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AIST J. Keith Brimacombe Memorial and AIME Keynote Lecture

› From Pilot to Plant — Scaling Innovation for Industrial Impact in Steel Production

The manufacturing of iron and steel has been a bedrock for industrial and social growth across the world. The most widely used metallic product, steel has seen an evolution which is astounding in terms of the breadth of products and applications. This growth in products and solutions has required the steel industry to innovate continuously.

More than any other metal industry, the margins we need to work with and the scale of our investments pose tremendous challenges to our engineers, technologists and scientists in all our institutions — industry, academia and research — to not only make products more robust and processes more efficient, but also to bring radical new concepts to industrial implementation.

Meeting these challenges demands not only technological advancement but also visionary leadership. Prof. Brimacombe exemplified this approach, championing innovation that extends beyond scientific discovery to deliver practical industrial impact, foster cross-sector collaboration and develop talent capable of turning research into real-world solutions.

Here, we present a thought exercise aimed at understanding why the journey from pilot success to stable industrial operation remains so difficult in steelmaking. It examines the gap between technical feasibility and everyday industrial performance, using a clear framework that looks at industrial viability, organizational embedment and the ability to replicate a technology across sites. Through selected steelmaking and cross-sector cases, we look at recurring patterns that shape outcomes and then distill the essential principles needed for reliable and repeatable scale-up. The path taken is to define the challenge, analyze real examples and extract the lessons that matter most for accelerating industrial deployment.

Introduction

Innovation in steelmaking has always depended on scale. Ideas matter only when they become reliable, safe and repeatable industrial practice. This lesson, strongly associated with the work of Prof. Brimacombe, remains central as the industry faces a new wave of transformation driven by sustainability, electrification, digitalization and artificial intelligence. These forces lead us to accelerate innovation, but they also have the potential to increase the cost of failure.

The transition from pilot to plant is therefore not a simple increase in size. It is a shift in uncertainty — from scientific feasibility to system-level industrial risk. At full scale, technologies must operate continuously under variability, integrate with tightly coupled process chains, comply with stringent safety and regulatory requirements, and sustain economic performance over long periods. Many promising innovations fail not because the science is wrong, but because critical uncertainties emerge only after capital has been committed.

In this lecture, we aim to build on excellent earlier works (e.g., References 1–7) to broaden the dialogue on what we need to innovate at speed. We bring forward three observations. First, scale-up failures in steelmaking are rarely technical alone; they result from insufficient learning, poor integration and incorrect sequencing under rising capital exposure. Second, successful industrialization requires progress along three distinct but interdependent dimensions: scale-up (industrial viability), scale-deep (organizational embedment) and scale-out (replication). Focusing on scale-up alone explains why many technologies work once but fail to deliver lasting impact. Third, acceleration is achieved not through linear hand-offs between disciplines, but by deliberately overlapping scientific research, engineering development, business case formation and operational readiness to expose risks earlier and reduce downstream disruption.

To explore these ideas, we apply a consistent analytical framework to selected steelmaking case studies and to cross-sector examples from other capital-intensive industries. These cases are used to identify recurring success factors and failure modes, with particular attention to the often-overlooked gap between first industrial success and repeatable deployment.

In the spirit of Prof. Brimacombe's work, the article argues that innovation is complete only when uncertainty has been converted into stable, repeatable industrial performance.

Discussion

The Scale-Up Challenge

Industrial innovation in steelmaking depends not on invention alone, but on embedding new technologies within tightly coupled, continuously operating systems while maintaining safety, reliability and economic performance. Because steel plants run long-lived assets under narrow margins and minimal tolerance for disruption, scale-up decisions carry heightened operational and financial consequences compared with less integrated industries.

Scale-up is best understood as a structured process of reducing uncertainty under increasing capital exposure, not simply enlarging equipment. Early uncertainties are scientific — reaction mechanisms, material behavior and basic feasibility. Closer to industrial deployment, uncertainty shifts to operability, reliability, maintainability, controllability, organizational readiness, regulatory acceptance and financial exposure.[1] In steelmaking's tightly integrated process chains, this transition represents a system-level transformation rather than a proportional increase in scale.

The most acute risks appear between pilot operation and First-Of-A-Kind (FOAK) industrial deployment — Technology Readiness Levels (TRL) 4–7, the "Valley of Death."[2,3] Here, tolerance for failure drops sharply while capital commitment grows. Technologies rarely fail due to flawed science; rather, failure occurs because learning lags behind investment.[1] When unresolved uncertainties become embedded in physical assets, correction becomes exponentially more costly and disruptive.

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A second, often underestimated, challenge emerges after FOAK deployment. While FOAK projects establish technical feasibility, they do not automatically lead to repeatable, bankable and competitive industrial solutions. The transition from FOAK to Nth-Of-A-Kind (NOAK) replication introduces new uncertainties related to reliability across operating contexts, learning curve realization, supply chain stabilization and risk perception. If these factors are not deliberately addressed, early industrial success remains a one-off achievement rather than a scalable industrial pathway. This postFOAK phase is increasingly recognized as a "missing middle" between demonstration success and sustained industrial diffusion.

The dominant challenge in innovation shifts with scale — from resolving scientific questions to managing system-level industrial risk. This ultimately determines whether innovation delivers lasting impact.

Stages of Industrial Technology Development: Industrial technologies typically progress through four development stages (Table 1). Each stage reduces specific uncertainties while introducing new integration challenges.

Staged development does not eliminate risk, but it enables learning while corrective actions remain technically and economically feasible.[4]

Scale-Up as Structured Uncertainty Reduction: Scale-up in steelmaking is inherently nonlinear. Governing mechanisms change as systems grow. Laboratory and pilot performance are dominated by intrinsic reaction kinetics and material properties, while industrial performance is increasingly governed by heat and mass transfer, flow distribution, equipment interaction, control dynamics, utilities, mechanical stress and human operation. Degradation mechanisms, maintenance demands and subsystem interactions often emerge beyond the predictive range of laboratory correlations.

As capital exposure increases, organizational confidence can grow faster than empirical certainty, creating pressure to advance prematurely. A reliable predictor of downstream instability is maturity at commitment — whether dominant uncertainties have been demonstrated underrepresentative, continuous operating conditions before design freeze and procurement.[4]

Industrial maturity is reached when uncertainty transitions from discovery to optimization. At that point, scale becomes replication rather than experimentation: reference architectures stabilize, supplier learning curves develop, commissioning becomes predictable and capital intensity declines through repetition. When learning leads scale, industrialization becomes replication. When scale leads learning, commissioning becomes experimentation — one of the most expensive and disruptive forms of learning available.

