO$_2$e** through energy **efficiency improvements**, gas development through environmentally friendly processes, refrigerant replacement, innovative technologies, and waste resource use by 2030 compared to 2016 level. In the industrial sector, the *roadmap* scopes to **reduce GHG emissions by 99 million tons**, including **11 million thanks to the improvement of industrial processes** and of energy efficiency and **10 million with the spread of innovative reduction technologies**, primarily CCUS technology and waste recycling system.
Hydrogen Economy Roadmap[319], 2019	Ensure the growth of the domestic hydrogen market in the long-term in order to establish an **ecosystem of hydrogen industry**, encompassing energy production, storage, transportation, safety and mobility. Vast majority of planned hydrogen production mainly focuses on fossil-fuel generated blue and gray hydrogen, which is expected to represent up to **87%** of the total hydrogen production by **2030**, while the government only seeks to make clean hydrogen accounts for **7.1%** of the nation's energy mix by 2036. Additionally, as part of this target to seed the development of a hydrogen economy, Yoon administration announced in January 2023 that it would invest a total of **KRW 240 billion** won (US$193 million) in pilot projects for hydrogen cities (Pyeongtaek, Namyangju, Dangjin, Boryeong, Gwangyang and Pohang).

[318] *Ministry of Environment, South of Korea, 2030 온실가스 감축 로드맵 수정안 및 2018~2020년 배출권 할당계획 확정 [Revised 2030 Greenhouse Gas Reduction Roadmap and Finalization of the Emission Allowance Allocation Plan for 2018–2020], July 24, 2018, https://www.me.go.kr/home/web/board/read.do?menuId=286&boardMasterId=1&boardCategoryId=39&boardId=886420.*

[319] *Netherlands Enterprise Agency (RVO), "Hydrogen Economy Plan in Korea," January 18, 2019, https://www.rvo.nl/sites/default/files/2019/03/Hydrogen-economy-plan-in-Korea.pdf.*

Korean policy towards industry decarbonization

Text	Industry Decarbonization measures
Korean Green New Deal[320], July 2020	In synergy with the **2050 Carbon Neutral Strategy** to move towards a carbon-neutral society, the Korea's **Renewable Energy 3020 Plan**, it has three main areas: 1. Green transition and infrastructures. 2. Low-carbon and decentralized energy supply. 3. Innovation in the Green industry.
	Invest **KRW 73.4 trillion (approximately €49 million), of which KRW 42.7 trillion** is from the Treasury (approximately €28.7 million), in green finance to support business investments in green transition and create 659,000 jobs by **2025, mostly for energy and infrastructure, but also for the following:** • To secure innovation in the green industry, it is expected that by 2025, the government will invest **KRW 7.6 trillion (approximately €5 billion)**, including KRW 6.3 trillion (approximately €4.2 billion) from the Treasury and will create 63,000 jobss.
	On innovation in the green industry: • **promote small businesses** to lead the green industry and the establishment of low-carbon and green industrial complexes, through the support of 9,000 small businesses in setting fine dust facilities, of 100 smart ecological plans and 1,750 clean factories and to set a green-integrated cluster for technological development, including **resource recycling** and **biomaterial** development. • It also aims to lay down the **foundation for green innovation** through active **investments in the R&D and financial sectors**. The government plans to provide a loan of KRW **1.9 trillion (approximately €1.3 billion)** in the green sector, mainly to support the commercialization of large-scale **CCUS technologies** by 2023 and promote **resource recycling**.
2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society[321], Dec 2020	Korean carbon neutrality strategy as published to the UNFCCC: 1. **The expansion of the use of clean power and hydrogen across all sectors** through the application of CCUS technologies when coal and other fossil fuel/LNG-powered energy are used and the expanding use of renewable energy sources, like solar, wind and hydro for energy supply. 2. **The improvement energy efficiency to a significant level**, considered as a more cost-effective option compared to ESS and hydrogen technologies. 3. **The Commercial deployment of carbon removal and other future technologies**, meaning to further investments in the development and commercialization of CCUS technologies and hydrogen. 4. **The Scaling up the circular economy to improve industrial sustainability**. 5. **The enhancement of carbon sinks**.
	The government plans to facilitate industry sector's transition to low-carbon production through 3 key means: • (1) To combine ICT and technologies 4.0 within industries' existing structures to favor the transition a high-value-added • (2) To use a combination of measures and incentives measures to stimulate energy efficiency • (3) To reinforce the commitment of policies and technology **development for waste and resources recycling**, that could drastically **diminish the utilization of raw materials and fuels**.

