Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 10/08/2026 - **Accepted:** 06/09/2026
Vol: 01.04
DOI: 10.66104/7g7kbj19
Pages: 1-57

Cooling and Off-Gas Treatment in Pyrometallurgical Processes: Technologies, Challenges, Industrial Integration, and Future Perspectives—A Critical Review

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Abstract

Pyrometallurgical off-gas treatment is frequently designed as a sequence of discrete unit operations, yet plant performance is governed by the coupling among gas generation, temperature history, particulate chemistry, condensation of volatile species, pressure drop, corrosion, heat recovery, pollutant capture, and residue management. This structured critical narrative review evaluates cooling and off-gas treatment across copper and other non-ferrous smelting, electric arc furnace (EAF) steelmaking, submerged arc furnace (SAF) ferroalloy production, primary aluminum, and secondary/e-scrap processing. The evidence-coded corpus contains 109 technical/scientific sources centered on 2020-August 2026 plus five regulatory documents; foundational engineering sources are used separately for conceptual background and are not included in the 114-record implementation-level classification. The review distinguishes gas cooling, conditioning, cleaning, and utilization; compares dilution, quench, radiant, indirect, and waste-heat-recovery pathways; and critically assesses cyclones, baghouses, electrostatic precipitators (ESPs), wet scrubbers, wet electrostatic precipitators (WESPs), and ceramic or metallic hot-gas filters. The central synthesis is formalized as the Temperature-Composition Trajectory Framework for Pyrometallurgical Off-Gas Design (TCTF), in which the decisive design variable is the complete reactor-to-stack gas-state trajectory rather than a single outlet temperature. Heat recovery is valuable only when fouling, accretion, pressure loss, condensation, and downstream chemistry remain manageable, whereas rapid quenching can improve conditioning at the expense of recoverable exergy. The TCTF integrates the dynamic gas-state vector, sequential technology gates, adaptive sensing, circularity, carbon-capture readiness, and annualized multi-objective metrics. The preferred train is therefore not the sequence of individually highest-efficiency devices, but the configuration that maximizes annualized plant value while maintaining safe operating windows and compliant multi-media outputs.

Keywords: pyrometallurgy; off-gas treatment; gas cooling; particulate control; waste heat recovery; emission control

Highlights

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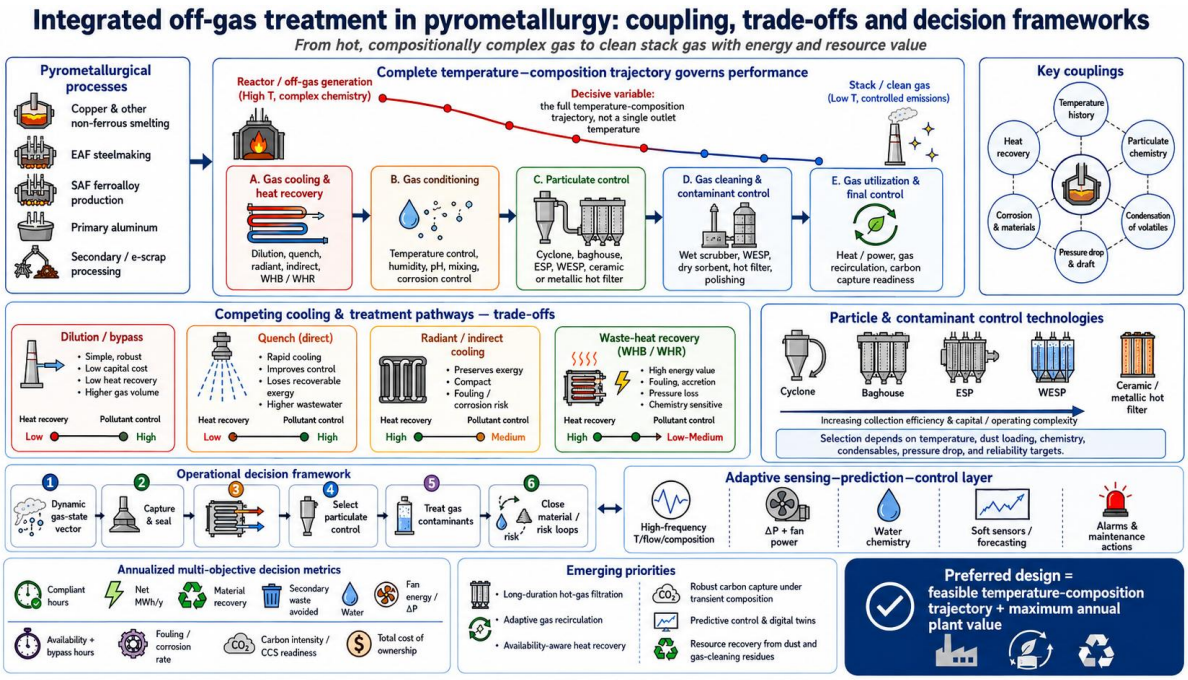
- The TCTF links reactor-to-stack temperature-composition history to technology selection and failure risk.
- Local removal efficiency is insufficient; annualized plant value, reliability, water, residues, and energy must be co-optimized.
- Quantitative literature values are case-specific evidence points, not normalized performance benchmarks.
- Carbon-capture readiness depends on upstream sealing, dilution, transience, impurities, and conditioning.

Graphical abstract



1. Introduction

Pyrometallurgical reactors intentionally operate at temperatures and chemical potentials that promote rapid reaction, phase separation, volatilization, or melting. The same conditions create an off-gas that can carry a substantial fraction of the process energy and, simultaneously, a concentrated mixture of dust, condensable salts and oxides, sulfur species, carbon monoxide, halogens, volatile metals, and trace hazardous compounds. Modern plant design therefore cannot regard the gas train as a peripheral environmental system. It is part of the process itself because draft, gas capture, post-combustion, heat extraction, dust recycle, sulfur recovery, and

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final stack conditions feed back to furnace stability, yield, energy consumption, and operational availability (Alexander et al., 2021; Bezuidenhout et al., 2026; Trunner et al., 2020; H. Liu et al., 2023; Martínez & Mercado, 2026; Strong et al., 2025).

Four functions should be distinguished. Gas cooling changes temperature and often gas volume; gas conditioning deliberately modifies temperature, moisture, oxidation state, or particulate properties to prepare the stream for the next operation; gas cleaning removes suspended solids and gaseous contaminants; and gas utilization recovers chemical or thermal value. In practice, these functions overlap. Air dilution cools a gas but increases volumetric flow and fan duty. Water quenching cools and conditions but may cross the acid dew point and create a wastewater route. A waste-heat boiler recovers energy, but can become the dominant availability constraint when dust is sticky or when condensable species form tenacious deposits. A baghouse removes fine particles efficiently, yet its safe operating window depends on the upstream thermal history. This coupling is the central premise of the present review.

The novelty of this review is its evaluation of the gas train through a common process-systems language: dynamic gas state, temperature-composition trajectory, contaminant phase change, pressure loss, material recovery, reliability, and annualized plant value. This review therefore follows a process-systems and decision-science logic rather than a device-ranking logic. Its central synthesis is formalized as the Temperature-Composition Trajectory Framework for Pyrometallurgical Off-Gas Design (TCTF), in which each unit operation is interpreted as a transition in a dynamic gas-state vector rather than as an isolated efficiency value. The analysis asks what gas state must be created before each treatment step, what energy, material, hydraulic, and reliability penalties are imposed in creating that state, and how the complete train should respond to the contaminant regime and transient behavior of the process.

Figure 1 summarizes the systems perspective used throughout this review. The figure explicitly places heat, dust, sulfur-bearing streams, and wastewater or residue routes inside the same design boundary as final air-emission control, thereby avoiding the common mistake of optimizing stack performance while

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shifting cost or environmental burden to another unit operation (Bezuidenhout et al., 2026; Trunner et al., 2020; H. Liu et al., 2023; Martínez & Mercado, 2026).

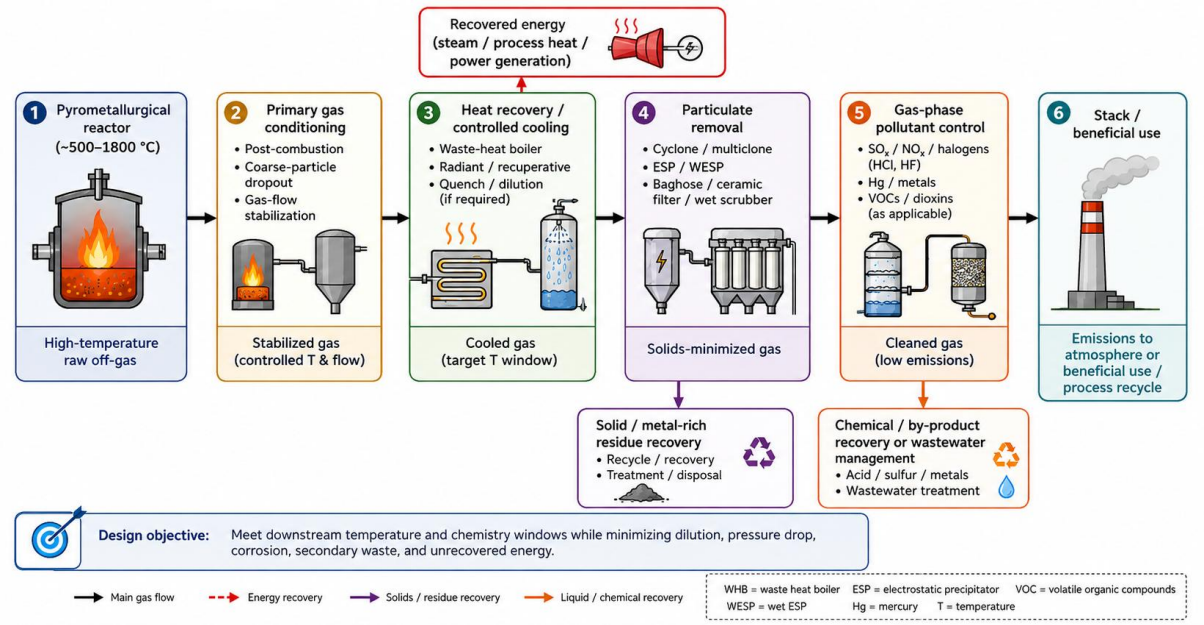

Figure 1. *Integrated architecture of a pyrometallurgical off-gas treatment system*

Note. Author-generated evidence-informed conceptual synthesis based on the design concepts discussed by Trunner et al. (2020), H. Liu et al. (2023), Bezuidenhout et al. (2026), and Martínez and Mercado (2026). It is a systems map, not a directly observed empirical flowsheet.

The architecture in Figure 1 also clarifies why a technology that is locally efficient can be globally inferior. Excessive dilution may protect a downstream filter while increasing gas volume, fan duty, and carbon-capture burden; aggressive wet scrubbing may achieve high removal efficiency while creating scaling-prone recirculating water and a metal-bearing bleed; and maximum theoretical heat recovery may be economically inferior when it reduces boiler availability. The relevant optimization target is therefore multi-objective: emission compliance, energy recovery, material recovery, fan power, water demand, equipment life, maintainability, carbon-capture readiness, and total cost of ownership. The preferred gas-treatment train is not the sequence of individually highest-efficiency devices, but the sequence that maximizes annualized plant value while maintaining safe operating windows and compliant multi-media outputs.

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2. Review Methodology and Evidence Assessment

2.1 Review design, scope, and corpus

This study was conducted as a structured critical narrative review rather than as a statistical meta-analysis or a PRISMA-claimed exhaustive systematic review. Its purpose was analytical integration across heterogeneous engineering evidence rather than estimation of a pooled treatment effect. The evidence-coded corpus comprises 109 technical/scientific sources published predominantly from 2020 through 31 August 2026 and five regulatory documents, for 114 classified records in total. Five earlier foundational engineering references are cited in the revised manuscript only to anchor durable principles of aerosol behavior, particulate collection, acid-dew-point corrosion, sulfuric-acid manufacture, and metallurgical process-gas engineering; they are not included in the 114-record implementation-level classification. During the present revision, the retained corpus and reference metadata were re-audited on 5 September 2026 for duplicate or superseded versions, author-year consistency, publication status, bibliographic traceability, relevance to pyrometallurgical gas systems, and linkage between each classified source and at least one claim, table, figure, or regulatory comparison. The five process archetypes—copper/non-ferrous smelting, EAF steelmaking, SAF ferroalloys, primary aluminum, and secondary/e-scrap processing—were selected because they span contrasting gas-state regimes rather than because they constitute an exhaustive taxonomy of pyrometallurgical operations.

