

Whitepaper

Thermal Energy Storage in the Steel Industry

Opportunities of flexible Waste Heat Recovery and Utilisation as well as flexible Electrification with TES

Thermal Energy Storage in the Steel Industry

Waste Heat Recovery and Electrification with TES · Short Version

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Summary

Steel mills release large quantities of waste heat above 350 °C across the value chain, from flare gases and electric arc furnace (EAF) off-gas to ladle preheating, coke dry quenching and sinter cooling. Much of this heat is lost not because too little is available, but because it arises at the wrong time, fluctuates strongly in temperature and power, or occurs far from a suitable heat sink. Thermal energy storage (TES) addresses the first two constraints directly: it decouples heat recovery from heat use and turns fluctuating waste heat into a stable supply.

This paper is a condensed version of a longer review of waste heat sources and sinks in steel production, based on published literature and documented industrial assessments. The processes covered are common to integrated blast furnace–basic oxygen furnace (BF-BOF) plants and EAF-based steelmaking worldwide. The key findings are:

- **Cyclic processes offer the strongest case for storage.** Electric arc furnaces, ladle preheating, coke charging and oxygen blowing release heat intermittently, which is where direct heat exchange reaches its limits.
- **Existing recuperation leaves potential.** One documented reheating furnace reached only about 60% overall efficiency despite a recuperator; flue gas losses (~7.3 MW) remained its largest loss category.
- **Flare gases are a large but poorly quantified pool.** The average European plant flares about 2% of its off-gases, roughly 162 GWh per year at an average facility (order-of-magnitude estimate).
- **Scrap and DRI preheating convert heat into saved electricity.** Preheating scrap can reduce EAF electricity demand by up to 20%; hot DRI charging saves 28–105 kWh/t of liquid steel. Dioxin formation during scrap preheating requires off-gas treatment.
- **Industrial-scale operation is demonstrated.** A 2 × 10 MWh TES system at the sinter cooler of Tata Steel in Jamshedpur, India, recovers heat at up to 600 °C. Measured dust levels were lower than assumed in the design.
- **Electrification is a second use case.** Where no waste heat is available, TES can be charged with low-cost electricity. Its economics depend mainly on electricity price spreads.

For packed-bed, air-based TES systems of the type considered here, suitability depends on four site-specific parameters: waste heat temperature (at least 350 °C) and thermal power (at least roughly 300 kW), dust load, distance to a sink (up to about 200 m for hot air, longer for steam, hot water or thermal oil) and the duty cycle of source and sink. These should be measured before a feasibility study is started.

1 Introduction

Global crude steel production more than doubled between 2000 and 2020, with most new capacity built in China. [1] Over the same period, scrap use, electric arc furnaces and direct reduced iron (DRI) gained market share. Overcapacity now limits investment in new plants, so producers are looking at their existing fleet for retrofits that improve efficiency, reduce pollution and lower their exposure to volatile fuel markets and rising industrial electricity prices.

Thermal batteries come in a variety of shapes, sizes and chemistries. [2] Those that cover a wide temperature range can serve a larger share of the processes found in a steel mill, and systems that can be adapted to the site are an advantage, as layout, available space and integration requirements vary considerably between plants. [3] Their simplest application is to store waste heat, which comes

at no fuel cost, and deliver it to a sink on demand. They can also support the electrification of heating processes by smoothing variable energy flows and using low-cost electricity.

India, Southeast Asia and Africa are projected to see the largest growth in steel demand in the coming decades. [4] This review is not comprehensive; it focuses on opportunities commonly found at standard production facilities.

2 Waste Heat Recovery with Thermal Energy Storage

Waste heat is commonly recovered directly, for example by recuperating it within the same process or by generating steam. Where there is no suitable sink nearby, or the timing of source and sink does not match, a storage system can make use of heat that would otherwise be lost.

Timing and fluctuation

In batch processes, heat is released intermittently. A TES system can recover heat from one or several batches and supply it later; in steel production, storage durations are typically a matter of hours. With several storage units, one can charge while another discharges, so that even a batch source can supply heat continuously.

Waste heat also fluctuates in power and temperature, for example through dilution with ambient air or process ramping. For direct use, the minimum power and temperature limit what can be supplied. A storage system can charge selectively at usable temperature levels, independently of the available power, while discharge to the sink is controlled by the fan speed (Fig. 1).