Korean policy towards industry decarbonization

Text	Industry Decarbonization measures
Establishment of the [Strategy for Technology Innovation for carbon neutrality], March 2021 (press release)[322]	The technology innovation strategy aims to drive to achieve carbon neutrality by 2050, through the support of technology innovation and inter-ministerial cooperation, which should be realized by focusing on five main actions plans: • The development of **ten core technologies** for carbon-neutral technology innovation: - **solar and Wind Power, Hydrogen, Bioenergy, Steel and Cement, Petrochemical Industrial Process Advancement**, Transport Efficiency, Building Efficiency, Digitalization and **CCUS**; - **differentiated** depending on their related issues, expected contributions to reduce GHG emissions and industrial demands, based on the Long-term low greenhouse gas Emission Development Strategies (LEDS). • The planning and promotion of carbon-neutral-**sector-focussed R&D projects** engaging all ministries. • The government's proactive support for the creation of **new green and/or digital industries**. • The emphasis on a private-led low-carbon conversion. - ***roadmap* for the successful commercialization and market settlement** of low-carbon technologies; - **establishing a standard/certification system** to regulate technology development; - **implementing tax exemption measures to incite private investments on low carbon, thus reducing the technology fee burden**. • The establishment of **sustainable research** foundations.
한국판 뉴딜 **2.0** 추진계획 **(Korean New Deal 2.0**[323]**, July 21**	• Creates both a **Green New Deal Fund of KRW 350 billion (approximately €235 million)** and a **Future Fund of KRW 142.6 billion** (approximately €96 million). • Additionally, the MOTIE announced its goal to scale up investments in the private sector up to **KRW 43 trillion (approximately €29 billion)** in the hydrogen sector and **KRW 36 trillion** (approximately €24 billion) (through a public–private investment plan) for floating offshore green power by 2030 • Additionally, as part of the Green New Deal , the MSS and the MOE pledged to invest a total of **KRW 200 billion (approximately €134.5 million)** in R&D for green growth and low-carbon transition for a total of 70 companies in 2021 • Finally, the document reiterates the government's commitment to move toward a net-zero society and industry, principally by expanding the scope of its support for R&D investments in CCUS technology's development (**KRW 159 billion** – approximately €107 million – to be invested by **2025**), as well for hydrogen production and the expansion of resource recycling facilities in the industry sector.

[320] *Government of South Korea, "The Korean New Deal: National Strategy for a Great Transformation," July 2020, https://content.gihub.org/dev/media/1192/korea_korean-new-deal.pdf.*

[321] *Government of South Korea, "2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society," December 2020, https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf.*

Korean policy towards industry decarbonization

Text	Industry Decarbonization measures
국가 탄소중립 · 녹색성장 기본계획 의결 **The 1st National Basic Plan for Carbon Neutrality and Green Growth (2023)**[324]	Updates the reduction target at **45.9%** by 2030 compared to 2018 levels, representing an additional 4 million tons reduction compared to the target set by the 2030 *roadmap* and also adapts reduction and absorption/removal targets by sector. Yet, **in the industrial sector the NCD target was lowered to 11.4% reduction by 2030 compared to 2018 levels, which represents a decrease of 8.1 million tons against previous NDC target**.
	In the industrial sector, this national strategy aims to foster low-carbon transition in the industry structure, primarily through technology development and an overhaul of systems such as the K-ETS by taking the following measures: • increasing the ratio of paid allocation of emission permits up to **75%** of total emissions. • adjusting to a **higher level of Benchmark Allocation**, based on emissions efficiency standards • **reinforcing tax support for low-carbon technologies**. • providing carbon neutrality-related policy financing, loan projects, and standards development. Additionally, this Basic Plan emphasizes the government's **support for CCUS technology development and commercialization**, as the main vector for decarbonization across all sectors, with an NDC target of GHG absorption/removal set at **11.2 million ton**s by 2030, entailing an increase of 900,000 tons against the previous NDC target.
제3차 국가 기후변화 적응대책 수립... 기후안심 국가 구현 **(The 3rd National Climate Change Adaptation Plan (2020) strategic plan for the period 2021-2025)**[325]	In the industrial sector, the main adaptation measures suggested implied: • improving the **energy efficiency** and maintenance of power system facilities; • **diversifying energy sources** to entail climate-resilient energy systems; • establishing a better energy management system, **including through smart grids** (target of building up to 5 million by 2025 vs. 150 in 2020); • developing **energy storage** capabilities.

