CLIMATE ANALYTICS

Towards a real zero transformation of Japanese steel

November 2025

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About Climate Analytics

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

Acknowledgments

The authors would like to thank the team at Transition Asia, who graciously assisted in providing and helping to modify the levelised cost of steel model we use; and Max van Someren, who provided guidance on the report; the reviewers; and others who provided expertise and support.

How to cite: Climate Analytics (2025). Towards a real zero transformation of Japanese steel

Supported by Fortescue

We would like to thank Fortescue for supporting this work.

Summary

Japan's climate plans favour a gradual transition away from carbon-intensive steelmaking. The national approach mostly promotes carbon capture and storage (CCS) and other purported solutions to "abate" ongoing emissions. Japanese steelmakers and officials reject an alternative transformation that would see rapid deployment of "real zero" technologies capable of eliminating emissions at-source.

In this report, we show that these preferences are flawed. Japanese stakeholders often present their approach as cost-effective climate action, and aligned with national energy and economic security concerns. However, a "real zero transformation" can be more cost-effective. It can be cheaper than even elements of business-as-usual (BAU) steelmaking. And real zero need not compromise energy or economic security — in some instances, it can better manage Japan's security concerns than BAU production.

Steelmaking accounts for up to 14% of Japan's CO_2 emissions. Yet the industry's current target is only a 30% emissions reduction by 2030 (from a 2013 baseline), compared with a 45% reduction goal for the broader Japanese economy. Government plans envision most emissions cuts coming from CCS applied to coal-dependent blast furnace-basic oxygen furnaces (BF-BOF), which generate 75% of Japan's steel.

We test whether and how Japanese steel production could be adapted to meet ambitious emissions reduction benchmarks, specifically the International Energy Agency's "near zero steel" definitions, and assess the implications for cost, as well as energy and economic security. Factors shaping our analysis include the comparatively old age of Japan's BF-BOF plants, and the need for steelmakers to decide whether to reinvest in about half the country's BF-BOF capacity by the end of 2030.

We assess potential production pathways for both "primary" (using mainly iron ore inputs) and "secondary" steel (using mainly recycled steel inputs), under ideal conditions.

We find Japan already has a real zero steel pathway capable of meeting our ambitious emissions benchmark in a more cost-competitive manner than its BAU equivalent. Secondary scrap-based steel produced in a 100% renewables-powered electric arc furnace (EAF) can outcompete BAU scrap EAF production drawing power from the grid. Japan could accordingly scale up this route, alongside renewable energy production.

Japan will continue to require substantial primary steel production. However, our analysis finds the BF-BOF route cannot remain cost-competitive against rival modes

while meeting our emissions benchmark. There is no viable real zero pathway for BF-BOF production, and a carbon-abated approach relying heavily on CCS would be too expensive. While it would lower costs, CCS retrofitted to existing BF-BOF plants cannot achieve Paris-aligned emissions reduction. Any apparent future-proofing of BF-BOF production inevitably relies on unrealistic assumptions on CO_2 capture rates.

While other potential options are emerging, the battle over cost-competitive, suitably climate ambitious primary steel production in Japan is currently closest in the alternative direct reduced iron-electric arc furnace (DRI-EAF) route. Japan does not currently use this technology at commercial scale, and fossil gas-dependent DRI-EAF production elsewhere remains too carbon-intensive.

DRI-EAF production can theoretically meet our emissions benchmark through either carbon-abated or real zero pathways. We consider two carbon-abated pathways: one uses fossil gas for energy and to "reduce" iron, while capturing plant emissions, and the other substitutes "blue hydrogen" for these purposes, with emissions captured from fossil feedstocks. We also consider a real zero pathway using renewables-powered "green hydrogen". We also consider trade variations, using imported hot briquetted iron (HBI, an easily shipped and handled form of DRI) for both blue (carbon-abated) and green (real zero) hydrogen-based DRI-EAF.

With the trade variation of imported HBI, real zero DRI-EAF could become a competitive option for Japanese primary steel production — cheaper than BAU DRI-EAF by the early 2030s. Carbon-abated DRI-EAF pathways appear more able to reach our emissions benchmark than carbon-abated BF-BOF alternatives. However, these options would again put production on course to be pricier than the trade-varied real zero DRI-EAF pathway (and would still rely on ambitious CCS assumptions).

Under current conditions, more domestically focused Japanese real zero primary steel production, utilising the DRI-EAF route, will remain uncompetitive against alternatives, largely due to Japanese challenges producing affordable green hydrogen.

Nevertheless, the associated "green premium" for domestic hydrogen-based real zero DRI-EAF in Japan could be relatively minor for steel end users, adding only 1-2% to the cost of a domestically produced car. Policy interventions, such as stronger hydrogen subsidies, carbon prices, and coordinated private or public demand could further improve the economics of real zero.

A real zero transformation of steelmaking need not clash with Japan's stated energy and economic security concerns. The cost-competitiveness of real zero suggests it is best positioned to future-proof Japan's steel production levels, and the national values attached to these, as the country achieves its climate goals.

Real zero transformation might also deliver discrete energy and economic security benefits. For example, scaling up renewables-powered EAF secondary steel production relative to BF-BOF primary production could reduce demand for imported iron ore and coal in favour of less material- and energy-intensive (and more domestically sourced) scrap and renewable energy. In addition, the trade variation of real zero DRI-EAF primary steel production, using HBI imports, would offshore the most energy-intensive stage of steelmaking, and related security concerns, to other countries.

Contrary to what Japanese steelmakers and officials claim, real zero is preferable to a carbon-abated approach on cost-competitiveness, as well as energy and economic security. It can even improve on BAU conditions in some circumstances.

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Introduction

Decarbonising steel production is a critical Japanese climate priority. Yet it currently lacks sufficient support from industry and policymakers. The steel sector is a pillar of Japan's economy, and it is crucial in facilitating export-focused high-end manufacturing. Steel underpins many Japanese strategic priorities, including retaining a resilient industrial workforce and asset base.

Steelmaking generates up to 14% of Japan's CO_2 emissions.[1] Yet, as a highly valued activity, officials have so far spared steelmakers the burden of pursuing immediate deep decarbonisation. Industry members target just a 30% emissions reduction by 2030 (from a 2013 baseline), compared with 45% for the broader Japanese economy.[2]

Japan's steel emissions ambition is in line with a national masterplan that seeks a "Green Transformation" (GX) but promotes highly conditional climate action.[3] The Climate Action Tracker (CAT) – which measures government progress on climate change – notes the *GX Basic Policy* (2023) "places more emphasis on economic growth and energy security, than on prioritising ambitious decarbonisation."[4]

This report presents Japan's steel decarbonisation approach as illustrative of the country's wider rejection of a "real zero transformation". Instead, Japan seeks to keep carbon-intensive steelmaking online and "abate" ongoing, or "residual", emissions, rather than rapidly deploy technologies for eliminating these emissions at-source.

A real zero approach would reduce global pressure on CO_2 removals to offset past emissions in Japan and elsewhere. It would help keep 1.5°C warming within reach and reduce the magnitude and duration of any overshoot. Conversely, pursuing carbon-abatement in place of real zero, in any sector or region, directly undermines 1.5°C.

Japan's near-term steel plans prioritise the use of carbon capture and storage (CCS) as well as hydrogen injection for blast furnace-basic oxygen furnace (BF-BOF) production. The BF-BOF route accounts for three-quarters of Japanese steelmaking and all its "primary" steel made from new iron ore. Remaining production comes from electric arc furnace (EAF)-produced "secondary" steel, made with mostly steel scrap.

[1] Waagsaether et al., *2023 STEEL POLICY SCORECARD*.
[2] Waagsaether et al., *2023 STEEL POLICY SCORECARD*.
[3] GR Japan, *Japan's Green Transformation (GX) Plans Updates*.
[4] Climate Action Tracker, "Japan. November 2023."

Japan has an opportunity to alter this production profile while limiting stranded asset costs; its BF-BOF fleet is relatively old, and its steelmakers must decide whether to reinvest in, or potentially retire, more than half of blast furnace capacity by 2030.[5]

We assess whether real zero transformation in Japanese steelmaking might be an effective and cost-competitive decarbonisation approach. We start from the perspective that business-as-usual (BAU) production must change. And, if the two alternative pathways for replacing it could achieve comparable emissions reduction over the same period, a real zero approach would be preferable to a carbon-abated approach. This is because real zero would avoid risks of underperforming abatement and residual emissions.

We then examine Japan-specific arguments against the feasibility of a real zero steel transformation. The most notable argument is that a carbon-abated approach can be cheaper and therefore more attainable. The cost pressures currently facing Japanese steelmakers in both domestic and export markets adds weight to this concern.

Japan's prominent energy and economic security priorities increase its scepticism of real zero. Japanese officials and industry members seek energy and material inputs to steel production that are both affordable and resilient to short- and long-term shocks.

We aim to show:

- in which contexts real zero might already be cost-competitive against carbon-abated and even BAU production
- the techno-economic or policy conditions that might improve the cost-competitiveness of real zero, or potentially limit the relevance of cost-competitiveness in economic decision-making
- in which contexts real zero can be compatible with Japan's energy and economic security concerns, and in which contexts real zero might better address these security concerns than even BAU production

Approach

To test cost-competitiveness, we assess the three technologies likely to inform Japan's future steelmaking choices: scrap-based EAF for secondary steel, and BF-BOF or direct reduced iron-electric arc furnace (DRI-EAF) for primary steel.

We consider the carbon-intensive BAU pathways for each route, whether and how each might need to be adapted through carbon-abated or real zero pathways, and the

[5] Rumsa et al., "Global Steel Decarbonisation Roadmaps."

implications on steel production costs. For this purpose, we use a levelised cost of steel (LCOS) model and Japan-specific values for capital and operational expenditure (see Appendix for an explanation of the LCOS methodology).

We crosscheck whether BAU, carbon-abated, and real zero production pathways can meet the relevant emissions benchmark (for primary and secondary steel) in the International Energy Agency's "near zero steel" (NZS) definitions.[6]

We consider that Japan will need to maintain both primary and secondary steelmaking. We examine how techno-economic shifts and policy interventions might impact costs. And we consider how much cost influences price and demand for steel end products, seeking to better understand economic competitiveness concerns.

In considering the energy and economic security implications of real zero vs. alternative steel production pathways, we reexamine our cost conclusions according to their impacts on factors such as industry output, the balance of domestic vs. imported energy and materials, employment, and productive vs. unproductive government spending.

We conclude by outlining the key implications of our findings, showing how, contrary to the dominant national narrative, real zero transformation is an optimal approach to decarbonising Japanese steel.

[6] IEA, "Definitions for Near-Zero and Low-Emissions Steel and Cement, and Underlying Emissions Measurement Methodologies."

The Japanese steel sector's pressing emissions and economic choices

Steelmaking is a major Japanese industry and a major source of Japan's emissions. There is a growing global need to decarbonise steel production to meet national climate goals. However, industry and policymaker appetite for deep transformation and use of innovative emissions-free technologies remains relatively low.