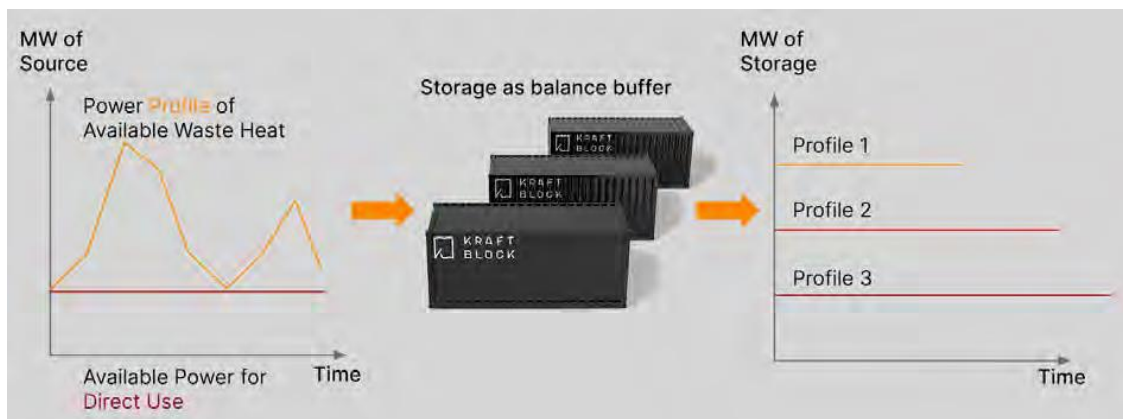


Fig. 1: Storage as balance buffer for a fluctuating waste heat profile, enabling stable supply profiles. Source: Kraftblock.

How waste heat recovery with packed-bed TES works

This paper considers packed-bed systems that use air as the heat transfer medium. Other TES designs, for example based on molten salt, phase-change materials or steam accumulators, differ in temperature range and integration. Off-gas is guided into the storage, filtered if necessary, and transfers its sensible heat to the storage material. Mineral storage media such as steel slag have been shown to be thermally stable up to at least 1,100 °C [5], and experiments with dust-laden exhaust gas from the steel industry found that around 98% of the dust is retained in the packed bed, concentrated near the inlet surface, without affecting the flow distribution. [6] Off-gas constituents can be treated downstream after the sensible heat has been transferred to the storage material; a heat exchanger upstream of the storage is also possible. To discharge, a fan blows ambient air through the storage to a heat exchanger or directly to the process.

Overview of waste heat sources

Table 1 summarises the processes reviewed in the following sections. Figures are drawn from published literature and documented industrial assessments; citations are given in the respective sections.

Process	Available temperature	Profile	Principal obstacle
Flare gases (COG, BFG, BOFG)	820–980 °C in practice; higher on controlled combustion	Irregular, plant-specific	Data scarce and confidential; surplus volume varies widely
Electric arc furnace off-gas	Up to 1,800 °C, ~600 °C after the cooled duct, ~700 °C after coarse filtration	Strongly cyclic within an 80 min tap-to-tap	Dust 4.5–8.5 g/m ³ ; composition varies through the heat
Pellet induration furnace	~450 °C at the preheating zone stack	Continuous	Heat leaves via four separate stacks; aggregation needed
Reheating furnace before hot rolling	~800 °C at full production, ~464 °C at idle	Near-continuous with idle periods	Recuperators already installed on most furnaces
Ladle preheating	1,000–1,100 °C at the station	Highly cyclic: 8–9 h after relining, 20–30 min in circulation	Gas escapes around the hood; capture requires an enclosure
Coke dry quenching	750–900 °C circulating gas	Quasi-continuous, discrete charging events	Existing waste heat boiler usually already serves steam demand
Sinter cooler	Up to 600 °C	Continuous, mild variation	High dust; hood design governs ambient air dilution
Basic oxygen furnace off-gas	1,450–1,650 °C, cooled to 800–1,000 °C	Highly intermittent: ~15 min blowing in a 30–40 min cycle	Dust 80–150 g/m ³ ; CO content creates explosion risk
Steel slag	High, not well characterised	Batch	No established capture method; experimental

Table 1: Overview of waste heat sources in steel production reviewed in this paper.