[322] *Ministry of Science and ICT, South Korea, "Establishment of the Strategy for Technology Innovation for Carbon Neutrality," 2021, accessed September 10, 2024, https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=&bbsSeqNo=42&nttSeqNo=495&searchOpt=ALL&searchTxt=.*

[323] *Joint Ministry of Related Departments, South Korea,* 한국판 뉴딜 *2.0 -*미래를 만드는 나라 대한민국 *-* 관계 부처 합동 *[Korean New Deal 2.0 – A Country Creating the Future], 2021, https://outlook.stpi.narl.org.tw/pdfview/4b1141007f9b57d9017fc0093b374d74.*

Korean policy towards industry decarbonization

Text	Industry Decarbonization measures
The 10th Basic Energy Plan for Electricity Supply and Demand (Feb 2023 [326]	The 2030 and 2036 targets for the proportion of renewable energy is lower against the 9th Basic Plan.
	Introduction of a long-term contract market for low-carbon power sources, mainly hydrogen and ESS. It also plans to support the development of ammonia co-firing and blue hydrogen in order to reduce GHG emissions and to **invest up to KRW 48.4 trillion (approximately €32.6 billion) in the accommodation of renewable energy storage**.
Factory Energy Management System [327]	This strategy aims to **maximize the productivity and improve the energy efficiency of the industrial sector**, by: • establishing a comprehensive plan for the management of factories production and non-production facilities in order to reduce GHG emissions. This strategy is in line with the 2030 Roadmap published in 2018 and the implementation of the K-ETS. • relying on **efficient energy management** using energy modeling benchmarking.

[324] *2050 Carbon Neutrality Commission, South Korea, 국가 탄소중립 • 녹색성장기본계획(안) [National Carbon Neutrality and Green Growth Basic Plan (Draft)], 2023, https://www.2050cnc.go.kr/download/BOARD_ATTACH?storageNo=1936.*

[325] *Joint Ministry of Related Departments, South Korea, 제3차 국가 기후변화 적응대책 [3rd National Climate Change Adaptation Plan], http://www.climate.go.kr/home/cc_data/policy/3_nation_climate_change_adaptation_step_summary.pdf.*

[326] *2050 Carbon Neutrality Commission, South Korea, [제10차 전력수급기본계획(2022~2036)] 확정 [Confirmation of the 10th Basic Plan for Electricity Supply and Demand (2022–2036)], 2023, https://www.2050cnc.go.kr/base/board/read?boardManagementNo=43&boardNo=1242&searchCategory=&page=1&searchType=&searchWord=&menuLevel=2&menuNo=73.*

[327] *Korea FA Systems, "Factory Energy Management System," accessed September 10, 2024, http://www.kfa.co.kr/en/sub/solution/solution.asp?idx=17.*