2.2 Search strategy, eligibility criteria, and source-selection audit

Source discovery and the revision-stage scope audit were organized into predefined thematic blocks combining process terms (pyrometallurgy, smelting, converting, EAF, SAF, ferroalloy, aluminum, e-scrap) with: (i) capture and sealing; (ii) post-combustion and gas conditioning; (iii) quenching, dilution, radiant/indirect cooling, gas recirculation, and waste-heat recovery; (iv) cyclones, baghouses, ESPs, WESPs, wet scrubbers, and hot-gas filtration; (v) SO_2/SO_3, CO, NOx, halogens, As, Se, Hg, volatile metals, and PCDD/F; (vi) corrosion, acid-dew-point

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phenomena, fouling, scaling, accretion, and pressure drop; (vii) carbon capture and gas utilization; (viii) monitoring, CFD, forecasting, machine learning, and digital control; and (ix) dust, sludge, sulfur, and residue recovery. Eligible evidence included peer-reviewed journal articles, metallurgically relevant conference proceedings, documented industrial case studies, pilot/demonstration studies, laboratory investigations, numerical/CFD/forecasting/techno-economic studies with explicit pyrometallurgical relevance, reviews used for cross-study context, and official regulatory documents. Preprints were excluded when a peer-reviewed version was available; generic air-pollution studies were excluded when transfer to metallurgical service could not be justified through comparable temperature, gas composition, particulate chemistry, contaminant phase behavior, or operating conditions. Duplicate/version resolution used DOI, normalized title, author-year combination, and publication version; where conference and journal records represented the same underlying work, the more complete traceable version was preferred unless the conference paper contained unique industrial operating information. The original discovery-stage database/platform log and database-specific hit counts were not retained and are not retrospectively fabricated. To support reproducibility without implying systematic exhaustiveness, Supplementary Appendix A reports the exact Boolean architecture used for the revision-stage scope audit, and Supplementary Table S2 provides a narrative source-selection flow with unavailable historical counts explicitly marked as not retained.

2.3 Implementation level, methodological quality, transferability, and coding procedure

The evidence hierarchy used in this review represents implementation level, not an ordinal ranking of intrinsic scientific quality. Level I denotes full-scale industrial operation or a documented plant case; Level II, pilot or demonstration scale; Level III, laboratory or materials-scale experiments; Level IV, numerical, CFD, forecasting, or techno-economic models; Level V, review/synthesis evidence; and Level R, regulatory sources. Three dimensions are therefore treated separately: (1) implementation level—how closely the evidence represents industrial operation; (2) methodological/reporting quality—the

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completeness and transparency with which methods, operating conditions, measurements, and limitations are reported; and (3) industrial transferability—the extent to which gas composition, temperature trajectory, particulate chemistry, transience, scale, and downstream constraints are comparable to the target application. A rigorous laboratory study can have high internal validity while remaining Level III, whereas a Level I plant case can have limited reporting completeness. Implementation-level coding in the present review was performed by a single reviewer. No independent human coder was available for this revision; consequently, no inter-rater reliability statistic is reported, and the levels must be interpreted as transparent, implementation-oriented interpretive classifications rather than reliability-tested measurements. Supplementary Table S1 provides the source-level matrix, including evidence level, process family, technology/function, contaminant class, reporting-completeness appraisal, principal limitation, and role in the synthesis, so that the coding can be independently audited or reclassified.

2.4 Review questions and the Temperature-Composition Trajectory Framework

The synthesis was guided by three decision questions: (1) what dynamic gas state must be created before each cleaning, recovery, utilization, or capture step; (2) what energy, material, hydraulic, and reliability penalties are imposed by creating that state; and (3) which complete train best satisfies the contaminant regime and transient behavior of the process? The TCTF represents the gas as the time-dependent state vector $x_g(t)$ = {T, flow, O_2, H_2O, CO/CO_2, SO_2/SO_3, halogens, dust loading, particle-size distribution, condensable fraction, dew-point margin}. Technologies are therefore compared as operating envelopes and transition functions, not as isolated efficiencies. Cross-sector inference is permitted only when the relevant state variables, contaminant chemistry, phase behavior, transience, and downstream constraints are demonstrably comparable.

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3. Off-Gas Generation and Contaminant Regimes

3.1 Temperature, flow, composition, and transient behavior

Pyrometallurgical off-gases span an unusually wide operating envelope. Reactor-exit temperatures can range from a few hundred degrees Celsius in some secondary or conditioned streams to well above 1,000 °C in smelting, converting, and electric-furnace service. More important than the nominal range is the combination of temperature, flow, oxygen potential, moisture, dust loading, and temporal variability. EAF steelmaking is intrinsically batchwise, with rapid changes in CO, CO_2, H_2O, temperature, and flow through charging, melting, oxygen injection, refining, and tapping; SAF and ferroalloy processes can be steadier but still show strong sensitivity to burden condition, furnace pressure, tapping, and prereduction; copper smelters may have relatively continuous furnace gas but highly consequential impurity partitioning and volatile-species behavior (Makki Abadi et al., 2024; Bond et al., 2026; Córdoba, 2026; Hay et al., 2021; Hosseini et al., 2022; Larssen & Tangstad, 2021; Madias, 2024; Matsanga et al., 2025; Oterdoom et al., 2026; Sitefane et al., 2021; Taskinen & Jokilaakso, 2021; Wang et al., 2020).

For design purposes, these variables should be treated as a time-dependent envelope rather than independent averages. The gas-state vector used in this review is xg(t) = {T, flow, O_2, H_2O, CO/CO_2, SO_2/SO_3, halogens, dust loading, particle-size distribution, condensable fraction, dew-point margin}. Peaks, lower-tail temperatures and the duration of excursions are as important as mean values because different downstream devices fail at different parts of this envelope.

The design implication is that average gas data are insufficient for equipment sizing and materials selection. Peak temperature sets refractory and filter protection requirements; peak volumetric flow controls ducts, fans, and collection-area sizing; minimum temperature governs condensation risk; and the frequency and duration of excursions influence fatigue, bag life, cleaning cycles, and control-system robustness. Recent EAF research has shifted toward second-by-second forecasting of CO_2, CO, and H_2O, specifically because downstream carbon

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capture and heat-recovery equipment must tolerate dynamic rather than steady-state gas compositions (Bond et al., 2026). Similar reasoning applies to pollutant-control systems: a short SO_3 or NOx spike can drive corrosion or emission excursions even when the time-averaged concentration appears benign (Aarhaug et al., 2023; H. Liu et al., 2025; Park et al., 2026).

3.2 Dust, condensable species, and volatile elements

Dust is not a single contaminant class. It may consist of mechanically entrained feed or slag particles, newly formed metal-oxide fumes, condensed chlorides or sulfates, carbonaceous particles, and agglomerates formed during cooling. Its size distribution and surface chemistry evolve through the gas train. Copper-smelting studies show that flue dust differs materially between furnace technologies and that arsenic and other impurities can redistribute among gas, dust, and condensed phases as temperature falls (Chen et al., 2020; Guo et al., 2022; Li et al., 2023; Lindgren et al., 2024; Ormeño-Aquino et al., 2025; Taskinen et al., 2024; Wan et al., 2023; Zhou, Liu, Zhang, & Zhou, 2021; Zhou, Liu, Zhang, Zhou, Mian, et al., 2021). In ferrochrome service, dust speciation is equally important because the environmental risk of chromium depends not only on total Cr but on oxidation state and phase association (Berryman & Paktunc, 2022; Berryman et al., 2022). In EAF systems, zinc-bearing dust can undergo secondary reactions, such as zinc ferrite formation, complicating both recycling and metallurgical recovery (Otero Olmos et al., 2026; Thottempudi & Roy, 2022).

Persistent organic pollutants add another dimension in secondary metallurgy. PCDD/F, dl-PCN, and related species can form or redistribute within temperature windows encountered during off-gas cooling, especially when chlorine, catalytic metals, carbonaceous material, and suitable residence time coexist. Evidence from secondary copper and EAF gas systems reinforces the importance of afterburning, temperature control, rapid passage through formation windows, sorbent or dust capture, and prevention of dust accumulation in hot zones (Dat et al., 2020; M. Dong, 2021; H. Li et al., 2021; Pereira, 2026; Sun et al., 2026). Thus, the

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gas train is also a chemical reactor: cooling rate and deposit inventory can control reaction pathways, not merely sensible heat removal.

Table 1 summarizes the main off-gas regimes and the design consequences that follow from them. The categories are deliberately qualitative because the same furnace type can occupy different operating windows depending on oxygen enrichment, feed composition, hooding, dilution, and production rate (Adham & Wong, 2025; du Preez et al., 2023; Kandalam et al., 2023a; Kandalam et al., 2023b; Madias, 2024; Matsanga et al., 2025; Nicol & Hogg, 2026; Nicol et al., 2025).

Table 1. *Representative off-gas regimes and dominant design consequences*

Process family	Characteristic gas features	Dominant particulate/volatile issues	Primary conditioning need	Critical integration question
Copper smelting/converting	Hot, SO_2-rich; impurity-bearing; often continuous	As, Se, Pb, Zn; sulfates/oxides; accretions	Heat recovery + controlled dust removal before acid plant	How much heat can be recovered without compromising boiler availability or acid-plant feed quality?
EAF steelmaking	Highly transient T, flow, $CO/CO_2/H_2O$; strong secondary-air influence	Fe/Zn/Pb oxides; fine fume; possible PCDD/F	Post-combustion, cooling, fine filtration	How can the train handle peaks while minimizing dilution and preserving heat/carbon-capture value?
SAF/ferroalloys	CO-rich for closed furnaces; variable dust and furnace pressure	Cr/Mn/Si-bearing dust; nanoscale fume; alkali/condensables	Temperature stabilization and dry/wet cleaning	Can chemical energy in CO-rich gas be used while meeting dust and safety constraints?
Primary aluminum	Large gas volume; relatively low contaminant concentrations; fluoride-related chemistry	Fine particulate, fluorides; variable SOx depending on feed/anodes	Dry or wet scrubbing integrated with alumina handling	How can very large gas volumes be treated with minimum pressure drop and carbon footprint?
Secondary/e-scrap	Highly feed-dependent; halogens, metals, VOCs; transient	Metal chlorides/oxides; condensables; PCDD/F precursors	Afterburning + rapid cooling + robust particulate/acid-gas control	How can variable chemistry be contained without creating corrosive or hazardous secondary residues?

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Note. Evidence-informed author synthesis based on Makki Abadi et al. (2024), du Preez et al. (2023), Kandalam et al. (2023a, 2023b), Madias (2024), Matsanga et al. (2025), Nicol et al. (2025), and Waseem et al. (2026). Categories are qualitative and transfer is conditional on the gas-state envelope.

Table 1 emphasizes that a process label does not uniquely define the cleaning train. The same baghouse that is appropriate after controlled EAF cooling may be unsuitable upstream of an acid plant where SO_3 and condensable arsenic species dominate. Likewise, a closed SAF can produce a relatively concentrated CO-rich gas attractive for utilization, whereas an open furnace or poorly sealed hood can dilute that resource into a much larger, lower-value stream. Gas capture and furnace enclosure are therefore upstream decarbonization and cost variables, not merely ventilation choices.

4. Cooling, Conditioning, and Heat-Recovery Technologies

4.1 Why cooling is required before cleaning

Cooling is normally justified by one or more downstream constraints: filter-media temperature limits, ESP electrical behavior, scrubber evaporation load, materials limits, prevention of dust sintering, or a desired gas state for chemical absorption. However, the target must be expressed as a safe operating window rather than a single design temperature. If the gas is too hot, bags, seals, fan components, and downstream sorbents may fail; if it is too cold, sulfuric acid, water, halide salts, or volatile-metal species can condense on ducts and equipment. The safe window also shifts as the composition changes, which is why direct or inferred SO_3 measurements are important when acid-dew-point corrosion is credible (Aarhaug et al., 2023; Hong et al., 2022; H. Liu et al., 2025; H. Liu et al., 2021).

Cooling can also determine particle behavior. Vapors that remain gaseous at the furnace outlet may nucleate, condense on existing particles, or form sticky deposits when the temperature falls. Accretion studies in copper systems show that arsenic- and antimony-bearing species can contribute to solid matrices and deposits in gas-cleaning equipment, while transient CFD work demonstrates that localized flow and heat-transfer conditions can focus accretion in waste-heat boilers (Diaz et al., 2025; Schmidt et al., 2022; Taskinen et al., 2024; Wan et al., 2023; D. Zhang & Ma, 2022). Therefore, designers should model or experimentally characterize not

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only the bulk gas temperature but also wall temperatures, boundary layers, local velocities, and likely condensation pathways.

