Good practice for Low Carbon and Environmental Friendly Steel

CONTENTS

1. Introduction

The steel industry plays a critical role in national economic development, as it is fundamental to the construction of infrastructure and the growth of key industrial sectors. Steel products are essential inputs for a wide range of applications, including electrical appliances, automotive manufacturing, bridges, highways, buildings, energy systems, packaging, and utility transmission towers. Beyond its contribution to physical infrastructure, the steel industry also generates substantial socio-economic benefits through employment creation, income generation, and the stimulation of downstream industries.

Despite its economic importance, steel production is associated with significant environmental impacts. The production chain—from raw material extraction and transportation to refining and manufacturing—contributes to air and water pollution, deforestation, and the depletion of natural resources. Steel manufacturing is also a major source of air pollutants, including particulate matter, soot, and smoke, which pose risks to both environmental quality and public health. Nevertheless, steel remains indispensable for modern society, particularly in construction, machinery, and automotive applications. Consequently, the challenge lies not in reducing steel use, but in transforming the industry toward sustainable development.

To address these challenges, the steel industry must adopt more efficient production processes that minimize environmental impacts while maintaining product quality and performance. The integration of sustainable manufacturing practices, including energy efficiency measures and environmentally friendly carbon capture technologies, is essential to reducing greenhouse gas emissions and other forms of pollution. Such measures are critical for aligning the steel sector with long-term sustainability goals.

This study focuses on best practices in steel mills producing materials for construction applications. Two primary categories of steel products dominate the construction sector: reinforcing steel and structural steel. Reinforcing steel bars (rebar) are used to enhance the tensile strength and structural integrity of reinforced concrete. These products are generally classified into round steel bars and deformed steel bars, each designed to improve bonding performance within concrete structures.

Structural steel, by contrast, refers to steel that is manufactured into standardized shapes to facilitate efficient construction and load-bearing performance. Common forms include sheets, bars, box sections, plates, and pipes, all of which are valued for their high durability and ease of installation. Structural steel is typically categorized into cold-rolled and hot-rolled products. Cold-rolled structural steel includes square hollow sections, rectangular hollow sections, and flat steel, while hot-rolled structural steel encompasses widely used profiles such as wide-flange (WF) beams, H-beams (HB), I-beams (IB), angle sections, and steel rails. These products are extensively applied in general structural works due to their strength, versatility, and reliability.

2. Steel bar production and the life cycle impact

Production Process	Input	Output	Waste
Steel Melting Process 			
1. Filling raw materials	Coke Scrap Lime.	Iron water	• Dust (Fe2, O3, ZnO, CaO, MnO, SiO_2, MgO, SO3) • Smoke (Mn, Ni, Cr, Co, Pb) • Gaseous (NOx, CO2, CO) • Heat Loss • Coolant • Hypothalamic (CaO, SiO2, Al2O3, MgO) • Refractory scrap • Used graphite rods
2. Sweeping out cassia			• Dust • Metal slag/ scrap
3. Pouring iron water into the socket			• Dust • Gaseous (SOx, No$_x$, CO2, CO) • Heat Loss • Refractory scrap

Flat Steel and Billet Casting Process

1. Flat Steel and Billet Casting	Iron water	Small billets Flat billet Big Billet	- Gaseous (SOx, No$_x$, CO2, CO) - Heat Loss - Wastewater

Steel Casting Process

1. Making templates and filling patterns	Iron water		- Dust

		Steel workpieces	• volatile organic compounds; • Scrap materials used to make templates or mold • Substandard mold inserts • Sand chips
2. Pouring molten steel into the mold and allowing it to cool.			• Chemical vapors • Heat Loss
3. Dismantling and cutting of the workpiece water head			• Steel dust • Sand dust • Metal Scrap • Sand chips
4. Sandblasting and finishing			• Steel dust • Metal Scrap
5. Baking			• Gas (SOx, NO_x, CO2, CO)
Steel Hot Rolling Process 			
1. Heating steel rods	Small billets Flat billet Big Billet	Steel Bar Wire Rod Structural Steel Steel Plate	- Gas (SOx, No_x, CO2, CO) - Heat Loss
2. Rolling down			- Coolant - Scale (Fe2O3)
3. Cutting to size or rolling into a coil.			- Metal Scrap
Steel Cold Rolling Process			

			
1. Rust Removal by Mechanical Rust Remover	Hot Rolled Steel	Cold Rolled Steel	- Steel dust
2. Acid bite			- Steel dust - Acid vapor - Wastewater - Active acid solution - Metal Scrap
3. Cold Rolling			- Dust - Renewable Oil - Lubricants
4. Annealing			- Gas (SOx, NO_x, CO2, CO)
5. Rolling balls for mechanical properties adjustment			- Lubricants
6. Cutting to size or rolling into a coil.			- Steel dust - Scrap

Additional Production Process Support Systems[1]

Process	Information
Air Pollution Treatment System	The treatment system depends on the features of the pollution to be caught and the budget.
Coolant System	Because the steel production process such as blast furnace and rolling has the need to control the temperature as needed, it can be used once or recycled. The water used to fill the system must be qualified. Reduces scale, corrosion and lichen

2.Life cycle assessment impact

Raw material extraction and recycle

The raw materials used to produce steel are iron ore. Mining results in direct and indirect environmental impacts. loss of biodiversity or contamination of soils, groundwater, and surface water from chemicals released by mining processes; These processes also affect the atmosphere through carbon emissions, which causes climate change. Introduction of steel into the production process In addition to using iron ore as a raw material, non-or disposed of iron can be recycled by re-entering the production process. Recycling steel can help reduce the impact on the environment.

Manufacturing

The steel production process is at the top of the industry. Steel mills also emit many types of air pollutants, such as: PM2.5 Sulfur Dioxide, Nitrogen Oxide Carbon monoxide It contains volatile organic compounds, and heavy metals such as lead, cadmium, and mercury, which are toxic and can cause other serious neurological and health problems, and dioxins and furans, which are highly toxic and may cause cancer and other health problems. However, technology now plays a role in many production processes. As a result, emissions are reduced.

Transportation and distribution

In the process of transportation and distribution, there will be pollution from truck exhaust pipes, including carbon monoxide. Nitrogen oxide gas, hydrocarbon compounds Smaller dust particles 10 Microns, lead and sulfur dioxide.

Use

The use of steel does not cause any environmental impact, as steel is often used as a residential structure. Pollution does not come directly from steel, but from iron-based materials.

Disposal or recycle

Steel is the most recycled material, and recycling iron reduces the use of iron ore mining as a natural resource. Recycling steel uses less energy in the production process than remelting iron ore. Reduce emissions and greenhouse gases

3. Good Practices in Steel Industries

3.1 Material EFFICIENCY and Circularity

3.1.1 Use of high-strength, lightweight steel

High-strength steel is an environmentally friendly choice. The steel used as a building material is made from recycled materials and is 100% recyclable, which will help reduce waste from the construction industry. Therefore, strength steel is a sustainable choice. In addition, the strong and durable steel makes it last longer than traditional construction steel. Reduces the need for replacement and repair, which is environmentally friendly.[1] Structural steel, with its strong construction, can withstand heavy loads and harsh weather conditions, including earthquakes, hurricanes, and other natural disasters. This ensures the safety and durability of structures, protecting both residents and investments.[2]

The high strength of steel makes it possible to create lighter structures. This reduces the environmental impact associated with transportation and construction. In addition, steel recycling reduces energy consumption and promotes the conservation of natural resources. This makes this type of steel a more environmentally friendly alternative.