Appendix 2
Japanese Policy toward Industry Decarbonization

Japanese policy towards industry decarbonization

Text	Industry Decarbonization measures
Green Growth Strategy Through Achieving Carbon Neutrality in 2050[328] **(Dec 2020)**	Funding: • Total of **JPY 240 trillion** (approximately €1.5 trillion) for Japanese companies. • The **Green Innovation Fund** with a budget of **JPY 3,000 trillion (approximately €19 trillion)**. • **JPY 2 trillion** (approximately €12.6 billion) at the New Energy and Industrial Technology Development Organization (NEDO).
	Object: 1. To establish a **new set of industrial policies** to create such a "virtuous cycle of economy and environment," setting high goals in 14 Industrial fields to realize the 2050 Carbon Neutrality goal. 2. In Industrial fields other than the power sector, **to decarbonize** through the promotion of **electrification** and form the basis of industrial competitiveness. 3. To build **resilient green and digital infrastructures** so as to nurture the growth of semiconductor/information and communication industrial fields. 4. To **expand R&D tax system, by raising the upper limit of tax deduction up to 30%** so as to foster investment in carbon-neutral innovation. 5. To develop s**ector-specific action plans** for 2050.
	Measures: • development of hydrogen reduction steelmaking; • promoting the **use of hydrogen**, the **methanation process**, **synthetic fuel** and **biomass**, as **energy sources**; • **establishing a sharing system for used products and materials to foster resource circulation**; • **increasing the use of biomass and recycled materials** and the development of recycling technology • CCUS: CO2-SUICOM for cement, artificial photosynthesis for chemicals.

[328] *Ministry of Economy, Trade and Industry, Japan, "Green Growth Strategy through Achieving Carbon Neutrality in 2050," December 25, 2020, http://web.archive.org/web/20240218065813/https://www.meti.go.jp/english/press/2020/pdf/1225_001b.pdf.*

Japanese policy towards industry decarbonization

Text	Industry Decarbonization measures
Environment Innovation Strategy[329] **(Jan, 2020)**	**Innovation Action plans** - estimate the technology's specific target cost and the extent to which they can contribute to GHG emissions reduction: • **increasing use of renewable energy and CO_2-free hydrogen**, through the development of zero-carbon steel with hydrogen reduction steelmaking technology, the improvement of metal resource circulation and the advancement of plastic resource circulation; • the development of **Carbon recycling technologie**s to **use CO_2 as a material and fuel source** through the production of plastics by artificial **photosynthesis technology**, the use of cement made from CO_2, **low-cost methanation**.
	Acceleration Plan: • establish an **inter-agency chain of command** through the inauguration of a Green Innovation Strategy Meeting; • **promote private ESG-related investments** through the promotion of green finance, so as to facilitate the dissemination of information on climate change among industrial companies.
Strategic Energy plan[330] **(Oct, 2021)**	Diversify the manufacturing process, including through the **introduction of hydrogen-reduction iron- and steelmaking** and highly functional **hydrogen-fired boilers**.
Clean Energy Strategy[331] **(May 2022)**	**Funding:** GX 150 billion in 10 years
	Measures: • tightly **monitoring supply and demand of energy**; • on **hydrogen/ammonia**, the government has planned to implement **support measures** by supporting the difference between the strike price and the reference price for hydrogen/ammonia *vis-à-vis* conventional fuels; • in the **steel industry**, the government scopes to support the development of innovative technologies, primarily hydrogen-reduction steelmaking, but also to promote investment in **energy efficiency** and **electrification**; • **CCUS technologies**, the government seeks to implement public support policy and to **improve the legislative framework for the commercialization of CCS technologies by 2030**.

[329] *Government of Japan, "Environment Innovation Strategy," January 21, 2020, https://unit.aist.go.jp/gzr/zero_emission_bay/en/images/kankyousenryaku2020_english.pdf.*

[330] *Ministry of Economy, Trade and Industry, Japan, "Outline of Strategic Energy Plan," October 2021, https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.*

[331] *Ministry of Economy, Trade and Industry, Japan, "Clean Energy Strategy Interim Report (Outline)," 2022, https://www.meti.go.jp/english/policy/energy_environment/global_warming/pdf/clean_energy_strategy.pdf.*