Successful industrialization rarely follows a linear sequence from research to engineering, business case development and operations. In practice, these activities must overlap. Early involvement of engineering, commercial and operational perspectives during the R&D phase helps expose constraints, assumptions and risks that may otherwise remain hidden until late stages. Overlapping disciplines do not slow innovation; they accelerate learning by ensuring that technical

› **Table 1** Stages of Industrial Technology Development

Stage	Primary objective	Key uncertainty	Typical limitation
Laboratory research	Establish scientific feasibility	Fundamental reaction or material behavior	Limited representativeness
Pilot operation	Validate process stability and operating parameters	Process operability	Controlled environment masks degradation and operational variability
Demonstration plant	Expose system integration behavior	Reliability and subsystem interaction	Commissioning instability and availability gaps
Commercial deployment	Achieve repeatable industrial performance	Economic and operational consistency	Capital exposure and contractual accountability

development is informed by industrial reality from the outset.

Because scale readiness depends on more than technical performance alone, complementary frameworks addressing industrial, commercial, regulatory and adoption dimensions, provide additional perspectives for assessing broader scaling readiness (see Annex: Complementary Frameworks to Industrial Scaling Readiness).

Methodology for Case Analysis

This article examines the challenge of scaling technologies from pilot to industrial application using a single, consistent analytical framework. The objective is not to compare technologies on technical merit alone, but to understand how learning, integration and organizational readiness influence industrial outcomes under rising capital exposure.

Analytical Structure: Each case was examined using a common three-part structure:

- Evaluation (What happened and why): Overview of the project trajectory and main drivers of the outcome.
- Key learnings (What industry learned): Operational, technical and governance insights from the experience.
- Acceleration insights (Implications for steelmaking): Relevance of these lessons for future steelmaking scale-up.

The analysis focuses on risk sequencing, system integration and operational performance, which often determine outcomes in large industrial projects. It is applied in two complementary ways:

- Steelmaking case studies form the core of the article and are examined in greater depth. The evaluation of what happened and why is often treated as a one-dimensional process. In steelmaking, that view is insufficient because technologies must progress along multiple dimensions to achieve lasting industrial impact. To capture this, the evaluation of the case studies was conducted using three complementary scaling perspectives: scale-up, scale-deep and scale-out.
- Cross-sector case studies are used to extract learning in a compact and comparative manner. Drawn from capital-intensive industries with similar scale-up characteristics to steelmaking, these cases help identify recurring patterns in risk sequencing, system integration, operational robustness and governance under increasing capital exposure. Their role is not to frame the steelmaking analysis, but to provide an external reference that highlights general industrial dynamics.

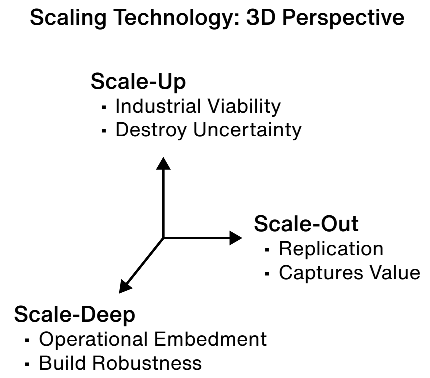

Fig. 1 Scaling dimensions used in the evaluation of the steelmaking case studies.

Evaluation of the Cases of Study of Steelmaking From Three Scaling Dimensions: In steelmaking, the evaluation of "what happened" cannot be reduced to a single notion of scale-up. Technologies must progress simultaneously along multiple dimensions to achieve lasting industrial impact. Industrial success requires not only making a technology work, but making it stick and making it repeat. To capture this complexity, each steelmaking case was assessed using three complementary scaling perspectives: scale-up, scale-deep and scale-out.

- Scale-up evaluates industrial viability (Does it work industrially?): It assesses whether a technology can transition from trials to sustained industrial operation with acceptable risk. This includes not only technical performance at larger scale, but also reliability, operability, maintainability, integration into existing plants, control stability, safety compliance and economic performance. A technology is considered scaled up when it operates continuously under normal industrial constraints.
- Scale-deep evaluates operational embedment (Does the organization learn to run it reliably?): Scale-deep assesses whether the organization and its ecosystem learn to operate the technology as part of normal production. This includes stable procedures, trained operators, effective maintenance practices, troubleshooting

capability and reliable supplier support. In heavy industry, scale-deep distinguishes a plant that works once from a plant that keeps working through variability, maintenance cycles and workforce turnover.

- Scale-out evaluates replication (Can it be replicated across sites?): Scale-out examines whether a technology can be deployed beyond the first industrial site. Replication requires repeatable commissioning, predictable ramp-up, stabilized reference designs and effective transfer mechanisms across plants, geographies and operating ecosystems. Industrial maturity is reached when scaling becomes replication rather than repeated experimentation.

The selected steelmaking and cross-sector case studies intentionally span successful standards, niche deployments and technologies that failed to achieve sustained industrial operation. This contrast allows identification of recurring success factors and failure modes under increasing capital exposure, rather than focusing only on retrospective success stories.

Scaling Technology in Steelmaking

In steelmaking, scaling is not about building bigger equipment; it is about making a new technology run safely, reliably, continuously and profitably within one of the most tightly coupled, high utilization and narrow margin production systems in industry. As a result, any innovation must withstand extreme operating conditions and integrate effectively with the full industrial system, utilities, logistics, maintenance, control, safety and organizational routines. At industrial scale, success depends on how well the entire plant works together, not on the stand-alone performance of individual technologies.

Scaling in steelmaking is therefore fundamentally an industrialization challenge, as demonstrated by decades of empirical evidence. Wasmund showed that scaling must be treated as a structured learning process in which learning precedes capital commitment and failure probability increases sharply when multiple innovations — new chemistry, new equipment, new supply chains and new operating models — are introduced simultaneously. Risk accumulates multiplicatively rather than additively.[5] Analyses by McNulty, drawing on large portfolios of industrial projects, reach the same conclusion.[6] More recent work by Cameron and coauthors confirms that projects entering investment decisions with unresolved technical, organizational or business risks consistently experience prolonged ramp-up, cost escalation and unstable operation. Across these cases, several recurring early warning signals of failure at first industrialization are identified.[5,7] Together, the works of Wasmund, McNulty and Cameron provide a consistent empirical foundation for understanding industrial scale-up as a learning-dominated process rather than a purely technical one.

