Beyond the arc: technologies to cut Scope 1 emissions of EAF steelmakers

Whilst switching to EAF based steel production is one of the most important methods for reducing steel sector emissions, it does not solve the entire decarbonisation challenge. On-site fossil fuel combustion remains a significant hurdle: reheating and annealing account for up to ~92% of Scope 1 emissions in the EAF process. While clean power supply underpins the broader EAF transition, this report focuses on the direct emissions profile of modern EAF operations and evaluates four technologies capable of replacing fossil fuels.

INTRODUCTION · THE CURRENT EAF PROCESS

Reheating, combined with annealing, can amount to 65–92% of Scope 1 emissions

Reheat furnaces alone account for approximately 44~57% of the process's Scope 1 emissions.

2 · ALTERNATIVE TECHNOLOGIES

Four options replace gas burners, with very different maturity

Electric heaters and hydrogen burners are commercial; plasma torches are at R&D/pilot; RotoDynamic heaters are at pilot stage.

3 · STEPS FOR EAF OPERATORS

Reheat furnaces first, direct electrification on RE, pilot now

1 Prioritise reheating furnaces. **2** Champion direct electrification powered by RE. **3** Investigate mature technologies despite commercial ambiguity.

Future competitiveness in the EAF sector will be tied to downstream Scope 1 reductions as well as RE adoption

2.32
tCO_2 per tonne of crude steel (tcs): global average for BF-BOF production[1]

1.43
tCO_2/tcs: global average for EAF production using direct reduced iron (DRI) as feedstock[1]

0.70
tCO_2/tcs: global average for scrap-based EAF production[1]

~90%
of Scope 1 emissions within EAF steelmaking come from reheating and annealing

Amidst growing demands from critical off-takers in the automotive and construction sectors for supply chain-wide (Scope 3) emission reductions, the future competitiveness of steelmakers hinges in part on climate action. While transitioning to EAF based production is widely recognised as one of the most viable near-term strategies, utilising scrap steel or lower carbon iron such as direct reduced iron (DRI), efforts cannot be confined to this singular technological process. To realise full value chain carbon neutrality, decarbonisation is important in downstream steel making processes, such as rolling and heat treatment, which transform molten steel into final products like steel sheets and long products. Currently, conventional Blast Furnace-Basic Oxygen Furnace (BF-BOF) production generates a global average of approximately 2.32 tCO_2 per tonne of crude steel (tcs).[1] In contrast, the global average emissions by EAF production are 1.43 tCO_2/tcs when utilising DRI as feedstock, and 0.70 tCO_2/tcs for scrap-based production.

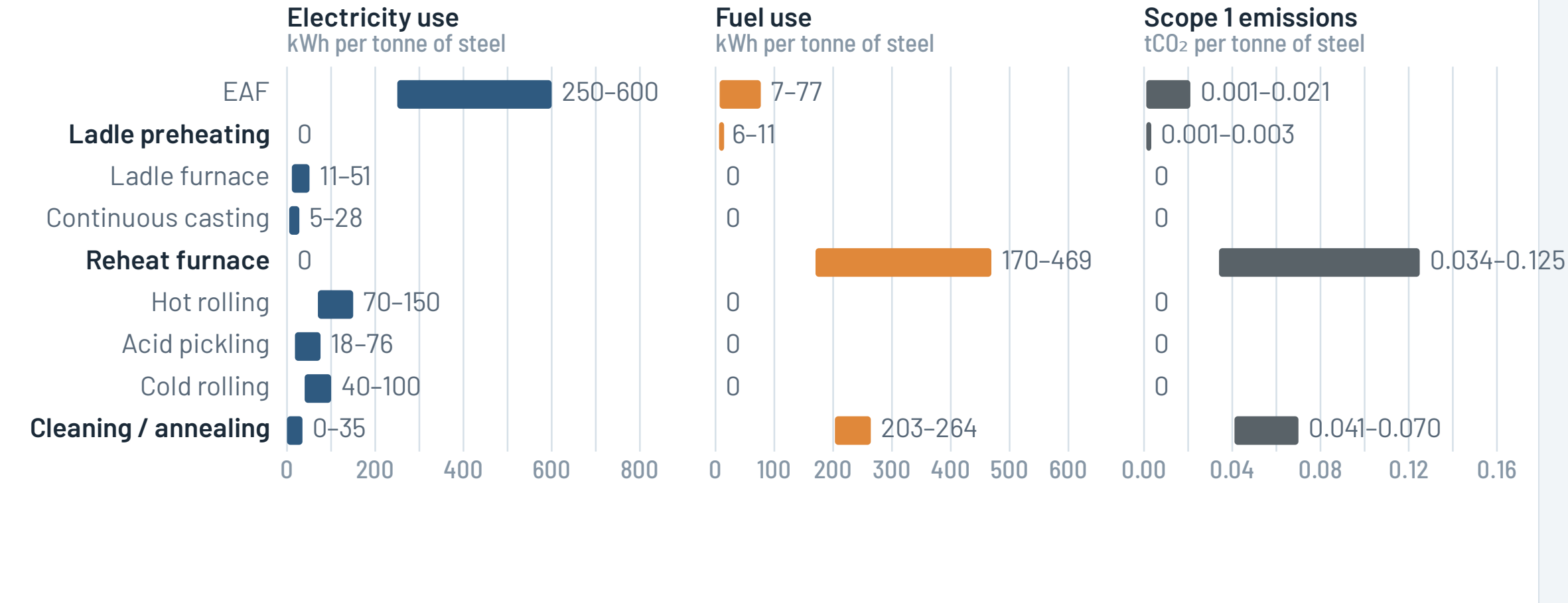
Whilst the majority of emissions from EAF based steel stem from the electricity consumed during charging, transitioning to renewable electricity alone is insufficient to remove process emissions required under increasingly stringent standards, counted at carbon borders, and included in reporting boundaries.[2,3] Achieving this 'near zero emissions' steel requires exhaustive upstream and downstream reductions. **Because reheating and annealing processes account for up to approximately 90% of Scope 1 emissions within the EAF steelmaking process, transitioning upstream and downstream furnace fuels to hydrogen alongside comprehensive equipment electrification is the next frontier for producing truly green steel products.** This report briefly outlines the emission profiles of current EAF steelmaking processes, before examining the alternative technologies poised to replace fossil fuels in downstream heating processes.