Japanese policy towards industry decarbonization

Text	Industry Decarbonization measures
The Basic Policy for Realization of GX- A *roadmap* for the next 10 years[332] **(Feb 2023)**	**Restructuring the manufacturing industry**, primarily **through fuel and feedstocks transition**, will allow for moving away from dependency on fossil energy sources
GX Promotion Act (May 2023)	**Funding:** • JPY 150 trillion (approximately €946.5 billion), of which JPY 20 trillion (approximately €126.2 billion) is public and the rest is private over 10 years. • Establishes **GX Transition Bonds**, with a total investment amount of approximately **JPY 20 trillion (approximately €126.2 billion)** over the **next 10 years**. • **GX League ETS**. • The GX Transition Bonds will be **funded by the Fossil Fuel Levy and the Specified Business Contributions**.
	Objectives: reduce GHG emissions by **46% by 2030** compared to 2013 levels.
	Measures: • requires the government to define a **strategy for the structural transition towards decarbonization**. **Government should support:** • investments on business projects which aim to reduce GHG emissions; • while improving industrial competitiveness and fostering sustainable economic growth; • risk decreases: and support private companies which seeks to develop technological innovation, **but yet remain hesitant due to the uncertainty** surrounding technological innovation.

[332] *Ministry of Economy, Trade and Industry, Japan. "The Basic Policy for the Realization of GX – A Roadmap for the Next 10 Years," 2023, http://web.archive.org/web/20231010040239/https://www.meti.go.jp/english/press/2023/pdf/0210_003a.pdf.*

List of All Interviewees and Stakeholders Consulted

This report builds on research interviews and consultations with about 500 European, Japanese, South Korean, and Chinese policymakers and stakeholders held between June 2023 until July 2024. The following tables provide an overview of the affiliation of the individuals interviewed or consulted (during working groups) as part of the research process for this report. These semi-structured interviews were conducted to gather expert insights and firsthand perspectives relevant to the topics discussed. They were conducted online or in-person during research trips in Europe, Japan, South Korea, and the UAE (COP28).

INTERVIEWS WITH CHINESE STAKEHOLDERS

Institution

- EDF Beijing Representative Office
- Energy Foundation China
- Environmental Defense Fund
- Chinese Academy of Science
- Chinese Academy of Social Science (CASS)
- Shanghai Institute for International Studies
- Research Institute for Carbon Neutrality of Beijing Da Xing
- WRI China
- National Center for Climate Change Strategy and International Cooperation
- Energy Research Institute
- The Administrative Center for China's Agenda 21 (ACCA21), Ministry of Science and Technology
- China Building Materials Federation (CBMF)
- China National Institute for Standardization
- Deep Rock

- Delong Steel
- Shanghai GEIT Co.
- Renewable Energy Development Center, Energy Research Institute, NDRC
- SINOPEC
- Baowu
- Greenovation: Hub
- National Development and Reform Commission (NDRC)
- Ministry of Industry and Information Technology (MIIT)
- Ministry of Ecological Environment (MEE)
- Shanghai Greenment
- China Beijing Green Exchange
- China Standardization Administration
- China National Institute of Standardization
- CNPC Research Institute of Safety and Environmental Technology
- Clean Energy Research Institute
- Chinalco
- Institute for Climate Change and Sustainable Development – Tsinghua University
- Biosphere 3
- Carbontrust China
- China Environmental United Certification Center
- Sinocarbon

INTERVIEWS WITH JAPANESE STAKEHOLDERS

Institution

- Mitsubishi Chemical Group Corporation
- New Industry and Technology Development Organization (NEDO)
- Global Environmentally Conscious Research Group
- Sumitomo Osaka Cement Co.

- Climate Change Task Force Department
- National Graduate Institute for Policy Studies (GRIPS)
- Ministry of Economy, Trade and Industry (METI)
- Ministry of the Environment of Japan (MOEJ)
- Sumitomo Osaka Cement Co., Ltd
- Sumitomo Chemical, Co., Ltd.
- UACJ – Aluminum
- Research Center for Advanced Science and Technology (RCAST)
- JFE Steel Corporation
- Mitsui Global Strategic Studies Institute
- Mitsui Chemicals, INC
- Taiheiyo Cement Corporation
- NEDO Representative Office in Europe
- Research Institute of Innovative Technology for the Earth
- The Central Research Institute of Electric Power (CRIEPI)
- Waseda University
- IGES
- Graduate School of Public Policies, REITI / University of Tokyo
- Toyota Motor Corporation
- Japan Aluminum Association
- Nippon Steel
- Marunouchi Innovation Partners
- Shizen Energy
- The Institute of Energy Economics
- Daichi Life
- Mitsubishi Heavy Industry
- CRIEPI