The use of high-strength steel is an important part of this, as it reduces fuel costs and reduces emissions. CO_2 It is known that strengthened steel is an approach that helps to solve problems more sustainably than conventional steel (SSAB, n.d.)

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[1] SHYAM STEEL. (n.d.). *ADVANTAGES OF USING HIGH-STRENGTH STEEL IN CONSTRUCTION*. Retrieved from SHYAM STEEL: https://shyamsteel.com/blogs/advantages-of-using-high-strength-steel-in-construction/

[2] A.J.Marshall. (n.d.). *The Benefits of High Strength Structural Steel*. Retrieved from A.J.Marshall: https://ajmarshall.com/benefits-of-using-high-strength-structural-steel/

Example 1

A.J. Marshall, England

High-strength structural steel varies in composition depending on its properties. Generally, structural steel has higher carbon and manganese content than ordinary steel. This increased carbon content increases strength, while manganese improves toughness, making it resistant to harsh conditions and wear.

High-strength steel possesses superior mechanical properties and corrosion resistance compared to conventional carbon steel. This is because it is specifically designed for high-precision applications, with strength levels exceeding 550 MPa. Because it is both strong and durable, high-strength steel has become an essential choice for various industries requiring robust structures and long service lives.For example,

High Strength OPTIM 700MC.

Extra high strength Optim™ 700 MC structural steel is highly flexible, easily bendable, weldable, and cut. Its lightweight design allows for increased load capacity on machinery and equipment, resulting in lower fuel consumption, greater environmental friendliness, and sustainable development.[3]

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[3] A.J. Marshall. (n.d.). *High Strength Steel*. Retrieved from A.J. Marshall: https://ajmarshall.com/high-strength-steel/

Example 2

beSteel, Magnelis steel

beSteel has undertaken a project to invent lightweight steel, an innovative material that is durable and easy to construct, suitable for all types of construction. Its lightness, strength, and precision allow for efficient construction and reduced environmental impact.

Every beSteel project's steel is designed digitally using BIM technology, guaranteeing millimeter-level accuracy from the initial design stage. The structures are then manufactured using Magnelis steel, a lightweight, corrosion-resistant material ideal for challenging environments. beSteel uses ArcelorMittal steel, produced using a hot-dip galvanizing process, followed by immersion in a bath with the following chemical composition: 93.5% zinc, 3.5% aluminum, and 3% magnesium. The magnesium used in the coating ensures stability and durability across the entire surface of the steel. It also guarantees more effective corrosion protection than coatings with lower magnesium content.[4]

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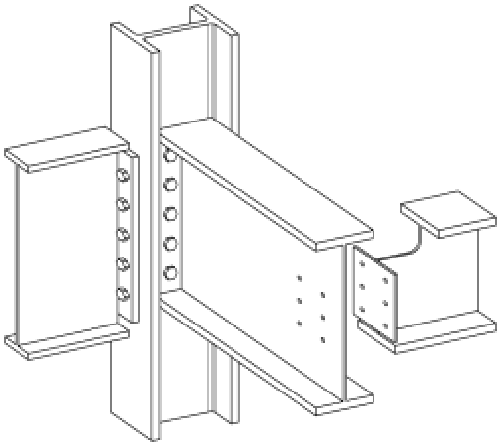
[4] beSteel. (n.d.). *CHEMICAL COMPOSITION OF MAGNELIS® STEEL*. Retrieved from beSteel: https://be-steel.eu/en/news/chemical-composition-of-magnelis-steel/

3.1.2 Design for disassembly and reuse

The use of easily disassembled products at the end of their lifecycle facilitates recycling and reuse of components. This design significantly reduces the environmental impact of products, as disassembly allows for easier repair, refurbishment, and recycling, ultimately extending product life and minimizing waste. Furthermore, easily disassembled and reassembled materials reduce e-waste and resource consumption by reusing used parts. It also enables more efficient recycling, as steel is broken down into smaller components, making it easier to melt and recycle, rather than being disposed of or buried after single use. This reduces waste, conserves resources, and decreases the need for new resources. Additionally, reducing carbon emissions in the industrial sector is crucial in addressing global climate change. This provides a framework for developing future structural systems that allow for easily disassembled and reusable products.[5]

Example 1

SCI in the UK



Designers need to design materials to be more reusable and to maximize future reuse. It may be designed to allow bolt-on steel welding instead of permanent interlocking welding, so that the structure can be dismantled during demolition. In addition, the fastening of the steel structure by welding should be used. Drill holes or secure them with nails as little as possible, and if possible, use clip-on fasteners instead.[6]

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[5] Kitayama, S., & Luorio, O. (2023, Aug 16). *Disassembly and Reuse of Structural Members in Steel-Framed Buildings: State-of-the-Art Review of Connection Systems and Future Research Trends*. Retrieved from ASCE Library: https://ascelibrary.org/doi/10.1061/JAEIED.AEENG-1615

[6] SteelConstruction.info. (n.d.). *Recycling and reuse*. Retrieved from SteelConstruction.info: https://www.steelconstruction.info/Recycling_and_reuse#Resources

3.1.3 Scrap recovery and closed-loop recycling systems

At present, the steel industry often uses electric furnaces in the production process, where the firebox uses scrap metal as raw material in the smelting process, allowing scrap metal to be reused. An electric furnaces produce less CO2 compared to steel production in furnaces that use iron ore and coke. It can help reduce the impact of greenhouse gases. In addition, recycling steel reduces the need to mine for new raw materials such as iron ore. It helps conserve natural resources and reduce the environmental impact of mining, such as habitat destruction and water and air pollution. Metal recycling saves energy and reduces carbon emissions, as it requires less energy to melt scrap metal than to produce new metals from primary resources. However, doing so requires sufficient scrap to recycle. Therefore, it is still necessary to use iron made from iron ore. But recycling significantly reduces the amount of waste that could end up in landfills. Reused scrap is not only returned to the production process. This will extend the life of landfills and reduce the burden of waste disposal.

It also has advanced sorting technology based on AI and machines that are integrated into the recycling plant. This makes the scrap metal recycled more pure. Innovations also facilitate the recycling of alloys with complex chemical compositions. This makes it more versatile to process and reuse materials.