Sources: see end notes 1–3 (World Steel Association, *World Steel in Figures 2025*; Steel Standards Principles; ResponsibleSteel).

Reading guide. The main pages give the findings and decisions. Supporting detail is in the appendix: **Appendix A** (p. 12) EAF process stages; **Appendix B** (p. 15) technology profiles; **Appendix C** (p. 19) method notes; **Appendix D** (p. 20) end notes (superscript numbers link to them).

Fuel, not electricity, drives Scope 1 emissions in an EAF mill, and reheat furnaces plus annealing emit 65–92% of them

Figure 1. Energy Consumption and Scope 1 Emissions by Process. Energy use and Scope 1 emissions by process; each bar spans the range from the low to the high value



Note: ranges merge sub-cases (with/without scrap preheating, with/without hot charging).

Source: Transition Asia analysis.[4,5,6,7,8,9,10,11,12,13,14,15]

44~57%

of the entire steelmaking process's Scope 1 emissions come from reheat furnaces alone

65–92%

of Scope 1 emissions come from reheat furnaces combined with annealing

Reheat furnaces alone account for approximately 44~57% of the entire steelmaking process's Scope 1 emissions. When combined with annealing, this figure can rise to between 65-92%. Consequently, targeting these specific heating processes yields the most substantial decarbonisation dividends.

Process detail: the 12 stages behind these figures (charging and melting through annealing) are described in **Appendix A** (p. 12).

Gas burners stay the industry standard for three reasons, yet keeping them means EAF steel will struggle to reach near zero emissions

Fossil fuel-based burners remain the industry standard for certain heating processes due to the following primary factors:

- **High-temperature capability:** The ability to provide heat rapidly and consistently.
- **Operational flexibility:** High turndown ratios allow for immediate adjustments to varying process conditions.
- **Technical maturity:** Decades of accumulated operational expertise and technical know-how.

While these established operational strengths form the basis of reliance on gas-fired systems, the continued use of these fuels mean EAF steel will struggle to reach near zero-emission steel production.

Next: To address this, the following section examines the current landscape, advantages, and commercial readiness of alternative decarbonisation technologies capable of replacing fossil fuels in heating processes.

Electric heaters and hydrogen burners are commercial, plasma torches are at R&D/pilot, and RDH pilots are only planned

Reheating and annealing account for up to 90% of an EAF mill's Scope 1 emission. Four technologies can replace the fossil-fuel burners in these steps, but they differ sharply in maturity, power demand and retrofit effort.

READINESS AT A GLANCE

Electric heater
Precision and High Efficiency
Up to 95% thermal efficiency
Fully commercialised

Plasma torch
High Energy and Compact Power
Plasma jet up to 5,000°C
R&D / pilot

Hydrogen burner
Familiar Operations, Zero Carbon
100% hydrogen combustion
Fully commercialised / H_2 ready

RotoDynamic Heater
The Kinetic Innovator
Process gas up to 1,700°C
Commercial-scale pilot planned

TABLE 1. DEPLOYMENT AND TECHNOLOGICAL READINESS OF DECARBONISATION ALTERNATIVES BY PROCESS

	ELECTRIC HEATER	PLASMA TORCH	H_2 BURNER	ROTODYNAMIC HEATER (RDH)
EAF		–	Commercial (Linde)	
Ladle Preheating	Commercial (KANTHAL)	R&D / Pilot Demonstration	Commercial (ArcelorMittal)	Commercial-scale pilot planned (JSW)
Reheat Furnace			Commercial (OVAKO)	
Cleaning / Annealing	Commercial (OVAKO, KANTHAL)	–	Commercial (H_2-ready) (tenova)	

Source: Various websites.

Commercial · R&D / pilot · Commercial-scale pilot planned · – Not applicable

Details in the appendix. Characteristics, applications, advantages, limitations, commercial maturity and example projects for each technology are in **Appendix B** (p. 15).