INTERVIEWS WITH KOREAN STAKEHOLDERS

Institution

- Presidential Committee for Net Zero
- Korea National Cleaner Production Center, Korea Institute of Industrial Technology (KNCPC/KITECH)
- Korea Institute for International Economic Policy (KIEP)
- Kim & Chang
- KB Kookmin Bank
- National Center for APEC Studies and the Pacific Economic Cooperation Council at Korea Institute for International Economic Policy (KIEP)
- KIEP (Korea Institute for International Economic Policy)
- Center for International Development Cooperation
- Seoul National University of Science and Technology (Seoultech)
- Korea Chamber of Commerce and Industry (KCCI)
- Korean Environmental Law Association
- Korean Institute of Energy Research Center
- Korean Advanced Institute of Science & Technology & Solution for Our Climate
- Korean Institute for Industrial Economics and Trade
- National Assembly Research Service (NARS)
- Ministry of Environment (ROK)
- Ministry of Trade, Industry and Energy
- Korean Presidency
- People's Party
- Korea Environment Institute
- Korea Chemicals Association
- Korea Energy Economic Institute (KEEI)
- Korean Cement Association
- Korea Testing & Research Institute
- Ministry of Strategy and Finance
- Carbonco

- Division of International Studies of Korea University in Korea
- Yonsei University
- CSDLAP
- Yulchon LLC
- VEOLIA Korea
- International School of Urban Sciences, University of Seoul
- POSCO Research Institute
- POSCO
- Eugene Corp Research Institute
- SK Chemicals
- Samsung
- Korea Cement Industry Association
- Delegation of the European Union to the Republic of Korea

INTERVIEWS WITH EUROPEAN STAKEHOLDERS

Institution
- European Commission
- DG Grow, European Commission
- DG Clima, EC
- DG Trade, EC
- DG Taxud, EC
- DG Energy, EC
- DG Grow, EC
- EEAS
- French Ministry of Economy and Finance
- French ministry of Industry
- Cleantech for Europe
- Institut du développement durable et des relations internationales
- (IDDRI)
- CEA (French Atomic Energy and Alternative Energies Commission)
- Institut Montaigne

- Wuppertal Institute for Climate, Environment and Energy
- Breakthrough Energy
- Ecocem Materials, Ltd.
- AFYREN
- ArcelorMittal
- German Federal Chancellery
- Renault
- BMWK
- BMW
- Airliquide
- Ardian
- Mitsubishi Electric, France
- The Boston Consulting Group France
- Copenhagen Infrastructure Partner
- OPmobility
- MEDEF
- Kéa
- VICAT
- Orano
- Ministry of Energy Transition, France
- Accenture France
- Archery Strategy Consulting
- Airbus
- Accuracy
- Hitachi Energy France
- Groupe Amundi
- Chubb France
- Bessé
- SGS, France
- EDF
- Schneider Electric
- ENEDIS
- TotalEnergies
- ArcelorMittal

- Evolen
- Solvay
- Thyssenkrupp Steel Europe
- BASF
- EUROFER (European Steel Association)
- Cembureau
- CEFIC (chemical federation)
- Holcim
- Siemens
- GTT (Gaztransport & Technigaz) SA
- Agora Energiewende
- The Climate Group
- L'Oréal Groupe
- IFP School / Laboratoire de Génie Industriel de CentraleSupélec
- Association française des Economistes de l'Energie
- VUB
- College of Europe
- IDDRI
- Clean Hydrogen Joint Undertaking
- Plastic Omnium
- Pergamon
- Engie
- E3G
- Enagas
- EnBW
- Hy24
- SNAM
- Climate Leadership Council
- European University Institute
- European Institute on Economics and the Environment
- International Institute for Sustainable Development
- Ministry of Ecological Transition, Italy
- Department for Business, Energy, and Industrial Strategy, UK
- Atlantic Council Global Energy Center