Japanese steel production has declined in recent years, influenced by cost pressures

Japanese production of primary and secondary steel, million tonnes per annum, 2022-2024

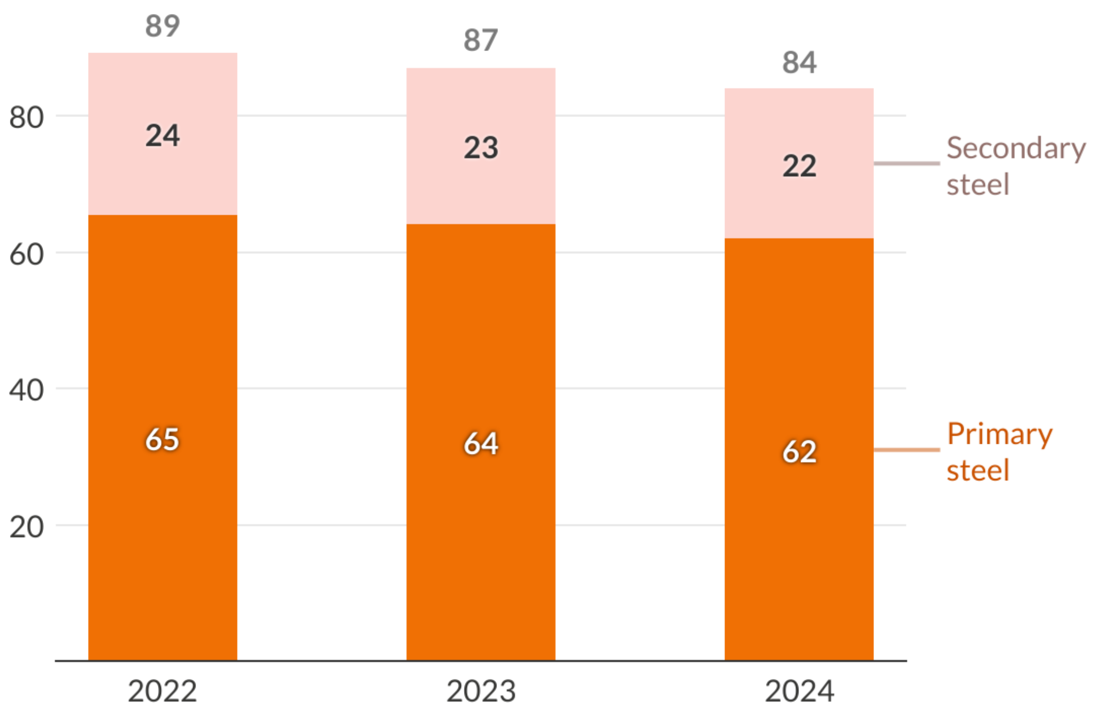

Figure 1. Japanese production of primary and secondary iron and steel, million tonnes per annum, 2022-2024. Source: Japan Iron and Steel Federation.[7]

[7] Japan Iron and Steel Federation, "Annual Statistics 2024 Calendar Year (Revised)."

Japan is the world's third-largest steelmaker and produced 84 million tonnes (Mt) of crude steel in 2024.[8] Japan is also the world's second-largest steel exporter and its second-largest net exporter. In 2024, Japan exported 31.2 Mt and imported 7.85 Mt of iron and steel products. Figure 1 shows Japanese steel production for 2022-2024.[9]

About three-quarters of Japanese steel production is "primary steel", produced from predominantly new iron ore. The remaining quarter is "secondary steel", produced from predominantly recycled "scrap" steel.[10] Secondary steel accounts for under 2% of Japan's steel exports and 8% of its imports.[11]

Japan generates between 30-40 Mt of steel scrap for recycling per year. About 85% of steel scrap is channelled back into domestic steelmaking, predominantly in EAFs but some in BF-BOFs, with the remainder exported.[12] In 2024, Japan exported 6.5 Mt of scrap — allowing for secondary production in destination countries — and imported just 0.1 Mt.[13] Policies related to retention vs. export of scrap strongly influence Japan's – and its trading partners' – ability to alter the primary-secondary production mix.

The industrial sector, which includes steel and steel-dependent manufacturing and construction activities, accounts for 29% of Japan's gross value-added economic activity and 24% of employment. These figures are significantly higher than OECD averages of 21% for both categories.[14]

Iron and steel subsequently generate up to 14% of Japan's total CO_2 and about 40% of its industrial CO_2 emissions.[15] As a highly developed country with the world's fourth-largest economy,[16]Japan has considerable ability to meet its climate goals by decarbonising steel production using mature technologies. With 37% of production exported, Japanese steelmakers also face climate-linked trade pressures, including exposure to European Union carbon border adjustment mechanisms and their second-order effects.[17]

[8] Japan Iron and Steel Federation, "Annual Statistics 2024 Calendar Year (Revised)."
[9] Japan Iron and Steel Federation, "Steel Imports and Exports 2024."
[10] Japan Iron and Steel Federation, "Annual Statistics 2024 Calendar Year (Revised)."
[11] Japan Iron and Steel Federation, "Steel Imports and Exports 2024."
[12] World Steel Association, *2025 World Steel in Figures*.
[13] World Steel Association, *2025 World Steel in Figures*.
[14] World Bank Group, "World Bank Open Data - Japanese and OECD Indicators for "employment in Industry (% of Total Employment)(Modeled ILO Estimate) and 'Industry, Value Added (% of GDP).'"
[15] Climate Group, "Japan's Transition to Green Steel."
[16] World Bank Group, "GDP (Current US$)."
[17] InfluenceMap, "Corporate Engagement by the Japanese and Korean Steel Industries with the EU CBAM."

Japanese policymakers acknowledge steel's climate challenge. The Green Transformation (GX) national climate and economic strategy pledges support for "shifts to non-fossil fuel energy" in steel and other energy-intensive industries, expansion of electric arc furnace (EAF) and hydrogen-based production, and creation of new "green steel" markets.[18] GX also introduced an emissions trading system. Steelmaker participation in the GX-ETS is mandatory from 2026, but the nature of sector coverage is still being determined.[19]

Numerous headwinds also limit Japanese ambition for steel decarbonisation. The 84 Mt of steel produced in 2024 represented Japan's third year of declining production.[20] Contributing factors include falling domestic demand and rising competition from cheaper imports and exports, mostly confined to primary steel.[21]

Japanese steelmakers are also struggling to maintain their traditionally strong integration with the plans and operations of steel customers, led by high-end Japanese carmakers. This follows shifting consumer preferences, including towards electric vehicles with differing material needs.[22]

Policymakers are reluctant to add to industry burdens. They value steel's contributions to GDP, employment levels, and more strategic interests, such as ensuring national defence at a time of increasing geopolitical instability. In this context, steelmakers and public officials have generally welcomed the diminished global climate ambition ushered in by the Trump-era United States, even as this American administration has increased more generic protectionism-based trade pressures.[23]

Carbon-intensive BF-BOF production still dominates Japanese steelmaking

Consistent with the approach of its dominant producer and the world's fourth-largest steelmaker, Nippon Steel, Japan's steel sector maintains an emissions reduction target of 30% by 2030 (from a 2013 baseline), on both an absolute and carbon-intensity of

[18] Government of Japan, "The Basic Policy for the Realization of GX - A Roadmap for the next 10 Years."
[19] Transition Asia, "Key Policy Developments in Japan for the Steel Industry."
[20] World Steel Association, *2025 World Steel in Figures*.
[21] Mizuho Bank Industry Research Department, "Steel In Pursuit of the Increasing Value of "Quantity" and the Enduring Value of "Quality."
[22] Mizuho Bank Industry Research Department, "Steel In Pursuit of the Increasing Value of "Quantity" and the Enduring Value of "Quality."
[23] Nikkei staff writers, "Japanese Steel and Chemical Producers Pull Back from Carbon-Cutting."

production basis.[24] This is out of step with steel's larger-than average contribution to national emissions and Japan having an economy-wide 2030 emissions reduction target of 46% – itself rated "insufficient" by the CAT.[25]

Continued declines in Japanese steel production could reduce the sector's absolute emissions. However, this would be insufficient to meet climate goals and misaligned with the long-term pursuit of zero emissions output.

The main obstacle to rapidly reducing steel emissions is Japan's dependence on BF-BOF production. This accounts for all of Japan's primary steel production, while scrap EAFs produce the remaining third of production, of secondary steel.[26] Japan currently has no commercial scale DRI-EAF primary steelmaking, despite this (currently fossil gas-reliant) route accounting for 8% of global crude steel output.[27]

Japan's BF-BOF share of production is slightly higher than the global average of 72%, though this figure is itself heavily skewed by the industry dominance of China and broader Asia, where BF-BOFs are atypically prevalent. Japan's production mix is significantly different to that of the US, where BF-BOFs produce 30% of steel, and Europe, where BF-BOFs produce 57% of steel (the remainder in each comes from scrap EAF and DRI-EAF).[28] Differing economic compositions, including the manufacturing share of GDP, influence these differing production mixes.

BF-BOF production is inherently carbon-intensive – about 90% of its energy supply (both for heating and "reducing" iron ore by removing its oxygen content) come from coal.[29] BF-BOF production generates more than 2300 $kgCO_2/t$ of crude steel at a global average level. Scrap EAF steelmaking generates an average of about 700 $kgCO_2/t$, and DRI-EAF production generates an average of about 1400 $kgCO_2/t$.[30]

Japan's future steel production choices are critical

Future decisions around the nature of the production mix should put Japan on the path to making steel with zero emissions, or as close as possible to it. This is vital to Japan contributing to global achievement of the Paris Agreement goals. To align with a 1.5°C

[24] The Government of Japan - JapanGov -, "The Road to Net Zero with Green Steel."
[25] Climate Action Tracker, "Japan. November 2023."
[26] Japan Iron and Steel Federation, "Annual Statistics 2024 Calendar Year (Revised)."
[27] World Steel Association, *2025 World Steel in Figures*.
[28] Yuko Nishida et al., *The Path to Green Steel: Pursuing Zero-Carbon Steelmaking in Japan*.
[29] World Steel Association, *Sustainability Indicators 2024 Report*.
[30] World Steel Association, *Sustainability Indicators 2024 Report*.

warming world, CAT estimates Japan would need to reduce emissions by more than 60% by 2030 (using the Japanese government's 2013 baseline).[31]

As with its global peers, Japanese stakeholders present steel as an inherently "hard-to-abate" sector. However, steel production still requires deep emissions reductions to meet Paris goals. In the 1.5°C-aligned Phase V REMIND mitigation pathways — from the Network for Greening the Financial System — CO_2 emissions from steel's combined process and energy use decline 52% (median) below 2020 levels by 2030 globally.[32]

Keeping 1.5°C in sight requires all sectors in all countries to keep residual emissions to an absolute minimum and pursue all feasible options for eliminating emissions at-source. Dependence on CCS or offsets jeopardises achievement of real abatement. Pressure on atmospheric CO_2 removals to achieve global level net zero emissions must be minimised and the potential for negative emissions limited to compensating for current and past emissions that were reduced too late and too slowly.

This report's assessments are confined to production choices. But other factors impact steel emissions, most obviously production levels and demand. Wang et al., for example, found the GHG intensity of global iron and steelmaking decreased 67% between 1900-2015, mainly through process efficiency, but net emissions increased 17 times due to a 44-fold production increase.[33] The authors concluded that effective steel decarbonisation required, among other things, more considerable demand reduction. Lighter vehicle construction can reduce steel use by a factor of four,[34] while 35-45% of steel use can be avoided by reducing overspecification in construction.[35]

If they cannot be adapted to a Paris-aligned future, steelmaking assets may need to be retired before the end of their economic lives. However, in Japan at least, there is an opportunity to reduce some attendant stranded asset costs. The average age of Japan's BF-BOF fleet is approximately 30 years. This compares to an expected lifespan of about 40 years and an average age of about 13–14 years for BF-BOFs globally.[36]

BFs must undergo major overhauls, or "relining", every 15-20 years. Operators of more than half of Japan's BF-BOF capacity must decide whether to reline, and thus extend

[31] Climate Action Tracker, "Japan. November 2023."
[32] NGFS, "NGFS Scenarios Portal."
[33] Wang et al., "Efficiency Stagnation in Global Steel Production Urges Joint Supply- and Demand-Side Mitigation Efforts."
[34] Wang et al., "Efficiency Stagnation in Global Steel Production Urges Joint Supply- and Demand-Side Mitigation Efforts."
[35] Ellen MacArthur Foundation, *Completing the Picture*.
[36] Rumsa et al., "Global Steel Decarbonisation Roadmaps."

the life of, their plants by 2030.[37] Relining can incur up to half of the cost of building a new blast furnace.[38] It also incurs several months of lost production and revenue.[39]

Iron ore miner BHP estimates relining still only accounts for up to 5% of the total capital cost of a BF-BOF facility and notes that, under current policies, “industry is strongly incentivised” to extend asset life over investing in alternative production.[40] Still, Japanese steelmakers — and Japanese policymakers — face a clear inflection point on their future production mix, certainly compared with countries with younger BF-BOF fleets.