This section examines the factors driving successful scaling of transformative steelmaking innovations. Case studies highlight how different pathways unfold and reveal the managerial, organizational and system-level decisions that determine industrial outcomes. This case-based approach follows Prof. Brimacombe's long-standing belief that the most durable lessons in steelmaking innovation emerge not from idealized designs, but from observing how technologies behave once exposed to real operating constraints, organizational dynamics and industrial time.

Case Studies: Lessons From Steelmaking Innovations

Case selection was based on a high-level review of the historical evolution of steelmaking. The selected cases span different stages of industrialization, from established standards and niche applications to pilots that failed, providing lessons from both success and persistent barriers. The selection of steelmaking case studies intentionally spans technologies that have progressed beyond FOAK deployment into post-FOAK phases.

We reviewed a broad set of industrial case studies and selected a limited number to illustrate distinct integration contexts and scaling outcomes. These include greenfield projects, where the operating context must be defined from the outset; brownfield integrations, where scale-up must minimize disruption to ongoing production; and cross-sector technology transfer, where acceleration depends less on technological novelty than on effective operational embedment within steelmaking's high-variability environment.

Application of the Methodology to Steelmaking Case Studies: The scale-up/scale-deep/scale-out framework was applied to selected steelmaking cases to understand why some innovations became industry standards while others remained niche or failed despite technical promise. Each case was assessed across three aspects: industrial viability — how the technology was first proven at scale; operational embedment — how it was integrated into stable operations; and replication — whether it was successfully deployed beyond the initial site.

To provide an actionable managerial perspective, each case is summarized in Table 4 into two elements: Key Learnings — the critical scaling decisions related to learning horizon, integration strategy and

› **Table 2** Illustrative Steelmaking Case Studies*

Case	Industrial purpose	Case category	Industrial installations
Thin-slab casting and direct rolling (CSP®) (TSCR/SCDR)[8–10]	Reset flat-steel cost, energy and footprint by directly linking thin-slab casting to hot rolling and using the casting heat	Industry standard; initially designed as greenfield. Now possible to integrate it into existing plants	>30
Multi-Purpose Interrupted Cooling (MULPIC®)[11–13]	Improve plate properties and reduce alloying cost via controlled accelerated cooling to enable AC, QST, or direct quenching with good flatness	Niche solution. Integration in an existing plant.	~30
Hybrid dust filter (HDF)	Achieve ultralow sinter dust emissions with reduced footprint and cost	Cross-sector technology transference from cement/power plants to steelmaking	<10
Direct strip casting (CASTRIP®) (DSC)[14–16]	Minimize rolling, energy and footprint via near-net-shape casting	Limited adoption	<10
Zinc jet vapor deposition (JVD)[17,18]	Hydrogen-free zinc coating of advanced high-strength steel (AHSS) with high uniformity, productivity and low CO_2 footprint	Post-First-Of-A-Kind (FOAK). First successful industrialization, progressing toward broad scope deployment	1
Iron carbide process (ICH)[19–23]	Low-impurity iron unit for electric arc furnace (EAF)/basic oxygen furnace (BOF) steelmaking via stable Fe_3C from fine ore by low-temperature fluidized-bed reduction	Industrial failure. Successfully demonstrated at pilot scale. Sustained industrial operation	Not yet

*Industrial deployment figures are indicative and represent orders of magnitude rather than exact counts. For MULPIC® and JVD, deployment information is additionally informed by technical discussions with CRM Group (Belgium). HDF deployment data is based on the authors' direct industrial experience.

risk exposure; and Acceleration Insights — practical guidance to accelerate the scale-up of future steelmaking innovations.

Steelmaking case studies illustrate how general principles of industrial innovation are intensified by sector-specific constraints: tightly coupled processes, continuous operations, brownfield integration and minimal tolerance for production disruption. Under these conditions, scale-up decisions carry amplified operational and financial consequences. To test whether these patterns are specific to steelmaking or structural to capital-intensive industries more broadly, selected cross-sector cases were examined.

Cross-Sector Selection of Cases of Studies

The case studies were selected from capital-intensive industries that face scale-up challenges comparable to those encountered in steelmaking, including aerospace, petrochemicals and mining. These sectors routinely develop and deploy FOAK technologies, operate highly integrated industrial systems and require extremely high levels of operational reliability.

These industries also share structural characteristics with steelmaking: large capital exposure, long asset lifetimes, complex system integration and limited tolerance for operational instability during ramp-up. As a result, they provide relevant learning environments for understanding how technological uncertainty, operational readiness and system integration are managed during industrial scale-up.

Both successful and problematic deployments were intentionally included. Studying contrasting outcomes allows identification of the conditions that enable reliable industrialization, as well as the recurring patterns

› **Table 3** Scaling Assessment of Selected Steelmaking Cases*

Case	Type of integration	Scale-up (industrial viability)	Scale-deep (operational embedment)	Scale-out (replication logic)
TSCR/ SCDR[8–10]	Initially greenfield integrated route; later replicated in brownfield contexts once mature. Relatively high system redundancy.	Commit full-plant FOAK early; accept system-level risk to reveal true value and constraints	Invest long-term to stabilize operations before optimization, learning horizon ~10 years	Replicate only after robustness and cost leadership are fully proven
MULPIC[11–13]	Brownfield, in-line integration with direct exposure to production stoppage risk	Integrate into existing mills; avoid plant redesign or disruption	Balance metallurgical ambition with operability; robustness over perfection	Scale-out accelerated by ASTM standardization, reducing adoption risk. Collaboration with licensing to an OEM for successful commercial deployment
HDF	Brownfield, integrated into existing facilities, with direct exposure to License to Operate risks	Transfer proven technology from other sectors; focus on steel integration	Close integration gaps through joint OEM–steelmaker R&D and semi-industrial pilots for operational learning	Accelerate replication once integration knowledge is codified and transferable
CASTRIP[14–16]	Brownfield integration with tight coupling to upstream and downstream operations	Push ambitious performance targets early	Low tolerance to variability limits learning and operational embedment	Limit deployment to narrow, well-defined product niches
JVD[17,18]	Brownfield, semi-decoupled finishing line with controlled production risk	Progress stepwise (lab → pilot → demonstrator) with early plant and customer involvement	Keep R&D embedded to stabilize automated, high-speed operation. A premature withdrawal of R&D support during early industrialization initially slowed operational stabilization, reinforcing the need to keep R&D embedded through ramp-up	Scale-out was constrained not by technical readiness but by customer acceptance and mono-sourcing barriers in the automotive market, making OEM licensing a necessary mechanism to unlock adoption rather than merely a replication choice
ICH[19–23]	Greenfield stand-alone FOAK; the technology constitutes the entire plant, with full system exposure	Concept and pilot succeeded; system risks emerged at industrial scale	FOAK failure driven by premature scale-up of fluidized-bed under limited modeling and cost/schedule pressure	Abandon scale-out due to unresolved system fragility and financial exposure

*Insights on MULPIC® and JVD are informed by technical discussions with CRM Group (Belgium), while HDF observations are based on the authors' direct industrial experience.