4.2 Dew point, fouling, scaling, and pressure-drop coupling

The classic reliability conflict is between keeping surfaces hot enough to avoid condensation and cool enough to protect materials and capture heat. In sulfur-bearing service, acid-dew-point behavior depends jointly on SO_3 and water-vapor partial pressures, so composition cannot be separated from temperature when setting minimum wall and gas temperatures (Verhoff & Banchero, 1974). SO_2-to-SO_3 conversion can also be catalyzed by metal oxides and dust, moving the acid-dew-point risk upstream (Aarhaug et al., 2023; Hong et al., 2022; H. Liu et al., 2025; H. Liu et al., 2021). Wet systems replace some dry-deposition problems with scaling and slurry-management problems. Scale formation in scrubbers depends on water chemistry, supersaturation, pH, temperature, and residence time and can transform a high-efficiency gas-cleaning device into an availability bottleneck (Eremeev et al., 2024; Fungene et al., 2023). The correct comparison is therefore not 'dry versus wet' in general, but the complete solids and water balance under the expected contaminant chemistry.

Figure 2 recasts technology selection as a set of qualitative operating envelopes rather than point coordinates. This avoids false precision: temperature is necessary for selection, but the feasible window also depends on moisture, acid-dew-point margin, dust stickiness, condensable species, particle-size distribution, chemical compatibility, and the desired balance between heat preservation and phase transfer. High-temperature filtration can preserve exergy only when materials and seals tolerate the real dust chemistry; wet systems accept sticky/soluble species but transfer the burden to liquid handling; and baghouses require a dry, non-sticky temperature window (F. Dong et al., 2021; Gregorovičová & Pospíšil, 2025; Krasnyi et al., 2024; H. Li et al., 2023; Räsänen et al., 2021; J. Xu et al., 2022; Yuan et al., 2022).

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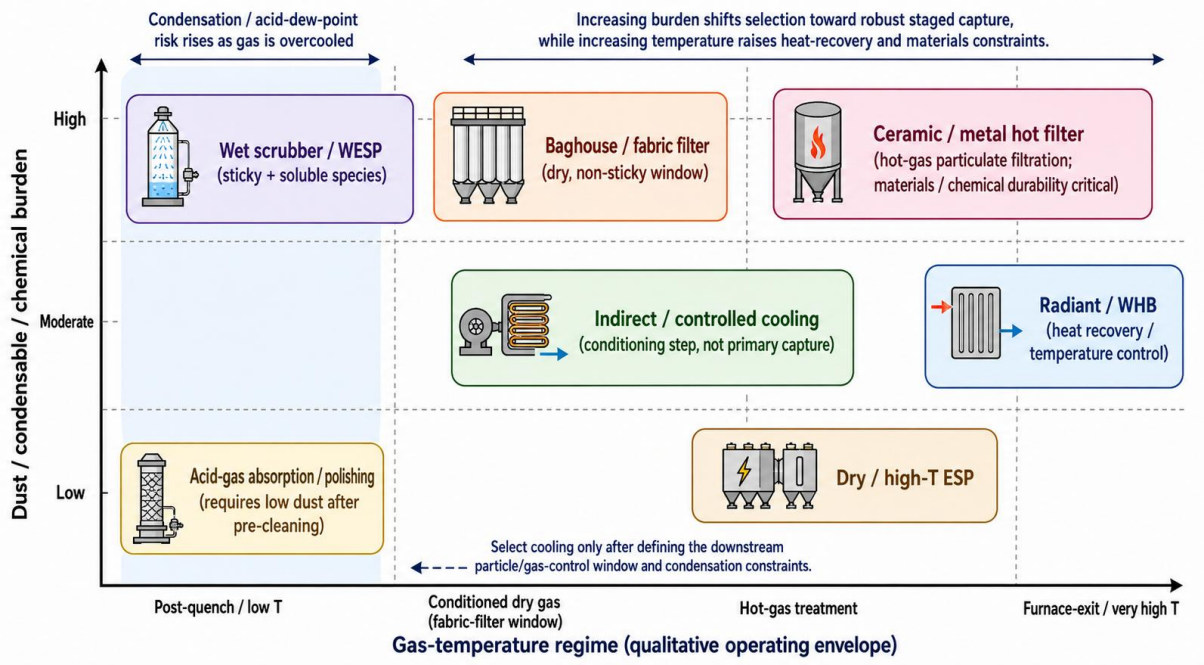

Figure 2. *Qualitative operating-envelope map for pyrometallurgical off-gas conditioning and cleaning*

Note. Author-generated evidence-informed conceptual synthesis based on F. Dong et al. (2021), Gregorovičová and Pospíšil (2025), Krasnyi et al. (2024), H. Li et al. (2023), Räsänen et al. (2021), J. Xu et al. (2022), and Yuan et al. (2022). The envelopes are qualitative and should not be interpreted as universal numerical limits.

A practical selection procedure begins with the most restrictive downstream condition and works upstream. The engineer identifies the required particle-removal mechanism and gas-phase treatment, determines their acceptable temperature and moisture windows, evaluates contaminant phase changes during cooling, and only then selects the cooling path. This reversed logic reduces the risk of installing a high-value heat exchanger that creates an unmanageable fouling regime or selecting a quench that unnecessarily destroys energy value.

4.3 Dilution and recycled-gas cooling

Air dilution is mechanically simple and highly responsive, which explains its widespread use as emergency or trim cooling. Its fundamental penalty is thermodynamic and hydraulic: cooling is achieved by adding mass, so the downstream fan, duct, filter, and stack must treat a larger

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gas volume. Added oxygen can also change post-combustion oxidation of metal vapors and PCDD/F chemistry. Recycled-gas cooling avoids some oxygen addition and can stabilize temperature, but requires a recirculation loop, fan capacity, and careful control of dust and corrosive species. EAF concepts that couple flue-gas recirculation with thermal storage illustrate how recirculation can serve as an active temperature-management tool rather than merely a means of dilution (Li et al., 2025).

4.4 Water spray, quench towers, and evaporative cooling

Direct water injection provides rapid, compact cooling and can suppress downstream temperature excursions. It is especially attractive when the downstream process is already wet or when rapid quenching is needed to limit undesirable gas-phase or surface reactions. The disadvantages are equally fundamental: latent heat is rejected rather than recovered, gas moisture increases, acid-dew-point margins can shrink, droplets or solids can deposit on walls, and the plant faces water-quality and wastewater-management problems. Real failure analysis of a sulfuric acid plant inlet duct and quench tower underscores that corrosion and hydrodynamic maldistribution can turn a nominally simple cooling device into a major reliability risk (Nazari et al., 2025).

4.5 Waste-heat boilers, radiant ducts, and indirect/cascade recovery

Waste-heat boilers (WHBs) recover high-grade energy as steam and are vital in smelting. Their main challenge is availability, as high dust loads, sticky particles, heat flux, deposition, and chemistry-driven accretion can reduce heat transfer and cause shutdowns. Industrial programs and CFD studies show boiler reliability depends on geometry, cleaning, gas distribution, surface temperature, and response to feed changes (Nanda et al., 2024; Schmidt et al., 2022; D. Zhang & Ma, 2022). Some furnaces use long radiant ducts or cooled sections as initial steps to reduce deposition, trading compactness for reliability.

Indirect gas coolers and recuperators are attractive for dry gas at moderate temperatures, but pressure drop and fouling often limit them more than heat transfer does. Organic Rankine cycle

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studies show that additional exchanger pressure loss can significantly affect energy recovery by increasing fan power (Nikolaisen & Andresen, 2021). EAF heat-recovery methods include direct steam, thermochemical storage, cascade recovery, and energy/steam valorization (Delikonstantis et al., 2024; M. Dong & Zhou, 2020; Hartfuß et al., 2020; Volchanska et al., 2025). The literature suggests prioritizing high-temperature heat recovery where deposition and pressure loss are manageable, and only using lower-grade recovery when energy gains outweigh hydraulic and reliability costs.

Use of quantitative values. Table 2 reports representative quantitative evidence only where the cited studies provide it. The values are intentionally case-specific and are not normalized performance benchmarks or universal design guarantees. Transfer requires checking evidence scale, gas composition, moisture, dust chemistry, operating hours, pressure drop, fouling, and maintenance regime. Figure 3 then shows the central trade-off between preserving recoverable exergy and rapidly creating a downstream-compatible gas state (Delikonstantis et al., 2024; M. Dong & Zhou, 2020; Hartfuß et al., 2020; G.-C. Li et al., 2025; Martynova et al., 2025; Nikolaisen & Andresen, 2021; Volchanska et al., 2025).

Table 2. *Evidence-based comparison of pyrometallurgical gas-cooling and heat-recovery pathways*

Cooling pathway	Evidence basis / representative quantitative indicator	Principal advantage	Principal limitation	System-selection implication
Air dilution	Established industrial trim/emergency practice; no intrinsic heat recovery, and downstream gas load increases with added dilution mass.	Simple, fast response; low equipment complexity.	Higher gas volume and fan/filter duty; O_2 addition can alter chemistry.	Use mainly for protection/trim; quantify downstream hydraulic and CO_2-capture dilution penalty.
Recycled gas	Numerical EAF studies show strong damping of flue-gas temperature fluctuations when recirculation is coupled with phase-change heat storage (Li et al., 2025).	Temperature control without equivalent fresh-air addition; can stabilize O_2 potential.	Recirculation fan and contamination loop; dust/corrosives can accumulate.	Prefer when concentration preservation and transient stabilization are valuable and recycle contamination is controlled.
Water spray/quench	Evidence from industrial failures shows that maldistribution, wall wetting, and corrosion can dominate	Very rapid, compact cooling; supports wet	Destroys sensible-heat value; increases	Use when rapid chemistry control or a wet downstream train outweighs lost exergy;

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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	reliability even when the target outlet temperature is achieved (Nazari et al., 2025).	treatment and rapid passage through POP re-formation windows.	humidity and wastewater/scaling risk.	protect dew-point margin.
Waste-heat boiler	Industrial and transient-CFD evidence identifies availability, accretion and heat-transfer degradation as governing metrics rather than theoretical heat duty alone (Nanda et al., 2024; Schmidt et al., 2022; D. Zhang & Ma, 2022).	High-grade steam/power recovery.	Fouling, slagging, tube wastage and high CAPEX; bypass can erase annual value.	Evaluate net annual MWh together with bypass hours, cleaning frequency and lost production.
Radiant cooling duct	Full-scale metallurgical practice; deliberately lowers surface heat flux before convective equipment and can reduce deposition severity.	Low-complexity first-stage cooling at very high temperature.	Large footprint; refractory/duct heat losses; possible particle settling.	Useful ahead of WHB/filters when velocity, residence time and maintainability are controlled.
Indirect / cascade / thermochemical recovery	For an EAF cascade model, reported electricity savings were 40–50 kWh/t (8–12%), with melting-time reduction of 5–8 min; a $Ca(OH)_2$ storage concept used a 14.7 MWth recoverable-heat basis and projected 2.8 MWel net generation (Hartfuß et al., 2020; Volchanska et al., 2025).	Keeps gas dry; enables staged heat integration and buffering of cyclic operation.	Pressure drop, exchanger fouling and model-to-plant scale-up uncertainty.	Compare net power/steam after fan penalty and availability derating; treat published values as case-specific, not universal.

Note. Evidence-informed author synthesis based on Dong and Zhou (2020), Hartfuß et al. (2020), Nikolaisen and Andresen (2021), Delikonstantis et al. (2024), G.-C. Li et al. (2025), Martynova et al. (2025), Nanda et al. (2024), Schmidt et al. (2022), and Volchanska et al. (2025). Reported numerical values are study-specific and should not be transferred without checking gas composition, scale, operating hours, fouling, pressure drop, and maintenance assumptions.

The comparison in Table 2 shows that the most energy-efficient cooler on a clean-gas heat balance may be the least efficient on a plant-availability basis. A realistic evaluation should annualize recovered energy, fan electricity, cleaning outages, tube or refractory replacement, water treatment, and the opportunity cost of production losses. This is why recent industrial work increasingly evaluates waste-heat recovery together with reliability and operating

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Nexus Science Review
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constraints rather than as an isolated thermodynamic potential (Gu et al., 2026; Nanda et al., 2024).