Even waiting until 2030 to change investment decisions could result in a significant emissions penalty. In a survey of global steel plants, Lei et al. found a 47% reduction in sector emissions was possible between 2020-2050 if low carbon strategies were applied five years later than scheduled retrofitting, but up to 66% was possible if available low emissions solutions were applied five years ahead of schedule.[41]

Changing the steelmaking mix is critical to meeting climate goals in Japan and globally. The IEA’s Paris-aligned Net Zero Emissions (NZE) Scenario shows unabated production from the BF-BOF route being replaced by scrap-based steelmaking and low-emissions technologies.[42] Recycled steel meets 48% of demand by 2050 at a global level. Figure 2 shows the distribution of different technologies from 2022-2050.

[37] Rumsa et al., “Global Steel Decarbonisation Roadmaps.”
[38] “What Steel Decarbonization Needs | Columbia Business School.”
[39] Vogl et al., “Phasing out the Blast Furnace to Meet Global Climate Targets.”
[40] BHP, “Pathways to decarbonisation episode two.”
[41] Lei et al., “Global Iron and Steel Plant CO2 Emissions and Carbon-Neutrality Pathways.”
[42] IEA, “Net Zero Roadmap.”

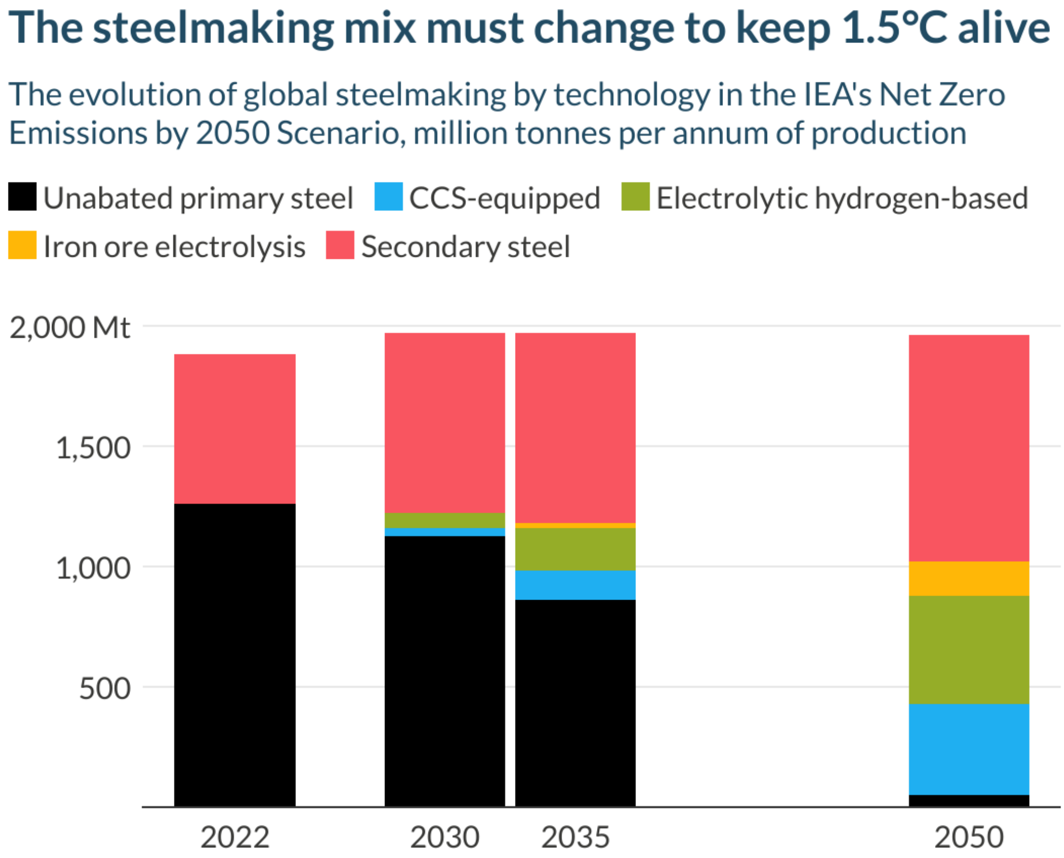

Figure 2. The evolution of global steelmaking by technology in the IEA's Net Zero Emissions by 2050 Scenario, million tonnes per annum of production. Source: IEA[43]

Japan has a relatively low percentage of scrap-based production (see Figure 3). It could move more in line with similarly mature economies such as the US and Europe, particularly if rebalancing its economy away from its strong manufacturing focus — which requires higher quality primary steel. With Japan having the world's highest steel stock per capita, relatively high recovery rates of obsolete steel, and significant net exports of scrap, materials availability is unlikely to be a barrier to near-term secondary steel production increases.[44]

However, secondary steel use remains limited by both application and materials availability at a global level — as the IEA NZE roadmap acknowledges. This means any emissions improvements resulting from shifts in Japan's own production mix could be offset by reduced scrap exports to other countries, which would likely increase production or use of primary steel. It is therefore important to identify Japanese pathways to produce both primary and secondary steel in a Paris-aligned fashion.

[43] IEA, "Net Zero Roadmap."
[44] Transition Asia, *Scrap Supply Should Not Hinder Japan's Steel Transition*.

Japan has potential to significantly increase the recycled share of steel production

Share of recycled steel use in crude steel production for select countries and regions, 2023

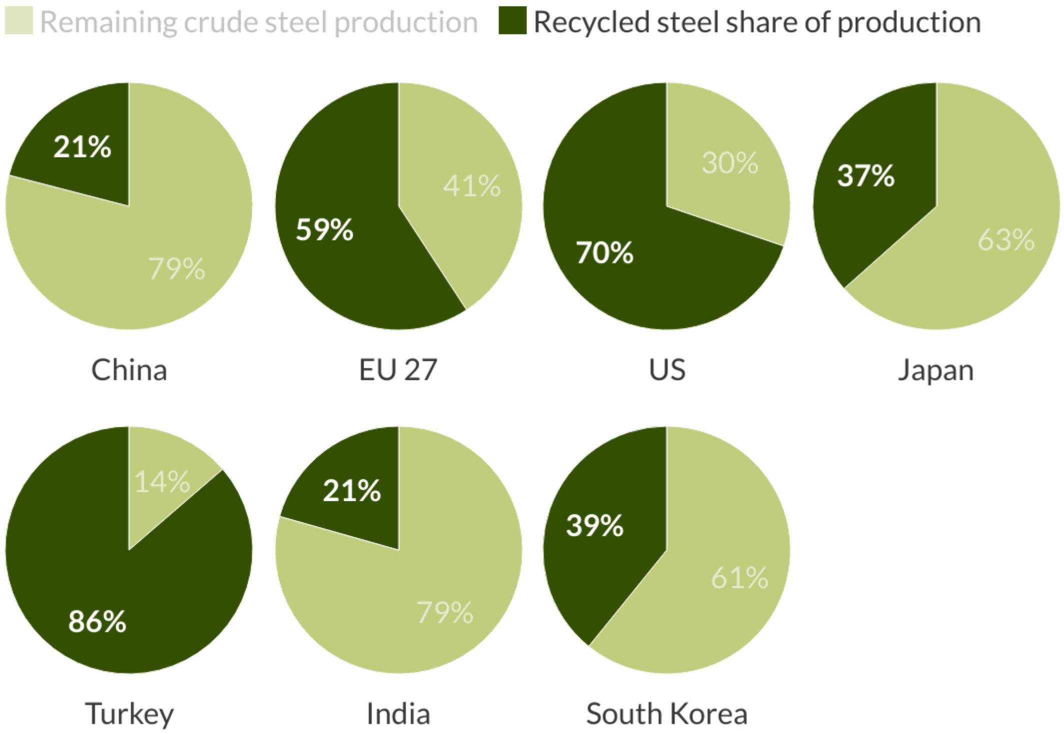

Figure 3. Share of recycled steel use in crude steel production for select countries and regions, 2023. Source: BIR[45]

Japan's potential real zero transformation

Japan's current steelmaking strategy seeks to retain significant carbon-intensive production assets, and lower, capture or offset continuing, or "residual", emissions. The lack of commercially deployed steel sector CCS raises concerns around the abatement potential of this strategy, as outlined in subsequent sections. Continued dependence on fossil fuels in steel production also generates fugitive methane emissions from coal and gas.

Japan's current approach thus implies future reliance on offsets or CO_2 removals (CDR) outside the steel sector to meet Paris goals. Alongside steel demand reduction strategies, Japan would ideally prioritise rapid deployment of production technologies

[45] Bureau of International Recycling, Ferrous Division, *World Steel Recycling in Figures 2019-2023*.

that operate at or near a zero emissions level. With reference to Japan's GX strategy, we call this potential future a "real zero transformation".

Real zero transformation would minimise residual emissions risk and pressure on CDR. But Japanese interests continue to promote carbon-abatement strategies, largely on the grounds that they represent the right balance of climate ambition and protection of international competitiveness. In ignoring the potential for more transformative climate action, the Japan Iron and Steel Federation (JISF) argues that the cost will be "enormous".[46] Meanwhile, GX steel sector guidance notes that:

> "…GX is considered to require significant capital investment, along with higher cost for raw materials and energy. Therefore, it is unlikely that GX will be advanced in the steel industry based solely on economic rationality, at least in the short term."[47]

Production cost is thus the preeminent metric for comparative analysis of Japan's future steelmaking mix. Japanese steelmakers already face competition from cheaper steel in both domestic and export markets (overwhelmingly for primary products). And global steel buyers are currently not paying a recognised "green premium" for more expensive but lower emissions steel (though, according to one industry survey, about half are willing to do so in future[48]).

Given the great challenges associated with residual emissions, we aim to comprehensively test whether real zero can be discounted as a climate solution relative to carbon-abated solutions and, ideally, even BAU production.

We begin by assessing whether the real zero, carbon-abated, and BAU steelmaking options available to Japan can meet technology-neutral emissions benchmarks, representing the limit of climate action estimated as now possible under optimal conditions. Specifically, we use the IEA's "near zero steel" (NZS) definitions:

- for primary steel from 100% iron, generating 400 $kgCO_2$-e/t
- for secondary steel from 100% scrap, generating 50 $kgCO_2$-e/t[49]

Figure 4 shows NZS benchmarks in relation to values for Japanese reference steel plants. These values are adapted from a levelised cost of steel (LCOS) model developed

[46] Dohnomae, "Green Steel Leading the Green Transition: JISF's Activities and JISF Case Study."
[47] Ministry of Economy, Trade and Industry, Government of Japan, *Green Steel for GX: Consolidated Summary of the Study Group on Green Steel for Green Transformation*.
[48] McKinsey, *Global Materials Perspective 2025*.
[49] IEA, "Definitions for Near-Zero and Low-Emissions Steel and Cement, and Underlying Emissions Measurement Methodologies.";

by Transition Asia, which we have modified with our own assumptions and data inputs (see Appendix for more details).