Manufacturer's participation in closed-circuit steel recycling in the industry Companies that focus on scrap recovery will reduce the demand for pure iron ore. As a result, carbon emissions are reduced and better ESG metrics are achieved .[7]

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[7] MD METALS. (2025, May 16). *Steel Scrap Recovery and Closed Loop Recycling: Connecting Processors, Mills, and Manufacturers*. Retrieved from MD METALS: https://www.mdmetals.com/2025/05/16/steel-scrap-recovery-and-closed-loop-recycling-connecting-processors-mills-and-manufacturers/

Example 1

Swiss Steel Group

An important aspect of scrap recycling is the reuse of alloying elements such as chromium, nickel, and molybdenum, which are often found in stainless steel. The Swiss Steel Group also focuses on the use of scrap within its production processes to improve operational efficiency and sustainability, and aims to reduce the purchase of scrap from outside.[8]

The recycling process in the steel industry is a complex and multi-step process that aims to bring scrap back into the production process. The process begins with the collection and sorting of scrap metal, which comes from sources, such as salvaged metals, vehicles, building debris, and manufacturing waste, are used to collect and sort the collected scrap metal according to quality and composition to ensure that the recyclable material meets specified standards. After sorting, the scrap metal is melted in electric furnaces (EAFs) at the Swiss Steel Group.

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[8] Fischer, L. (2024, Sep 29). *Recycling in the steel industry - the environmentally friendly process from scrap to new steel*. Retrieved from Swiss Steel Group: https://swisssteel-group.com/en/journal/recycling-in-the-steel-industry

Example 2

TATA STEEL THAILAND

Tata's main raw materials are from scrap metal from all over the country feeding in the recycling process to produce about 500,000 tons of steel bars to the market annually. They focus on the waste management in order to utilize waste materials of their factories in accordance with the principles of circular economy.[9] In 2021, the 55,706 tons of scrap were purchased.[10]

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[9] Scsc, H. (2022, June 4). Retrieved from Facebook: https://web.facebook.com/photo/?fbid=4728331077273481&set=pcb.4728332710606651

[10] TATA STEEL THAILAND. (n.d.). *นโยบายเศรษฐกิจหมุนเวียน (CIRCULAR ECONOMY)*. Retrieved from TATA STEEL (THAILAND): https://tatasteelthailand.com/sustainability/CIRCULAR-ECONOMY/

3.2 Decarbonizing Production

3.2.1 Transition from BF-BOF to Electric Arc Furnace (EAF) using scrap

The steel industry is shifting from using traditional furnaces (BF) to an electric arc furnace (EAF) in order to reduce carbon emissions and meet the growing demand. It is expected that steel production will also be EAF Globally increase from 28% to 41% by 2030. This obvious change is especially evident in North America and Europe.

In 2022, the use of EAF furnaces can reduce CO2 emissions per ton of crude steel, both directly and indirectly, while the BF-BOF process emits about 2.2 tons of CO2 per 1 ton of steel.

Using an EAF (Electrical Air-Filter) furnace has lower initial costs (CAPEX) than using a BF-BOF (Boiler-Boiler-Filter) furnace. Furthermore, the EAF process does not require the construction of large-scale steel plants with multiple processes such as coke furnaces, smelters, and blast furnaces, thus reducing renewable energy costs and increasing the cost-effectiveness of the production process. In addition, the EAF process is more flexible in its operations because it can shut down production at a lower cost than blast furnaces during periods of low steel market prices.

Steel is the most recycled material in the world, having the highest trading volume of all metals. The EAF process enables the efficient recycling of scrap metal, reducing the need for raw materials such as iron ore and coke, which not only conserve natural resources but also reduces the environmental impact associated with mining and transporting raw materials.[11]

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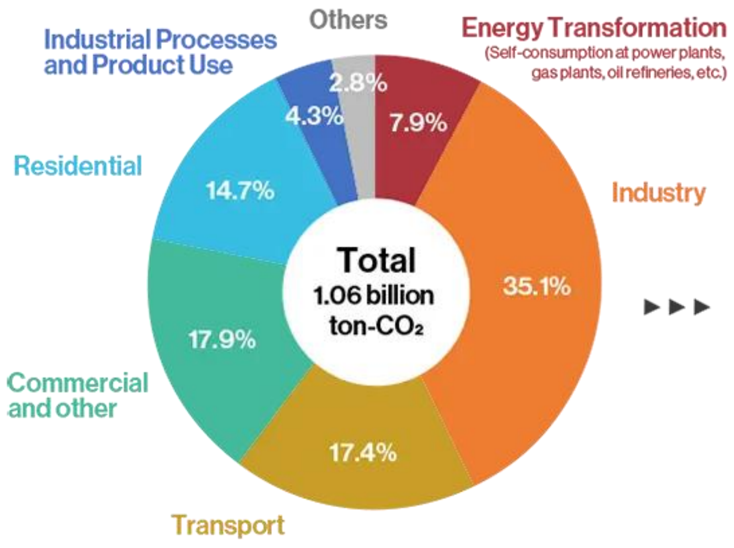
[11] Aboura, D., & Riva, E. (n.d.). *Blast Furnace to EAF Transition: Navigating Challenges and Market Gaps*. Retrieved from Steel Hub: https://www.steelhub.com/blast-furnace-to-eaf-challenges-and-market-opportunities/

<u>Example 1</u>

Japan

Breakdown of CO_2 emissions by various parts of the Japanese economy



Use of proceeds under the Japan Climate Transition Bond

Energy Transformation
Next-generation solar power, offshore wind power generation
Development of submarine DC power grid
Zero-emission thermal power generation
Utilization of nuclear power
Industry
Structural transformation of manufacturing industry (Fuel/raw material conversion)
Transport
Decarbonization of the transportation sector (promotion of EV, FCV, PHEV)
Development of synthetic fuel
Commercial and other
Promotion of installation of high-efficiency water heaters in households
Cross-departmental initiatives
Thorough promotion of energy conservation
Promotion of energy-saving materials in housing/buildings
Storage battery industry
Power semiconductor
Support for introducing hydrogen and ammonia
Carbon recycling/CCS

Created by JCR based on the Ministry of the Environment's "Japan's National Greenhouse Gas Emissions and Removals in Fiscal Year 2021 (Final Figures)"

In Japan, there is a policy to support subsidies from the Japan Climate Transition Bond, which supports the transition from BF-BOF furnaces to steel production through the EAF process.

Industry EAF industries of the top five steel-producing countries have carbon concentrations ranging from 0.28 to 0.37 tCO2/tcs, while the top three BF-BOF (Bio-Fueled Steel) industries in Japan have carbon concentrations between 2.06 and 2.61 tCO2/tcs.[12]

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[12] Kubokawa, K., & Kanno, A. (2025, Mar 10). *Japanese Electric Arc Furnace Steel – A Market Ready for Low-Carbon Growth*. Retrieved from Transition asia: https://transitionasia.org/japanese-eaf-steel/

Example 2

Nucor

On average, the extractive BF-BOF steelmaking process emits 2.33* tons of CO_2 for every ton of steel produced, while Nucor's circular EAF process emits on average 0.77* tons of CO_2 per ton of steel produced, resulting in less than one-third of the greenhouse gas (GHG) intensity compared to the global average of BF-BOF steelmaking (*Source: Worldsteel, 2023).