Each alternative pairs a clear advantage with a specific challenge

TABLE 2. ADVANTAGES AND CHALLENGES OF EACH ALTERNATIVE TECHNOLOGY

	ELECTRIC HEATER	PLASMA TORCH	H_2 BURNER	ROTODYNAMIC HEATER (RDH)
Key Advantages	**+ ~95% Efficiency:** Near zero exhaust heat loss	**+ Extreme Heat:** Up to 5,000°C, rapid transfer	**+ Efficient Combustion:** Very high flame temperatures	**+ ~90-95% Efficiency:** Direct kinetic-to-thermal conversion
	+ High Control: Uniform temp, low maintenance	**+ Compact Footprint:** Strong retrofit potential	**+ Low Pollutants:** Low SOx & particulates	**+ Gas Agnostic:** Operates on air, N_2, CO_2, CH_4, etc.
Key Challenges	**- Grid Constraints:** Requires major electrical upgrades	**- High OPEX:** Massive electrical demand; +25% energy vs fossil gas	**- Flame Dynamics:** Shorter, intense flame risks uneven heating	**- Unproven at Scale:** Lack of long-term industrial operating data
	- Material Degradation: Elements prone to thermal shock/oxidation	**- Refractory Wear:** Intense thermal loads need upgraded materials	**- NOx & Flashback Risks:** Requires redesigned nozzles & valves	

Source: Various websites, TA analysis.

Full profile of each technology: **Appendix B** (p. 15).

Electric heaters and RDH need the least electricity, while hydrogen burners need the most because green hydrogen requires electrolysis

Power consumption for the implementation of each alternative technology is calculated based on the assumptions outlined in Table 2. For plasma torches, nitrogen is assumed as the process gas, while for hydrogen burners, the analysis includes the power consumption required for hydrogen production. For processes where commercialisation or pilot demonstrations have not yet been established, the alternative technology with the lowest energy consumption is assumed.

A side-by-side comparison of these alternative technologies reveals substantial variations in energy efficiency and resource demands. Electric Heaters and RotoDynamic Heaters (RDH) have the lowest total electricity requirements. Alternatively, hydrogen burners demand the highest aggregate power input due to the energy-intensive nature of upstream water electrolysis for green hydrogen production.

TABLE 3. ENERGY, NITROGEN, HYDROGEN, AND WATER CONSUMPTION BY ALTERNATIVE TECHNOLOGY[16]

PARAMETER		VALUE
Thermal Efficiency[17,18,19]	Gas Burner · Ladle Preheating	20%
	Gas Burner · Other processes	30–60%
	Electric Heater and RotoDynamic Heater (RDH)	90–95%
The Ratio of Electricity Consumption of a Plasma Torch compared to NG consumption of a Gas Burner[20]		56–69%
N_2 Consumption for Plasma Torch[21]		0.14 kg-N_2/kWh
Electricity Consumption for making H_2[22]		50–55 kWh/kg-H_2
Water Consumption for making H_2[22]		11 L/kg-H_2
Energy content of H_2[23]		33.3 kWh/kg-H_2

Source: Various websites.

How this was calculated: assumptions and system boundaries are in **Appendix C** (p. 19); sources are in **Appendix D** (p. 20).

Hydrogen burners demand the most power and water, while plasma torches require significant nitrogen

24–68 kg/t

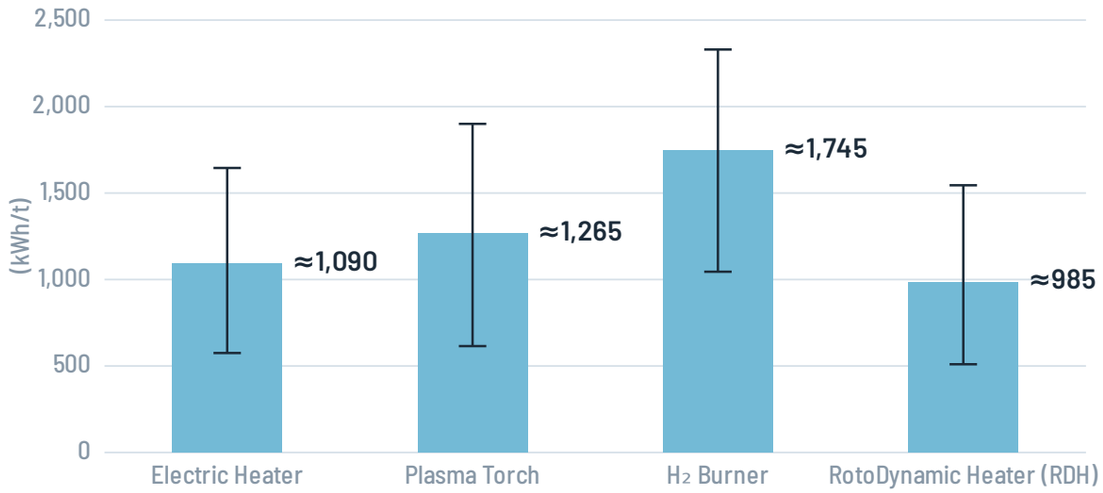
kg of nitrogen per tonne of steel if plasma torches are deployed across both ladle preheating and reheating furnaces

137–271 L/t

litres of water per tonne of steel if every process is converted to hydrogen burners

Accounting the inputs required for these technologies; deploying plasma torches across both ladle preheating and reheating furnaces consumes between 24 and 68 kg of nitrogen per tonne of steel. Converting every process to hydrogen burners requires 137 to 271 L of water per tonne of steel. **While RDH systems also depend on process gases, specific consumption metrics remain unavailable and have consequently been omitted from this report.**