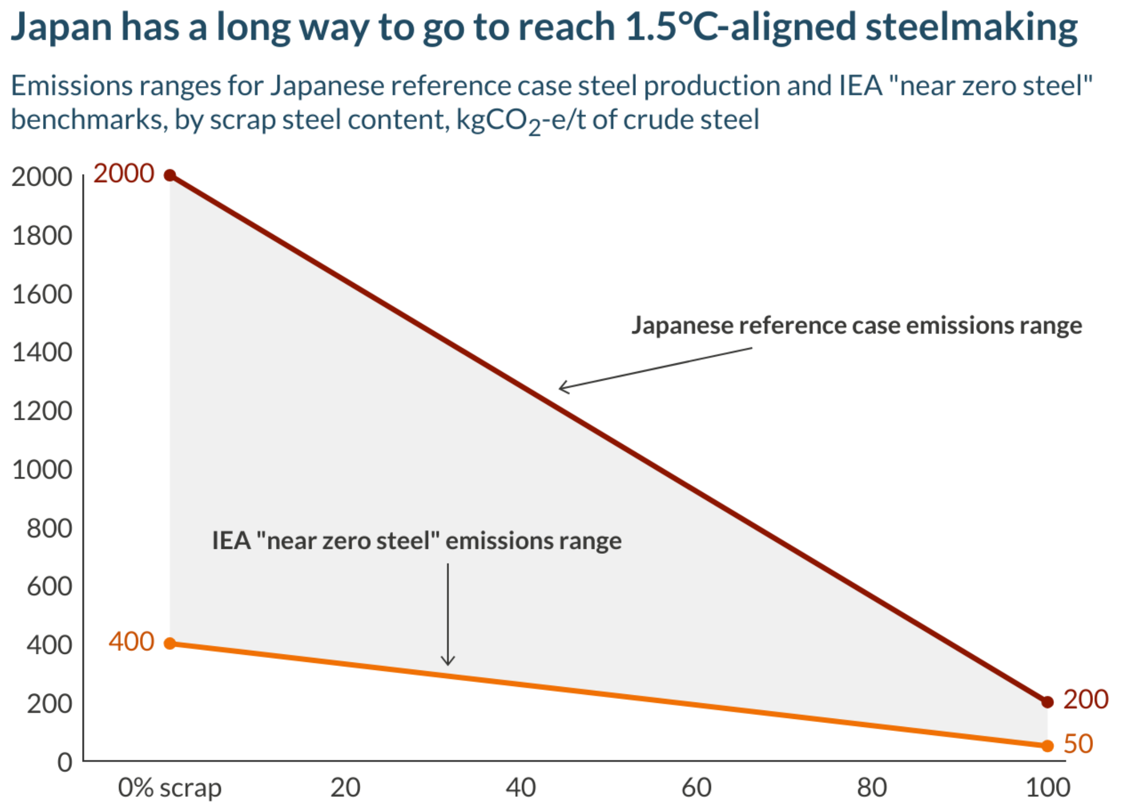

Figure 4. Emissions ranges for Japanese reference case steel production and IEA "near zero steel" benchmarks, by scrap steel content, kgCO_2-e/t. Source: Author's formulation, based on near zero steel benchmarks from IEA[50] and Climate Analytics/Transition Asia LCOS model[51]

Reference case values are already well below global average figures for BF-BOF and scrap EAF production (see "Carbon-intensive BF-BOF production still dominates Japanese steelmaking" above). Japanese steelmakers do enjoy some low emissions advantages over global rivals, including world-leading energy efficiency. But values also represent theoretical best-in-class steel plants, operating under optimal conditions, and with an atypical composition of either 100% scrap or 100% iron inputs. Carbon intensities are calculated with a view to methodology outlined in the IEA NZS documentation.[52] Reference case values should be considered indicative only.

[50] IEA, "Definitions for Near-Zero and Low-Emissions Steel and Cement, and Underlying Emissions Measurement Methodologies."
[51] Climate Analytics modification of Transition Asia LCOS model for Japan
[52] IEA, "Definitions for Near-Zero and Low-Emissions Steel and Cement, and Underlying Emissions Measurement Methodologies."

Table 1 presents some other definitions of near-zero emissions steel (or related concepts), which other organisations have developed in recent years.[53]

Emerging definitions and standards for "near zero steel" or similar

	Product	Approach	Primary steel	Secondary steel
IEA	Crude steel	Sliding scale	**0.4 tCO_2-e/t** (0% scrap)	**0.05 tCO_2-e/t** (100% scrap)
Responsible Steel	Crude steel	Sliding scale	**0.4 tCO_2-e/t** (0% scrap)	**0.05 tCO_2-e/t** (100% scrap)
Low Emissions Steel Standard	Hot-rolled steel	Sliding scale	**<0.52 tCO_2-e/t** Reinforcing and structural: **<0.47 tCO_2-e/t** (both figures 0% scrap)	**<0.17 tCO_2-e/t** Reinforcing and structural: **<0.12 tCO_2-e/t** (both figures 100% scrap)
Climate Bonds Initiative	Finished steel product	Weighted pathway	**1.81 tCO_2-e/t** by 2030 **0.12 t CO_2/t** by 2050	**0.32 tCO_2-e/t** by 2030 **0.12 tCO_2-e/t** by 2050
Global Steel Climate Council	Hot-rolled steel	Product-based pathway	Flat products: **1.31 tCO_2-e/t** by 2030 **0.12 tCO_2-e/t** by 2050 Long products: **1.11 tCO_2-e/t** by 2030 **0.12 tCO_2-e/t** by 2050	N/A
China Iron & Steel Association	Crude/hot-rolled steel	Sliding scale	**0.4 t tCO_2-e/t** (0% scrap)	**0.05 tCO_2-e/t** (100% scrap)

Table 1. Emerging definitions and standards for low-emissions steel. Source: European Commission[54]

[54] European Commission JRC, *Defining Low-Carbon Emissions Steel*.

Beyond basic economic metrics, Japan's emphasis on balancing climate action with maintaining "energy security" and "economic security" also strongly influences its steel production choices.[55] The third section explores these in more detail.

Current approaches will achieve minimal abatement

From the outset, it is clear that Japan's current efforts will struggle to achieve deep decarbonisation of steel. The COURSE50 industry program, a major national R&D project, targets a 30% reduction in BF-BOF emissions intensity, while the SuperCOURSE50 program targets a 50% reduction. The upper estimated emissions savings from hydrogen blending under COURSE50 is 10% and 20% for SuperCOURSE 50.[56] CCS is expected to produce most abatement in each case. But there are considerable obstacles to the success of this technology (see next section "Testing the cost-competitiveness of real zero steel").

Japanese companies are certainly investigating more scrap-based steelmaking and non-BF-BOF-based primary production. But progress is likely to remain slow. Plans by Japan's second-largest steelmaker, JFE, to transition its fleet of seven BF-BOFs to five BFs and one EAF by 2028 is indicative of this.[57] Meanwhile, JISF envisions an industry transition period with "gradual emissions reduction" will last until 2040, with innovative technologies for deep decarbonisation only implemented thereafter.[58]

JISF has also promoted, with Japanese government support, a "corporate mass balance" emissions accounting framework for steel production. Improvements under this scheme are likely to be misleading, in that companies can pool emission reductions across their operations and allocate them to individual products via certificates.[59]

Even if Japan does moves away from BF-BOF dominance, there is a danger of continued incrementalism. Increases in scrap-EAF production could continue to be powered by carbon-intensive electricity. If DRI-EAF primary production emerges as a preferred BF-BOF alternative, it may rely on fossil gas, either unabated or with plant-level CCS, or on abated fossil-sourced "blue hydrogen."

But Japan does have transformational real zero options. For secondary production, scrap-based EAF production could be powered by 100% renewable electricity. For

[55] GR Japan, *Japan's Green Transformation (GX) Plans Updates*.
[56] "Decarbonising the Steel Industry."
[57] Transition Asia team, "JFE AGM 2025 Information Pack."
[58] Dohnomae, "Green Steel Leading the Green Transition: JISF's Activities and JISF Case Study."
[59] Ministry of Economy, Trade and Industry, Government of Japan, *Green Steel for GX: Consolidated Summary of the Study Group on Green Steel for Green Transformation*.

secondary production, there is no option to eliminate emissions at-source in the BF-BOF route – but DRI-EAF production can use renewably produced “green” hydrogen, coupled with 100% renewable-powered EAF steelmaking.

Table 2 outlines technology pathways we consider most likely to inform Japan’s future primary and secondary steelmaking choices, which we assess in the remainder of this report. This includes possible trade variations for DRI-EAF routes, using imported iron, specifically hot briquetted iron (HBI) – an easily handled and transported form of DRI. Under these, HBI is produced with either blue or green hydrogen in optimal locations (those with access to affordable iron ore and either gas or renewable energy), depending on the pathway. HBI is also more easily transported than hydrogen itself.

Each pathway has different implications for emissions, cost-competitiveness, and energy and economic security. The remainder of this report assesses which pathway can produce optimal results across these measures.

Matrix for assessing Japan’s future steelmaking choices

	Business-as-usual (unabated emissions)	Carbon-abated	Real zero (eliminated emissions)
Primary steel	Blast furnace-basic oxygen furnace (BF-BOF)	BF-BOF + CCS	N/A
	Direct reduced iron-electric arc furnace (DRI-EAF)	DRI-EAF + CCS	DRI-EAF + green H_2
		DRI-EAF + blue H_2	DRI-EAF + (green H_2) HBI imports
		DRI-EAF + (blue H_2) HBI imports	
Secondary steel	Scrap EAF (grid electricity)	N/A	Scrap EAF (100% renewable electricity)

Table 2. Matrix used to assess the cost-competitiveness, and impacts on energy and economic security, of Japanese steel production choices in this report.

Testing the cost-competitiveness of real zero steel

In this section, we investigate the cost-competitiveness of three technologies likely to inform Japan's steelmaking future. We consider the levelised cost of steel (LCOS) for reference plants operating under BAU and, where applicable, carbon-abated or real zero pathways. We crosscheck costs against the ability of technologies to meet the relevant IEA NZS emissions benchmarks identified in the previous section.

For carbon-abated pathways, we mainly input different CO_2 capture rates to alter levels of abatement achieved. We also consider fugitive methane implications in some cases.

It is important to note from the start that some assessed CO_2 capture rates we consider are highly unlikely to be achievable. For BF-BOF production, multiple emissions point sources and complex exhaust gas composition create significant CCS barriers. A detailed IEA study found that about 60% of BF-BOF emissions can be captured in a best-case scenario.[60] For DRI-EAF, a capture unit on the vertical shaft furnace exhaust at the Emirates Steel facility in Abu Dhabi can capture 45% of stack emissions but only 27% of total plant emissions.[61] Industry-produced blue hydrogen literature typically promises 90% or above capture rates, which could also prove illusory.[62]

We assume deployment of the production pathways we consider is already technically feasible in Japan as of 2025 and use best available associated cost estimates. As a reminder, assessments reflect best-in-class reference plants under optimal conditions.

We aim to show where real zero production can be cost-competitive starting today. We also take a forward-looking view to 2050 to consider possible cost crossover points. We begin our assessments under current conditions. But we also consider impacts of policy and techno-economic shifts, including increased carbon pricing.

Real zero scrap EAF is already a winner on cost

Our cost analysis reveals that for one Japanese steel production route, scrap-EAF, a real zero pathway can already be more cost-competitive than its BAU, carbon-intensive alternative. Real zero scrap-EAF, which would use 100% renewable electricity sourced

[60] Hooey et al., *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill) - IEAGHG*.
[61] Hare et al., *Hard-to-Abate: A Justification for Delay?*
[62] Schlissel and Juhn, *Blue Hydrogen: Not Clean, Not Low Carbon, Not a Solution*.

through power purchase agreements, can be cheaper than current EAF production using more carbon-intensive grid electricity.