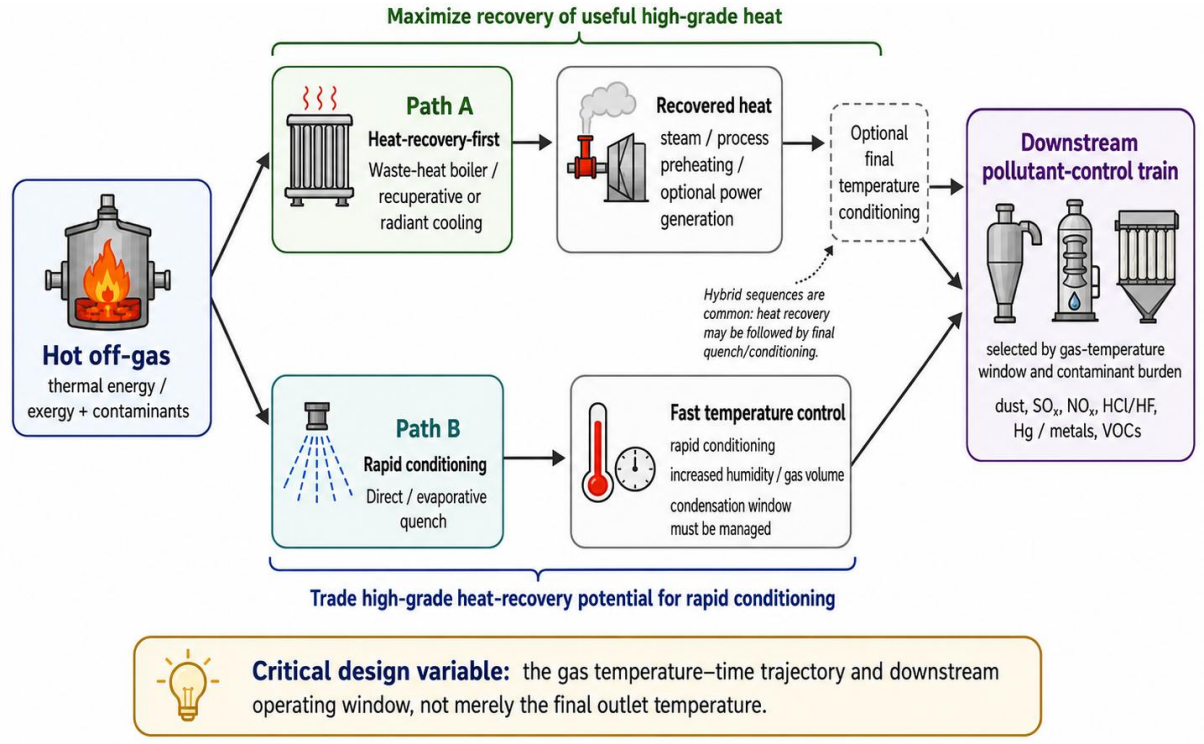

Figure 3. *Energy recovery versus rapid-conditioning pathways for hot off-gas*

Note. Author-generated evidence-informed conceptual synthesis based on Delikonstantis et al. (2024), Dong and Zhou (2020), Hartfuß et al. (2020), Nikolaisen and Andresen (2021), and Volchanska et al. (2025). The pathways illustrate trade-offs and are not empirical performance guarantees.

Figure 3 highlights a useful design principle: the relevant variable is the temperature trajectory. Two trains can reach the same baghouse inlet temperature but differ radically in recovered steam, gas humidity, particulate chemistry, deposit formation, and pressure drop. Consequently, the front-end cooling train should be optimized concurrently with the final pollutant-removal train.

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5. Particulate Removal and Gas Cleaning

5.1 Inertial separation and pre-collection

Cyclones, multicyclones, drop-out chambers, and gravity sections remain valuable because they protect high-efficiency downstream equipment from coarse particles and large dust loads. Classical aerosol and gas-cleaning principles show why inertial collection becomes progressively weaker as aerodynamic particle size decreases, while pressure loss and re-entrainment remain practical design constraints (Cooper & Alley, 2011; Hinds, 1999). Fine fumes and submicron condensation products are therefore poorly controlled by inertial separation alone. The modern design opportunity is not to treat cyclones as final control devices, but to use gas distribution and pre-separation strategically to reduce erosion, local loading, and pressure-drop variability in downstream filters. Recent post-combustion and drop-out chamber work in copper refining exemplifies this integrated approach (Kalisch et al., 2026).

5.2 Baghouses and advanced fabric/metal filters

Baghouses are the workhorse for fine particulate control where gas temperature, moisture, and dust properties are compatible with the filter medium. Their high collection efficiency can be undermined by non-uniform flow, excessive local dust loading, pulse-cleaning imbalance, bag abrasion, condensation, and chemical attack. Recent CFD-guided bag arrangement research indicates that internal geometry can sharply reduce vortex intensity and improve flow and dust distribution uniformity while lowering pressure drop, demonstrating that collector housing design is as important as filter media selection (Cao et al., 2026; Hu et al., 2025). Pulse-cleaning models similarly show that cleaning dynamics influence the spatial distribution of deposited particles and long-term resistance (W. Liu, Xu, & X. Liu, 2023).

High-temperature metal and ceramic filters are strategically important because they can move fine-particle removal upstream, preserving sensible heat and reducing the need for dilution or quenching. Practical ceramic-filter experience and reviews of metal and composite filter concepts show a rapidly expanding design space, while calcium-hexaaluminate porous

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 10/08/2026 - **Accepted:** 06/09/2026
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ceramics illustrate materials development for hot-gas filtration (Gregorovičová & Pospíšil, 2025; Krasnyi et al., 2024; Yuan et al., 2022). The unresolved challenge is durability under realistic chemical transients, thermal cycling, sticky dust, and alkali/halide attack. High capture efficiency alone is therefore insufficient evidence for industrial readiness.

5.3 Electrostatic precipitation, wet scrubbing, and WESP

Electrostatic precipitators (ESPs) can treat large gas volumes with relatively low pressure drop and tolerate higher temperatures than many fabrics. Their performance, however, depends on particle resistivity, gas composition, electrical conditions, and re-entrainment. Pilot studies of high-temperature ESPs in copper smelting demonstrate simultaneous particle collection and heavy-metal migration, while advanced tubular ESP designs aim to improve performance at elevated temperatures (Wu et al., 2023; J. Xu et al., 2022). Wet electrostatic precipitators (WESPs) are particularly useful as polishing devices for fine mist and aerosol after wet gas treatment; the collector-plate configuration can materially influence performance (Syu et al., 2022).

Wet scrubbers effectively remove many sticky or soluble contaminants and offer cooling, particulate removal, and gas absorption. High-efficiency systems such as dynamic-wave and Venturi use intense gas–liquid contact to achieve excellent mass transfer and fine-particle removal (F. Dong et al., 2021; Räsänen et al., 2021). Costs include liquid circulation, pumping, pressure drops, solids separation, scaling control, bleed management, and water treatment. In ferroalloy plants, the clarification of recirculating water is an operational subsystem (Eremeev et al., 2024). The key criterion is whether moving contaminants from gas to liquid enables controllable recovery or disposal.

Use of quantitative values. Table 3 separates implementation evidence from nominal technology capability and reports quantitative results only when the cited study provides them. These values are representative evidence points, not normalized effect estimates or universal efficiency guarantees. Particle chemistry, resistivity, size distribution, moisture, temperature, transience, scale, and maintenance can dominate field performance (Bazhin & Masko, 2022;

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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Cao et al., 2026; F. Dong et al., 2021; Gregorovičová & Pospíšil, 2025; Krasnyi et al., 2024; Li et al., 2023; W. Liu, Xu, & X. Liu, 2023; Räsänen et al., 2021; Sokolov et al., 2023; Syu et al., 2022; Wu et al., 2023; J. Xu et al., 2022; Yuan et al., 2022).

Table 3. *Evidence-based comparison of particulate-removal technologies*

Control device	Evidence basis / representative quantitative indicator	Thermal / particle window	Main strength	Main failure/selection risk
Cyclone / multicyclone	Industrial pre-collection evidence; the review corpus supports use primarily to remove coarse load and protect downstream high-efficiency devices rather than as final control for submicron fume.	High-temperature tolerant; best for coarse/inertial particles.	Rugged, low complexity, low water demand.	Poor fine-fume capture; erosion and re-entrainment at high solids loading.
Baghouse	CFD optimization reduced airflow non-uniformity from 13% to 2%, pressure drop by 15%, and improved energy efficiency by >10% in the studied straight-through collector (Cao et al., 2026).	Fine and submicron dust after suitable cooling; temperature is media- and chemistry-dependent.	Very high fine-dust control with dry recoverable residue.	Blinding, condensation, local overload, bag wear and thermal excursion.
Dry / high-T ESP	Pilot copper-smelting HT-ESP achieved 99.5% particle collection at optimum conditions; 8.8% Cu, 7.9% Pb, 8.3% As and 45% Se migrated from gas to hopper particles. A tubular HT-ESP was tested at 1073–1373 K and reached 98.22% collection at 1173 K in one condition (Wu et al., 2023; J. Xu et al., 2022).	Large gas flows; conventional to high-temperature service depending on electrode/material design and particle resistivity.	Low pressure drop; can operate upstream of deeper cooling.	Resistivity, re-entrainment, electrical stability and volatile-element repartitioning.
Wet scrubber / Venturi	Industrial-scale and experimental evidence confirms strong gas–liquid contact and fine-particle capability, but performance is coupled to energy input, liquid rate and downstream solids/water treatment (F. Dong et al., 2021; Räsänen et al., 2021).	After sufficient cooling; useful for sticky particles and soluble gases.	Simultaneous cooling, absorption and particulate removal.	High ΔP for fine capture; scaling, mist carryover and wastewater burden.
WESP	For the tested collector plates, most-penetrating-particle-size penetration was <6% for stainless-steel and conductive-glass ESPs; wet operation reduced penetration of original-	Low-temperature, saturated polishing after wet stages.	Excellent aerosol/mist polishing; mitigates high-resistivity dust-cake problems.	Corrosion, water quality, internal distribution and ozone/electrical considerations.

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	glass plates to <20% (Syu et al., 2022).			
Ceramic / metal hot filter	Metal filters are evaluated for high-temperature service (>200 °C), while CA_6 porous ceramics exhibited 68.1% open porosity, 7.9–62 MPa compressive strength, and Darcy permeability of 5.19×10^{-7}–2.01×10^{-6} m^2 in material testing (Gregorovičová & Pospíšil, 2025; Yuan et al., 2022).	Hot-gas fine filtration; exact window depends on material, seals, alkali/halide attack and dust stickiness.	Preserves heat and enables dry upstream fine-particle removal.	Long-duration industrial chemical durability, thermal cycling and pulse-cleaning fatigue remain limiting evidence gaps.

Note. Evidence-informed author synthesis based on F. Dong et al. (2021), Räsänen et al. (2021), Syu et al. (2022), J. Xu et al. (2022), Wu et al. (2023), H. Li et al. (2023), Krasnyi et al. (2024), Gregorovičová and Pospíšil (2025), Cao et al. (2026), and Yuan et al. (2022). Quantitative results are conditions reported by the cited studies and should not be interpreted as guaranteed field performance.

Table 3 reinforces the value of staged removal. Coarse pre-collection can protect a baghouse; a dry ESP can protect an acid plant; a scrubber can remove soluble species before a WESP polishes aerosols. The optimum sequence is contaminant-specific and should minimize the number of phase transfers that do not create a useful recovery pathway.

6. Control of Gaseous Pollutants and Volatile Impurities

6.1 Sulfur oxides and acid-gas chemistry

SO_2 management in non-ferrous metallurgy is fundamentally different for concentrated and dilute streams. Concentrated furnace gas is a resource and should preferentially be converted to sulfuric acid or another sulfur product when technically and economically feasible; dilute or intermittent gas often requires wet, dry, or semi-dry scrubbing. Foundational copper-metallurgy and sulfuric-acid engineering literature establishes that acid-plant performance depends on the entire gas-preparation train, including dust removal, impurity control, drying, catalytic conversion, absorption, and thermal integration (King et al., 2013; Schlesinger et al., 2011). Recent work on wet lime/limestone scrubbing in aluminum pot exhausts and dry SO_2 capture in metallurgical service illustrates the wide range of sulfur-control contexts (Broek, 2026; Weber et al., 2020). SO_3 deserves separate attention because small concentrations can govern acid dew point, corrosion, aerosol formation, and downstream acid-plant performance

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Nexus Science Review
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(Aarhaug et al., 2023; Hong et al., 2022; H. Liu et al., 2025; H. Liu et al., 2021; W. Liu, Min, et al., 2023).

The sulfur-control train should therefore be designed from a sulfur balance rather than from stack concentration alone. The balance must include sulfur captured as product acid, scrubber solids, wastewater sulfate, condensed acid, and dust-associated sulfur. Where acid production is available, upstream dust and impurity removal must protect catalyst and product quality. Where scrubbing is used, reagent cost and the fate of gypsum or other solids become material. The critical question is whether sulfur is recovered as a saleable or reusable product or converted into a larger-volume disposal stream.

6.2 CO, NOx, halogens, and persistent organic pollutants

CO can be an emission, a safety hazard, or an energy carrier. Closed ferroalloy furnaces can generate CO-rich gas with potential for fuel substitution or other utilization, while EAF off-gas commonly requires controlled post-combustion for energy recovery and safety (Kero & Dalaker, 2025; Madias, 2024). NOx control is strongly process-dependent because thermal NOx, fuel NOx, oxygen lancing, air ingress, and furnace electrical conditions vary across operations. The emergence of early-warning systems for NOx spikes in ferroalloy EAF plants indicates that prediction and operational control can complement end-of-pipe abatement (Park et al., 2026).