› **Table 4** Steelmaking Case Studies: Key Learnings and Acceleration Insights*

Case	Key learnings	Acceleration insights
TSCR/SCDR[8–10]	Accepted long learning horizon and full-system exposure early	Commit early only when cost advantage is structural and durable
MULPIC[11,12]	Matched ambition to brownfield constraints and market reality. Remained a niche solution deliberately, as its value proposition was strongest in site-specific brownfield contexts where flexibility and operability outweighed full standardization	Do not force universal scale-out where value is site-specific
HDF	Focused on integration rather than reinventing core technology	Treat integration capability as a strategic asset
CASTRIP[14–16]	Optimized performance before learning robustness	Delay excellence; design first for learning and variability
JVD[17,18]	Governed scale-up as a system, not a project	Keep R&D, plants and customers engaged through ramp-up
ICH[19,20–23]	Advanced to FOAK with unresolved system risks	A technology should not be scaled until its operability and controllability are proven under realistic, continuous conditions; chemistry alone is never sufficient.

*Insights on MULPIC® and JVD are informed by technical discussions with CRM Group (Belgium), while HDF observations are based on the authors' direct industrial experience.

that lead to instability, cost escalation or operational underperformance.

The objective is not to compare sectors directly, but to extract practical insights from analogous scale-up experiences that can inform the deployment of emerging steelmaking technologies.

Application of the Methodology to Cross-Sector Case Studies: Each case illustrates a different approach to managing technological uncertainty during scale-up, ranging from structured experimental learning programs to large-scale deployments where multiple unresolved risks were integrated simultaneously. Together, these cases provide empirical insight into how organizations manage the transition from technological promise to reliable industrial performance.

The cross-sector comparison reveals several recurring patterns that are directly relevant for steelmaking innovation.

Across industries, projects that achieved stable industrial performance typically followed structured validation pathways, progressing from pilot to demonstration before committing to large-scale deployment. This staged approach allowed dominant technical and operational uncertainties to be resolved before major capital exposure.

In contrast, projects that encountered major difficulties often attempted to introduce multiple new technologies simultaneously at commercial scale, transferring unresolved risks into industrial operations. In many cases, this resulted in instability, cost escalation and prolonged ramp-up phases.

Overall, the comparison suggests that industrial outcomes depend not only on scientific feasibility, but critically on how effectively learning, system integration and operational readiness are managed during scale-up. These cases matter for steel because they show that many scale-up failure patterns are structural rather than purely sector-specific.

› **Table 5** Cross-Sector Industrial Scale-Up: Case Evaluations, Key Learnings and Acceleration Insights

Sector	Case	Evaluation	Key learnings	Acceleration insights
Aerospace[24]	SpaceX Starship[25]	Structured experimental program using rapid, instrumented testing and controlled failure before commercial operation. Learning isolated from revenue pressure.[26]	Failures used as data, integrated system testing early, strong configuration control, learning cycles shortened dramatically	Acceleration requires engineered learning. Failures must occur before commercialization. Integrated testing must precede scale deployment.
	Space shuttle[27]	Technical success but industrial failure. Reusability created extreme maintenance burden, preventing economic scalability.	Maintainability underestimated, inspection workload dominated cost, learning occurred inside operations, operational cadence never achieved	Performance ≠ scalability. If maintenance is not designed up front, life cycle cost destroys value proposition.
Petrochemicals	Methanol-to-olefins (MTO)[29]	Sequential pilot → demo → industrial pathway; retired catalyst and thermal risks before scale expansion	Dominant risks isolated first, demonstrations prioritized stability, conservative early scaling, rapid replication after validation	Slow early learning enables fast industrial rollout. Scale becomes safe once uncertainty is frozen.
	Kemper IGCC[30]	Multiple FOAK subsystems integrated simultaneously at commercial scale; instability and cost escalation followed	Stacked innovation amplified risk, learning deferred to production, no stop-loss governance, integration complexity underestimated	Stacked uncertainty kills projects. FOAK technologies must be sequenced, never deployed simultaneously at megascale.
Mining/ hydrometallurgy[31]	Pressure oxidation (POX)[32]	Early industrial failures resolved after redesign focused on durability, materials and availability rather than chemistry	Availability became a success metric, materials engineering critical, maintenance designed in, demonstration plants used for life cycle learning	Industrial success equals uptime. Reliability and maintainability, not chemistry, determine scalability.
	High-pressure acid leach (HPAL)[33]	Pilot success failed to translate industrially due to variability, corrosion and operability challenges underestimated at scale	Pilots missed long-term stressor, ore variability underestimated, availability far below assumptions, risks accumulated simultaneously	Pilot success is not industrial readiness. Durability and variability validation require dedicated demonstration phases.

Ensuring Industrial Reliability: Lessons Learned for Scaling Innovation

This section focuses on why promising technologies fail to deliver sustained industrial reliability, synthesizing recurring failure mechanisms observed across the cases of study of steelmaking and cross-sector.

This synthesis follows a deliberate progression: from steelmaking sector constraints to operational lessons, to cross-sector validation and finally to the structural dimensions of the pilot-to-plant gap. While much attention has traditionally focused on the "Valley of Death" before first industrial deployment, industrial experience shows that an equally critical gap emerges after FOAK success. This "missing middle" — between technical demonstration and repeatable, bankable industrial deployment — often plays a decisive role in whether innovation delivers lasting impact or remains a one-off achievement.

Scaling innovation in steelmaking requires more than technological breakthroughs; it demands the ability to deploy new technologies reliably at industrial scale. Many promising technologies succeed in laboratory or pilot environments but encounter significant challenges during full-scale implementation. Achieving reliable deployment requires integrating lessons from steelmaking case studies, cross-sector experience and structured analysis of the pilot-to-plant gap. This section synthesizes these insights into a unified framework, highlighting the organizational, technical, financial and ecosystem capabilities critical for successful industrial scale-up.