In our model, scrap EAF is estimated capable of emissions intensity as low as 32 kgCO_2-e/t—well below the NZS benchmark for secondary steel, of 50 kgCO_2-e/t. This compares with more than 200 kgCO_2-e/t emissions from BAU production — well outside the NZS benchmark. But emissions benchmarking is not necessary to show real zero's benefits on cost-effective climate action: as of 2025, it would cost 416 USD/t of crude steel, compared with 422 USD/t of crude steel for carbon-intensive BAU scrap-EAF.

This, then, already begins to shift the narrative on real zero, that switching from BAU dependence brings inevitable cost and competition challenges, and carbon-abated production pathways provide the best avenue of minimising this challenge.

Real zero's advantages incentive accelerated uptake of scrap-EAF steel production in Japan. Just as important, there is a need to accelerate Japan's renewable energy buildout to power EAF production. Increased scrap availability, including through export curbs and maintaining high recovery rates, is also needed. In addition, improved material use strategies could extend the market penetration of secondary steel.

However, as already noted, the climate benefits of increased Japanese recycled steel use could easily be offset by declining scrap use elsewhere. Primary production must also be put on a path towards Paris alignment. An EAF buildout could, however, still be beneficial from this perspective, given the ability to accommodate more DRI inputs.

Real zero can outcompete BF-BOF primary production relatively quickly through trade variation

Japan's current economic composition requires considerable ongoing production of primary steel, to produce high-quality products for downstream applications and export customers. Japanese steelmakers face strong competition in both domestic and foreign markets, underlining the imperative of cost-competitiveness.

There is no viable real zero pathway for transforming BF-BOF production, making cost-competitiveness comparisons impossible. However, a real zero pathway does exist for adapting DRI-EAF primary production using green hydrogen and 100% renewables-powered EAF steelmaking. Carbon-abated pathways are also available to modify both BAU BF-BOF production and BAU DRI-EAF production. Comparing emissions and costs across these various primary production pathways is therefore valuable.

According to our LCOS model, there is no time between 2025 and 2050 at which real zero DRI-EAF production using Japanese-produced green hydrogen will overtake BAU BF BOF production on cost when using Japanese-produced hydrogen. But, based on current expectations, the carbon intensity of Japanese BF-BOF production will barely budge by 2050. Much deeper and more rapid carbon abatement would be required to meet climate goals – well in advance of those anticipated under the COURSE50 and superCOURSE 50 programs.

Our model also shows that newbuild BAU BF-BOF production would already be more expensive than newbuild BAU DRI-EAF production in Japan as of 2025 (with a LCOS of 514 USD/t vs 491 USD/t). BAU DRI-EAF production could potentially also halve the emissions of BAU BF-BOF production, to a little over 1000 kgCO_2-e/t (though still remaining well outside the NZS benchmark level).

This already suggests Japanese preferences for retaining BF-BOF production are mostly informed by the cost advantages of operating existing, fully depreciated plants, where capital expenditure does not factor into LCOS assessments. The need for relining to keep BF-BOF production online could negate some of this cost benefit. The cost of BAU BF-BOF production in our model is also anticipated to climb, not fall, in a future carbon-constrained world, reaching 679 USD/t by 2050.

More importantly, to align with the NZS benchmark, BF-BOF production would require considerable costly carbon abatement added to either newbuild or existing plants. This would make newly built plants uncompetitive against rival primary steel pathways when these also operate under the NZS benchmark level – most notably, the trade variation of real zero DRI-EAF, with imported HBI, which is capable of operating well below the NZS benchmark, with as little as 82 kgCO_2-e/t under optimal conditions. Once again, getting either existing or newbuild BF-BOF steel to the NZS benchmark would also require unrealistic assumptions about CO_2 capture rates.

Japan's BAU primary steel production is artificially cheap through unpriced emissions

Levelised cost of steel for primary steel production routes, including BAU, carbon-abated, and real zero pathways in Japan, 2025 estimate, USD/t of crude steel

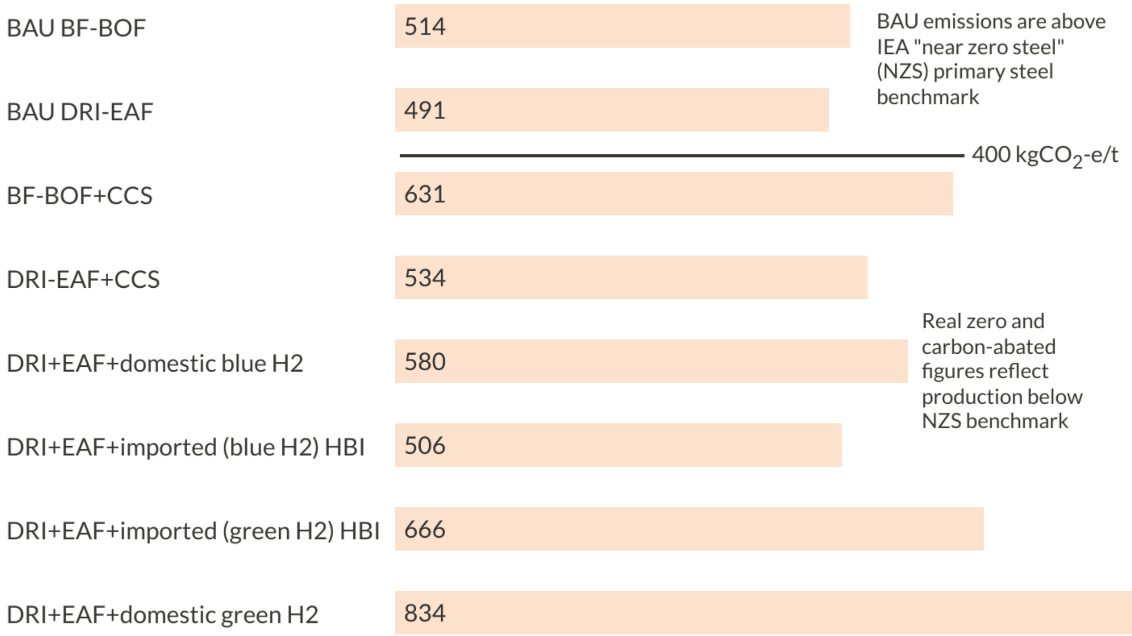

Figure 5. Levelised cost of steel (LCOS) for primary steel production routes in Japan, including business-as-usual, carbon-abated, and real zero pathways, 2025 estimate, USD/t of crude steel. Source: Climate Analytics/Transition Asia[63]

Figure 5 shows the cost estimates for BOF-BF and DRI-EAF production routes, including their unabated BAU, and real zero and carbon-abated pathways – with the latter two operating under the NZS benchmark – assessed as of 2025.

With CCS capturing just 60% of emissions, our reference case BF-BOF plant would still generate about 800 $kgCO_2$-e/t of crude steel – well outside the necessary range. To fall to the 400 kgCO2-e/t NZS benchmark, CCS would need to capture more than 80% of emissions. This is highly unlikely and, on present day estimates, it would also push production costs from 514 USD/t to 631 USD/t.

At a 631 USD/t cost, carbon-abated BF-BOF would be almost as expensive as trade-varied real zero DRI-EAF with imported HBI, which is assessed to cost 666 USD/t under present conditions.

[63] Climate Analytics modification of Transition Asia LCOS model for Japan

With iron trade, real zero could quickly outcompete Japan's carbon-intensive BF-BOFs

Levelised cost of steel for real zero DRI-EAF vs BAU and carbon-abated BF-BOF pathways for primary steel production in Japan, USD/t, 2025-2050

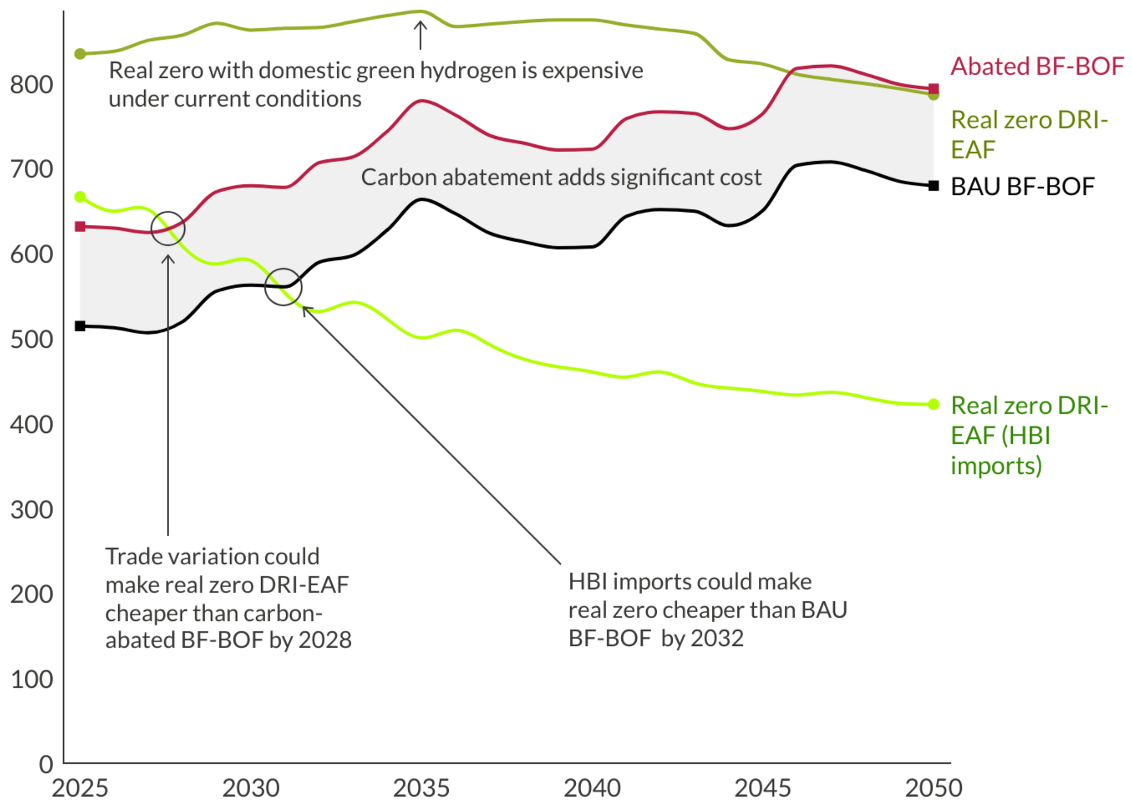

Figure 6. Levelised cost of steel for real zero direct reduced iron-electric arc furnace (DRI-EAF) vs business-as-usual (BAU) and carbon-abated blast furnace-basic oxygen furnace (BF-BOF) primary steel production, USD/t, 2025-2050. Source: Climate Analytics/Transition Asia[64]

Projected cost reductions could in turn see trade-varied real zero DRI-EAF become cheaper than carbon-abated BF-BOF production by 2028 (608 USD/t compared with 636 USD/t). This real zero route could, indeed, become more competitive than even unabated BAU BF-BOF production by 2032 (see Figure 6).

These assessments also do not fugitive methane emissions tied to coal and gas use into account. If these fugitive emissions, assessed at current levels, were factored into emissions benchmarking, plant level CCS would need to capture an even more improbable 95% of emissions to bring BF-BOF production below the NZS benchmark.