Figure 2. Power Consumption Required for Decarbonising All Heating Processes (kWh/t)



Note: bars show the central value and whiskers the low–high range. Values are read off the published chart and are approximate. Where commercialisation or pilot demonstrations have not been established (Table 1), the alternative technology with the lowest energy consumption is assumed.[24]

Source: TA analysis.[24]

Early CAPEX estimates vary widely across technologies and overall cost transparency remains low

USD 0.6–5.3m
per MW for electric heaters (USD 622,000 to USD 5,349,000)[25]

≤USD 383
per tonne of liquid steel capacity for plasma torches (upper bound)[26]

~40%
of the overall furnace CAPEX to retrofit existing natural gas furnaces to hydrogen burners[27,28]

n/a
RDH cost structures remain undisclosed to the public[29]

Cost transparency remains significantly constrained across these technologies, making comprehensive financial comparisons challenging. Nevertheless, available data provides a preliminary baseline for evaluating the capital expenditure (CAPEX) associated with each alternative technology.

For electric heaters, CAPEX varies greatly and is estimated between USD 622,000 and USD 5,349,000 per MW.[25] While this estimation is derived from 10 MW petrochemical furnace retrofits, the financial requirements for steel industry applications are anticipated to be comparable.

In the case of plasma torches, expenditure is projected at up to USD 383 per tonne of liquid steel capacity.[26] This figure represents an upper CAPEX bound, inclusive of a 20% uncertainty margin, calculated by aggregating the costs of the EAF and the plasma torch itself.

Conversely, the financial profile for hydrogen burners is primarily understood through the lens of retrofitting existing natural gas furnaces, which typically demands an investment equivalent to approximately 40% of the overall furnace CAPEX.[27,28]

Finally, concrete cost structures for the emerging RDH remain undisclosed to the public. However, developers assert that the technology will ultimately offer a competitive capital expenditure profile relative to incumbent fossil-fuel heating systems.[29]

Sources: see end notes 25–29 (UK government, *Future opportunities for electrification to decarbonise UK industry*; ScienceDirect; Hy4Heat; Coolbrook).

Three steps for EAF operators: start with reheating furnaces, electrify directly with renewable electricity, and pilot now

Step 1 · Process priority

Prioritise reheating furnace decarbonisation

Given that reheating furnaces alone account for over 44% of the steelmaking process's Scope 1 emissions, interventions in this specific process will yield the highest proportional GHG abatement.

Step 2 · Technology route

Champion direct electrification powered by RE

Acknowledging the heavy energy penalties associated with hydrogen electrolysis, direct electrical heating technologies should serve as the primary decarbonisation vector. Electrification must be powered with RE to eradicate subsequent Scope 2 emissions.

Step 3 · Timing

Investigate mature technologies despite commercial ambiguity

Heating alternatives for every process traditionally reliant on gas burners are technologically mature. Whilst comprehensive economic comparisons are currently hindered by CAPEX ambiguity, EAF operators would benefit from proactively engaging in pilot projects now to validate operational efficiencies and ensure they are positioned to scale as these technologies advance.

Evidence behind these steps: technology profiles in **Appendix B** (p. 15), method notes in **Appendix C** (p. 19), sources in **Appendix D** (p. 20).

Appendix contents

A · EAF process stages	p. 12
CHARGING AND MELTING	P. 12
TAPPING, LADLE AND CASTING	P. 13
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B · Technology profiles	p. 15
B1 ELECTRIC HEATER	P. 15
B2 PLASMA TORCH	P. 16
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B4 ROTODYNAMIC HEATER (RDH)	P. 18
C · Method notes	p. 19
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The EAF steelmaking process relies on a combination of electrical power and fossil fuels