- Department for Energy Security and Net Zero, UK
- Resources for the Future
- Hydrogen Europe
- Transformation Factory
- Jeantet
- Suez
- Vulog
- Hogan Lovells France
- Breakthrough Energy
- Wavestone
- Gide Loyrette Nouel
- RTE
- ABB France
- I4CE
- iQo
- Natural Grass
- Federal Ministry of Economy Climate Protection, Germany
- Carbios
- Cimpor
- Aequilibria
- Global Cement and Concrete Association
- ADEME
- Secrétariat Général à la Planification écologique (France)
- Wupperthal Institute
- H2 Green Steel
- French Ministry of Europe and Foreign Affairs
- SIS
- The Directorate General for Enterprise (DGE), Industry Service: Industrial Policies, France
- Advisor to the Green Group at the European Parliament
- Aluminum Dunkerque
- Delegation of the European Union to the Republic of Korea
- Delegation of the European Union to China
- EDF

- AXA
- Thyssenkrupp
- German State Secretariat for Energy
- Adelphi
- AgoraEnergiewende

OTHERS

Institution

- UNIDO
- OECD
- IEA
- International Organization for Standardization
- Climate Club
- World Bank
- Global CCS Institute
- Rio Tinto
- World Economic Forum
- International Sustainability Standard Board
- IRENA

Acknowledgments

This report and the research conducted for it were made possible by the support of Japan's New Energy and Industrial Technology Development Organization (NEDO). The author expresses his gratitude to NEDO Europe's team and the NEDO Industry Decarbonization Team in Kawasaki for their valuable support and collaboration.

This report builds on a policy dialogue held in January 2024 with 40 stakeholders from industrial sectors from Europe, Japan, and South Korea, as well as policymakers from the European Commission (DG CLIMA, DG GROW, DG TRADE, DG TAXUD) and Member State governments (the German Federal Chancellery, the German Federal Ministry for Economic Affairs and Climate Action, the French Ministry for Europe and Foreign Affairs, the French Ministry of Ecological Transition, the French Ministry of Economy and Industry), Japanese policymakers from the Ministry of the Economy, Trade, and Industry (METI) and the Ministry of the Environment of Japan (MOEJ), and South Korean policymakers from the Ministry of the Environment, the Presidential Net Zero Committee, the Ministry of Economy, Trade, and Economy (MOTIE), and the Ministry of Foreign affairs. The author is grateful to his interlocutors for their time and willingness to share ideas and insights.

The author gratefully acknowledges the invaluable support of his colleagues in the Asia Program at Institut Montaigne. **Dr. Mathieu Duchâtel**, **Prof. François Godement**, **Ms. Claire Lemoine**, and **Mr. Pierre Pinhas** provided many helpful comments on earlier drafts of this report. The author is also thankful to **Thomas Maddock**, **Juliette Odolant**, **Inès Miral**, **Ange Vaucher**, **Sarah Isabey**, **Alix Lemaire**, and **Rosalie Klein**, who assisted with the organization of the policy dialogue, the research for this report, and the editing.

The author thanks the external independent reviewers, including **Dr. Lukas Hermwille** (Wuppertal Institute for Climate, Environment and Energy) and **Prof. Lee Sanjun** (Korea Institute for Industrial Economics and Trade / Seoul National University), for their valuable remarks. The author remains solely responsible for the conclusions and recommendations of this research paper.

INSTITUT Montaigne

Chairman

Henri de Castries Chairman, Institut Montaigne

Members of the board

David Azéma Partner, Perella Weinberg Partners
Emmanuelle Barbara Senior Partner, August Debouzy
Marguerite Bérard Head of French Retail Banking, BNP Paribas
Jean-Pierre Clamadieu Chairman of the Board of Directors, ENGIE
Paul Hermelin Chairman of the Board of Directors, Capgemini
Marwan Lahoud Chairman Private Equity, Tikehau Capital
Natalie Rastoin President, Polytane
René Ricol President, Ricol Lasteyrie
Jean-Dominique Senard Chairman of the Board of Directors, Groupe Renault
Arnaud Vaissié Chairman and CEO, International SOS
Natacha Valla Economist, Dean of Sciences Po's School of Management and Innovation
Florence Verzelen Executive Vice President, Dassault Systèmes
Philippe Wahl Chairman and CEO, Le Groupe La Poste