Halogens and organic contaminants become critical in secondary feeds, e-scrap, and chloride-bearing processes. The most robust strategy is prevention by feed control where possible, followed by complete high-temperature oxidation of organics, rapid cooling through re-formation windows, sorbent capture, and efficient fine-particle removal. Evidence from secondary copper, EAF gas systems, and chlorination–calcination processes supports this multi-barrier logic (Dat et al., 2020; M. Dong, 2021; H. Li et al., 2021; Pereira, 2026; Sun et al., 2026). No single device can compensate for prolonged residence in a chemically favorable PCDD/F formation window combined with accumulated catalytic dust.

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6.3 Arsenic, selenium, mercury, and heavy metals

Volatile metals and metalloids illustrate why temperature history must be coupled to residue management. Arsenic can volatilize in hot zones, condense or react in the off-gas line, accumulate in ESP dust, and later require stabilization, pyrometallurgical treatment, hydrometallurgical recovery, or controlled disposal (Henao et al., 2021; Q.-Z. Li et al., 2023; Taskinen et al., 2024; Wan et al., 2023; G. Zhang et al., 2026; Zhou, Liu, Zhang, & Zhou, 2021; Zhou, Liu, Zhang, Zhou, Mian, et al., 2021). Heavy-metal flow studies in copper smelters show that dust-control decisions redistribute valuable and hazardous elements across internal recycle and waste streams rather than making them disappear (X. Li et al., 2023; J. Zhang et al., 2022). Similar whole-process thinking is needed for selenium and mercury, where acid-plant sludges and scrubbing solutions can become secondary resources if selective recovery is designed into the flowsheet (Chen et al., 2023; H. Liu et al., 2023; Yang et al., 2021).

Table 4 connects major gaseous or volatile contaminant classes to the controlling process variables and preferred strategy. It deliberately includes secondary-residue consequences because a control technology is incomplete unless the captured contaminant has a stable destination (Chen et al., 2023; Henao et al., 2021; Li et al., 2023; Liu et al., 2023; Liu, Min, et al., 2023; Wijenayake & Sohn, 2023; Yang et al., 2021; Zhang et al., 2026).

Table 4. *Pollutant-control logic for pyrometallurgical off-gases*

Contaminant	Key controlling variables	Preferred control logic	Typical secondary stream	Critical risk
SO_2 / SO_3	Concentration, O_2, moisture, dust catalysis, temperature	Recover concentrated SO_2 as acid/SO_2; scrub dilute streams; control SO_3/dew point	Acid product, gypsum/sulfate, acidic bleed	Corrosion, acid mist, reagent-intensive dilute scrubbing
CO	Furnace sealing, oxygen potential, post-combustion, variability	Recover chemical/thermal value where concentrated; oxidize safely where required	CO_2-rich gas/heat	Explosion/toxicity; dilution destroys fuel value
NOx	Peak temperature, air ingress, oxygen/fuel practice	Process control + selective abatement where required	Spent catalyst/reagent residues where applicable	Short spikes can defeat average-based control

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HCl/HF/halogens	Feed halogens, moisture, temperature	Feed control + dry/wet sorption after suitable cooling	Chloride/fluoride salts or scrubber liquor	Severe corrosion and secondary aerosol formation
As/Se/Hg/heavy metals	Volatility, speciation, condensation temperature, dust chemistry	Temperature-managed capture + selective recovery/stabilization	Metal-rich dust, acid sludge, scrubber solution	Internal recycle can concentrate hazardous species
PCDD/F and related POPs	Chlorine, carbon, catalytic metals, residence time, cooling rate	Complete oxidation + rapid quench + sorbent/particulate capture	Spent sorbent/dust	De novo re-formation in cooling train and deposits

Note. Evidence-informed author synthesis based on H. H. Li et al. (2021), Q.-Z. Li et al. (2023), Hong et al. (2022), F. Chen et al. (2023), H. Liu et al. (2023, 2025), W. Liu, Min, et al. (2023), Pereira (2026), Sun et al. (2026), and G. Zhang et al. (2026). Control logic is conditional on speciation, temperature history, and the destination of captured material.

The key conclusion from Table 4 is that the same physical cooling step can either enable or undermine chemical control. For example, cooling may bring a gas into a scrubber's mass-transfer window but also cause it to cross a condensation zone that creates sticky deposits upstream. Similarly, rapid quenching can suppress re-formation of persistent organics but eliminates sensible-heat recovery. These conflicts should be resolved explicitly through plant-wide value and risk analysis.

7. Heat Recovery, Gas Utilization, and Carbon Management

7.1 Heat recovery and process integration

The energy content of off-gas can be recovered as steam, electricity, combustion-air preheating, feed drying, thermochemical storage, or low-temperature power. The economic hierarchy depends on temperature level, operating hours, local steam/power demand, fouling behavior, and pressure drop. Steel-industry case studies demonstrate that valorization to both steam and electricity can be attractive when a stable sink exists, while EAF-focused studies explore total heat-recovery devices, dehydration-based thermochemical storage, and cascade systems (Delikonstantis et al., 2024; M. Dong & Zhou, 2020; Hartfuß et al., 2020; Volchanska et al., 2025). Ore-thermal furnace studies similarly seek to improve recovery of exhaust gases (Martynova et al., 2025).

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INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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A persistent methodological weakness in heat-recovery studies is the use of theoretical sensible heat without sufficient derating for gas variability, fouling, bypass operation, maintenance, and fan power. Copper-smelter assessments increasingly incorporate multi-criteria weighting, while industrial WHB improvement programs focus on availability because a small gain in heat recovery is not valuable if it causes lost smelter production (Gu et al., 2026; Nanda et al., 2024). Pressure-drop effects are particularly important for low-temperature recovery devices such as ORCs, where extra exchanger resistance can consume part of the recovered power (Nikolaisen & Andresen, 2021).

For comparative screening, the minimum annualized accounting boundary can be written conceptually as: $V_{annual,net} = V_{energy} + V_{materials} + V_{avoided\ waste} - C_{fan} - C_{water} - C_{maintenance} - C_{residue} - C_{bypass} - C_{lost\ production}$. Recovered energy and material value are credited only after incremental fan power, water treatment, maintenance, residue handling, bypass losses, and production losses are deducted. This expression is not proposed as a universal economic model or as a substitute for project-specific cash-flow analysis; it is a reporting boundary intended to prevent theoretical heat recovery or instantaneous removal efficiency from being mistaken for annualized plant value.

7.2 CO-rich gas utilization and decarbonization

Gas utilization can be more valuable than heat recovery when the off-gas retains chemical energy. CO-rich gas from manganese ferroalloy production can serve as a fuel or feedstock, provided dust, contaminants, and compositional variability are controlled (Kero & Dalaker, 2025). Furnace sealing therefore has a multiplicative benefit: it reduces gas volume, increases calorific value, decreases downstream equipment size, and can improve carbon-capture readiness. Conversely, uncontrolled air ingress converts a potentially useful gas into a large-volume low-value stream.

Carbon capture and storage (CCS) introduces a new design constraint: the capture plant must operate within a gas envelope it can tolerate. Aluminum-smelting studies show increasing attention to capturing fundamentals and to integrating capture with cogeneration or waste-heat

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recovery (Abdelsamie & Hassan Ali, 2025; Broek & Versteeg, 2025; Versteeg et al., 2026). Industrial metal-recycling pilots provide evidence on solvent operation and degradation under real flue-gas conditions (Ros et al., 2025). Hydro-jet cyclone research represents an alternative route to intensifying CO_2 mass transfer (Duan et al., 2024). The central issue is again upstream conditioning: dust, SOx, NOx, oxygen, moisture, temperature, and transient CO_2 concentration determine solvent degradation, absorber size, and energy consumption.

Machine-learning forecasting of EAF off-gas offers a particularly important bridge between process dynamics and carbon capture. Rather than overdesigning downstream equipment for a single worst-case snapshot, probabilistic forecasts can define realistic envelopes for flow and composition, thereby supporting adaptive operation (Bond et al., 2026). Decarbonization of metallurgical exhaust gas must therefore combine furnace-side emission reduction, heat and fuel recovery, concentration preservation, and capture, rather than treating CCS as an isolated final box (Bazhin et al., 2024; Dock & Kienberger, 2022; Nielsen et al., 2025).

8. Process-Specific Off-Gas Treatment Flowsheets

The strongest evidence for integrated design emerges when technology is examined within process-specific flowsheets. Figure 4 compares five deliberately contrasting archetypes—copper smelting, EAF steelmaking, SAF/ferroalloys, primary aluminum, and secondary/e-scrap processing. The figure is intentionally simplified: it identifies dominant conditioning logic and interfaces rather than prescribing a universal process flow diagram (Adam et al., 2024; du Preez et al., 2023; González et al., 2025; Madias, 2024; Nicol & Hogg, 2026; Waseem et al., 2026).

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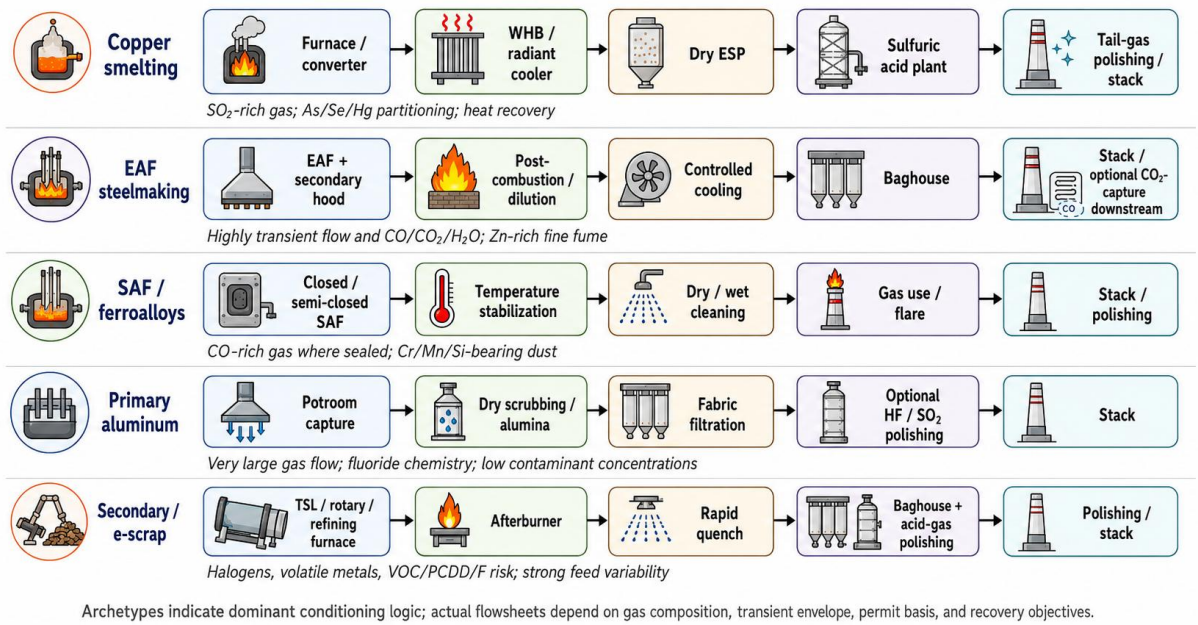

Figure 4. *Representative off-gas treatment archetypes for five contrasting pyrometallurgical process families*

Note. Author-generated evidence-informed conceptual synthesis based on Adam et al. (2024), du Preez et al. (2023), Madias (2024), Nicol and Hogg (2026), González et al. (2025), and Waseem et al. (2026). The archetypes identify dominant interfaces and do not prescribe universal process flow diagrams.

8.1 Copper and other non-ferrous smelting

In copper smelting, the furnace-to-acid-plant interface governs much of the gas train. Modern flash, bath, and top-submerged-lance systems differ in gas volume, SO_2 concentration, dust generation, oxygen enrichment, and impurity behavior, but all benefit from high capture efficiency and stable gas delivery to downstream sulfur recovery (Adham & Wong, 2025; Alexander et al., 2021; Kandalam et al., 2023a; Kandalam et al., 2023b; Nicol & Hogg, 2026; Nicol et al., 2025; Strong et al., 2025; Taskinen & Jokilaakso, 2021; Wrobel et al., 2023). Waste-heat boilers and ESPs are common front-end elements because they recover heat and remove dust before the acid plant. Their performance is strongly affected by arsenic/antimony condensation, accretion, and feed impurities (Chiong et al., 2025; Diaz et al., 2025; Lindgren et al., 2024; Nanda et al., 2024; Schmidt et al., 2022; Taskinen et al., 2024; Wan et al., 2023).