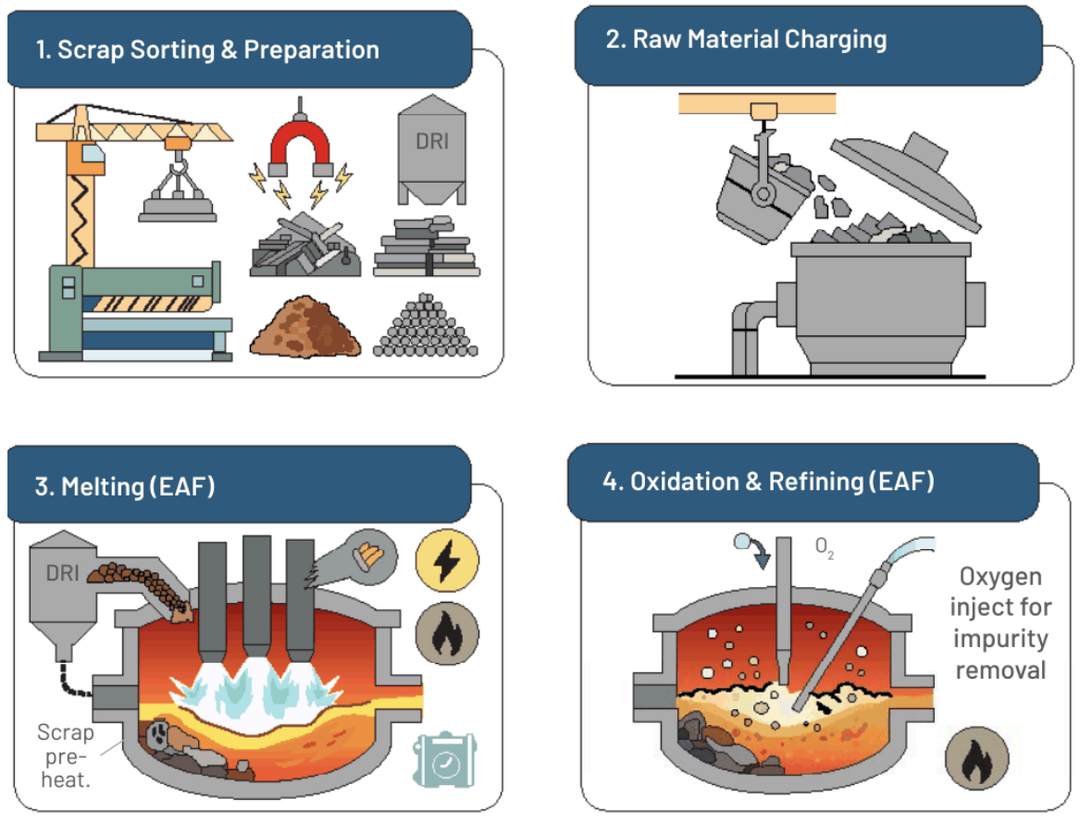
1. Charging and Melting

Incoming metal is initially preheated using natural gas or recovered exhaust heat from prior EAF charges. The EAF operates on a 45 to 73-minute cycle; following a 5 to 8-minute charging phase, auxiliary burners and heat from an electrical arc discharge melt the scrap or DRI over 25 to 35 minutes.[30,31]

45–73 min
minute EAF cycle[30,31]

5–8 min
minute charging phase

25–35 min
minutes to melt scrap or DRI with auxiliary burners and the electric arc



Overview of the EAF Process Flow (split into 12 panels). Panels 1–4: Scrap Sorting & Preparation; Raw Material Charging; Melting (EAF), with DRI feed and scrap preheat; Oxidation & Refining (EAF), with oxygen injected for impurity removal.

Fossil-fuel burners preheat the ladle to 800–1,000°C before casting

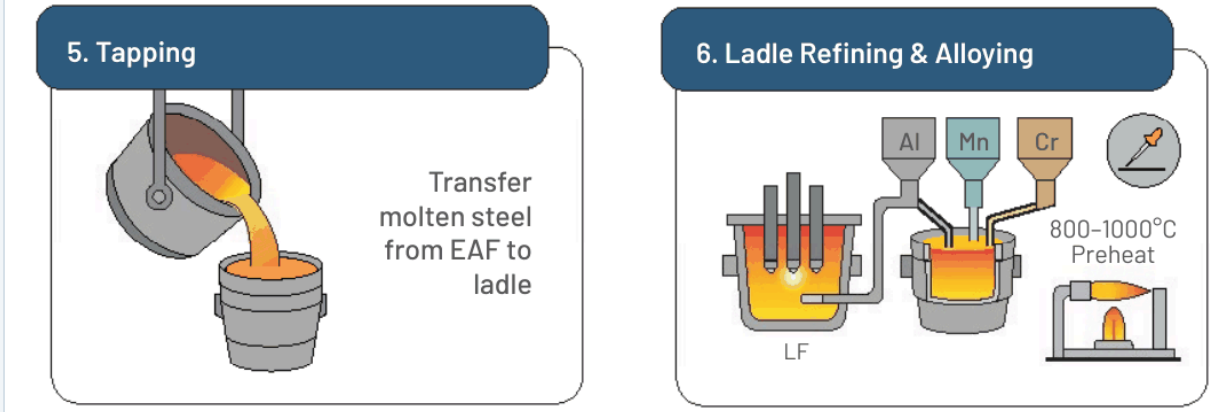
Subsequently, the molten metal is discharged into the ladle furnace. The ladle furnace refines the liquid steel for 10 to 15 minutes while maintaining optimal temperatures. **To prevent severe thermal loss and thermal shock to the refractory lining, the ladle is preheated to 800°C–1000°C using fossil fuel-based burners; depending on the ladle's initial state, this preheating process takes between 30 and 240 minutes.**[32,33]

Thereafter, the continuous casting process, which draws a continuous base electrical load, cools and solidifies the liquid steel into semi-finished shapes, such as slabs and billets.

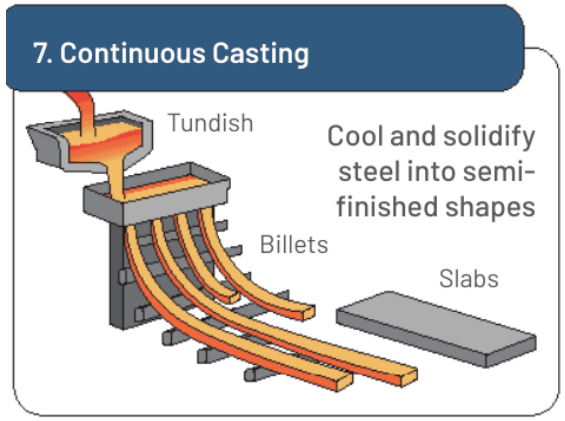
10–15 min
minutes of ladle furnace refining

800–1,000°C
ladle preheat temperature, set by fossil fuel-based burners[32,33]

30–240 min
minutes of ladle preheating, depending on the ladle's initial state



Panels 5–6. Tapping: transfer molten steel from EAF to ladle. Ladle Refining & Alloying: Al, Mn and Cr additions in the ladle furnace (LF), with an 800–1000°C preheat.