Nucor's steel production model, which is based primarily on Electric Arc Furnace (EAF) technology, represents a set of good environmental practices when compared with the traditional Blast Furnace–Basic Oxygen Furnace (BF–BOF) route. While the BF–BOF process depends heavily on mined iron ore and coke, EAF-based steelmaking predominantly utilizes recycled scrap steel as its main raw material. This significantly reduces reliance on virgin resources and minimizes the environmental impacts associated with mining and long-distance transportation of raw materials.

The use of recycled scrap steel also results in substantial energy savings. Scrap steel melts at lower temperatures than iron ore, thereby reducing the energy required during the melting stage. As a result, EAF steel production generates lower greenhouse gas emissions per ton of steel produced. Moreover, steel can be recycled repeatedly without degradation of its mechanical properties, allowing EAF-based recycling to conserve natural resources while maintaining product quality. These practices also reduce the volume of waste sent to landfills and further mitigate environmental pressures linked to extractive activities.

Water efficiency is another key environmental advantage of Nucor's EAF operations. Water is primarily used for cooling purposes, including furnaces and casting equipment. Nucor has implemented closed-loop water management systems equipped with on-site treatment facilities. Process water is collected, filtered, cooled, and reused within the production cycle, significantly reducing freshwater withdrawal and overall water demand.

In addition to material and water efficiency, Nucor promotes by-product recycling through industrial partnerships. The company collaborates with specialized firms, such as TMS International, to recover and process EAF slag into usable construction materials. Processed slag is repurposed as recycled aggregate for applications including road bases, backfill materials, driveways, and parking areas, thereby diverting waste from disposal and supporting circular economy principles.

Furthermore, Nucor applies advanced air pollution control technologies during the EAF process. Filtration systems capture fine dust particles generated during steelmaking, which contain valuable metals, particularly zinc. Through investments in specialized dust recovery and processing technologies, these materials are extracted for further recycling, reducing hazardous waste and recovering secondary resources.

Overall, Nucor's EAF-based steel production demonstrates a comprehensive set of environmentally friendly practices, including resource efficiency, waste reduction, water reuse, by-product valorization, and emissions control. These practices collectively contribute to lower environmental impacts and support the transition toward more sustainable steel manufacturing.[13]

3.2.2 Green hydrogen-based Direct Reduced Iron (DRI) pathways

Hydrogen-based ironmaking pathways can be broadly categorized into three technological approaches, each representing different levels of maturity and emissions reduction potential. First, hydrogen injection into existing steel furnaces partially substitutes hydrogen for coke, pulverized coal, natural gas, or other reductants. While this approach can lower carbon emissions, it does not eliminate carbon use entirely and therefore offers only incremental reductions.

Second, Plasma Hydrogen Smelting Reduction (HPSR) employs plasma-generated hydrogen to reduce iron ore. This technology has the potential to achieve near-zero emissions; however, it remains at an experimental or pilot stage and is not yet commercially viable.

Third, and currently the most advanced pathway, is hydrogen-based Direct Reduced Iron (H_2-DRI). In this process, hydrogen replaces natural gas or coal as the reducing agent, removing oxygen from iron ore and producing water (H_2O) instead of carbon dioxide as the primary reaction by-product. As a result, H_2-DRI offers a fundamentally low-carbon alternative to conventional ironmaking.

Hydrogen-based DRI is typically integrated with Electric Arc Furnaces (EAFs) for steel production. In the DRI process, iron ore is reduced in the solid state to produce sponge iron, characterized by a high iron content and a porous structure suitable for subsequent melting in an EAF. When natural gas is used in DRI-EAF systems, emissions are already lower than those of BF–BOF production, averaging approximately 1.5–1.7 tonnes of CO_2 per tonne of steel. When green hydrogen is used instead, overall emissions can be reduced by up to 95%, making H_2-DRI–EAF the most feasible pathway for achieving near-zero emissions in steelmaking.

Despite its environmental advantages, large-scale deployment of hydrogen-based DRI requires substantial supporting infrastructure. Continuous and reliable hydrogen supply is essential, necessitating the development of large-scale electrolysis facilities, often at the gigawatt scale. These systems involve complex power generation, transmission, and distribution designs to ensure stable operation.

Technology providers such as Hitachi Energy play a critical role in supporting steel producers through the design and integration of electrolysis plants and power systems. Their expertise has been applied in several flagship green hydrogen projects worldwide, including the H2

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[13] Nucor. (n.d.). *THE CIRCULARITY IN STEEL SERIES, PART 3: BENEFITS OF ELECTRIC ARC FURNACE (EAF) STEELMAKING*. Retrieved from NUCOR: https://nucor.com/newsroom/the-circularity-in-steel-series-part-3-benefits-of-electric-arc-furnace-eaf

Green Steel DRI plant in Sweden. Such projects demonstrate that replacing coal with green hydrogen in iron reduction can achieve up to a 95% reduction in carbon dioxide emissions compared with conventional steel production routes.[14]

Example 1

MIDREX H_2™: Greenfield Deployment of Hydrogen-Based Direct Reduction Integrated with Electric Arc Furnace Steelmaking

The MIDREX H_2™ process represents an advanced hydrogen-based Direct Reduced Iron (DRI) technology designed to significantly reduce greenhouse gas emissions from primary steel production. In a greenfield configuration, the MIDREX H_2™ plant is purpose-built to integrate hydrogen-based direct reduction with downstream Electric Arc Furnace (EAF) steelmaking, enabling a near-zero-carbon production pathway.

In the MIDREX H_2™ process, iron ore pellets or lump ore are reduced using hydrogen as the primary reducing agent, either exclusively or in high hydrogen concentrations, instead of natural gas or coal-derived reductants. Hydrogen reacts with oxygen in the iron ore to produce metallic iron, with water vapor (H_2O) as the primary reaction by-product, thereby substantially eliminating carbon dioxide emissions at the ironmaking stage. The resulting product, commonly referred to as hot or cold DRI (sponge iron), exhibits high metallization and is well suited for charging into an EAF.

The integration of MIDREX H_2™ with an EAF in a greenfield setting allows for optimized system design, including material handling, heat integration, and energy efficiency measures. When powered by renewable electricity and supplied with green hydrogen produced via electrolysis, the combined DRI–EAF route can achieve carbon dioxide emission reductions of up to 90–95% compared with conventional blast furnace–basic oxygen furnace (BF–BOF) steelmaking.

Key advantages of the MIDREX H_2™ greenfield configuration include the elimination of coke ovens and blast furnaces, reduced dependence on fossil fuels, and improved operational flexibility. The system is also designed to be hydrogen-ready, allowing gradual transition from natural gas-based DRI to high-hydrogen or fully hydrogen-based operation as hydrogen availability and infrastructure expand.

Overall, the MIDREX H_2™ greenfield DRI–EAF pathway is widely regarded as one of the most technically mature and scalable solutions for deep decarbonization of the steel industry, supporting national and corporate net-zero targets while maintaining high product quality and industrial competitiveness.