Another necessary caveat is that current CCS cost assessments in our model (in the range of 40-100 USD/tCO_2) do not consider CO_2 transportation, storage and

[64] Climate Analytics modification of Transition Asia LCOS model for Japan

monitoring costs. These could add an additional 20-100 USD/tCO_2-e depending on storage location (figure based on shipping for transportation).[65]

These assessments suggest there is no room for sustained BF-BOF production if Japan is to achieve cost-competitive deep decarbonisation of steel. Ambitious emissions reduction would require very high CCS capture rates, which, even if they could be achieved, would make production uncompetitive with alternative routes. This conclusion is already apparent under near-term cost estimates. This should influence decision-making on the future of BF-BOF capacity.

While our assessments do not consider the cost advantages of established BF-BOF capacity, these assets would still require very high CCS capture rates to achieve suitable decarbonisation, adding significant cost even if retrofitted. Supporting these conclusions, Bachorz et al. (2025) find that BF-BOF steel plants (fully depreciated and recently relined) retrofitted with CCS can be a more cost-effective solution than green hydrogen-based DRI-EAF only for "incomplete" mitigation, and up to a certain hydrogen cost (given as 50 EUR/MWh in the study).[66]

BF-BOF retrofitted with CCS loses significant cost-competitiveness when achieving "full" mitigation as required by the Paris Agreement. In this scenario, the breakeven point with green hydrogen DRI-EAF more than triples, to 150 EUR/MWh (for newbuild BF-BOFs, it reaches 230 EUR/MWh). Bachorz et al. conclude that "while retrofitting CCS can be an economical abatement option in the short term…full mitigation…is often more cost-effective with newly built H2-DRI-EAF."[67]

It is important to reiterate that the CO_2 capture rates needed to bring the BF-BOF route below the NZS benchmark are likely beyond the realm of technical achievement in any timeframe. Meanwhile, a real zero primary steel option – green hydrogen-based DRI-EAF with imported HBI – is already worthy of investment in Japan today. And, once again, an EAF buildout could complement more scrap-based steelmaking.

Real zero can also compete in the remaining steel battleground: DRI-EAF for primary production

We have outlined how BF-BOF steelmaking is unlikely to align with Japan's climate goals, particularly not in a cost-competitive manner. This means Japan will need to

[65] DNV, *Potential for Reduced Costs for Carbon Capture, Transport and Storage Value Chains (CCS).*
[66] Bachorz et al., "Exploring Techno-Economic Landscapes of Abatement Options for Hard-to-Electrify Sectors."
[67] Bachorz et al., "Exploring Techno-Economic Landscapes of Abatement Options for Hard-to-Electrify Sectors."

embrace other primary production technologies, most likely DRI-EAF, in future. Japan could pursue the DRI-EAF route under its current carbon-abated preferences or through a real zero approach.

The emissions vs. cost battle is fiercest when confined to the DRI-EAF route. If Japan were to favour domestically produced green hydrogen, real zero would again remain prohibitively expensive against BAU production and even carbon-abated pathways. According to our model, DRI-EAF production with Japan-produced green hydrogen, could still cost about 786 USD/t in 2050 under current policy settings.

However, real zero can again quickly become relatively cost-competitive even against BAU DRI-EAF, with trade variation. In our model, real zero DRI-EAF with HBI imports would cost 522 USD/t of crude steel by 2034, at which point it would be cheaper than gas-based BAU DRI-EAF with unabated emissions, at 569 USD/t.

Carbon-abated gas DRI-EAF might achieve NZS benchmark emissions with a CO_2 capture rate of about 60%. This performance level could again be overambitious. In any event, its extra costs could make it more expensive than real zero DRI-EAF with imported HBI slightly earlier than for unabated BAU DRI-EAF, around 2033 (see Figure 7).

Blue hydrogen-based DRI-EAF is assessed as able to achieve more significant carbon abatement than direct fossil gas-based DRI-EAF, which utilises plant level CCS. The most optimistic scenario sees steam methane reformation coupled with CCS capture 90% of emissions from fossil gas, to produce abated blue hydrogen. Under optimal conditions, using blue hydrogen for energy and reduction could allow carbon-abated DRI-EAF production with less than half NZS benchmark emissions for primary steel.

In our LCOS model, carbon-abated DRI-EAF with Japan-produced blue hydrogen is assessed to be significantly cheaper than real zero DRI-EAF produced with Japanese green hydrogen – 580 USD/t compared with 834 USD/t as of 2025. While this cost gap is expected to narrow over time, it is not expected to close by 2050. Trade variation through imported HBI made with blue hydrogen abroad could further lower costs, to 506 USD/t as of 2025. As of 2025, costs for the two blue hydrogen-based DRI-EAF costs are both also lower than the 666 USD/t for trade-varied real zero DRI-EAF.

However, even with trade variation, Japan's blue hydrogen-dependent carbon abated DRI-EAF production is not on a trajectory to outcompete trade-varied real zero DRI-EAF (with imported HBI) in the longer-term. CCS costs, combined with increased fossil gas prices in a carbon-constrained world, put carbon-abated options on a more volatile trajectory. Real zero pathways, by contrast, are likely to benefit from more cost reductions and efficiency improvements in solar, wind, batteries, electrolysers, and iron production technologies, including in optimal HBI production and export locations.

Real zero can outcompete DRI-EAF rivals only slightly later than BF-BOF rivals

Levelised cost of steel for real zero vs BAU and carbon-abated pathways for DRI-EAF primary steel production in Japan, USD/t, 2025-2050

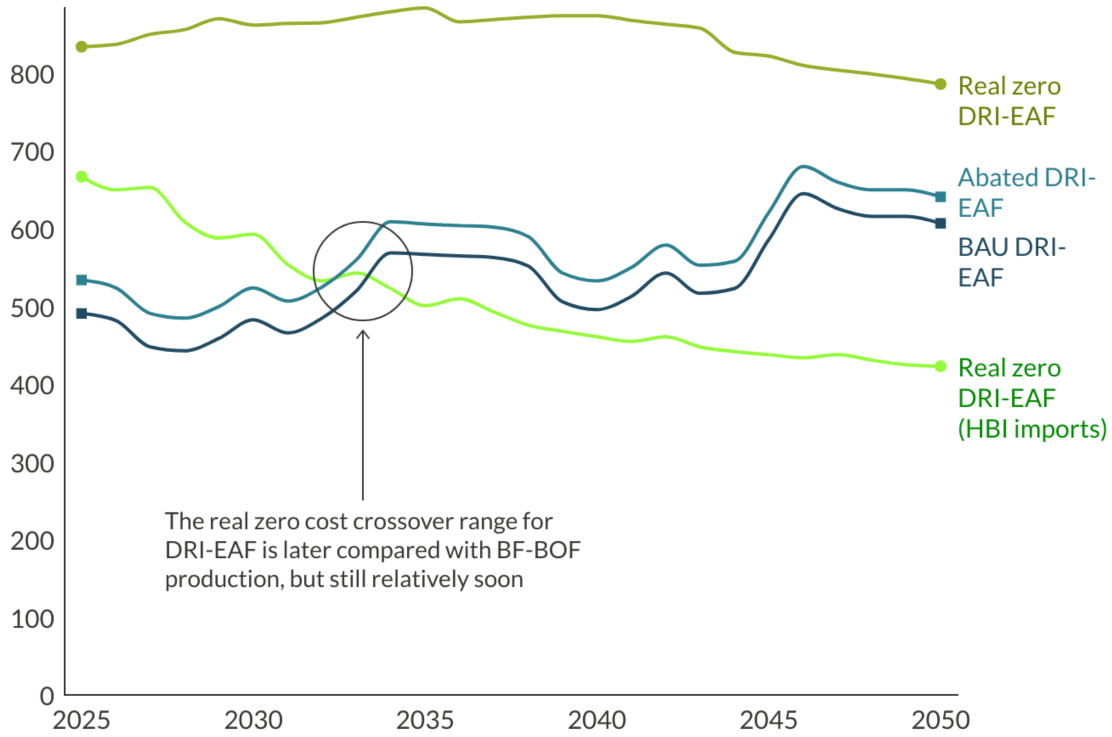

Figure 7. Levelised cost of steel for real zero vs business-as-usual (BAU) and carbon-abated pathways for direct reduced iron-electric arc furnace (DRI-EAF) primary steel production in Japan, USD/t, 2025-2050. Source: Climate Analytics/Transition Asia[68]

In our LCOS model, trade-varied real zero DRI-EAF with imported HBI can overtake carbon-abated DRI-EAF production with Japan-produced blue hydrogen by 2032 (531 vs 574 USD/t). Trade-varied green hydrogen-based real zero DRI-EAF can in turn reach cost parity with trade-varied blue hydrogen-based carbon-abated DRI-EAF by roughly 2035 (when both would cost 500 USD/t), before becoming cheaper out to 2050.

Large caveats must again be applied to fossil gas and fossil hydrogen-based steelmaking. As shown above, CCS infrastructure is unlikely to perform to industry-claimed standards. Fugitive methane emissions also pose considerable and largely unaddressed challenges.

[68] Climate Analytics modification of Transition Asia LCOS model for Japan

Techno-economic shifts, aided by policy, could bring real zero crossover points closer

So far, we have assessed costs under current conditions. Additional changes, led by strong carbon pricing, could further swing the balance in real zero's direction. For example, our model shows that even a modest additional carbon price of 15 USD/tCO_2 could make trade-varied real zero DRI-EAF reach parity with unabated BAU BF-BOF production (at 593 USD/t) by 2030 – two years earlier than currently anticipated.

A 50 USD/t carbon price would bring forward the crossover point for trade-varied real zero DRI-EAF and unabated BAU BF-BOF to 2028 (when real zero would cost 612 USD/t vs 622 USD/t for BAU BF-BOF). Meanwhile, an 80 USD/t carbon price – around the level currently generated in the European Union Emissions Trading System – could make trade-varied real zero cheaper than BAU BF-BOF as of 2025 (673 USD/t for real zero; 680 USD/t for BAU BF-BOF).

Carbon pricing can bring forward real zero's cost-competitiveness

Date when Japanese real zero DRI-EAF (HBI imports) could reach cost parity or below with BAU production for BF-BOF and DRI-EAF, by carbon price, USD/tCO_2

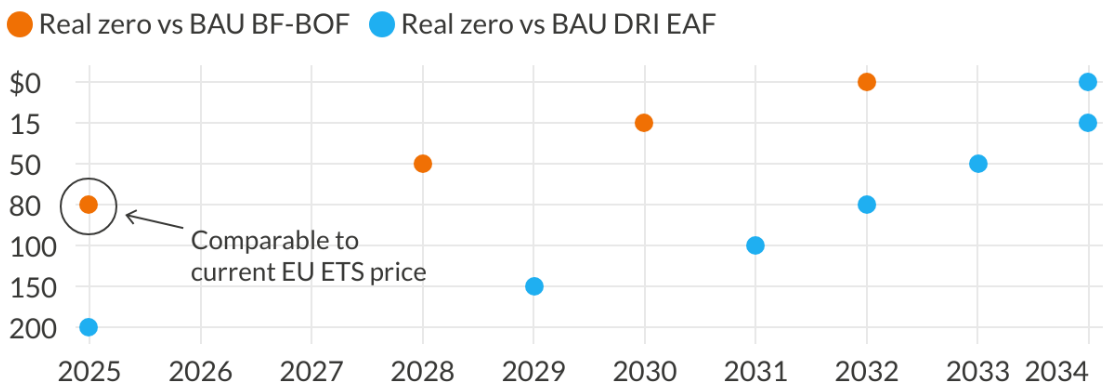

Figure 8. Date at which Japanese real zero steel production (green hydrogen direct reduced iron-electric arc furnace with hot briquetted iron imports) could reach cost parity or below with business-as-usual blast furnace-basic oxygen furnace and direct reduced iron-electric arc furnace production, under different carbon pricing scenarios. Source: Climate Analytics/Transition Asia[69]

A carbon price of 80 USD/tCO_2 would also make trade-varied real zero DRI-EAF cheaper than the unabated BAU DRI-EAF production route by 2032 (538 USD/t vs 561 USD/t) – two years earlier than under current conditions. A 100 USD/t carbon price would make 2031 the cost parity point for these two technologies (both at 561 USD/t),

[69] Climate Analytics modification of Transition Asia LCOS model for Japan

with trade-varied real zero becoming cheaper thereafter. A more significant carbon price of just under 200 USD/t would be required to make trade-varied real zero DRI-EAF cheaper than BAU DRI-EAF under today's conditions.