Panel 7. Continuous Casting. Cool and solidify steel into semi-finished shapes (tundish, billets, slabs).

Reheating and annealing are the fossil-fuelled steps in downstream processing; hot rolling, pickling and cold rolling run on electricity

Then, a continuously operating, fossil fuel-fired reheat furnace is utilised to heat the semi-finished products from room temperature to approximately 1,200°C immediately prior to hot rolling. **Although "hot charging", the direct feeding of uncooled, high-temperature semi-products into the furnace, enhances efficiency, achieving 100% hot charging remains difficult for high-grade products like automotive steel due to production scheduling misalignments.**[34,35,36]

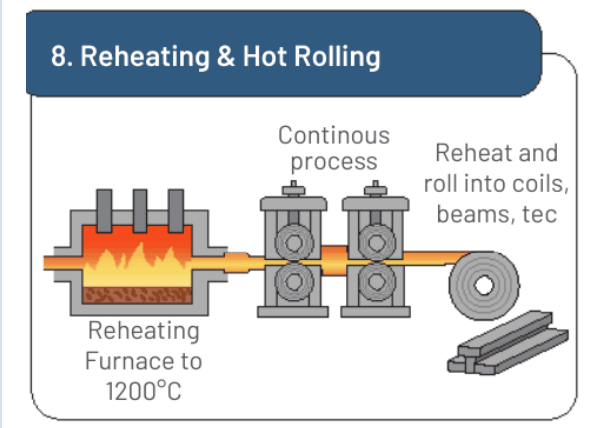
The heated steel then proceeds to the electrically powered hot rolling stage, where it is passed through rollers under pressure to achieve specified thickness reductions.

Next, the acid pickling process employs hot hydrochloric or sulphuric acid solutions alongside inhibitors to remove the oxide scale formed during hot rolling. This electrically driven process can be completed in mere seconds for the continuous processing of steel strips; conversely, batch processing is utilised for complex shapes, such as pipes, to ensure the complete dissolution of scale in overlapping or intricate areas, which can take from 30 minutes to several hours.[37]

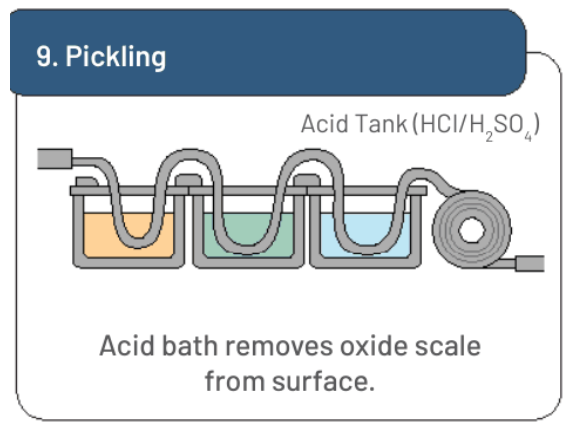
The cold rolling process then further reduces the strip thickness at room temperature using heavy rollers, operating on a continuous electrical base load.

In the final cleaning and annealing stage, dedicated cleaning lines first utilise high-temperature alkaline solutions to remove organic residues and lubricants deposited during cold working. **Subsequently, annealing is performed, via gas burner heat treatment, to restore the ductility of the steel hardened during the cold working process.**

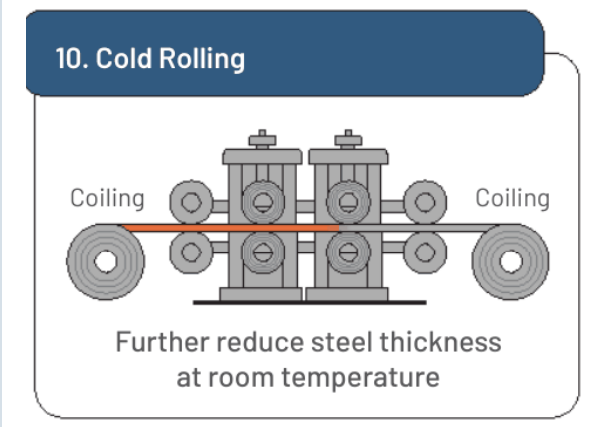
In a continuous process mill, the steel strip undergoes rapid heating to approximately 700°C, followed by a holding period at roughly 400°C, and final cooling to room temperature, with the entire sequence completed within about 10 minutes.[38,39,40] Because this method heats the uncoiled strip, it ensures high dimensional and quality uniformity across the length and width, making it highly suitable for mass production. Conversely, batch processing is primarily used for specialised grades or small-lot orders; this method involves stacking coils and heating them in an enclosed environment via thermal conduction, which requires 4 to 24 hours to complete.