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Variable-SO_2 Ausmelt service demonstrates the importance of designing utilization and acid-plant interfaces for real concentration dynamics rather than nominal values (Starev & Doganov, 2020).

8.2 Electric-arc-furnace steelmaking

EAF systems are dominated by transience and by the distinction between primary furnace extraction and secondary/fugitive capture. Modern gas cleaning typically combines post-combustion or duct oxidation, temperature control, coarse drop-out where useful, and fabric filtration. The dust is itself a metallurgical resource and environmental liability because it contains zinc, iron, lead, and other elements (Madias, 2024; Thottempudi & Roy, 2022; Trunner & Steinparzer, 2025). Modeling work, developments in plant gas cleaning, and studies of zinc-ferrite formation show that the off-gas system influences not only emissions but also the recoverability of EAF dust (Makki Abadi et al., 2024; Hay et al., 2021; Otero Olmos et al., 2026). Heat recovery and oxyfuel concepts are increasingly linked to CO_2 utilization or capture, but large fluctuations in gas flow and composition remain the principal integration challenge (Cavaliere et al., 2022; Bond et al., 2026; Dock & Kienberger, 2022; M. Dong & Zhou, 2020; Hartfuß et al., 2020; G.-C. Li et al., 2025; Volchanska et al., 2025).

8.3 SAF and ferroalloy production

SAF and ferroalloy systems span closed, semi-closed, and open furnace configurations. Closed operation can preserve CO-rich gas for use, whereas open configurations often require much larger ventilation flows. Ferrochrome and manganese production additionally generate dusts with process-specific metal speciation and environmental concerns (Berryman & Paktunc, 2022; Berryman et al., 2022; du Preez et al., 2023; Matsanga et al., 2025; Oterdoom et al., 2026; Wang et al., 2020). Gas-cleaning performance must be evaluated alongside furnace pressure control, tapping, pre-reduction, and feed preheating, as changes in the furnace affect the gas load (Larssen & Tangstad, 2021; Moholwa et al., 2025; Sitefane et al., 2021). Pilot and industrial data also show the importance of continuous temperature measurement and particle

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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monitoring for designing reliable ducts and filters (Bazhin & Masko, 2022; Sitefane et al., 2021; Sokolov et al., 2023).

8.4 Aluminum and secondary/e-scrap processing

Primary aluminum gas treatment is characterized by very large gas volumes and stringent control of particulate and fluoride-bearing emissions, while increases in amperage can challenge existing gas treatment centers (Majed et al., 2022; Neate & Currell, 2021; Sørhuus et al., 2020). Current research adds carbon-capture readiness to this traditional gas-cleaning function (Abdelsamie & Hassan Ali, 2025; Broek & Versteeg, 2025; Versteeg et al., 2026). Secondary and e-scrap furnaces face a different problem: highly variable feed chemistry can introduce halogens, volatile metals, organic compounds, and precursors of persistent organic pollutants. TSL and dedicated e-scrap gas-cleaning designs therefore emphasize robust afterburning, rapid cooling, dry/wet removal, and materials selection (Adam et al., 2024; González et al., 2025; Kandalam et al., 2023a; Kandalam et al., 2023b; Waseem et al., 2026). Table 5 converts these process differences into design priorities. It also shows why borrowing a flowsheet from another metallurgical sector is risky unless the gas volume, chemistry, and transient envelope are demonstrably comparable (Bezuidenhout et al., 2026; Martínez & Mercado, 2026).

Table 5. *Process-specific off-gas design priorities*

Process	Primary objective	Preferred front-end logic	Downstream emphasis	Dominant integration risk	Carbon-capture readiness constraints
Copper smelting/converting	Capture SO_2 and recover heat while controlling impurities	Tight gas capture → WHB/radiant cooling → dry dust removal	Acid plant/sulfur recovery + polishing	WHB accretion; As/Se/Hg partitioning; acid-plant stability	Usually secondary to the SO_2-rich acid-plant objective; SOx, trace impurities, gas concentration, and acid-plant integration define the capture boundary.
EAF steelmaking	Handle highly transient fume and fine dust	Primary + secondary capture → post-combustion → controlled cooling	Baghouse; heat recovery/CCS increasingly relevant	Peak T/flow, bag protection, dilution, PCDD/F window	High dilution; cyclic CO_2 concentration; O_2/H_2O excursions; dust; rapid flow/composition transients; pretreatment

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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					and dynamic turndown are critical.
SAF ferroalloys	Control dust while preserving CO-rich gas where possible	Closed/sealed furnace → cooling → dry or wet cleaning	Gas utilization, flare, or stack	Furnace pressure, Cr/Mn dust chemistry, explosive CO mixtures	Furnace sealing can preserve a concentrated CO/CO_2 stream; combustible CO, dust pretreatment, oxygen ingress, and explosion safety govern integration.
Primary aluminum	Treat very large gas flow efficiently	Distributed capture → dry/wet scrubbing depending on technology	Fluoride/SOx control; alumina integration; future CCS	Pressure drop, energy demand, capture dilution	Very large dilute flow; low CO_2 concentration; fluoride/SOx impurities; fan duty and regeneration energy can dominate capture economics.
Secondary/e-scrap	Manage variable halogens, metals, VOC/POPs	Afterburning → rapid conditioning → robust dust/acid-gas control	Polishing + hazardous-residue management	Feed variability, corrosion, re-formation of POPs	Highly variable CO_2 plus halogens, VOCs, dust, and trace metals; extensive oxidation, particulate, and acid-gas pretreatment may be required.

Note. Evidence-informed author synthesis based on Trunner et al. (2020), Sørhuus et al. (2020), Madias (2024), Adam et al. (2024), González et al. (2025), Matsanga et al. (2025), Bezuidenhout et al. (2026), and the carbon-capture evidence synthesized in Section 7.2. The table is a conditional process-archetype comparison, not a universal flowsheet or capture-readiness ranking.

Table 5 makes it clear that the common design language should be expressed in terms of gas-state variables and failure mechanisms rather than equipment names. Both an EAF and an e-scrap furnace may use a baghouse, for example, but the upstream chemistry controlling its safe operation can be fundamentally different. Cross-sector transfer should therefore be treated as conditional rather than analogical. A technology, operating window, or performance indicator derived from one pyrometallurgical sector should be transferred to another only when the relevant gas-state vector, contaminant chemistry and phase behavior, operating transience,

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particulate properties, and downstream process constraints are demonstrably comparable. Similar equipment names do not establish equivalent service conditions.

9. Materials of Construction, Corrosion, Scaling, and Deposits

Materials selection for off-gas systems is unusually difficult because the operating environment varies along the train. Refractory-lined hot ducts face thermal cycling, abrasion, and chemical attack; metallic WHB surfaces face hot corrosion, erosion, and deposits; cooler ducts may cross sulfuric-acid or water dew points; wet scrubbers face acidic or saline liquors; and fans can be exposed to residual mist or fine solids. A single alloy specification cannot compensate for a poorly chosen temperature profile. The first corrosion-control action is therefore process control: keep surfaces outside aggressive condensation windows where practical, control air ingress and moisture, and prevent stagnant zones that accumulate deposits (Aarhaug et al., 2023; Hong et al., 2022; H. Liu et al., 2025; Nazari et al., 2025).

Accretions are best understood as coupled thermal–chemical–hydrodynamic phenomena. Local cold surfaces promote condensation; low-velocity regions increase particle residence and sticking; dust chemistry controls sintering and reaction; and deposits, in turn, alter flow and heat transfer, creating a positive feedback loop. Copper-smelter studies of arsenic condensation and WHB accretion illustrate this feedback (Diaz et al., 2025; Schmidt et al., 2022; Taskinen et al., 2024; Wan et al., 2023). Slagging studies in bottom-blown smelting boilers similarly show that deposit behavior must be incorporated into heat-recovery design (D. Zhang & Ma, 2022). Online cleaning devices at furnace uptake transitions are an example of directly incorporating maintainability into the process (Chiong et al., 2025).

Wet systems exchange deposit chemistry for precipitation chemistry. Scrubber scaling can result from hardness, sulfate, carbonate, or other sparingly soluble species, while recycle concentrates dissolved solids over time (Fungene et al., 2023). Clarification and bleed treatment are therefore not utilities but part of the gas-cleaning flowsheet (Eremeev et al., 2024). Where valuable or hazardous metals accumulate in the water circuit, selective recovery

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

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can reduce both disposal burden and freshwater demand (Chen et al., 2023; Wijenayake & Sohn, 2023; Yang et al., 2021).

Table 6 summarizes the dominant degradation mechanisms and their preventive logic. Figure 5 then shows how local degradation can propagate through the entire system (Chiong et al., 2025; Fungene et al., 2023; Nanda et al., 2024; Nazari et al., 2025; Schmidt et al., 2022; D. Zhang & Ma, 2022).

Table 6. *Materials and operability risk matrix for off-gas systems*

Location	Dominant mechanism	Trigger	Primary prevention	Typical consequence if uncontrolled
Hot uptake / radiant duct	Refractory attack, accretion, erosion	High T, sticky dust, local low velocity	Geometry, refractory selection, online cleaning, temperature control	Plugging, pressure excursion, forced outage
Waste-heat boiler	Fouling/slagging, tube wastage, hot spots	Radiation, condensables, dust loading, maldistribution	Surface-temperature control, soot/hammer cleaning, robust circulation	Heat-transfer loss, leakage, boiler unavailability
Cooled dry duct / filter inlet	Acid condensation, sticky dust	SO_3/H_2O, cold walls, overcooling	Dew-point margin, insulation/heat tracing, controlled cooling	Corrosion, bag blinding, deposits
Baghouse/ESP	Media/electrode degradation; uneven loading	T excursions, chemistry, flow maldistribution	Flow equalization, temperature alarms, appropriate media/materials	Bag rupture, opacity spikes, electrical trips
Wet scrubber/WESP	Scaling, acidic corrosion, solids deposition	Recirculating salts, pH, supersaturation	Water chemistry control, bleed, compatible alloys/linings	Nozzle blockage, ΔP rise, leakage, reduced removal
ID fan / stack	Erosion, corrosion, vibration	Residual mist/solids, high ΔP, maldistribution	Upstream demisting, material selection, condition monitoring	Draft loss, fugitive emissions, unplanned shutdown

Note. Evidence-informed author synthesis based on Fungene et al. (2023), Nanda et al. (2024), Nazari et al. (2025), Chiong et al. (2025), and Zhang and Ma (2022). Failure mechanisms are conditional on materials, gas chemistry, operating trajectory, and maintenance practice.

The risk matrix in Table 6 reinforces a useful distinction between material resistance and environment prevention. Premium alloys or linings are justified where aggressive service is unavoidable, but they should not be used to normalize chronic overcooling, uncontrolled SO_3, poor gas distribution, or deficient water chemistry. Process and materials engineering must be conducted together.

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 10/08/2026 - **Accepted:** 06/09/2026
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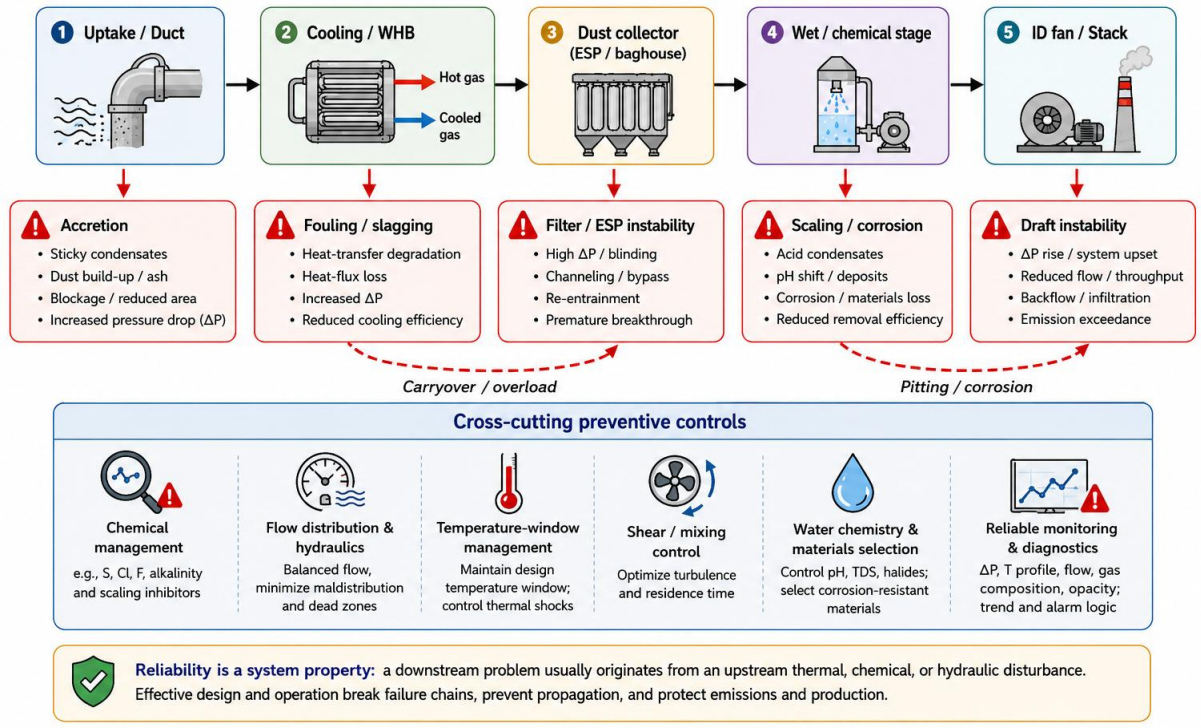

Figure 5. *Failure propagation and root-cause coupling in a pyrometallurgical off-gas train*

Note. Author-generated evidence-informed conceptual synthesis based on Schmidt et al. (2022), Fungene et al. (2023), Nanda et al. (2024), Chiong et al. (2025), Nazari et al. (2025), and Zhang and Ma (2022). The propagation paths are conceptual causal links, not measured probabilities.