Honorary Chairman

Claude Bébéar Founder and Honorary Chairman, AXA

Institut Montaigne
59 rue La Boétie, 75008 Paris
Tél. +33 (0)1 53 89 05 60
institutmontaigne.org/en

Printed in France
Legal filing: October 2024
ISSN : 1771-6764

Cover picture: © Pauline Faure

Corporate Members

INSTITUT Montaigne

ABB France
AbbVie
Accenture
Accor
Accuracy
Actual Group
Adeo
ADIT
Air Liquide
Airbus
Allianz
Amazon
Amber Capital
Amundi
Antidox
Antin Infrastructure Partners
ArchiMed
Ardian
Arquus
Arthur D. Little
AstraZeneca
August Debouzy
AXA
A&O Shearman
Bain & Company France
Baker & McKenzie
BearingPoint
Bessé
BNP Paribas
Bolloré
Bouygues
Bristol Myers Squibb
Brousse Vergez
Brunswick
Capgemini
Capital Group
CAREIT
Carrefour
Chubb
CIS
Clariane
Clifford Chance
CNP Assurances
Cohen Amir-Aslani
Conseil supérieur du notariat
D'Angelin & Co.Ltd
Dassault Systèmes
Delair
Deloitte
De Pardieu Brocas
Maffei
Domia Group
Edenred
EDF
EDHEC Business School
Ekimetrics France
Engie
EQT
ESL & Network
Eurogroup Consulting
FGS Global
Forvis Mazars
Getlink
Gide Loyrette Nouel
Google
Groupama
Groupe Bel
Groupe M6
Groupe Orange
Hameur et Cie
Henner
Hitachi Energy France
Howden
HSBC Continental Europe
IBM France
IFPASS
Incyte Biosciences France
Inkarn
Institut Mérieux
International SOS
Interparfums
Intuitive Surgical
Ionis Education Group
iQo
ISRP
Jeantet Associés
Jolt Capital
Katalyse
Kea
Kearney
KPMG S.A.
Kyndryl
La Banque Postale
La Compagnie Fruitière
Lenovo ISG
Linedata Services
Lloyds Europe
L'Oréal
LVMH - Moët-Hennessy - Louis Vuitton
M.Charraire
MACSF
Média-Participations
Mediobanca
Mercer
Meridiam
Microsoft France
Mitsubishi France S.A.S
Moelis & Company
Moody's France
Morgan Stanley
Natixis
Natural Grass
Naval Group
Nestlé
OCIRP
ODDO BHF
Oliver Wyman
Ondra Partners
OPmobility
Optigestion
Orano
PAI Partners
Pelham Media
Pergamon
Polytane
Publicis
PwC France & Maghreb
Qualisocial
Raise
RATP
Renault
Ricol Lasteyrie
Rivolier
Roche
Roche Diagnostics
Rokos Capital Management
Rothschild & Co
RTE
Safran
Sanofi
SAP France
Schneider Electric
ServiceNow
Servier
SGS
SIER Constructeur
SNCF
SNCF Réseau
Sodexo
SPVIE
SUEZ
Synergie
Teneo
The Boston Consulting Group
Tilder
Tofane
TotalEnergies
TP ICAP
Transformation Factory
Unicancer
Veolia
Verian
Verlingue
VINCI
Vivendi
Wakam
Wavestone
Wendel
White & Case
Willis Towers Watson France
Zurich

This Institut Montaigne research report offers vital insights into the future of the EU Clean Industrial Deal and the positioning of European industry in the post-carbon world. Building on interviews with over 500 stakeholders across Europe and Asia, it provides a comparative analysis of decarbonization strategies in key industries such as steel, aluminum, chemicals, and cement. The report concludes with actionable recommendations to strengthen Europe's competitiveness in a rapidly evolving, low-carbon economy.

10 €
ISSN : 1771-6764
RAP2410-02