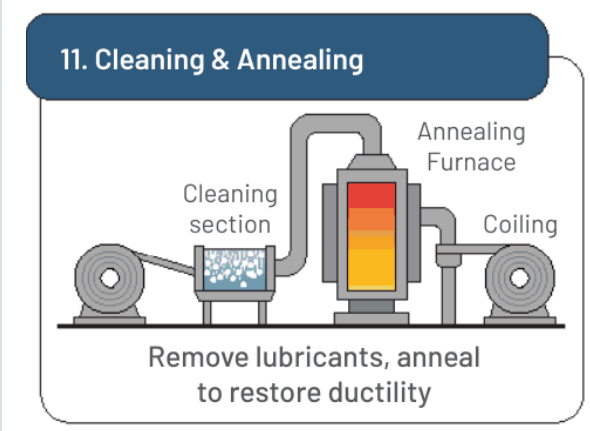
Panel 8. Reheating & Hot Rolling. Reheating furnace to 1200°C; continuous process; reheat and roll into coils, beams, etc.



Panel 9. Pickling. Acid bath (HCl/H_2SO_4) removes oxide scale from the surface.



Panel 10. Cold Rolling. Further reduce steel thickness at room temperature.





Panels 11–12. Cleaning & Annealing: cleaning section, annealing furnace, coiling; remove lubricants, anneal to restore ductility. Final Products & Logistics: final inspection and shipment to customers.

~1,200°C
reheat furnace temperature, from room temperature, immediately before hot rolling[34,35,36]

30 min to hours
batch pickling of complex shapes such as pipes[37]

~10 min
continuous annealing: ~700°C heating, ~400°C hold, cool to room temperature[38,39,40]

4–24 h
batch annealing of stacked coils by thermal conduction

Electric heaters are fully commercial and reach up to 95% thermal efficiency, but need significant grid and electrical upgrades

Electric heater

APPENDIX B1 · PRECISION AND HIGH EFFICIENCY

FULLY COMMERCIALISED

~95%

thermal efficiency, thanks to zero exhaust heat loss[41,42,43]

~90%

of Ovako's heat treatment capacity electrified since 2014[44,45,46]

Fully commercialised

commercial maturity

CHARACTERISTICS OF THE TECHNOLOGY: PRECISION AND HIGH EFFICIENCY

Electric heaters offer a direct and highly efficient electrification route by converting electrical energy into heat within a sealed chamber using resistance elements, such as $MoSi_2$ or SiC.[47,48]

ADVANTAGES

Because there is zero exhaust heat loss, they can achieve a thermal efficiency of up to 95%. They are highly suitable for retrofitting, require lower maintenance than traditional gas burners, and provide exceptional temperature control that yields superior product quality.[41,42,43]

COMMERCIAL MATURITY

Fully Commercialised

WHERE IT CAN BE APPLIED

Ladle preheating, reheating furnaces, and annealing processes.

LIMITATIONS

Facility-wide adoption requires significant grid and electrical upgrades. Additionally, heating elements can degrade via thermal shock or oxidation at extreme temperatures, and current industry perception tends to bias this technology towards smaller-scale heating applications.[49,50,51]

REPRESENTATIVE PROJECTS / COMPANIES

Nordic special steel manufacturer Ovako pioneered this approach for annealing in 2014, successfully electrifying approximately 90% of its heat treatment capacity.[44,45,46]

Plasma torches deliver up to 5,000°C in a compact footprint, but remain at R&D and pilot stage and may need ~25% more energy than gas burners

Plasma torch

APPENDIX B2 · HIGH ENERGY AND COMPACT POWER

R&D / PILOT

5,000°C
plasma jet temperature, with intense and rapid heat transfer[52,53,54]

~25%
higher overall system energy demand than gas burners, because of high cooling demands[55,56,57]

R&D / pilot
commercial maturity

CHARACTERISTICS OF THE TECHNOLOGY: HIGH ENERGY AND COMPACT POWER

By ionising gases (N_2, Ar, CO_2, O_2, etc.) via an electric arc, they generate a high-temperature, high-energy plasma jet.[58,59,60]

ADVANTAGES

They provide intense and rapid heat transfer (up to 5,000°C) and feature a compact footprint that allows for retrofitting into existing facilities. Furthermore, their rapid start-and-stop capabilities support highly flexible plant operations.[52,53,54]

COMMERCIAL MATURITY

R&D and Pilot stages

WHERE IT CAN BE APPLIED

Ladle preheating, reheating furnaces.

LIMITATIONS

Intense thermal loads can accelerate refractory wear within the ladle or reheating furnaces. High cooling demands mean the overall system energy demand may be approximately 25% higher than that of gas burners, necessitating increased power procurement. Operators must also manage potential NOx generation risks if air or nitrogen is utilised as the process gas.[55,56,57]

REPRESENTATIVE PROJECTS / COMPANIES

For ladle preheating, computational fluid dynamics (CFD) simulations demonstrate technical viability: 100 kW to 1.5 MW plasma torches can achieve bottom temperatures of 1,000°C or higher via enhanced convection, rivaling natural gas.[61] Additionally, a Swedish pilot project successfully utilised a 250 kW DC plasma torch on a lab-scale reheating furnace, achieving uniform heating to 1,200°C within practical timeframes.[62]

Hydrogen burners are commercial or H_2-ready for every heating process, but short flames, flashback and NOx risks demand redesign

Hydrogen burner

APPENDIX B3 · FAMILIAR OPERATIONS, ZERO CARBON

FULLY COMMERCIALISED / H_2 READY

100%

hydrogen combustion units directly substitute fossil-fuel burners

4

processes where hydrogen burners are listed as applicable: EAF, ladle preheating, reheat furnace, annealing

Fully commercialised

commercial maturity (or H_2-ready)

CHARACTERISTICS OF THE TECHNOLOGY: FAMILIAR OPERATIONS, ZERO CARBON

Hydrogen burners allow for the direct substitution of fossil fuel burners with 100% hydrogen combustion units.