2.1 Flare Gases

Integrated steel plants generate three principal combustible by-product gases: coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG). Most of it is used in processes or combusted for heat, but where production does not match demand and gas storage is insufficient, the surplus is flared, continuously at some sites and irregularly at others. [7]



Fig. 2: Flaring at an integrated steel plant.

The average European steel plant flares roughly 2% of its off-gases. [8] Based on the volume streams given by Collis et al. and assuming continuous operation, this corresponds to roughly 162 GWh per year at an average facility, an order-of-magnitude estimate rather than a measurement. [9] An Australian review cites typical flaring shares of around 2.5% of COG, 5.5% of BFG and 26% of BOFG, and notes that at BlueScope Steel's integrated plant at Port Kembla, COG and BFG are almost entirely used on site, while all BOF gas was being flared at the time of the review. [10] A 2010 US Department of Energy assessment reported flaring rates between 0.1% and 22% [11], and one JSW Steel plant in India still reports BFG flaring of 10% and COG flaring of 4% after optimising its gas network. [12]

Data on flared gas is scarce and usually confidential. The characteristics of the stream, however, suit thermal storage: irregular schedules and volumes and fluctuating power and temperature. A connection to the gas network also allows flexible siting. The EU Horizon-funded Hall A project investigated combusting flare gas directly into a storage unit instead of the flare; Fig. 3 shows a test set-up with an electrified burner and a mobile 20-ft storage unit.

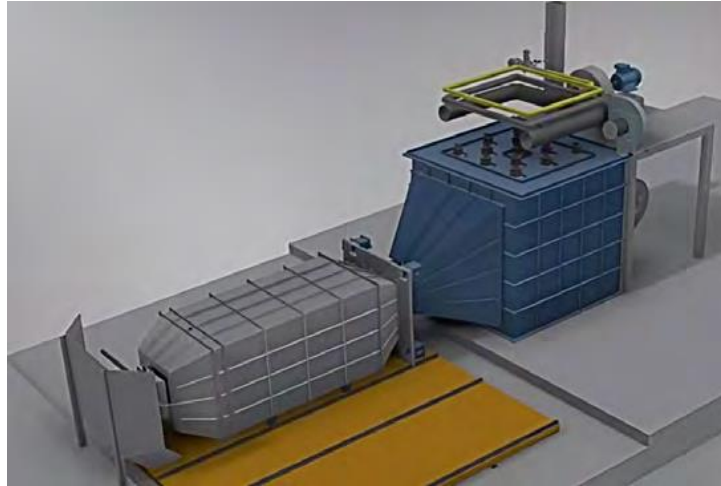


Fig. 3: Burner system for flare gas with storage vessel.

In practice, flare combustion is regulated between 820 and 980 °C to balance gas destruction and NO_x emissions. [13] For the Hall A project, combustion temperatures of 1,100–1,300 °C were calculated, which would also make hot air for the blast furnace a possible use.

2.2 Electric Arc Furnace (EAF) Off-Gas

EAF off-gas can reach 1,800 °C and cools to around 600 °C in the water-cooled duct. [14][15][16] Its dust load of 4.5–8.5 g/m³ limits direct use; after a coarse dust filter, where a TES system could be connected, around 700 °C would be available. [10][15]

The off-gas is strongly cyclic. Gandt et al. examined a sample batch from a 145 t EAF with three charged baskets and a tap-to-tap time of 80 minutes (Fig. 4).