More dramatic interventions could close the gap between domestic real zero and alternative technologies

The above assessments clearly outline how trade variation in the form of imported green HBI is key to making real zero steel cost-competitive with alternatives in Japan. As noted in the next section, embrace of this trade variation of HBI imports for green hydrogen-based DRI-EAF production not come at the expense of Japan's energy or economic security concerns. However, Japanese industry stakeholders and officials might prefer to maintain a more domestic value chain.

Under current conditions, Japan retaining an iron and steel value chain in green hydrogen-based production would entail significant additional costs and could undermine profitability. Carbon pricing would need to be very significant to close the gap with BAU steel production. A carbon price of 100 USD/t would not make domestic green hydrogen-based DRI-EAF cheaper than BAU BF-BOF until 2044 (827 vs 834 USD/t). Even a price of 200 USD/t would leave BAU DRI-EAF out of range by 2050 (763 vs 787 USD/t for real zero).

Putting legitimate doubts about CO_2 capture rates to the side for the moment, emissions benchmarking can makes things more, not less challenging, for real zero under high carbon price scenarios, as CO_2 avoidance costs and total LCOS become comparatively lower for carbon-abated pathways.

Greater-than-anticipated reductions in major input costs, led by green hydrogen, would be needed to ensure Japan can cost-competitively pursue more domestically focused real zero DRI-EAF. The levelised cost of green hydrogen (LCOH) in our model is about 7.60 USD/kg as of 2025, falling to about 5 USD/kg by 2050. If the LCOH instead started at 5 USD/kg in 2025 and fell to about 3.30 USD/kg by 2050, it would significantly lower the total LCOS of domestic real zero DRI-EAF.

On this alternative green hydrogen cost curve, a carbon price of 50 USD/t could see domestic green hydrogen-based real zero DRI-EAF become cheaper than unabated BAU BF-BOF by 2034. An 80 USD/t carbon price could see crossover between these two technologies achieved as of 2025. Policy interventions, such as increased hydrogen production subsidies, could help usher in these types of conditions.

More expensive production could still find a market

In addition, when considering how steel costs are passed through to final consumers, more expensive production would not necessarily need to result in a large "green premium" relative to higher emissions production.

Our estimate of the current price for domestically produced green hydrogen DRI-EAF In Japan is 834 USD/t, compared with 514 USD/t for BF-BOF production. This equates to a green premium of 320 USD/t of crude steel. For an average passenger car using about 0.9 tonne of steel, this would raise the praise by 288 USD/t, or about 1.5% for an average priced car of 20,000 USD.[70] Under a reduced hydrogen cost of 5 USD/kg, the final green premium for a passenger car would be less than 1% at present.

Government and industry action could help lower the green premium. Policy interventions such as hydrogen production subsidies and stronger carbon pricing could reduce the difference between low and high emissions hydrogen production, as the critical price determinant in real zero DRI-EAF.

Green public procurement and private buyers club commitments could first absorb the green premium, then help to steadily lower it. Early demand can improve the "bankability", or financial viability, of low emissions production, leading to enhanced economies of scale, learning rates, and cost reductions.

The same logic might apply to the cost pass-through of carbon-abated production achieved with the addition of expensive CCS. But appropriately robust emissions assessments and product certification regimes – unlike the corporate mass balance approach favoured by JISF – would discredit any claims to this being a genuine green premium. As we have shown, carbon-abated pathways cannot achieve the same emissions mitigation as real zero in a cost-effective manner.

Future breakthroughs are also possible

We have also focused on what we see as the most likely options for Japan's future steel mix. But steelmakers and technology providers are also investigating numerous other production methods. POSCO is exploring non-agglomerated iron ore for hydrogen-based DRI in a fluidised bed reactor.[71] Primetals is exploring a similar technology.[72] Other producers are re-purposing rotary kilns to work with 100% hydrogen.[73] Fortescue

[70] Transition Asia, "Green Steel Economics - Japan Factsheet."
[71] POSCO, "Hyrex - POSCO."
[72] Primetals, "Hydrogen-Based Ironmaking Plant to Be Implemented in Linz."
[73] HyIron, *Technology & Product*.

is investigating electric smelting furnaces to allow lower-quality iron ore use.[74] Both high and low temperature electrolysis options could also lead to emissions-free steelmaking.

These technologies are still in development, and do not have publicly available capital and operational expenditure figures, including in the Japanese context. However, there is a possibility they could further shift the narrative around the economic benefits of real zero production in the future.

Conclusion: the cost-competitiveness case against real zero does not hold up

Based on our assessments, the cost-competitiveness case against real zero ultimately holds only where it is incorrectly assumed that retention of BAU production capacity, or use of carbon-abatement technologies, can produce suitably ambitious climate action. We have shown that this is not the case. Real zero production can be an affordable and preferable route to genuine 1.5°C-alignment for the Japanese steel sector.

For secondary steel production, a commercially viable real zero technology is already the most economically appealing. Production of scrap steel in an EAF powered by 100% renewable energy can generate minimal emissions and can be cheaper than the BAU alternative of scrap-based steel reliant on the current grid.

For primary steel production, the trade variation of green hydrogen-based DRI-EAF production, using HBI imports, can make real zero cost-competitive against unabated BAU BF-BOF production by 2032 and unabated BAU DRI-EAF production by 2034.

And carbon abatement costs for both the BF-BOF and DRI-EAF production routes will bring forward the dates at which real zero production can be more cost-competitive. Once again using the trade variation of HBI imports, green hydrogen-based DRI-EAF could compete with carbon-abated BF-BOF by 2028 and carbon-abated DRI-EAF by 2033.

These Japanese primary and secondary steel assessments suggest that investing in real zero solutions is worthwhile starting today. While domestically produced green hydrogen-based DRI-EAF steel is likely to remain expensive in the long-run, there are also options for Japan to create market opportunities for this technology if desired.

Real zero investment remains desirable even if accounting for the lower cost of production from existing BF-BOF assets, which we have not explicitly modelled. BF-

[74] Fortescue, “Green Iron Metal Project.”

BOF can only achieve deep decarbonisation through very high and likely unrealistic assumptions around capture rates for carbon abatement. Further developments, including carbon pricing and consideration of fugitive methane emissions, could further erode Japan's ability to balance cost and climate considerations under the current steelmaking mix. Costs incurred in attempting to avoid stranded assets – such as relining blast furnaces— can be considered wasted from this perspective.

The energy and economic security impacts of real zero transformation

In this section, we consider how Japan's BAU, real zero, and carbon-abated steelmaking choices intersect with the energy security and economic security considerations that also influence national industrial decision-making.

The cost assessments performed in the previous section remain highly relevant to this discussion. These were influenced by the relative cost of energy, materials, and capital for different production methods.

Japanese energy and economic security strategies prioritise servicing certain national ideals, which go beyond what markets alone can deliver. Analysts have, for example, cited steel's strategic importance in generating jobs and national security-enhancing manufacturing and construction as guaranteeing future government support.[75] But realising these outcomes remains dependent on having affordable inputs.

Japan's security concerns also seek "resilience" of energy and material supply chains. This is a less directly measurable value than cost. But it is important to still assess some related claims against the viability of real zero. If dismissed as unfalsifiable, security arguments can be used to justify continued BAU or carbon-abated production.

Energy and economic security in the Japanese context

Energy security is most simply defined as "uninterrupted availability of energy sources at an affordable price", though some definitions also incorporate the need to meet

[75] Bowen, *Toward Comprehensive Green Security for Asia and the Pacific*.

environmental objectives.[76] Yet, even without environmental considerations, energy security and climate action are not mutually exclusive.[77] That is, countries can achieve or even enhance the affordability and availability of energy supplies while decreasing fossil fuel use.

Renewable energy is more domestically available and also becoming cheaper than fossil fuels in most locations.[78] Electrification of fossil fuel combustion also lowers energy demand and the complications tied to it: fossil fuel inefficiencies are largely responsible for an estimated two-thirds of primary energy being wasted across production, transportation, and use on a global basis.[79]

Yet, despite being almost entirely dependent on imports for fossil fuels, Japanese officials and policy documents mostly seek security *in* rather than *from* fossil fuels.[80] Following the 2021 Russia-Ukraine-linked energy market chaos, Japan has mostly promoted fossil fuel ties with "trusted" export partners – prominently Australia.[81]

Japan's fossil-based energy security thinking is likely informed by its fears of becoming economically uncompetitive under what can be considered real zero energy and economic systems. Research has shown Japan can cost-competitively replace fossil fuels in the power sector.[82] However, as trade variations in our steel LCOS assessment showed, Japan will be less competitive against rival countries deploying renewables and green hydrogen in trade-exposed, energy-intensive sectors such as steel.

These energy security dynamics bleed into Japan's economic security concerns. Japan's energy choices often seek concurrent leadership in related technology markets. This already appears a mark against real zero, inasmuch as Japanese stakeholders have mostly sought to pursue opportunity in sectors such as gas, CCS, and blue hydrogen.[83]

Japan's *Economic Security Promotion Act* of 2022 seeks enhanced protection against genuine economic threats, but also the sort of changing global economy that climate change necessitates.[84] A 2025 national economic security action plan noted the need to

[76] Ang et al., "Energy Security."
[77] Bowen, *Toward Comprehensive Green Security for Asia and the Pacific*.
[78] IRENA, "Renewable Power Generation Costs in 2023."
[79] Walter et al., *The Incredible Inefficiency of the Fossil Energy System*.
[80] Cahill et al., *How Japan Thinks about Energy Security*.
[81] Bowen, *Toward Comprehensive Green Security for Asia and the Pacific*.
[82] Shiraishi et al., *The 2035 Japan Report: Plummeting Costs of Solar, Wind, and Batteries Can Accelerate Japan's Clean and Independent Electricity Future*.
[83] Budgen, "Japan Uses 'Diplomatic Muscle' to Push Carbon Capture as Fossil Fuel Panacea."
[84] "Act on the Promotion of Ensuring National Security through Integrated Implementation of Economic Measures - English - Japanese Law Translation."

maintain competitiveness in steelmaking, steel-using sectors such as shipbuilding, and steel-linked "decarbonisation technologies" such as hydrogen.[85]

Many issues which cause Japan to experience energy security anxiety can induce broader economic security anxiety. Japan is again almost entirely dependent on imports of iron ore and coal for BF-BOF steelmaking, adding costs and supply chain insecurities relative to domestic production.[86] Finished steel imports have also risen in recent years, suggesting long-term threats to domestic market share.

Figure 9 shows that energy and resources, including major steelmaking inputs coal, iron ore, and fossil gas – which would become more important under gas-based DRI-EAF pathways – account for a large share of Japan's goods imports, influencing related security concerns.