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[14] Nicholas, S., & Basirat, S. (2024, Nov 14). *Steel CCUS update: Carbon capture technology looks ever less convincing*. Retrieved from Instutute for Energy Economics and Finantial Analysis: https://ieefa.org/resources/steel-ccus-update-carbon-capture-technology-looks-ever-less-convincing

Example 2

Brownfield Case: Integration of Direct Reduction into Open Bath Furnace Steelmaking

In a brownfield context, the integration of Direct Reduced Iron (DRI) into existing open bath furnace steelmaking facilities represents a transitional decarbonization pathway for steel producers seeking to reduce emissions while utilizing existing assets. Unlike greenfield developments, brownfield applications focus on retrofitting or adapting current furnace infrastructure—such as open bath furnaces or basic oxygen furnaces (BOFs)—to accommodate higher shares of DRI or hot briquetted iron (HBI) as alternative iron inputs.

In this configuration, DRI produced via natural gas–based or hydrogen-enriched direct reduction processes is charged into the open bath furnace to partially replace hot metal derived from blast furnaces. The introduction of DRI reduces the overall carbon intensity of the steelmaking process by lowering coke consumption and decreasing reliance on coal-based ironmaking. When hydrogen-based DRI (H_2-DRI) is employed, additional emission reductions are achieved through the avoidance of carbon-intensive reduction reactions.

From a technical perspective, the use of DRI in open bath furnaces requires careful control of bath chemistry, temperature, and slag composition to ensure stable operation and product quality. Modifications may include enhanced oxygen blowing strategies, improved scrap and DRI charging systems, and adjustments to flux addition and process control systems. While these adaptations do not fully eliminate carbon use, they enable meaningful emission reductions without the need for complete plant replacement.

The brownfield DRI–open bath furnace pathway offers several advantages, including lower capital investment compared with greenfield DRI–EAF systems, shorter implementation timelines, and the ability to leverage existing workforce skills and infrastructure. However, the decarbonization potential is inherently constrained by the continued use of carbon-based fuels and reductants within the furnace.

Nevertheless, this approach serves as an important intermediate step toward deep decarbonization. By progressively increasing the share of hydrogen-based DRI and reducing hot metal input, steel producers can achieve incremental emissions reductions while preparing for future transitions to fully hydrogen-based DRI–EAF configurations. As such, brownfield integration of DRI into open bath furnaces plays a strategic role in bridging current production systems with long-term net-zero steelmaking pathways.[15]

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[15] Campos, T., & Tim, O. (n.d.). *Synergies between SMS Group & Midrex offer innovative ironmaking solutions*. Retrieved from Midrex: https://www.midrex.com/tech-article/pathways-to-green-steel/

3.2.3 Deployment of CCUS at integrated steel plants

Carbon Capture, Utilization, and Storage (CCUS) has been explored as a potential decarbonization pathway in the steel industry; however, its adoption has shown a declining trend in recent years. This decline is primarily attributed to several structural and economic limitations associated with CCUS deployment in steelmaking. High capital and operational costs, combined with relatively low carbon capture rates, mean that CCUS systems often capture only a fraction of total plant emissions. As a result, CCUS projects in steel fabrication facilities tend to fall short of achieving deep or comprehensive emissions reductions.

At present, there are very few large-scale operational CCUS facilities integrated with steel production. One of the most notable examples is the Al Reyadah CCUS project in the United Arab Emirates, which is linked to the Emirates Steel plant in Abu Dhabi. This facility remains the only commercial-scale CCUS project currently operating in direct association with steel production, underscoring the limited global deployment of the technology within this sector.

Beyond capture costs, the transportation and long-term storage of carbon dioxide present additional challenges. CO_2 transport infrastructure requires significant investment, particularly where suitable storage sites are located far from emission sources. Furthermore, geological carbon sequestration is highly site-specific, as each storage project faces unique geological conditions, risks, and performance uncertainties. These factors limit the transferability of technical knowledge across projects, making it difficult to achieve economies of scale or reduce costs through standardization.

Despite these constraints, some steel producers continue to regard CCUS as a complementary component of their decarbonization strategies, particularly in regions where blast furnace–based production remains dominant. In Japan, for example, Nippon Steel has maintained its commitment to CCUS research and development as part of its long-term emissions reduction roadmap. The company is conducting pilot and demonstration projects in collaboration with partners such as BHP, Mitsubishi Heavy Industries, and Mitsubishi Development, reflecting continued interest in advancing CCUS technologies.

In Europe and the Middle East, CCUS projects increasingly emphasize carbon utilization alongside storage. At the Emirates Steel plant, captured carbon dioxide is reused for enhanced oil recovery (EOR) operations. Approximately 800 kilotonnes of CO_2 are captured annually and injected into oil reservoirs operated by the Abu Dhabi National Oil Company during the final stages of oil extraction. While such utilization pathways contribute to emissions management, their net climate benefits remain subject to ongoing debate.

Looking forward, the role of CCUS in the steel industry remains uncertain. While advancements in alternative decarbonization pathways—particularly green hydrogen-based steelmaking—are expected to reduce costs over time and attract greater investment, CCUS may continue to serve as a transitional or supplementary solution in regions where hydrogen infrastructure is limited. As such, CCUS is likely to play a niche but potentially strategic role in achieving near-term emissions reductions rather than serving as a primary pathway toward net-zero steel production.[16]

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[16] Basirat, S., & Nicholas, S. (2024, November). *Steel CCUS update: Carbon capture technology*. Retrieved from Institute for Energy Economic and Financial Analysis: https://ieefa.org/sites/default/files/2024-11/BN_Steel%20CCUS%20update-%20Carbon%20capture%20technology%20looks%20ever%20less%20convincing_Nov24.pdf

Example 1

Reyadah in Abu Dhabi launched by Emirates Steel

Al Reyadah's CCUS plant in Abu Dhabi , serving Emirates Steel, remains the first and only commercial carbon capture plant in collaboration with a steel mill launched in 2016. The plant can capture wet carbon dioxide from Emsteel's direct reduction (DR) process and then inject it into ADNOC's wells to Enhanced Oil Recovery (EOR).