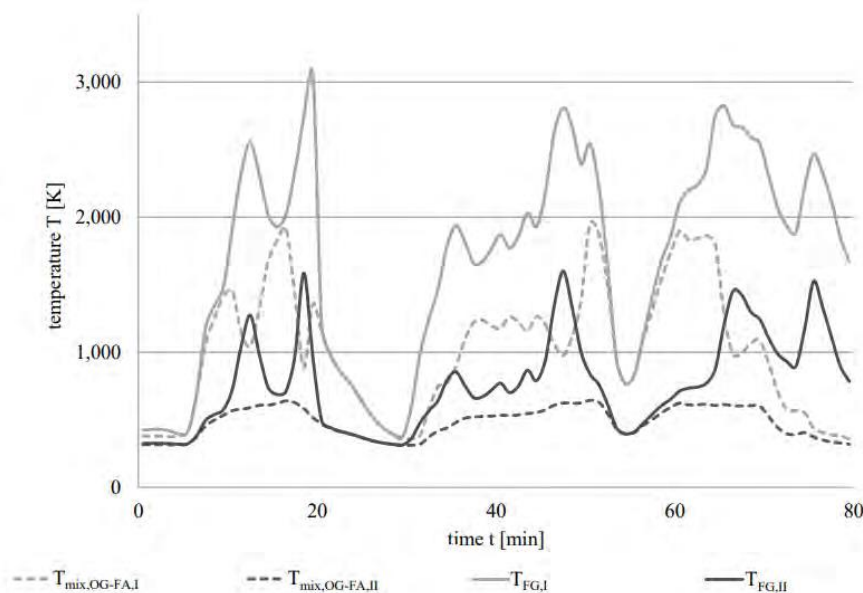


Fig. 4: Flue gas temperatures T_{FG} in comparison to mixture temperatures $T_{mix,OG-FA}$; OG: off-gas, FG: flue gas, FA: false air. Source: Gandt et al. [14]

A storage system can use the high-temperature peaks for charging and ignore the troughs, which increases energy density and reduces problems with constituents such as SO_x and NO_x. The more constant base supply of around 400 °C is sufficient for steam generation. [14] Gandt et al. measured

an average exergy flow of 9.4 MW, of which 35% (3.2 MW) is sensible heat and the remainder chemical energy in the off-gas. [14] For an EAF at Georgsmarienhütte, Germany, Schliephake et al. report 112 kWh of sensible and 122 kWh of chemical energy per tonne of steel. [16] Researchers in Spain have also investigated TES for EAF off-gas. [17] Recovering the sensible heat is the easier first step, as the low calorific value and fluctuating composition make the chemical energy difficult to use. [15]

2.3 Pellet Induration Furnaces

Iron ore pellets are the required feedstock for DRI processes and are increasingly used in blast furnaces. Induration in grate-kiln or straight-grate furnaces is the most energy-intensive step, with around 800–900 °C in the drying and preheating zone and above 1,200 °C in the heating zone. [18] Both designs already recover heat from the cooling zone, but room for improvement remains: at LKAB's grate-kiln operations in Sweden, around 55 MW of heat was found to leave the system via four stacks. [19] Targeting the preheating zone stack, at around 450 °C, may be the simplest application. Stored heat could be returned to the heating zone to reduce fuel demand, and the same system could support electrification.

Magnetite ores react exothermically during induration, while hematite ores do not, so hematite-rich ores require more external heat. [20] TES therefore has a greater opportunity at operations processing hematite. Australia and Brazil are today the two largest hematite iron ore mining countries.

2.4 Reheating Furnaces Before Hot Rolling

Reheating furnaces heat slabs, billets and blooms to around 1,200–1,250 °C before hot rolling and can have a thermal power of up to 200 MW. [21][22][23] Recuperators that preheat combustion air are widespread [24], but they do not recover all available heat. An industrial study of a reheating furnace at Gerdau Ameristeel, operating at around 85 t/h at full production, found an overall efficiency of about 60% despite a recuperator; flue gas losses of about 7.3 MW at around 800 °C remained the largest loss category. [25] The furnace ran at full production for only about half of the operating period, and during idling the flue gas temperature fell to around 464 °C. [25] Storage could buffer such fluctuations, depending on the capacity factor of the furnace.

A well-investigated use is billet preheating. In the same case, preheating billets to 315 °C with flue gas at around 815 °C was estimated to save 60,323 GJ per year, with a payback period of about three years. [26] Another study reports fuel savings of around 18.9% from load preheating and 13.2% from combustion air preheating. [27] TES could increase the amount of heat recovered and deliver it flexibly, for example to keep furnaces and preheating zones warm during idle periods.

2.5 Ladle Preheating

Ladles are preheated to around 1,150–1,200 °C before they return to service, predominantly with gas burners. [28][29] A study at JSW Steel Salem, India, reports around 8–9 hours of heating after refractory relining and 20–30 minutes for ladles in circulation. Exhaust gas of up to 1,000–1,100 °C escapes around the burner hood, and around 50–60% of the heat is lost with the flue gas. An experimental heat exchanger for combustion air preheating recovered around 14% of the available waste heat and reduced LNG consumption from about 224 to 197 kg/h. [28]

A TES system could take the place of the heat exchanger, recover a larger share of the heat and supply it to subsequent heating cycles. This is especially relevant for short cycles, where the required

temperature must be available immediately. Recovery would require a hood over the preheating station.