Combined Lessons From Steelmaking and Cross-Sector Experience: Steelmaking case studies show that general principles of industrial innovation are amplified by sector-specific constraints: tightly coupled processes, continuous operations, brownfield integration and minimal tolerance for production disruption. Cross-sector experience reinforces these insights, emphasizing that outcomes depend less on scientific feasibility and more on how organizations manage learning, integration and operational readiness.

Key lessons include:

- Safety as a transversal principle: Safety must guide every stage of development and scale-up. As systems increase in size and complexity, risks shift from localized hazards to system-level interactions. In steelmaking, safety functions as a transversal principle, guiding engineering, integration and operations while maintaining long-term license to operate.
- Investment and learning:
  - Align investment strategy with deployment context: Scale-up failures often result from applying inappropriate investment logic. Disruptive greenfield technologies typically require early capital commitment to reveal system-level value and risks that cannot be observed at pilot scale. Brownfield integrations, in contrast, require staged investments that preserve operational stability. Early investment in greenfield projects is not a deviation from the learning-before-scale principle; it is often essential to identify dominant integration risks.
  - Prioritize learning before scale: Industrial failures frequently occur when investment exceeds knowledge. Structured, deliberate and early learning mitigates risk, prevents costly downstream corrections, and ensures that unresolved technical, operational or organizational issues are addressed before committing to full-scale deployment.
  - Replication requires portability, not mere repetition: Successful scale-out depends on transferring performance across sites rather than replicating locally optimized solutions. Stabilized reference designs, codified integration knowledge and supporting ecosystems enable consistent performance. Local adaptation may be necessary, but the underlying industrial logic must remain intact to ensure predictable outcomes.
- Organization and capability:
  - Teams and organizational design drive performance: Industrial outcomes rely on cross-functional teams embedded in operations. High-performing teams think in systems rather than isolated assets, remain engaged through early industrial operation and treat operational signals as learning opportunities. Multidisciplinary collaboration, clear governance and strong partnerships are decisive enablers of successful deployment.
  - Leadership and project champions are a critical component of organizational capability during scale-up. While cross-functional teams and formal governance structures are essential, experience shows that complex first-of-a-kind technologies rarely advance through committees of equals alone. Successful programs often depend on identifiable champions with the authority, credibility and persistence to sustain focus through early uncertainty, protect learning time and maintain strategic intent when setbacks occur. Champions help translate long-term vision into day-to-day decisions, align technical and operational priorities, and prevent premature abandonment of immature but promising technologies. At the same time, champions can be controversial and the leadership profile required may evolve as technologies transition from exploration to stable operation. Building organizational capability

for scale-up therefore requires not only robust processes and teams, but also deliberate attention to leadership continuity and timely transition as projects mature.

- Maintaining focus over the long technology development journey is equally critical. Industrial innovation unfolds over many years, and progress depends on the ability to concentrate effort on the right objectives at the right time. Focus is rarely achieved through broad consensus alone; it is typically driven by individuals or small leadership cores with a clear vision of the intended outcome and an understanding of the pathway to success. Early decisions to invest in sufficiently large pilots, representative demonstrations or front-end engineering activities help crystallize technical direction, align stakeholders and build credibility with partners and funding institutions. By establishing focus early, organizations create momentum, reduce fragmentation of effort and position technologies for broader collaboration and scale-up when conditions mature.
- Scaling as a continuous organizational capability: Scaling is not a single milestone but an ongoing organizational capability. Competitive organizations learn faster than uncertainty evolves, adapt systems without disrupting production and exercise discipline when further expansion would increase risk. Governance must orchestrate scale-up, scale-deep and scale-out activities over time.

› Platforms and integration:

- Dedicated learning platforms: Learning by chance during pilot or full-scale operations is valuable but insufficient. At industrial scale, interactions between legacy systems, new technologies and operational variability are tightly coupled, making root-cause identification difficult. Structured semi-industrial platforms, advanced modeling and digital twins reproduce extreme operating conditions, isolate dominant mechanisms and accelerate redesign cycles. Successful scaling combines structured experimentation with openness to unplanned discoveries.
- Demonstration plants as system-integration learning platforms: Pilot and demonstration facilities should function as experimentation platforms to reveal hidden interactions, degradation mechanisms and operational challenges. These platforms allow organizations to test integration, operational readiness and scalability before committing to full industrial deployment.

Bridging Lessons to the Pilot-to-Plant Gap: Technical and Organizational Dimensions: Even when technologies succeed in pilot or demonstration phases, many fail at industrial scale. Continuous throughput, variable feedstocks, integrated utilities and high capital exposure expose vulnerabilities invisible at pilot scale. Closing this gap requires coordinated attention across five dimensions: technical scalability, materials durability, financial bankability, ecosystem readiness and human capital.[34]

› Technical scalability: Variations in heat transfer, mass transfer, mixing and pressure often require redesign rather than simple geometric scaling. Tools such as digital twins, real-time monitoring, adaptive control and structured scale-up frameworks help anticipate and manage these challenges.[34]

› Material durability: Components may fail under continuous thermal, chemical and mechanical stress.[21] Feedstock variability and long-term operational demands increase degradation and maintenance needs. Accelerated testing, predictive maintenance, high-performance materials and condition monitoring are essential to ensure reliability at scale.[35]

› Financial bankability: Industrial deployment demands substantial capital while residual technological risks remain. Uncertainties in operational costs, energy, consumables and revenue can hinder financing. Technoeconomic modeling, risk analyses, stage-gated investment and blended financing structures help align investment with industrial realities.[4]

› Ecosystem readiness: Dependencies across infrastructure, utilities and supply chains can delay commissioning and ramp-up. Modular design, integrated planning, supply chain simulation and strategic partnerships are critical to ensure the supporting ecosystem can reliably deliver operational performance.[4]

› Human capital and workforce: Technologies may fail if operator knowledge and cross-functional skills are not codified and transferred. Gaps in workforce readiness manifest as inconsistent output, frequent redesigns and sensitivity to variability. Targeted training, knowledge management and multidisciplinary collaboration are required to build operational competence and sustain performance.[36]

Ultimately, industrial reliability emerges when technology, organization, finance, ecosystem and workforce capabilities evolve in parallel. Organizations must manage system-level uncertainty, integrate complex operational systems, build continuous learning structures, ensure bankable and ecosystem-supported investments, and develop workforce expertise. This integrated approach provides a blueprint to scale steelmaking innovations safely, efficiently and reliably.

Accelerating Industrialization

The mechanisms that undermine industrial reliability are the same mechanisms that ultimately constrain the pace of industrialization. The distinction lies not in the nature of the challenges, but in how deliberately learning, design and capital commitment are orchestrated. Building on the diagnostic insights of the previous section, this section examines how steelmakers can accelerate industrial deployment while preserving reliability, safety and bankability.