Figure 5 emphasizes root-cause propagation rather than local symptom treatment. Rising collector differential pressure can originate from upstream quenching that creates sticky dust; fan overload can originate from wet-stage scaling; and boiler fouling can originate from feed-driven changes in volatile and condensable species. Reliability-centered design therefore requires cross-unit health indicators that combine temperature/composition excursions, flow distribution, ΔP, water chemistry, and maintenance history (Chiong et al., 2025; Fungene et al., 2023; Nanda et al., 2024; Nazari et al., 2025; Schmidt et al., 2022; D. Zhang & Ma, 2022).

10. Industrial Reliability, Monitoring, Modeling, and Digitalization

Industrial off-gas systems fail most often at interfaces: furnace-to-duct, duct-to-boiler, cooler-to-filter, dry-to-wet transition, and fan/stack. These interfaces combine abrupt changes in temperature, velocity, particulate behavior, or materials. Case studies on uptake cleaning,

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WHB availability, quench-tower failure, and accretion formation show that maintainability and access must be engineered from the beginning (Chiong et al., 2025; Nanda et al., 2024; Nazari et al., 2025; Schmidt et al., 2022). Redundancy alone is not a substitute for understanding the failure mechanism because parallel trains can share the same upstream deposit chemistry or temperature excursion.

Computational modeling has become particularly valuable for identifying flow maldistribution that is difficult to diagnose from plant instrumentation. EAF and HIsarna models resolve post-combustion, mixing, and reaction behavior; baghouse CFD studies optimize flow distribution; and discrete-phase models support filter-cleaning design (Makki Abadi et al., 2024; Hay et al., 2021; Hosseini et al., 2022; Hu et al., 2025; W. Liu, Xu, & X. Liu, 2023). The value of modeling is highest when it changes a design decision—duct geometry, chamber volume, baffle arrangement, bag layout, cleaning sequence, or sensor placement—rather than merely reproducing a velocity field.

Monitoring is also moving from compliance measurement toward process-state estimation. Nanoscale-particle monitoring in ore-thermal-furnace gas cleaning, furnace-duct temperature datasets, SO_3 assessment methods, and early NOx-spike detection demonstrate the widening set of observable variables (Aarhaug et al., 2023; Bazhin & Masko, 2022; Park et al., 2026; Sitefane et al., 2021). The challenge is data quality: sensors in dusty, corrosive, high-temperature service drift, foul, or fail. Redundant measurements and soft sensors that infer difficult variables from robust signals are therefore attractive.

The strongest emerging direction is predictive operation. EAF time-series forecasting shows how machine learning can generate probable future off-gas trajectories for equipment design and control (Bond et al., 2026). In baghouses, recent geometry optimization demonstrates that CFD and data can be combined to reduce non-uniformity and resistance rather than simply accepting pressure drop as an operating cost (Cao et al., 2026). A mature digital architecture should integrate furnace signals, gas composition, temperature, differential pressure, cleaning

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Nexus Science Review
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cycles, fan power, water chemistry, and emissions into a set of common health indicators. Digitalization is useful only when connected to actuators and maintenance decisions.

11. Environmental Performance and Regulatory Comparison

Environmental performance should be assessed as a multi-media balance. Low stack dust with high hazardous-metal generation in an unrecoverable filter residue is not equivalent to low stack dust with a controlled recycle or recovery route. Likewise, wet scrubbing can lower gaseous emissions while increasing water use and wastewater burden. Comparative environmental studies of copper smelting, heavy-metal flow analyses, ferrochrome waste-management reviews, and persistent-organic-pollutant studies support this broader system boundary (Alexander et al., 2021; Dat et al., 2020; du Preez et al., 2023; H. Li et al., 2021; X. Li et al., 2023; H. Liu et al., 2023; Sun et al., 2026; J. Zhang et al., 2022).

Regulatory architecture differs substantially among major jurisdictions. In the European Union, industrial emission permits are anchored in the Industrial Emissions Directive and sectoral Best Available Techniques (BAT) conclusions; the 2024 amendment to the Directive strengthens the integrated pollution-prevention framework, while the non-ferrous metals BAT conclusions remain a central reference for permit conditions. For copper production, the BAT conclusions include process-specific associated emission levels and identify sulfur recovery, dust filtration, wet scrubbing, and rapid quenching among relevant techniques. In the United States, requirements are organized through Clean Air Act programs including source-category NESHAP standards, with specific rules for EAF steelmaking, ferroalloys, and primary/secondary non-ferrous sources. China uses national and sector-specific emission standards, including GB 25467 for the copper, nickel, and cobalt industries, as well as separate standards or comprehensive control programs for iron, steel, ferroalloys, and industrial furnaces. These frameworks are not directly interchangeable because averaging periods, oxygen corrections, source definitions, and permit conditions differ (European Commission, 2016; European Parliament & Council of the European Union, 2024; Ministry of Environmental Protection of the People's Republic of China & General Administration of

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Nexus Science Review
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Quality Supervision, Inspection and Quarantine, 2010; Ministry of Ecology and Environment of the People's Republic of China et al., 2019; National Emission Standards for Hazardous Air Pollutants for Area Sources: Electric Arc Furnace Steelmaking Facilities, 2025).

Table 7 compares regulatory architectures rather than ranking jurisdictions numerically. Values are shown only where the cited source provides a defensible process-specific example; direct numerical comparison is otherwise inappropriate because averaging periods, reference oxygen, dry/wet basis, source definitions, monitoring rules, and permit conditions differ. The regulatory section is therefore contextual and is not a compliance guide. Applicable legislation, current amendments, national transposition, and site-specific permit conditions must be checked and updated before engineering design, permitting, or compliance assessment.

Table 7. *Comparison of regulatory frameworks relevant to pyrometallurgical off-gas control*

Jurisdiction	Regulatory architecture	Examples relevant to pyrometallurgy	Design implication	Important qualification
European Union	IED + sector BAT conclusions; permit values linked to BAT-AELs	Non-ferrous BAT: Hg 0.01–0.05 mg/Nm³ for specified pyrometallurgical cases; copper dust commonly 2–5 mg/Nm³ in listed processes; PCDD/F ≤0.1 ng I-TEQ/Nm³ for specified secondary-copper operations; SO_2 ranges are process-specific	Design against BAT-compatible integrated performance, including energy/resource efficiency and emissions	BAT-AELs are process- and condition-specific; permits and reference conditions govern compliance
United States	Clean Air Act; NSPS/NESHAP and permits by source category	EAF steelmaking area-source NESHAP; ferroalloy and non-ferrous source categories	Equipment and monitoring must match source classification and hazardous-air-pollutant requirements	Limits and work-practice standards vary by source category and permit; no single national metallurgical limit applies
China	National/sector emission standards + industrial-furnace control programs	GB 25467 for Cu/Ni/Co; separate standards for Al, Pb/Zn, ferroalloys, iron/steel and secondary non-ferrous industries	Sector-specific design basis with increasingly stringent local implementation in key regions	National standards can be supplemented by local or ultra-low-emission requirements

Note. Regulatory synthesis based on European Commission (2016), European Parliament and Council of the European Union (2024), Ministry of Environmental Protection of the People's Republic of China and General Administration of Quality Supervision, Inspection and Quarantine (2010), Ministry of Ecology and Environment of the People's Republic of China et al. (2019), and National

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Emission Standards for Hazardous Air Pollutants for Area Sources: Electric Arc Furnace Steelmaking Facilities (2025). Values are illustrative regulatory references, not universal design guarantees. This contextual comparison does not replace site-specific legal and permit review.

The comparison in Table 7 implies that technology claims should avoid simplistic statements such as 'baghouse is BAT' or 'scrubber meets the standard.' Compliance is achieved by an integrated system whose capture efficiency, availability, monitoring, residue management and operating practices remain effective under normal and abnormal conditions. Technology selection must therefore be permit-aware but not permit-limited, with explicit reference conditions and allowance for feed variability, future tightening and decarbonization integration.

12. Integrated Decision Framework, Research Gaps, and Future Perspectives

12.1 Temperature-Composition Trajectory Framework for Pyrometallurgical Off-Gas Design (TCTF)

The central contribution of this review is the Temperature-Composition Trajectory Framework for Pyrometallurgical Off-Gas Design (TCTF), which translates the reactor-to-stack temperature-composition trajectory into sequential design gates. The starting point is not an equipment list but the dynamic gas-state vector and its peak/percentile envelope. The designer first defines capture and sealing; then decides whether chemical energy should be preserved or safely post-combusted; selects a thermal trajectory under fouling, condensation, and dew-point constraints; matches particulate control to the resulting dust state; treats remaining gaseous contaminants; and closes material and water loops. At every gate, the preferred option is the one that maintains feasible downstream operating windows without shifting an uncontrolled burden to energy use, water, residues, reliability, or carbon capture.

Figure 6 formalizes this logic and adds an adaptive sensing–prediction–control layer. The framework deliberately separates instantaneous device efficiency from annualized plant value: compliant operating hours, net recovered MWh/y, recovered metals or sulfur, secondary waste avoided, water consumption, fan energy/ΔP, bypass hours, fouling/corrosion rate, carbon intensity/CCS readiness and total cost of

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Received: 10/08/2026 - **Accepted:** 06/09/2026
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ownership are evaluated simultaneously (Bezuidenhout et al., 2026; Bond et al., 2026; Cao et al., 2026; Gu et al., 2026; Martínez & Mercado, 2026; Nicol & Hogg, 2026).

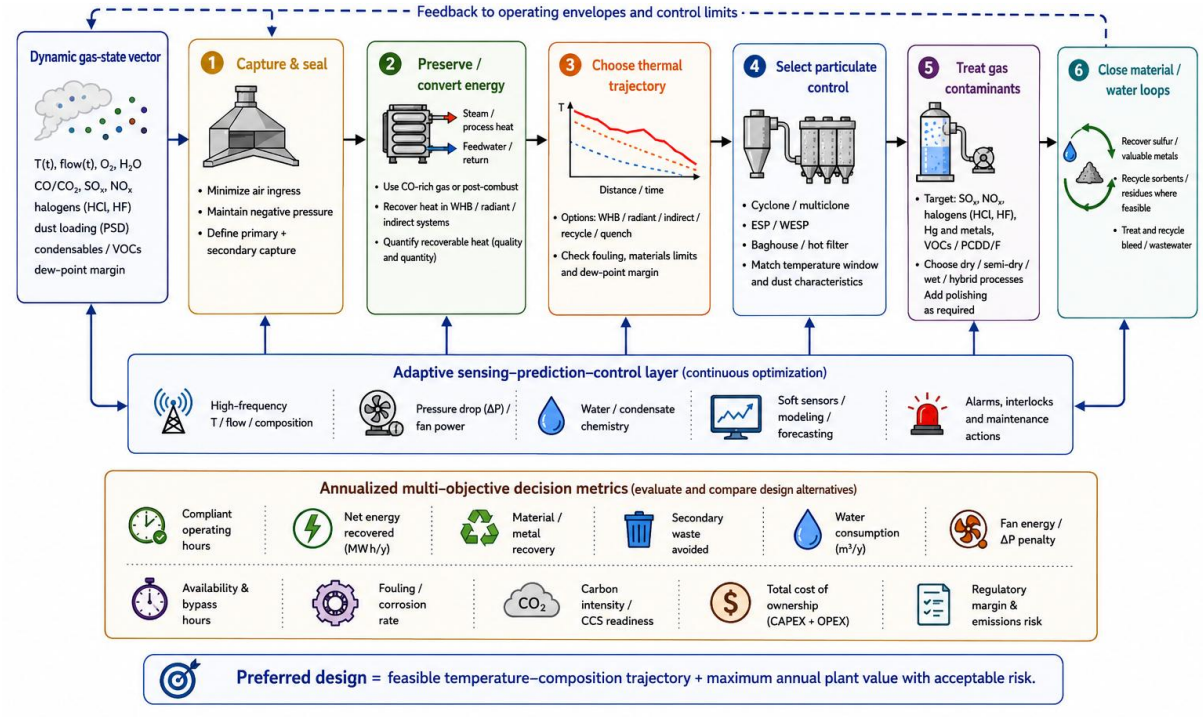

Figure 6. Temperature-Composition Trajectory Framework (TCTF) for pyrometallurgical off-gas design

Note. Author-generated evidence-informed conceptual framework based on Bezuidenhout et al. (2026), Bond et al. (2026), Cao et al. (2026), Gu et al. (2026), Martínez and Mercado (2026), Nicol and Hogg (2026), and the cross-process evidence synthesized in this review. The TCTF is a decision framework, not a directly observed empirical result or a universally validated design rule.