2.6 Coke Dry Quenching

In coke dry quenching (CDQ), hot coke at around 800–1,200 °C is cooled in a closed loop with circulating inert gas, usually nitrogen, and the heat is conventionally used in a waste heat boiler (Fig. 5). [30][31] The circulating gas typically reaches around 750–900 °C [30][32], and around 1.35–1.5 GJ of heat per tonne of coke can be recovered. [31][33]

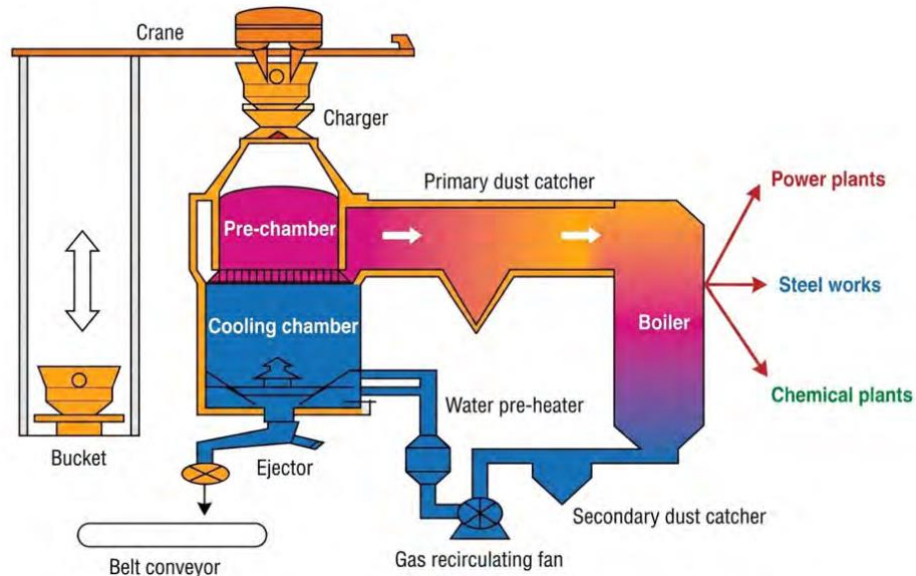


Fig. 5: Schematic of CDQ with waste heat steam boiler. Source: Zhou et al. [34]

As the existing boiler usually already serves the steam demand, additional recovery has to be assessed individually. A TES system could provide process heat at a higher temperature, using the gas after the primary deduster, or be installed in parallel with the boiler to balance fluctuations. Fig. 6 shows a configuration with three storage units in the nitrogen loop: one charging, one discharging to hot air via a gas-gas heat exchanger and one available for changes in the waste heat stream.

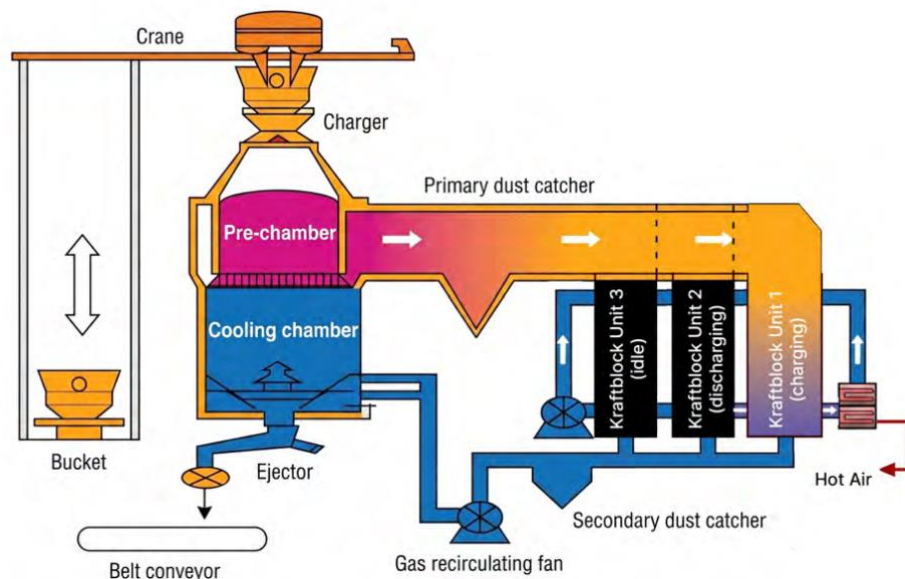


Fig. 6: Schematic of a TES use case in CDQ, based on Zhou et al. [34], edited by Kraftblock.