Across capital-intensive sectors, successful industrial transformations follow a common pattern.

FOAK projects typically establish technical feasibility, while large-scale impact emerges in subsequent deployments NOAK, when learning stabilizes designs, reduces risk and improves financing conditions. Industrial scaling therefore follows a learning-curve dynamic, where successive deployments progressively convert technical learning into operational reliability and cost reduction.

Industrial acceleration is systemic, emerging from coordinated advancement across five domains: learning, design maturity, financing, replication and ecosystem readiness, rather than from technical performance alone.[1,37]

In practice, industrial scale-up depends on several reinforcing drivers that determine how rapidly uncertainty declines, designs mature and capital can be committed with confidence:

- Learning velocity as the primary scale variable: Industrialization is strongly influenced by the speed at which uncertainty declines over time, known as learning velocity. Premature scaling embeds immature knowledge into capital-intensive assets, while delayed scaling slows cost reductions and weakens competitiveness. Effective programs focus on key uncertainties and combine digital simulation with targeted physical testing to accelerate learning. Digital twins enable stress testing of degradation, operational variability and system disturbances that pilots cannot replicate economically, making scale-up primarily a function of information generation.[38]
- Design maturity and digital industrialization: Most project outcomes are determined during the design phase, yet historically the greatest effort occurs during construction and commissioning. Modern industrialization shifts risk resolution upstream through rigorous front-end engineering, simulation and validation. Testing layouts, maintenance access, control strategies and operational transitions ahead of construction (while design changes remain inexpensive) reduces cost overruns and commissioning instability.[38]
- Modularization and replication economics: Industrial scale increasingly depends on standardized and repeatable architectures rather than bespoke megaprojects. Replication stabilizes performance, converts learning into routine operations and lowers costs through supplier experience and predictable commissioning. Frequent redesign between projects limits cumulative learning, whereas stable architectures allow knowledge to build across deployments.[3]
- Managing risks and bankable innovation: Early industrial deployments must address the higher uncertainty associated with FOAK technologies. Industrial deployment therefore requires financial structures capable of managing early-stage risk while maintaining predictable returns. Blended finance, guarantees and performance-linked contracts help allocate risk and support reliable cash flows during initial commercialization. At this stage, FOAK installations should not necessarily be expected to outperform established alternatives in financial performance, as their primary role is to validate the technology under industrial conditions and reduce uncertainty. Economic competitiveness typically improves in subsequent deployments (N+1, N+X, or NOAK), where learning effects, design stabilization and operational experience progressively lower costs and risks.[39,40]
- Industrial-as-a-service and risk distribution: Service-based models separate technology operation from asset ownership, allowing adoption before full technical certainty. Providers retain operational responsibility and accumulate learning across installations, while adopters reduce up-front risk. Performance guarantees shift competition toward reliability and

efficiency, supported by digital monitoring and AI-enabled maintenance.[39,41,42] This approach may accelerate learning across early installations and facilitate the transition from FOAK projects toward broader industrial adoption.

- Policy and market-driven acceleration: Industrial deployment increasingly depends on demand creation in addition to technological progress. Instruments such as carbon contracts for difference, green public procurement and lead-market standards reduce revenue uncertainty by guaranteeing value for low-emission products during early deployment. These mechanisms convert environmental performance into bankable economic signals, aligning policy design with financing requirements and enabling faster industrial scaling.[43,44]
- Technology synergies for industrial growth: Industrial growth increasingly arises from the interaction of multiple technological domains. Advances in artificial intelligence, robotics, advanced materials and digital infrastructure reinforce one another, generating compounding productivity gains across industrial systems. Integrating digital intelligence into physical processes enables adaptive control, predictive maintenance and continuous optimization. In practice, scaling AI depends less on algorithms than on governance, data architecture and organizational integration that embed digital capabilities into operational workflows.[42,29,45]
- Ecosystem readiness and governance: Technical maturity alone is insufficient for large-scale deployment. Infrastructure, supply chains, logistics, workforce capabilities and institutional capacity must develop in parallel.[20] Effective governance, supported by empirical benchmarking, realistic schedules, modular architectures and independent review, helps preserve learning, reduce coordination complexity and avoid premature commitment to immature designs.[46]

Industrial acceleration occurs when technical, financial, organizational and ecosystem factors align, letting learning outpace capital commitment and reduce early-stage uncertainty. Design maturity, modular replication, market formation, digital capabilities and system integration work together to enable innovation to scale across projects.

Key Insights

This section distills the recurring causes of industrial instability observed across the steelmaking and cross-sector cases, focusing on why promising technologies fail to achieve sustained reliability at scale. Pilot success is not a proxy for industrial reliability. Across the steelmaking and cross-sector cases examined, failures consistently emerge when technologies are exposed to continuous operation, variability and system-level integration that pilot and demonstration environments cannot fully replicate.

Key insights from this study highlight the multidimensional nature of industrial acceleration:

- Scale-up is the management of uncertainty, not the expansion of equipment size: Industrial projects fail when capital commitment advances faster than validated knowledge. Acceleration therefore requires front-loading learning through staged validation, digital twins and extended demonstration phases that retire dominant risks before design freeze.
- Industrial performance emerges from system coherence rather than technological excellence: In steelmaking especially, modifications propagate across upstream and downstream processes, altering thermal balances, logistics and operational stability. Successful deployment prioritizes integration engineering and system simulation early, shifting design from asset optimization toward chain equilibrium.
- Learning velocity is the hidden variable governing industrial acceleration: Projects scale fastest when uncertainty decreases faster than investment grows. Combining physical pilots with digital experimentation increases validated learning per unit time, enabling overlap of development phases without increasing execution risk.
- Replication, not redesign, creates industrial scale: Historical successes stabilize reference architectures before expansion. Modular design and standardized configurations convert FOAK uncertainty into NOAK learning, allowing supplier learning curves, predictable commissioning and declining capital intensity across deployments.
- Bankability determines deployment speed as much as technology readiness: Technologies reach industrialization when risks are translated into financeable structures. Revenue certainty, standardized contracts, blended finance mechanisms and risk-sharing project models accelerate Final Investment Decisions more effectively than marginal technical optimization.
- Industrial scale requires ecosystem maturity: Infrastructure, permitting, supply chains,

workforce capability and market formation must mature alongside engineering development. Lead markets, green procurement frameworks and coordinated ecosystem planning reduce adoption friction and transform demonstrations into replicable industrial pathways.