The framework also makes the strength of the evidence explicit. A new hot-filter medium can be technically promising at laboratory scale while remaining a high-risk plant choice until long-duration chemical durability and sealing are demonstrated; conversely, a mature baghouse may be the lower-risk option even if it requires deeper cooling. Similarly, a heat-recovery concept should be credited only for the net annual energy after accounting for fan power, bypasses, fouling, and lost-production penalties. This evidence-aware logic is used in the research priorities that follow.

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12.2 High-temperature dry cleaning and advanced equipment

High-temperature dry filtration is one of the most consequential research directions because it can decouple fine-particle removal from deep gas cooling. Ceramic, metal-fiber, and composite filter systems could protect heat-recovery or catalytic processes while preserving exergy and avoiding wet residues (Gregorovičová & Pospíšil, 2025; Krasnyi et al., 2024; Yuan et al., 2022). Their scale-up challenge is not filtration efficiency under clean laboratory gas but long-duration tolerance to sticky dust, thermal shock, chemical corrosion, sealing leakage, and pulse-cleaning fatigue. Demonstration programs should therefore report availability, pressure-drop evolution, cleaning energy, element partitioning, and failure modes rather than capture efficiency alone.

Equipment geometry is also becoming a design variable. Advanced post-combustion/drop-out chambers, optimized bag layouts, and new gas-cleaning-plant design approaches show that CFD-informed flow management can reduce both emissions and energy consumption (Cao et al., 2026; Kalisch et al., 2026; Martínez & Mercado, 2026). This is a shift from selecting catalog equipment to engineering the gas path itself. The research gap is robust validation across process scales and variable dust properties.

12.3 Adaptive heat recovery and decarbonization integration

Future heat-recovery systems must be adaptive to transient furnaces. Phase-change heat storage, cascade recovery, and advanced cogeneration are examples of architectures designed to buffer fluctuations or increase the fraction of usable energy (Abdelsamie & Hassan Ali, 2025; Delikonstantis et al., 2024; G.-C. Li et al., 2025; Volchanska et al., 2025). The next step is integration with furnace scheduling, electricity prices, steam demand, and carbon capture. A heat-recovery system that lowers gas temperature to the ideal carbon-capture inlet condition while supplying regeneration steam may create more value than one optimized solely for electrical efficiency.

Carbon capture in metallurgy remains constrained by dilution and impurities. Progress in aluminum and metal-recycling applications indicates that both capture chemistry and upstream

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gas conditioning require development (Broek & Versteeg, 2025; Duan et al., 2024; Ros et al., 2025; Versteeg et al., 2026). Furnace sealing, oxygen use, post-combustion strategy, and gas recirculation can increase CO_2 concentration or stabilize flow before the absorber, potentially reducing capture equipment size. The strongest research programs will therefore connect furnace operation to capture-system design rather than treating the two as separate disciplines (Bazhin et al., 2024; Bond et al., 2026; Dock & Kienberger, 2022; Nielsen et al., 2025).

12.4 Circularity, contaminant recovery, and whole-process optimization

A second major trend is the reclassification of dust and gas-cleaning residues from wastes to intermediate materials. Copper-smelter dust contains recoverable Cu, Zn, Pb, As, and other elements, but internal recycling can also concentrate impurities and destabilize the furnace (Guo et al., 2022; Q.-Z. Li et al., 2023; X. Li et al., 2023; B. Xu et al., 2020; G. Zhang et al., 2026). The optimal route may therefore include selective hydrometallurgical or pyrometallurgical treatment rather than direct recycling. Selenium, mercury, copper, and antimony recovery from acid sludges or waste-acid streams further demonstrates the potential to couple emission control with resource recovery (Chen et al., 2023; Henao et al., 2021; Wijenayake & Sohn, 2023; Yang et al., 2021).

The same circularity logic applies to gas-cleaning water. Closed water loops reduce freshwater demand but accumulate salts and trace metals; treatment should target both hydraulic reuse and selective contaminant removal (Eremeev et al., 2024; Fungene et al., 2023). In high-SO_2 systems, sulfuric acid production is the clearest example of converting an emission into a saleable co-product. Future 'zero-emission' smelter concepts will only be credible if they account for the fate of captured elements in solids and liquids, not just the stack.

12.5 Digital optimization and research priorities

Digitalization becomes valuable when it closes the loop between sensing, prediction, control and maintenance rather than merely producing dashboards. Table 8 consolidates the principal research gaps and decision-oriented metrics, including evidence scale/TRL where applicable.

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The intent is to shift research reporting from isolated device efficiency toward variables that determine industrial implementation (Abdelsamie & Hassan Ali, 2025; Bezuidenhout et al., 2026; Bond et al., 2026; Cao et al., 2026; Gregorovičová & Pospíšil, 2025; Gu et al., 2026; Krasnyi et al., 2024; G.-C. Li et al., 2025; Martínez & Mercado, 2026; Martynova et al., 2025; Nikolaisen & Andresen, 2021; Otero Olmos et al., 2026; Park et al., 2026; Ros et al., 2025; Versteeg et al., 2026; Waseem et al., 2026; G. Zhang et al., 2026).

Table 8. Priority research gaps and industrially meaningful metrics

Research area	Current limitation	Priority development	Metrics that should be reported
Transient gas characterization	Steady-state averages mask peaks and composition cycling	High-frequency datasets + probabilistic forecasting	Peak/percentile T, flow and composition; prediction error; sensor uptime
High-temperature filtration	Promising media but limited long-duration chemical/transient validation	Pilot hot-gas filtration on real dust	Capture efficiency, ΔP evolution, cleaning energy, element partitioning, hours to failure, evidence level/TRL
Heat recovery	Theoretical heat often overstates annual recoverable value	Availability- and pressure-drop-aware integration	Net recovered MWh/y, fan power, fouling rate, bypass hours, lost production, evidence level
Carbon capture	Dilute/transient gas and impurities challenge capture systems	Integrated furnace-conditioning-capture pilots	Capture rate, specific regeneration energy, solvent degradation, dynamic turndown, operating hours
Dust/residue circularity	Direct recycle can concentrate hazardous impurities	Selective recovery and impurity-bleed strategies	Metal recovery, impurity rejection, waste mass, recycle stability
Reliability/digital control	Monitoring often disconnected from action	Health indices, soft sensors, predictive maintenance	False alarm rate, avoided downtime, maintenance interval, control response
Regulatory/environmental comparison	Stack-only metrics shift burden to water/solids	Multi-media and life-cycle assessment	Air/water/solid releases, reference O_2/basis, averaging period, energy, carbon, water use, toxicity-weighted burden

Note. Evidence-informed author synthesis based on the 2020-2026 literature reviewed in this article, with emphasis on industrial off-gas design, filtration, heat recovery, carbon capture, digital forecasting, and residue recovery. Research priorities are author-generated and should be interpreted as a decision-oriented agenda rather than ranked universal needs.

The research priorities in Table 8 are deliberately industrial. Pyrometallurgical gas systems are mature enough that marginal increases in laboratory removal efficiency are less valuable than

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validated evidence on durability, dynamic control, recoverability of captured material, and annualized availability. This is also where cross-sector learning is most powerful: an insight from EAF forecasting can inform secondary-smelter capture design; a hot-filter material developed for one furnace may enable upstream heat recovery in another; and arsenic-management strategies in copper smelting can inform broader approaches to volatile-impurity capture.

12.6 Limitations of the review

Several limitations should temper interpretation of this review. First, the underlying literature is heterogeneous in gas normalization, reference oxygen, dry/wet basis, temperature basis, particle-size reporting, pressure-drop definitions, sampling duration, and operating time, preventing direct normalization of many quantitative values. Second, industrial reliability evidence is disproportionately reported through conference proceedings, technical case studies, and partially disclosed plant data, whereas peer-reviewed journal literature is richer in laboratory and modeling studies; implementation level should therefore not be interpreted as methodological quality. Third, coverage is uneven across process families: copper smelting and EAF steelmaking are better represented than several aluminum, ferroalloy, and secondary-metallurgy applications. Fourth, CAPEX, OPEX, maintenance, bypass, and production-loss data are frequently proprietary, limiting quantitative comparison of total annualized value. Fifth, the original discovery-stage search log did not preserve complete database/platform-specific identification and screening counts. For this reason, the study is explicitly presented as a structured critical narrative review and does not claim exhaustive systematic coverage. Sixth, inclusion of conference and industrial case evidence can introduce selection and publication bias because successful implementations and technically notable failures are more likely to be publicly reported than routine operating experience. Seventh, very recent 2026 publications, advance-online records, proceedings, and regulatory documents may undergo bibliographic, pagination, or regulatory-status changes after the final technical literature cutoff; stable DOI, publisher URL, or official-document identifiers were therefore checked where

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available during the revision-stage metadata audit. Eighth, implementation-level assignments involve interpretive judgment and were produced by a single reviewer; no independent human coder was available, so no inter-rater reliability statistic is reported. The classifications should therefore be read as transparent implementation-oriented judgments rather than reliability-tested measurements. Supplementary Table S1 exposes the source-level coding to independent audit. Finally, cross-sector conclusions are conditional: transfer of a technology, operating envelope, or performance indicator requires comparability in the gas-state vector, contaminant chemistry and phase behavior, particulate properties, operating transience, and downstream constraints. These limitations reduce confidence in universal numerical comparison but do not prevent identification of recurring process-system relationships, failure mechanisms, and evidence gaps.

13. Conclusions

Pyrometallurgical off-gas treatment should be designed as an integrated process system rather than a sequence of independent environmental control devices. The Temperature-Composition Trajectory Framework (TCTF) formalizes this principle by treating the complete reactor-to-stack temperature-composition history as the decisive design variable, expressed through a dynamic gas-state envelope rather than a single nominal temperature. That trajectory determines recoverable thermal or chemical energy, dust phase and stickiness, condensation of volatile species, corrosion risk, filter operability, gas-phase treatment efficiency, carbon-capture readiness, and the characteristics of captured residues.

No cooling or cleaning technology is universally superior. Dilution is robust but increases gas volume; quenching is rapid but sacrifices recoverable exergy and introduces water-management challenges; waste-heat boilers can create high-value steam but may become the dominant availability constraint; baghouses provide excellent fine-dust removal within a controlled thermal and moisture window; ESPs offer low pressure drop for large gas flows; wet systems are powerful for sticky and soluble contaminants but transfer the burden to liquid

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treatment; and hot ceramic or metallic filtration may preserve energy value but still requires long-duration industrial validation.

The strongest future configurations will simultaneously manage emissions, energy, materials, water, reliability, and carbon through the TCTF sequence of evidence-aware decisions: capture and sealing, energy preservation or conversion, thermal-trajectory selection, particulate control, gas-phase treatment, carbon-capture conditioning where relevant, and closure of material/water loops. Progress should be measured by annualized plant performance—compliant operating hours, net recovered energy, valuable material recovered, secondary waste avoided, water use, fan energy, availability, carbon intensity, and total cost of ownership—rather than isolated removal efficiency. The framework is intentionally conditional: it organizes evidence and design questions, but does not confer universal superiority on any technology class.

Supplementary Material

Supplementary material accompanying this revision includes Supplementary Appendix A (revision-stage search architecture and eligibility rules), Supplementary Table S1 (source-level evidence matrix for all 114 classified records), Supplementary Table S2 (narrative source-selection flow), and Supplementary Table S3 (coding definitions and reporting-completeness rubric).

Declarations

Funding: No external funding was received for this work.

Conflicts of interest: No conflicts of interest are declared.

Data availability: No new experimental datasets were generated. The review is based on the published literature listed in the References section and the source-level coding supplied as supplementary material.

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INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 10/08/2026 - **Accepted:** 06/09/2026
Vol: 01.04
DOI: 10.66104/7g7kbj19
Pages: 1-57

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