2.7 Sinter Cooler

Hot sinter is cooled with air, which leaves the cooler at up to 600 °C. The usable energy of this stream depends on four factors:

- a) the output of the hot sinter, which is largely continuous;
- b) the amount of ambient air drawn in, which depends mainly on hood design;
- c) the dust level, which determines whether a filter is needed; dust is commonly assumed to be too high for direct use, but measured values can turn out lower (see 2.8);
- d) the distance to the storage, usually the most influential factor for integration costs and usable temperature. Up to about 200 m is acceptable for hot air; if the heat is discharged to hot water, steam or thermal oil, longer distances are possible.

The recovered heat can be used to preheat combustion air or sinter, dry feedstock, supply hot water for sinter mixing [35][36] or generate steam. An Australian review cites fuel savings of 0.55 GJ/t of sinter and additional electricity generation of 1.4 kWh/t of sinter from a retrofitted heat recovery system at a plant in the Netherlands. [10]

2.8 Use Case: Sinter Cooler Heat Recovery at Tata Steel, Jamshedpur

An industrial-scale installation at Sinter Plant 3 of Tata Steel in Jamshedpur, India, recovers waste heat from the sinter cooling section. [37] The heat is transported to two storage units with a capacity of 10 MWh each, supplied by Kraftblock, and reused in sinter mixing; the exact application and temperature are confidential.



Fig. 7: The thermal energy storage system at Tata Steel's Sinter Plant 3.

Parameter	Value
Charging power	up to 1.5 MW _{th}
Storage capacity	2 × 10 MWh _{th}
Discharging power	up to 1.8 MW _{th}
Temperature level	up to 600 °C
Reported energy savings	equivalent to 110 GWh natural gas per year
Reported emission savings	22,000 t CO ₂ /year
Use	multiple times a day

Table 2: Project data of the Tata Steel installation. Savings as reported by the project partners; they have not been independently verified. [37]

Figs. 8 and 9 show the charging and discharging modes of the system.

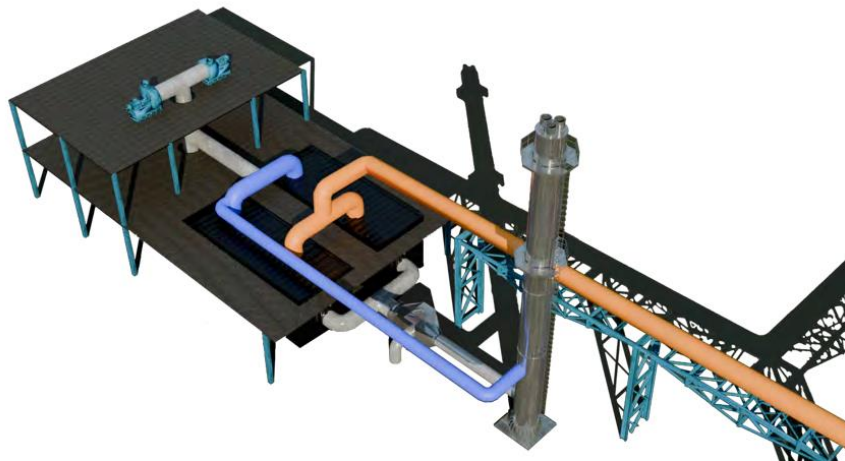


Fig. 8: Schematic of charging both units in the Tata Steel system. The air goes to the chimney after heat transfer to the storage material.

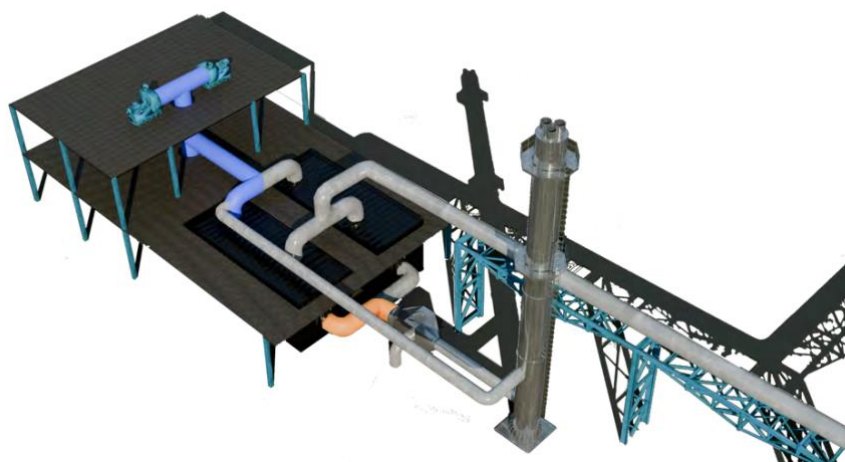


Fig. 9: Schematic of discharging one unit in the Tata Steel system. The hot air transfers heat in a heat exchanger.