However, the overall capture rate of total emissions of steel mills is significantly lower than 45%, with data from 2020-2023 showing that factories can only capture 19.3% to 26.6% of total emissions of steel mills. This is because this technology can only partially reduce emissions. It does not deal with all sources of pollution. However, the company has implemented more efficient strategies, including the procurement of low-emission electricity, and is considering a long-term transition from natural gas to green hydrogen.[17]

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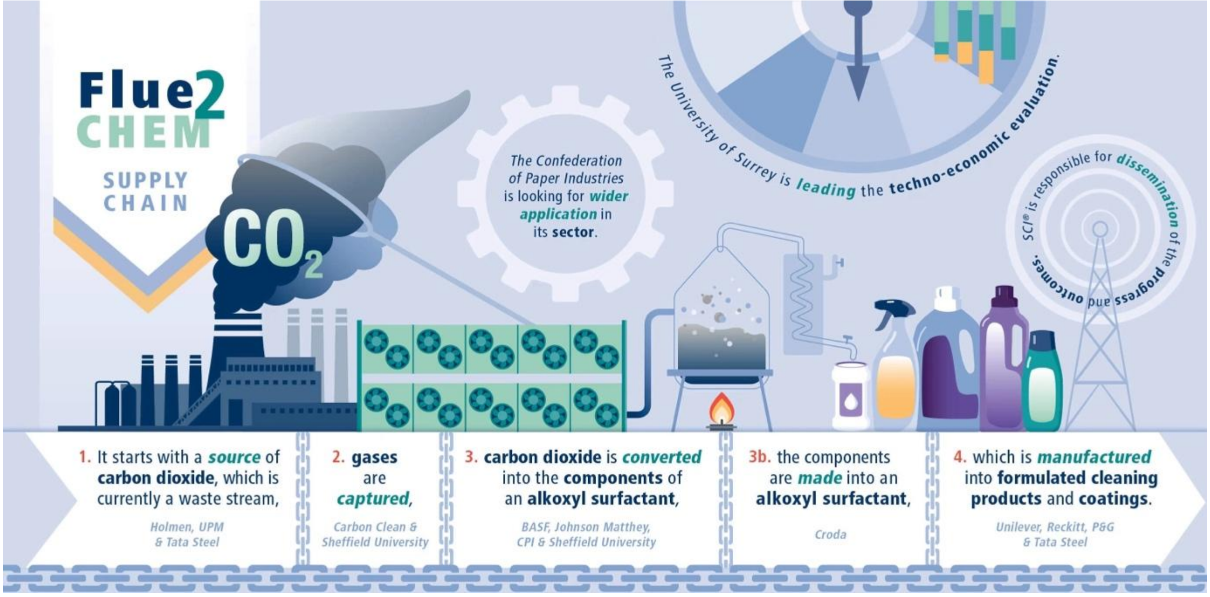
[17] Basirat, S., & Nicholas, S. (2024, November). *Steel CCUS update: Carbon capture technology*. Retrieved from Institute for Energy Economic and Financial Analysis: https://ieefa.org/sites/default/files/2024-11/BN_Steel%20CCUS%20update-%20Carbon%20capture%20technology%20looks%20ever%20less%20convincing_Nov24.pdf

Example 2

Holmen plant of Tata Steel and UPM



The Flue2Chem project took two years to develop a value chain that could be used to convert industrial waste gases into sustainable materials for consumer products. This could reduce CO2 emissions by 15-20 million tonnes per year in the UK, thanks to a £2.68 million grant from Innovate UK's Transforming Foundation Industries (TFI) Challenge.

Carbon Clean's fully modular CycloneCC carbon capture technology captures 10 TPD of CO2 from three industrial facilities – at Holmen, Tata Steel and UPM – as part of the project.[18]

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[18] Carbon Capture Journal. (2023, Feb 2). *Carbon Clean joins with industry to demonstrate CO2 conversion technology*. Retrieved from Carbon Capture Journal: https://www.carboncapturejournal.com/news/carbon-clean-joins-with-industry-to-demonstrate-co2-conversion-technology/5407.aspx? Category=all

3.3 Energy and Process Optimization

3.3.1 Electrification and renewable energy integration

Electricity from renewable energy sources, such as wind and solar power, is an important source of energy to reduce carbon emissions in the steel industry. Using electricity allows steel mills to switch from fossil fuels to cleaner alternatives. This significantly reduces carbon emissions.

Example 1

Evraz North America Pueblo, The world's first solar-powered steel mills

In 2021, the Evraz North America Pueblo plant became the world's first steel plant to run almost entirely on solar power. The 240-megawatt Bighorn Solar facility supplied up to 95% of Pueblo Steel's electricity needs and reduced emissions by 50%. In 2022, the Solar Industry Association ranked Evraz North America as one of the top 10 companies utilizing solar power and a leading organization in using solar energy in steel production.[19]

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[19] Evrazna. (n.d.). *Sustainability We Lead The Way In Sustainability* . Retrieved from https://www.evrazna.com/sustainability

The project has a 300 MW DC solar plant and 240 MW AC. It is located on an area of 7.3 square kilometers. This makes it the largest solar plant in the United States dedicated to a single customer. The 750,000 solar panels in this plant can supply almost all of the plant's annual electricity needs.[20]

Example 2

Tata Steel and Tata Power

Two Tata Group companies, Tata Steel and Tata Power, have jointly developed a solar power project connected to the state-owned power grid in Jharkhand and Odisha. The two companies have signed a 25-year power purchase agreement (PPA) to establish a 41-megawatt solar power project, incorporating rooftop, floating, and ground-mounted solar panels. Within this project, Tata Power will also develop photovoltaic (PV) power generation for Tata Steel in Jamshedpur (21.97 MWp) and Kalinganagar (19.22 MWp).

Under the Power Purchase Agreement (PPA), Tata Power will develop a rooftop solar power plant with a capacity of 7.57 MWp in Jamshedpur, and generate electricity from rooftop and ground-mounted solar panels totaling 10.80 MWp and 3.6 MWp, respectively. Ground-mounted solar panels will be installed at Sonari Airport in Jamshedpur, while Kalinganagar will have a rooftop PV capacity of 9.12 MWp and a floating PV capacity of 10.10 MWp.

The 41.19 MWp solar power project is expected to generate 6,0280,095 kW of electricity in its first year, and over its lifespan (25 years), total energy production will reach 1,40,9361,488 kWh. This project will save 45,210 tons of CO2 per year and 1,057,021 tons over its lifespan (25 years).[21]

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[20] worldsteel. (n.d.). *Solar energy is fuelling more sustainable steel production*. Retrieved from worldsteel ASSOCIATION: https://worldsteel.org/media/steel-stories/infrastructure/solar-energy-fuels-sustainable-production-of-rails/

[21] Tata Steel. (2021, Oct 29). *Tata Steel collaborates with Tata Power to set up 41MW grid connected solar projects in Jharkhand and Odisha* . Retrieved from TATA STEEL: https://www.tatasteel.com/media/newsroom/press-releases/india/2021/tata-steel-

3.3.2 Digitalization for process monitoring and emissions control

Digital technology is driving the development of green technologies that can help reduce the use of natural resources and improve the efficiency of materials and energy use. Digital technology plays a strategic role in enhancing technological efficiency, aiming to reduce and optimize energy and material use throughout the steel production process. For example, optimizing and monitoring production processes is crucial for optimal energy management throughout the steel production process. Furthermore, real-time monitoring helps control product quality, resulting in reduced bi-products and waste. New tools are also used to quickly characterize solid and liquid slag, and AI models can add value and increase the reuse and recycling of slag. Additionally, AI-powered predictive models are used for maintenance and optimal production scheduling. Therefore, digital technology can effectively support green manufacturing.[22]

Example 1

Environmental Impact Assessment and Effective Resource Management in Steel Production (EIRES)

Advanced modeling is applied in conjunction with environmental performance monitoring through key performance indicators (KPIs) under the European Union-funded project "Environmental Impact Assessment and Effective Resource Management in Steel Production with EAF" (EIRES). This research focuses on energy and resource efficiency, and the developed tool allows for the assessment of various operating scenarios and conditions, promoting increased slag reuse. Furthermore, the model can represent energy and water consumption, gas emissions, and the chemical composition of slag and steel, aiding in the analysis of product quality, yield, and process efficiency, as well as variables related to environmental impact.