WHERE IT CAN BE APPLIED

EAF, ladle preheating, reheat furnace, and annealing

ADVANTAGES

They offer a decarbonisation pathway that is highly feasible via retrofitting, achieve very high flame temperatures, and significantly improve furnace atmospheric conditions by producing minimal SOx and particulate emissions.[63,64]

LIMITATIONS

The high combustion velocity results in shorter flames, which risks uneven heating profiles. Additionally, the lack of soot in hydrogen flames reduces radiant heat transfer, often demanding fundamental furnace redesigns to compensate. From a safety and emissions standpoint, operators must mitigate elevated flashback risks through nozzle and valve redesigns, alongside addressing heightened NOx generation risks caused by the extreme temperatures.[65,66,67]

COMMERCIAL MATURITY

Fully commercialised (or H_2-ready)

REPRESENTATIVE PROJECTS / COMPANIES

Example projects include Ovako's reheating furnace at Hofors and ArcelorMittal's ladle preheater at the Sestao plant.[68,69,70] Both facilities are powered by green hydrogen.

RotoDynamic heaters could reach up to 1,700°C at 90–95% efficiency, but are still at pilot stage without long-term industrial data

RotoDynamic Heater (RDH)

APPENDIX B4 · THE KINETIC INNOVATOR

COMMERCIAL-SCALE PILOT PLANNED

1,700°C
process gas temperature the RDH is capable of reaching[71,72]

90–95%
thermal efficiency, gas-agnostic (air, N_2, CO_2 or CH_4)[73,74]

Pilot
commercial deployment was initially targeted for 2025[75]

CHARACTERISTICS OF THE TECHNOLOGY: THE KINETIC INNOVATOR

RDH employs electric motors to spin bladed rotors at extraordinary speeds. This motion accelerates the process gas to generate shockwaves, converting kinetic energy directly into thermal energy capable of reaching up to 1,700°C.[71,72]

ADVANTAGES

The RDH boasts exceptional thermal efficiency of roughly 90% to 95% and is gas-agnostic, able to operate on air, nitrogen, carbon dioxide, or methane.[73,74] Furthermore, its small footprint is highly conducive to retrofitting.

COMMERCIAL MATURITY

Pilot demonstration phase. While commercial deployment was initially targeted for 2025, developmental progress seems to remain actively ongoing.[75]

WHERE IT CAN BE APPLIED

EAF, ladle preheating, reheat furnace, and annealing

LIMITATIONS

As an emerging technology, its primary challenge is that it currently lacks prolonged operational data at a full industrial scale.

REPRESENTATIVE PROJECTS / COMPANIES

A large-scale pilot conducted in 2023 at the Brightlands Chemelot Campus in the Netherlands successfully demonstrated temperatures exceeding 1,000°C, highlighting the technology's potential to eventually reach up to 1,700°C.[76] As a significant step forward, a 2024 agreement was reached with JSW Steel in India to collaborate on a future commercial-scale pilot demonstration at its Vijayanagar plant, though no further updates regarding the project's specific status have been disclosed to date.[77,78]

How the figures and comparisons in this report were built

TOPIC	HOW IT IS TREATED IN THIS REPORT
Figure 1 ranges	Ranges merge sub-cases (with/without scrap preheating, with/without hot charging). Each bar spans the low to the high value.[4,5,6,7,8,9,10,11,12,13,14,15]
Table 3 efficiencies	Values represent direct heating efficiency, to maintain consistent system boundaries across all technologies. They exclude peripheral system requirements, such as the massive cooling demand for plasma torches (which pushes overall system energy demand +25% higher, as discussed in Section 2).[16]
Plasma torch process gas	Nitrogen is assumed as the process gas.
Hydrogen burners	The analysis includes the power consumption required for hydrogen production (50–55 kWh/kg-H_2 of electricity; 11 L/kg-H_2 of water; 33.3 kWh/kg-H_2 energy content).[22,23]
RotoDynamic heater	Process gases are also needed, but specific consumption metrics remain unavailable and have been omitted.
Processes without commercial or pilot technology	For processes where commercialisation or pilot demonstrations have not yet been established (based on Table 1), the alternative technology with the lowest energy consumption is assumed.[24]
Electric heater CAPEX	Derived from 10 MW petrochemical furnace retrofits; steel industry requirements are anticipated to be comparable.[25]
Plasma torch CAPEX	Upper bound, inclusive of a 20% uncertainty margin, calculated by aggregating the costs of the EAF and the plasma torch itself.[26]
Hydrogen burner CAPEX	Understood through retrofits of existing natural gas furnaces: approximately 40% of overall furnace CAPEX.[27,28]

Sources: end notes 4–16, 22–29. The report relies on publicly available, self-reported information that the authors did not seek to validate (see Data and disclaimer).

End notes

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