Temperatures of up to 600 °C are extracted, subject to fluctuation, and the hood design keeps the intake of ambient air low (Fig. 10). A candle filter was installed because dust levels were expected to be too high for direct use (Fig. 11). In operation, dust levels proved acceptable, and a bypass was

added to use the heat unfiltered at higher temperatures. Dust levels should therefore be measured rather than assumed.



Fig. 10: Hood for waste heat recovery at the sinter cooler of Sinter Plant 3 in Jamshedpur.



Fig. 11: Candle filter in the recovery system.

The constraints encountered here, namely dust, hood geometry and transport distance, apply equally to waste heat recovery elsewhere in the plant.

2.9 Other Possible Sources

BOF off-gas is released during oxygen blowing, which takes around 15 minutes of a 30–40 minute cycle. It leaves the converter at 1,450–1,650 °C and is cooled to 800–1,000 °C, with a dust load of around 80–150 g/m³. [38][39] Using its sensible heat would require a high-temperature filter and a gas-gas heat exchanger to avoid the risk of CO explosion. Heat recovery from steel slag has no established capture method and remains experimental. Both would require detailed feasibility studies.

3 Waste Heat Utilisation Opportunities (Sinks)

When discharged heat is transferred to steam, hot water or thermal oil, it can be transported over several hundred metres, so sources and sinks do not need to be adjacent. Common sinks include combustion air preheating, direct hot air use, stable steam generation, drying, and scrap or DRI preheating. Where gas is burned only to generate heat, hot air from storage, topped up by gas burners where necessary, can reduce fuel use.

3.1 Preheating Scrap for the EAF

Steam generation from EAF off-gas is highly volatile: at Georgsmarienhütte, it rose from 20 to 75 t/h within 7.5 minutes and fell to 10 t/h within the next 7.5 minutes, with periods of no production at all. [16] A storage system between a coarse filter and the waste heat boiler allows a constant steam supply.

Alternatively, the heat can be used to preheat scrap. Each 100 °C of preheating may save 15–20 kWh_e/t in the EAF. [15] A supplier of scrap preheating equipment reports that preheating to up to 700 °C can reduce EAF electricity demand by up to 20%, or 50–100 kWh/t of steel, and shorten cycle times. [40] Electrode consumption is also reduced by 0.15–0.3 kg/t. [16][40]

However, dioxin concentrations in EAF gas can increase significantly during scrap preheating, and dioxins, furans, sulphides and chlorides may form. [16][40] Off-gas treatment is possible but increases operating costs, may require stricter scrap sorting and must be included in any business case.

3.2 Preheating of DRI

Waste heat, especially from the EAF, could also be used to preheat DRI. MIDREX reports that hot DRI (HDRI) can be charged at up to 650 °C, with energy savings of 28–105 kWh/t of liquid steel and a productivity increase of 4–17% (Table 3). [41]

Dimension	100% CDRI	100% HDRI	Nominal (80% HDRI / 20% CDRI)
Power (kWh/t)	650	470	500
Tap-to-tap time (min)	60	43	48
Power-on time (min)	50	35	38
Production (avg. heats/day)	24	34	30

Table 3: Results of charging HDRI vs. CDRI (reported by Tosyali Algérie). Source: MIDREX. [41]

Many EAFs do not produce DRI on site, so the DRI arrives cold. TES could reheat it close to the furnace and reduce the transport distance for hot material. This is relevant wherever new DRI-EAF capacity is planned.

3.3 Drying and Moisture Control

Drying reduces energy consumption in downstream processes. Coal moisture control reduces the moisture of coking coal from around 8–9% to 3–5%; the Japan Iron and Steel Federation reports fuel savings of around 0.29 GJ/t of coke (about 81 kWh/t). [42] In pellet induration, around 25% of the total energy is used for drying. [43] As drying takes place at medium temperatures, waste heat that cannot be used elsewhere, or fluctuating waste heat stabilised by storage, can supply it.