- New industrial business models can compress the scale-up gap: Industrial-as-a-service and performance-based deployment models reduce up-front capital exposure and shift adoption decisions from asset ownership toward operational outcomes. By aligning supplier incentives with plant performance, these models enable earlier adoption while preserving financial discipline.

Together, these points underscore that industrial success depends not only on technology, but on coordinating learning, capital, talent and ecosystem readiness to convert pilot successes into reliable, replicable industrial performance.

Looking Forward: Scaling Innovation for Future Steelmaking

The steel industry stands at a defining moment of transformation. Pressures from sustainability, electrification, digitalization, workforce evolution and heightened safety expectations are reshaping not only the technologies we develop but also the way they are industrialized. The challenge is no longer merely invention, it is industrializing innovation at speed and scale, building resilient and adaptive systems capable of thriving in a rapidly changing and interconnected world.

Steel remains strategically indispensable, forming the backbone of infrastructure, energy systems, mobility and economic development. Yet it operates within a market shaped by persistent overcapacity, intense global competition and growing trade distortions that compress margins and amplify risk. At the same time, sustainability and decarbonization have become defining boundary conditions, no longer distant ambitions but immediate drivers of technological and industrial change.

In parallel, digitalization, workforce evolution and rising safety expectations are reshaping how steel plants are designed and operated. These trends increase both opportunity and risk and they fundamentally change how innovation must be industrialized.

Yet these pressures also create a powerful opportunity: to rethink not only what technologies are developed, but how they are industrialized.

Key Drivers Shaping Future: Several structures forces will define the next generation of steelmaking innovation:

- Safety and license to operate will remain non-negotiable. New processes must be demonstrably safe under upset conditions, not only under nominal operation, and must integrate seamlessly with existing safety cultures and regulatory frameworks.
- Environmental performance and decarbonization constraints will increasingly define feasibility. Technologies will be evaluated on not only technical performance, but on life cycle emissions, resource efficiency and their compatibility with evolving policy instruments and market mechanisms.
- System complexity and interdependence will grow. As steelmaking integrates new energy carriers, digital control layers and external infrastructures. Scale-up will therefore involve managing interfaces beyond the plant boundary.
- Capital discipline under uncertainty will intensify. Larger investments, longer payback horizons and evolving markets will demand stronger evidence of robustness, bankability and replicability before full commitment.
- Workforce transformation will accelerate. Automation, digital tools and new operating regimes will require new skill sets, while experience-based industrial knowledge must be retained and transferred across generations. Digital technologies, including physics-based and data-driven digital twins, will be crucial for effective workforce development by enabling realistic, immersive and repeatable virtual training environments.
- The innovation ecosystem will diversify and fragment. Future steelmaking innovation is likely to involve a growing number of entrepreneurial technology developers operating alongside established industrial actors, often outside existing operating systems. A key challenge will be to engage these players through a structured pilot-to-plant pathways that preserve agility while ensuring disciplined learning, risk management and safe integration into complex industrial systems.

In this landscape, the greatest risk is not moving too slowly but scaling innovations that cannot adapt. Technologies often fail not because they are flawed, but because they are too rigid to respond to evolving operational, environmental and economic realities.

Tools, Skills and Mindset for Future Scale-Up: Addressing these challenges requires expanding the traditional engineering toolbox:

- Artificial intelligence, advanced modeling and digital twins to evaluate variability, degradation and failure modes before major capital commitments.
- Structured demonstration platforms that reveal system-level risks rather than simply confirm expected performance.
- Integration engineering capabilities to coordinate across processes, utilities, digital systems, supply chains and connected infrastructures.
- Data-driven operational learning, combining real-time sensor feedback, analytics and rapid iteration to accelerate industrial maturity.
- Governance and independent challenge to ensure confidence grows alongside evidence.
- Cross-disciplinary teams, integrating metallurgy, process engineering, automation, maintenance, safety, finance and operations into a unified industrialization mindset.

Beyond technical expertise, successful scaling also depends on navigating uncertainty, communicating risk transparently and aligning ambition with operational and economic realities.

Scaling Steelmaking: Short-, Medium- and Long-Term Perspectives: Scaling innovation requires more than technical capability; it demands a strategy that integrates learning, operational readiness and replication across time horizons:

- Short term: Prioritize flexibility and learning. Early demonstration projects should retire dominant uncertainties and validate operability under realistic conditions. Adaptability takes precedence over speed, ensuring innovations are robust before broader deployment.
- Medium term: Emphasize replication readiness. Technologies that establish proven baseline designs, capture operational knowledge and integrate with emerging energy, supply chain and workforce ecosystems scale more effectively than technically superior but fragile solutions.
- Long term: Treat scale-up as a core industrial capability. Organizations that embed continuous learning, modular plant architectures, digital intelligence and ecosystem partnerships into their operating model can transform innovation into enduring industrial advantage. Scaling becomes disciplined, repeatable and adaptive, enabling resilient, sustainable steelmaking for decades to come.

In steelmaking, the future will belong not to the fastest inventors, but to those who industrialize learning faster than uncertainty evolves.

Final Remarks

Innovation has always been central to steelmaking's ability to adapt, endure and lead. From the expansion of blast furnaces that enabled mass industrialization to the rise of electric arc furnaces that reshaped resource use and operational flexibility, progress in steel has depended not on invention alone, but on the disciplined translation of ideas into reliable, repeatable and safe industrial systems. Today, the industry faces a convergence of challenges — sustainability imperatives, capital discipline, increasing system complexity and workforce transition — that amplify the consequences of premature scale-up. In this environment, accelerating innovation does not mean accepting higher risk; it means engineering learning more deliberately, earlier and at system level. The cases discussed in this article demonstrate that industrial success is ultimately a system outcome rather than a component-level achievement, and that industrial leadership is defined by the ability to convert uncertainty into stable, continuous operation. Advanced tools such as digital twins, simulation and artificial intelligence significantly enhance learning and optimization, but they cannot replace human judgment. Successful industrialization depends on people and organizations capable of integrating physics, materials, automation, operations and safety into systems that perform day after day under real industrial constraints. Scale-up is therefore never a solo journey: it requires coordinated ecosystems of talent, infrastructure, capital and governance. Looking forward, steelmaking will thrive through resilient and adaptive technologies, modular and replicable designs, and integrated digital intelligence that allow innovation to scale while remaining robust. Ultimately, transformation is delivered by engineers, operators, researchers and leaders who turn knowledge into action and invention into enduring industrial value.