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collaborates-with-tata-power-to-set-up-41mw-grid-connected-solar-projects-in-jharkhand-and-odisha/

[22] Branca, T. A., Coll, V., Murri, M. M., & Schröder, A. J. (2024, Feb 13). *The Impact of the New Technologies and the EU Climate Objectives on the Steel Industry*. Retrieved from SPRINGER NATURE Link: https://link.springer.com/chapter/10.1007/978-3-031-35479-3_4

Example 2

The RFCS project

The RFCS project, "Development of a Tool for Reducing Energy Demand and CO2 Emissions in the Iron and Steel Industry Based on Energy Registration, CO2 Monitoring, and Waste Thermal Energy Production" (ENCOP), has leveraged this calculation to optimize waste gas supply within steel plants. This involves considering the optimization of the storage system, which is illustrated in a graph derived from theoretical principles. This is used to manage waste gas system issues, thereby improving system efficiency and reducing CO2 emissions.[23]

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[23] Colla, V., Pietrosanti, C., Malfa, E., & Peters, K. (2021, Feb 4). *Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes*. Retrieved from Matériaux & Techniques: https://www.mattech-journal.org/articles/mattech/full_html/2020/05/mt200062/mt200062.html

Summary analyzes possible approaches for Thailand.

This study identifies several technological and operational approaches that can contribute to the reduction of carbon dioxide emissions in industrial facilities, particularly within the steel sector. While these approaches vary in terms of effectiveness, cost, and operational complexity, their successful implementation depends largely on the commitment of manufacturers to reducing their carbon footprint.

For Thailand, a practical and impactful starting point is the transition away from coke-fired furnaces toward electric-based steelmaking, particularly Electric Arc Furnaces (EAFs). This shift can reduce carbon dioxide emissions by up to three times compared with traditional coke-based processes. In addition, EAF technology promotes the recycling of scrap steel, thereby reducing the need for virgin raw material extraction. This, in turn, mitigates environmental impacts associated with iron ore mining, including ecosystem degradation, noise, dust generation, and groundwater contamination. As such, the conversion from coke-fired furnaces to electric furnaces represents a foundational step for structural change in Thailand's steel industry.

Beyond process transformation, product-oriented strategies also play a critical role in emissions reduction. The development of high-quality steel products that are high-strength, lightweight, and durable can reduce material demand and extend product lifespans, thereby lowering emissions across the value chain. Furthermore, steel products designed for easy disassembly enhance end-of-life recycling efficiency, contributing to circular economy objectives. However, the successful development of such products requires substantial research and development investment and a strong industry-wide commitment to quality and environmental performance. These attributes not only reduce carbon emissions but also increase product competitiveness and consumer acceptance.

Another important pathway for decarbonization is the adoption of alternative and clean energy sources. Replacing fossil-based energy with renewable sources such as solar, wind, and hydropower can significantly reduce greenhouse gas emissions over the long term. In the Thai context, solar energy is particularly promising due to the country's high solar irradiation and favorable climatic conditions. In addition, hydrogen-based energy presents a longer-term opportunity, particularly for iron reduction processes. Hydrogen can serve as a reducing agent to remove oxygen from iron ore, producing water (H_2O) instead of carbon dioxide as a by-product. Although hydrogen is not yet a primary energy source in Thailand, it is gaining increasing attention for research, development, and future deployment.

Technological innovation and digitalization are also becoming increasingly important in achieving emissions reduction targets. Advanced monitoring systems, data analytics, and modeling tools can support pollution tracking, emissions accounting, and process optimization, thereby enhancing overall efficiency and environmental performance. While Carbon Capture, Utilization, and Storage (CCUS) is another available option, its adoption in steel manufacturing remains limited due to relatively low capture rates and high installation and operational costs. Consequently, CCUS deployment in Thailand would depend largely on individual corporate strategies rather than sector-wide implementation.

In conclusion, Thailand’s steel industry should pursue a phased transition strategy. Initial efforts should focus on converting to electric furnace technology and maximizing steel recycling. This should be complemented by the development of more efficient and environmentally friendly steel products, gradual integration of clean energy sources, and the adoption of advanced production and monitoring technologies. Collectively, these measures can significantly reduce carbon and greenhouse gas emissions, supporting Thailand’s progress toward carbon neutrality and net-zero targets, while contributing to global efforts to address climate change.

References

A.J. Marshall. (n.d.). *High Strength Steel*. Retrieved from A.J. Marshall: https://ajmarshall.com/high-strength-steel/

A.J. Marshall. (n.d.). *The Benefits of High Strength Structural Steel*. Retrieved from A.J.Marshall: https://ajmarshall.com/benefits-of-using-high-strength-structural-steel/

A.J.Marshall. (n.d.). *The Benefits of High Strength Structural Steel*. Retrieved from A.J.Marshall: https://ajmarshall.com/benefits-of-using-high-strength-structural-steel/

Aboura, D., & Riva, E. (n.d.). *Blast Furnace to EAF Transition: Navigating Challenges and Market Gaps*. Retrieved from Steel Hub: https://www.steelhub.com/blast-furnace-to-eaf-challenges-and-market-opportunities/

Basirat, S., & Nicholas, S. (2024, November). *Steel CCUS update: Carbon capture technology.* Retrieved from Institute for Energy Economic and Financial Analysis: https://ieefa.org/sites/default/files/2024-11/BN_Steel%20CCUS%20update-%20Carbon%20capture%20technology%20looks%20ever%20less%20convincing_Nov24.pdf

beSteel. (n.d.). *Discover the beSteel system: a light steel frame, ideal for building, elevating, expanding, and meeting the challenges of the most complex construction sites.* Retrieved from beSteel: https://be-steel.eu/en/lightweight-steel-frame/

beSteel. (n.d.). *CHEMICAL COMPOSITION OF MAGNELIS® STEEL*. Retrieved from beSteel: https://be-steel.eu/en/news/chemical-composition-of-magnelis-steel/

beSteel. (n.d.). *The advantages of beSteel lightweight steel frame in 9 points*. Retrieved from beSteel: https://be-steel.eu/en/advantages-of-steel-frames/

Branca, T. A., Coll, V., Murri, M. M., & Schröder, A. J. (2024, Feb 13). *The Impact of the New Technologies and the EU Climate Objectives on the Steel Industry*. Retrieved from SPRINGER NATURE Link: https://link.springer.com/chapter/10.1007/978-3-031-35479-3_4

Campos, T., & Tim, O. (n.d.). *Synergies between SMS Group & Midrex offer innovative ironmaking solutions*. Retrieved from Midrex: https://www.midrex.com/tech-article/pathways-to-green-steel/