4 Electrification with TES in the Steel Industry

Electrified TES systems convert electricity into high-temperature heat and store it, allowing electricity to be purchased when prices are low, for example during periods of high solar or wind generation. This is particularly relevant in grids with large daily price spreads, such as Australia's National Electricity Market, where midday prices are frequently low or negative. Processes that already use steam, hot air or thermal oil generated from fossil fuels are the most straightforward candidates (Fig. 12).



Fig. 12: Schematic of an electrified TES system with resistive heater, storage module and steam generator. Source: Kraftblock.

A fan discharges the heat to a heat exchanger or mixing chamber, where it is adapted to the process requirements. One downstream example is the heating of zinc baths for galvanising, typically below 5 MW at 450–470 °C, where burners could be replaced by hot air from storage.

4.1 Electrification of Scrap/DRI Heating

Where EAF waste heat is insufficient or already used elsewhere, scrap or DRI could be preheated with electrified TES. Preheating by 650 K would require about 90 kWh/t of scrap, assuming 90% thermal efficiency and a specific heat capacity of 0.45 J/(g·K); as the heat capacity of steel increases with temperature, this is a lower bound. This is of the same order of magnitude as the EAF savings of 50–100 kWh/t of steel cited in section 3.1 [40], so electrified preheating is roughly neutral in energy terms. Its economic case depends mainly on the price spread between charging periods and EAF operation, on capital costs and on off-gas treatment. Shifting demand from the EAF to a flexibly operated storage system can also reduce grid demand during EAF operation.

4.2 Hot-Blast Stoves

Hot-blast stoves already work on a principle similar to packed-bed storage, supplying blast at around 1,100 °C, or 1,200–1,300 °C in modern systems. [44][45][46] They are typically configured in groups of three to five. [47][48][49] A TES system charged with flare gas or electricity could replace or retrofit one or more stoves and supply some cycles with low-cost electricity, reducing natural gas demand. Such a system would be first-of-a-kind and would require extended feasibility studies with a plant operator and the furnace equipment manufacturer.

5 Limitations and Open Questions

TES is one of several options for using waste heat in steel mills, and it is not the preferred option in every case. The following points should be weighed against the opportunities described in this paper.

Capital costs. Investment costs depend on storage capacity and temperature level, and above all on integration: hoods, ducting, filters and heat exchangers can account for a significant share of project costs in brownfield steel plants. For long-duration TES in general, a 2026 cost benchmarking by

LDES/EPRI reports total plant costs of 29–114 USD per kWh of storage capacity (approximately 41–160 AUD/kWh), as summarised in a guide prepared for the Australian Renewable Energy Agency (ARENA). [50] Site-specific integration costs can differ considerably from such benchmarks. The payback period depends on the price of the displaced fuel, CO₂ costs and the number of charging cycles per year.

Space requirements. Packed-bed storage requires considerably more volume than a direct heat exchanger. As transport distances for hot air are limited (see 2.7), available space close to the source or the sink is often the decisive constraint in existing plants.

Standby losses. Stored heat is gradually lost through the insulation. Depending on design and scale, the standing losses of TES systems can be as low as 1–2% per day. [50] For storage durations of a few hours, as is typical in steel production, they are therefore moderate; over longer periods, for example during extended plant stops, they increase.

Additional losses and auxiliary power. Every heat transfer step via filters, heat exchangers or mixing chambers lowers the usable temperature. Fans for charging and discharging consume electricity, which must be included in the energy balance.

Alternatives. Where waste heat is available continuously and a suitable sink is nearby, direct recuperation or waste heat boilers are usually simpler and less expensive. Where there is no heat sink, ORC systems can convert waste heat into electricity. Other storage technologies, such as molten salt, phase-change materials or steam accumulators, differ in temperature range, heat transfer medium and technical maturity. TES of the type described here adds most value where timing or fluctuation prevents the direct use of waste heat.

Technical maturity. Apart from the sinter cooler installation at Tata Steel, the applications described in this paper are based on literature and assessments rather than operating installations. Heat recovery from BOF off-gas and steel slag, as well as TES for hot-blast stoves, is conceptual and would require detailed feasibility studies.

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