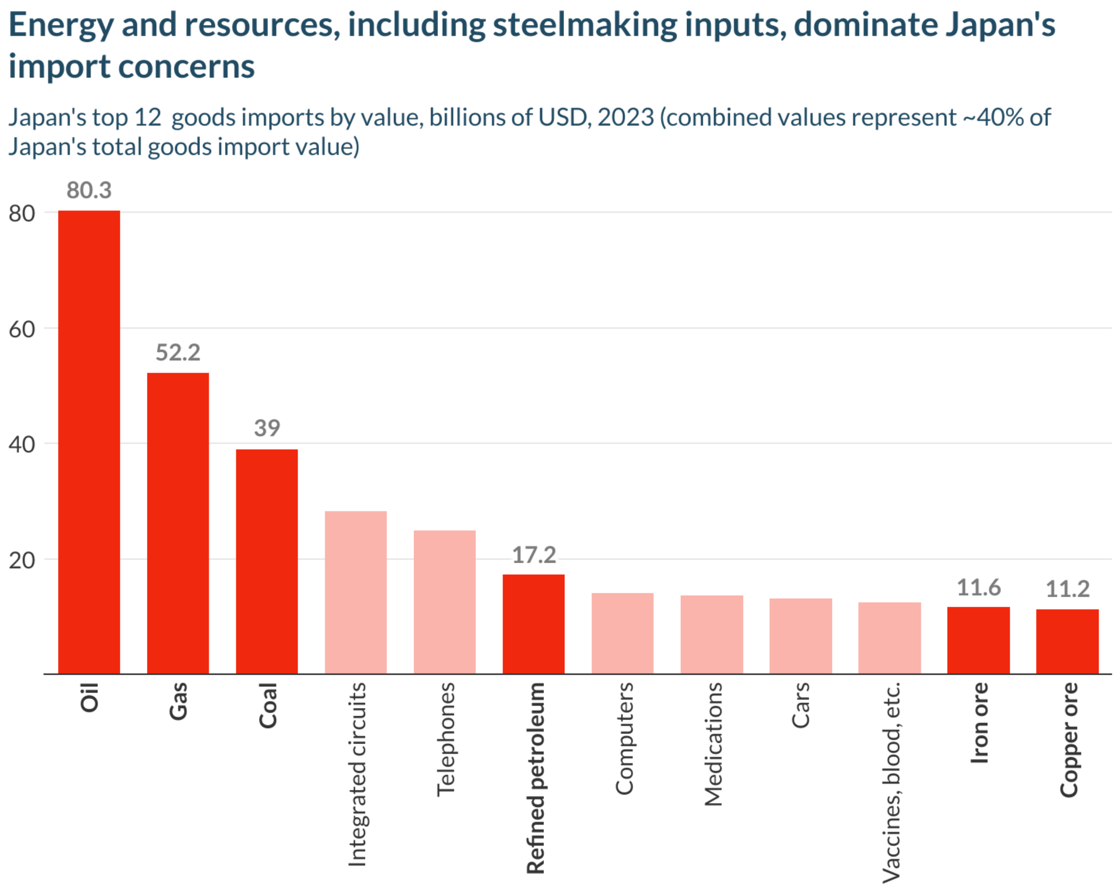

Figure 9. Japan's top 12 goods imports by value, billions of USD, 2023 (combined values represent ~40% of Japan's total goods import value). Source: Harvard Growth Lab[87]

[85] "Revised Edition of the Action Plan to Strengthen Industrial and Technological Basis for Economic Security Released."
[86] World Steel Association, *2025 World Steel in Figures*.
[87] Harvard Growth Lab, "The Atlas of Economic Complexity."

Real zero need not clash with energy and economic security

Japanese policy documents mostly question the energy and economic security implications of decarbonisation on the basis that it threatens security strategies which are carefully calibrated towards protecting BAU development – or emerging carbon-abated preferences. Disruption of these arrangements is considered a *prima facie* security threat. Once again, however, this assumes that BAU or carbon-abated production can be consistent with the necessary pace of emissions reduction.

Our assessments of the cost and emissions interactions of Japan's future steelmaking choices already suggest that real zero production is not in tension with energy or economic security, if assuming ambitious climate action. The cost-competitiveness of real zero production is, in large part, a function of the proven cost-competitiveness of its energy, material and technology inputs. Real zero production pathways are, by extension, best able to futureproof Japanese steelmaking and the interests tied to it.

Real zero might even enhance energy and economic security

There are, at the same time, many discrete energy and economic security advantages apparent in real zero steelmaking vs. carbon-abated and even BAU options.

The emissions and relative cost advantages of real zero scrap-based EAF, for example, incentivise that it be scaled up. Scrap-based steelmaking can use less than a tenth of the 20 GJ/t or more energy use in the BF-BOF route.[88] If achieving a fully renewable electricity supply, Japan would also be able to considerably reduce its fossil fuel imports.

As a recycled product, secondary steel is also more materials efficient and inherently "secure" than primary steel, that is, it can use both less and more domestically sourced material, in the form of scrap steel (including through potential curbs on exports and improved material recovery rates) in place of imported coal and iron ore.

Japan will still need significant primary steel to meet both domestic and export needs. There would also be energy security benefits to pursuing the most cost-competitive real zero method here, using imported green HBI for DRI-EAF production. This would mean offshoring energy-intensive ironmaking to countries with greater renewable energy and green hydrogen advantages, coupled to iron ore mining. Japan would correspondingly offshore energy security concerns around producing or importing hydrogen. Real zero could help Japan significantly reduce its energy needs, given that about 80% of energy in primary steelmaking currently comes from ironmaking.[89]

[88] IEA, *Iron and Steel Technology Roadmap*.
[89] Sun et al., "Material and Energy Flows of the Iron and Steel Industry."

By embracing green HBI imports, Japanese steelmakers would also see economic security improvements relative to the counterfactual of moving too slowly on climate. They would be able to gain and/or retain market share in a decarbonising market. Importantly from the economic security perspective, they could also retain about 90% of total sector jobs, which are concentrated at the final stage of production.[90]

Wholly domestically-focused real zero primary steel production will remain expensive in Japan under currently anticipated conditions. However, if Japanese stakeholders value the economic security benefits of retaining more of the steelmaking value chain, they could also devote more policy support to enhancing the cost-competitiveness of domestic green hydrogen production and related DRI-EAF. Enhanced carbon pricing, increased hydrogen production subsidies, and support for genuine green premiums could help achieve this.

On the technology leadership front, we have shown that CCS in steelmaking has limited ability to cost-competitively reduce emissions. Japan would also need to establish new foreign partnerships to store its captured CO_2, given its limited domestic capacity. It has faced pushback from some destinations due to supposed "carbon colonialism".[91]

Green hydrogen technology leadership would be a preferable option. Japanese conglomerates such as Kobe Steel, Mitsubishi Heavy Industries, and Primetals, and trading houses such as Mitstui and Sumitomo, have considerable interests in production and supply chain development tied to hydrogen and hydrogen-based DRI, albeit with interests in fossil- alongside renewable-based production at present. Institutions such as the Japan International Cooperation Agency could also play an improved role in mobilising real zero steel-linked investment.

Japan's necessary partners in real zero steelmaking can also be "trusted". There is little anticipated need for increased dependence on China – a major source of Japanese anxiety – in any of our identified cost-competitive steel production pathways. There is, on the other hand, significant potential for enhanced cooperation between Japan and Australia, a favoured Japanese energy partner on fossil fuels, and also a prospective producer and exporter of cost-competitive green HBI.[92]

At the macro level, real zero transformation promises lower costs and more rapid climate action. This suggests public or private expenditure on alternative endeavours

[90] Agora Industry, *15 Insights on the Global Steel Transformation 15 Insights on the Global Steel Transformation*.
[91] Oil Change International, "Funding Failure."
[92] Bowen and Wyche, *Australia's Green Iron Key: Unlocking Asian Steel Decarbonisation, Securing Australia's Economic Future*.

will be unproductive. By extension, it will be unproductive to maintain energy and economic security strategies tied to other pathways. Japan could avoid considerable continued investment in areas such as CCS, gas, and blue hydrogen, and in propping up BAU steel production. It could divert these resources to productive real zero outcomes.

Implications for transforming Japanese steel

The conclusion of our assessments is that Japanese steelmakers, supported by the Japanese government, should embrace real zero transformation. Real zero production can be cost-competitive while achieving ambitious emission reductions in a manner that carbon-abated alternatives cannot. Real zero production even has options for outcompeting BAU emissions-intensive production on cost.

Where cost competitiveness is more difficult to achieve immediately or under currently anticipated conditions, policy interventions might help change the calculus. There is also potential for market conditions to shift, including through government intervention, to recognise green premiums for steel production that is on a zero emissions track.

Real zero production in the form of 100% renewable-powered scrap EAF can already provide the lowest cost pathway for secondary steel production. Renewable scrap EAF could also help replace some primary steelmaking capacity.

New primary steel options will still be required, but there are already cost-competitive options here, most notably green hydrogen DRI-EAF with imported HBI from more cost-competitive locations. The competitiveness of this route could arrive even quicker with further policy interventions, such as stronger carbon pricing.

Wholly domestically focused real zero primary steel production remains expensive under currently anticipated conditions. However, the cost-competitiveness of these pathways could also be improved through policy interventions such as increased carbon pricing and hydrogen subsidies. The green premium of these routes is also relatively minor when passed through to final consumers.

There is also no inherent tension between Japan pursuing real zero transformation and maintaining energy security and economic security. The proven cost competitiveness of real zero is to a large extent a function of the proven affordability of its energy and material inputs.

Further, real zero production can improve the resilience of Japan's energy and economic systems. This includes reducing national needs for imported energy and materials (in favour of domestic equivalents) and reducing the energy and materials intensity of industrial production in general. Moreover, investment in pathways that are proven to align with ambitious climate action are most assured to be productive uses of finite resources. They can help future proof Japanese steel production – and the economic and strategic values tied to it – against future domestic and external pressures.

The implications for the Japanese steel sector include the need to:

- expedite retirement of BF-BOF production, avoiding residual emissions and economic costs tied to sustained investment
- scale up 100% renewables-powered EAF steelmaking to the greatest degree possible
- promote cost-competitive real zero primary steelmaking, led by green hydrogen-based DRI-EAF production with HBI imports from optimal locations
- extend policy support to other real zero DRI-EAF pathways to lower costs/attract and eventually lower green premiums, and remain aware of alternative, potentially lower cost primary real zero production routes
- ensure full accounting of emissions and related cost implications of BAU, carbon-abated, and real zero production routes, including with respect to upstream methane and CCS abatement
- tailor future energy and economic security perspectives and strategies to meeting the needs and realising the opportunities of real zero production

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Appendix

Calculating the levelised cost of steel (LCOS) in Japan

We use and modify a levelised cost of steel (LCOS) model, and Japan-specific input values, developed by Transition Asia for its Green Steel Economics project.[93] This LCOS model also informs TransitionZero's TZ-OSeMOSYS-STEEL modelling of cost-optimal scenarios for decarbonising Japanese steel.[94]

The LCOS model considers the cost, in USD, of producing a tonne of crude steel from BF-BOF, DRI-EAF, and scrap EAF routes, operating under BAU, carbon-abated, and real zero conditions. The model inputs Japan-specific assessments of average capital and operational expenditure over the operating lifetime of a newly built reference case steel plant. The model includes projected LCOS to 2050, based on anticipated input changes, represented in present day values.

Our model also calculates the emissions intensity of producing one tonne of steel from the BF-BOF, DRI-EAF, and scrap EAF routes, operating under BAU, carbon-abated, and real zero conditions, using emissions factors applied to energy and material inputs. Two different emissions intensity calculations are provided. We mainly use one that does not include fugitive methane emissions but consider it where relevant.

The model also allows for varying CCS capture rates and carbon pricing levels. We alter CCS capture rates to assess where carbon-abated production pathways might meet a benchmarked emissions intensity level, represented by the relevant IEA definitions (for primary and secondary steel) of "near zero steel". Our model does not reflect relative production costs under existing assets, only newbuild assets.

[93] Transition Asia, "Green Steel Economics."
[94] "Decarbonising the Steel Industry."

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