Carbon Capture Journal. (2023, Feb 2). *Carbon Clean joins with industry to demonstrate CO2 conversion technology*. Retrieved from Carbon Capture Journal: https://www.carboncapturejournal.com/news/carbon-clean-joins-with-industry-to-demonstrate-CO2-conversion-technology/5407.aspx? Category=all

Chevron. (2022, May 18). *explainer: what is carbon capture, utilization, and storage?* Retrieved from Chevron: https://www.chevron.com/newsroom/2022/q2/what-is-carbon-capture-utilization-and-storage

Colla, V., Pietrosanti, C., Malfa, E., & Peters, K. (2021, Feb 4). *Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes*. Retrieved from Matériaux & Techniques: https://www.mattech-journal.org/articles/mattech/full_html/2020/05/mt200062/mt200062.html

EVRAZ. (n.d.). *Sustainable Steel for a Stronger North America*. Retrieved from EVRAZ North America: https://www.evrazna.com/

Evrazna. (n.d.). *Sustainability We Lead The Way In Sustainability* . Retrieved from https://www.evrazna.com/sustainability

Fischer, L. (2024, Sep 29). *Recycling in the steel industry - the environmentally friendly process from scrap to new steel*. Retrieved from Swiss Steel Group: https://swisssteel-group.com/en/journal/recycling-in-the-steel-industry

Fischer, L. (2024, Sep 29). *Recycling in the steel industry - the environmentally friendly process from scrap to new steel*. Retrieved from Swiss Steel Group: https://swisssteel-group.com/en/journal/recycling-in-the-steel-industry

Global Energy Wiki Monitor. (2024, May 3). *Carbon Capture and Storage in Iron and Steel Industry*. Retrieved from Global Energy Wiki Monitor: https://www.gem.wiki/Carbon_Capture_and_Storage_in_Iron_and_Steel_Industry

Goela, J. (2024, 9 24). *CCUS: Paving the Way for Decarbonization in India's Steel Industry*. Retrieved from GAS LAB ASIA: https://www.ssgaslab.com/ccus-decarbonization-steel-industry-india.html

Kitayama, S., & Luorio, O. (2023, Aug 16). *Disassembly and Reuse of Structural Members in Steel-Framed Buildings: State-of-the-Art Review of Connection Systems and Future Research Trends*. Retrieved from ASCE Library: https://ascelibrary.org/doi/10.1061/JAEIED.AEENG-1615

Kubokawa, K., & Kanno, A. (2025, Mar 10). *Japanese Electric Arc Furnace Steel – A Market Ready for Low-Carbon Growth*. Retrieved from Transition asia: https://transitionasia.org/japanese-eaf-steel/

MD METALS. (2025, May 16). *Steel Scrap Recovery and Closed Loop Recycling: Connecting Processors, Mills, and Manufacturers*. Retrieved from MD METALS: https://www.mdmetals.com/2025/05/16/steel-scrap-recovery-and-closed-loop-recycling-connecting-processors-mills-and-manufacturers/

MIDREX. (2025, Mar). *Hydrogen in Iron and Steelmaking: Ore-Based Metallics & Carbon-Neutral Steel*. Retrieved from MIDREX: https://www.midrex.com/tech-article/hydrogen-in-iron-and-steelmaking-ore-based-metallics-carbon-neutral-steel/

Nicholas, S., & Basirat, S. (2024, Nov 14). *Steel CCUS update: Carbon capture technology looks ever less convincing*. Retrieved from Instutute for Energy Economics and Finantial Analysis: https://ieefa.org/resources/steel-ccus-update-carbon-capture-technology-looks-ever-less-convincing

Nucor. (n.d.). *THE CIRCULARITY IN STEEL SERIES, PART 3: BENEFITS OF ELECTRIC ARC FURNACE (EAF) STEELMAKING*. Retrieved from NUCOR: https://nucor.com/newsroom/the-circularity-in-steel-series-part-3-benefits-of-electric-arc-furnace-eaf

Petropoulos, G. (2025, April 19). *How Can Design For Disassembly Impact Sustainable Product Design Through Circular Economy Principles In Engineering*. Retrieved from inorigin: https://www.inorigin.eu/how-can-design-for-disassembly-impact-sustainable-product-design/

Scsc, H. (2022, June 4). Retrieved from Facebook: https://web.facebook.com/photo/?fbid=4728331077273481&set=pcb.4728332710606651

SHYAM STEEL. (n.d.). *ADVANTAGES OF USING HIGH-STRENGTH STEEL IN CONSTRUCTION*. Retrieved from SHYAM STEEL: https://shyamsteel.com/blogs/advantages-of-using-high-strength-steel-in-construction/

SSAB. (n.d.). *The environmental benefits of high-strength steel*. Retrieved from SSAB: The environmental benefits of high-strength steel

SSAB. (n.d.). *Upgrade to advanced high-strength steels for strength, durability and light weight designs*. Retrieved from SSAB: https://www.ssab.com/en-us/ssab/blog/upgrade-to-advanced-high-strength-steel

SteelConstruction. (n.d.). *SteelConstruction.info*. Retrieved from Recycling and reuse: https://www.steelconstruction.info/Recycling_and_reuse#Resources

SteelConstruction.info. (n.d.). *Recycling and reuse*. Retrieved from SteelConstruction.info: https://www.steelconstruction.info/Recycling_and_reuse#Resources

Tata Steel. (2021, Oct 29). *Tata Steel collaborates with Tata Power to set up 41MW grid connected solar projects in Jharkhand and Odisha* . Retrieved from TATA STEEL: https://www.tatasteel.com/media/newsroom/press-releases/india/2021/tata-steel-collaborates-with-tata-power-to-set-up-41mw-grid-connected-solar-projects-in-jharkhand-and-odisha/

TATA STEEL THAILAND. (n.d.). *นโยบายเศรษฐกิจหมุนเวียน (CIRCULAR ECONOMY)*. Retrieved from TATA STEEL (THAILAND): https://tatasteelthailand.com/sustainability/CIRCULAR-ECONOMY/

THE CCUS HUB. (n.d.). *Understanding CCUS*. Retrieved from THE CCUS HUB: https://ccushub-ogci-com.translate.goog/ccus-basics/understanding-ccus/?_x_tr_sl=en&_x_tr_tl=th&_x_tr_hl=th&_x_tr_pto=tc#elementor-action%3Aaction%3Dpopup%3Aclose%26settings%3DeyJkb19ub3Rfc2hvd19hZ2FpbiI6InllcyJ9

worldsteel. (n.d.). *Solar energy is fuelling more sustainable steel production*. Retrieved from worldsteel ASSOCIATION: https://worldsteel.org/media/steel-stories/infrastructure/solar-energy-fuels-sustainable-production-of-rails/

Office of Air Quality and Noise Management   Retrieved from https://www.pcd.go.th/wp-content/uploads/2020/05/pcdnew-2020-05-20_07-19-28_148578.pdf