In the spirit of Prof. Brimacombe's work, it is this evolution of uncertainty — from scientific questions to system-level industrial risk — that ultimately determines whether innovation delivers lasting impact or remains an unrealized promise. Innovation is complete not when a technology works once, but when it works every day — consistently, safely and in a way that empowers people, improves real decisions and withstands industrial reality.

Annex: Complementary Frameworks for Industrial Scaling Readiness

While Technology Readiness Levels are widely used to assess technological maturity, they are insufficient to capture the full complexity of industrial scaling.[47] Industrialization depends on multiple dimensions beyond technical feasibility, including organizational capability and ecosystem conditions.

This annex presents a set of complementary readiness and maturity frameworks that describe technological progression across technical, industrial, commercial, regulatory and adoption dimensions. Together, these frameworks provide a broader basis for assessing whether technologies are not only technically viable, but also industrially deployable and scale in real-world operating environments, as summarized in Table 6.

Table 6 Overview of Innovation Readiness and Maturity Frameworks

Framework	Focus area	Core question	Year of creation / formalization
Technology Readiness Level (TRL)[47]	Technical validation	Does the technology function as intended under relevant conditions?	1980s (NASA); standardized in 1990s
Integration Readiness Level (IRL)[48]	System interoperability	Can the system integrate reliably with other components?	~2007 (systems engineering literature, U.S. defense/aerospace context)
Manufacturing Readiness Level (MRL)[49]	Production scalability	Can the technology be manufactured consistently at scale?	~2005–2010 (U.S. Department of Defense formalization period)
Commercial Readiness Level (CRL)[50]	Commercial viability	Can the solution be financed, sold, and scaled in markets?	~2010s (venture and clean-tech practice, no single standard origin)
EU Policy and Funding Readiness (ETRF/EART)[51]	Regulatory alignment	Is the solution aligned with regulatory, policy and funding frameworks?	~2015–2020 (EU innovation and funding ecosystem evolution)
Adoption Readiness Level (ARL)[52]	User/system adoption barriers	What barriers prevent real-world adoption at scale?	~2010s (diffusion of innovation extensions in practice)
Disciplined Entrepreneurship for Climate and Energy Ventures (DE4-CEV)[53]	System and business durability	Is the venture structurally robust for long-term deployment and growth?	2013 (core framework); climate adaptation ~2020s

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About the Author

Pinakin Chaubal has been group chief technology officer since May 2019 and has taken on the additional responsibility of R&D, capital goods and capital projects since January 2025. He started his career in 1987 at Inland Steel and joined the group in 1998 after the acquisition of Inland Steel by Ispat International. He has a background in process metallurgy and has held several positions in research, operations and technology for various organizations. With the creation of ArcelorMittal Global R&D in 2007, he moved to Europe as general manager responsible for process research and development globally. In 2014, he relocated to the U.S. and took on additional responsibilities as head of research management Americas, whilst continuing to act as process portfolio leader and a member of the global R&D leadership team. Chaubal holds a Bachelor of Technology degree in metallurgical engineering from the Indian Institute of Technology, Madras, India. He also holds an M.S. degree in metallurgical engineering from the Missouri University of Science and Technology, and a Ph.D. in the same discipline from the University of Utah. *Iron & Steel Technology* spoke with Pinakin Chaubal about his career. The transcript of that interview appears on the following pages.

An Interview With AIST J. Keith Brimacombe Memorial and AIME Keynote Lecturer, Pinakin C. Chaubal

Congratulations on being selected as the Brimacombe Memorial Lecturer. What does receiving this honor mean to you?

While, of course, it's an award that's given to one person, I really think that it's more a recognition of all the teams that I've been associated with and the work that we have done, to kind of follow in the footsteps of Prof. Brimacombe, making sure that we use sound scientific principles, making sure that we are continuing to innovate and evolve our processes. So I am humbled that I was asked to give this lecture because when I look at the past award winners, most of them are people I've worked with and respected and learned a lot from. I'm truly humbled to be considered part of this group.

What first drew you to metallurgy and when did you realize it would become your focus?

As a young student in high school, chemistry was always my favorite subject. I grew up in India, and there was what is called the National Science Talent Competition. I picked a project in chemistry where I was looking at extracting aluminum from alumina ores, and that kind of got me interested in metallurgy.

Then when I went to university, two courses stood out for me when I started in metallurgy. One was just a phenomenal lecture on the iron-carbon diagram, and the other one was on blast furnace and an open-hearth processes in steelmaking. I knew then I'd made the right choice to be in metallurgy. But over my career, I've had the good fortune of being able to do projects in all aspects of metallurgy, from mineral processing through extraction, whether through high temperature or aqueous electrolysis, to better understand metals and alloys. So that's really how my interest in metallurgy developed and continued all the way through.

Your career bridges industry and research. How do you balance scientific curiosity with practical application?

So, you know, everyone says if you can measure something, you can improve it. But I would like to put a little bit of a twist to that. If you can *explain* something, you can improve it. And really, that's been at the core of everything that I have done as a young engineer and continue to challenge our teams today to make sure that you understand and develop the scientific basis behind any process that you're trying to improve. And with that in mind, it's very easy to always look and keep your scientific curiosity alive because it's what then drives you to improve on the processes that you're working on and also on the practical development of concepts and taking up new ideas and new solutions into the marketplace.

What has been the most rewarding part of seeing your work applied practically?

One of the really fun things for me as an engineer in iron- and steelmaking — and even before I started in iron and steel, I was working on nonferrous — is that our reactors are very large, and it's not so easy to see inside our reactors. To be able to use scientific principles and mathematical modeling, which is what my focus has been, to explain what's going on in processes and then use that to improve processes really has been the most rewarding part. I've been very lucky that I've had the opportunity to actually take those ideas that come out of this kind of an evaluation and make changes on these large processes. And when you see these huge reactors actually starting to produce and behave in the way you expected them to from your fundamental understanding, that's absolutely a fantastic feeling.

What do you see as the most transformative technological shift currently happening in the industry?

Everybody talks about digitalization and artificial intelligence, and I think that this field is really the most evolving. And it's actually been amazing to see what it is that we can do, not only to develop an understanding of the processes, but also to make changes and control our processes. We are using these techniques in every aspect of what we do, whether it's in maintenance, whether it's on operational changes, whether it's on our projects. And that's why, for me, using the developments in digitalization and AI intelligently and in the right way is the most important transformational tool that we have today (combining these tools with thermodynamic kinetics, computational fluid dynamics, etc.). And I see that this will continue to be a critical part of how our industry develops utilizing these tools.

In your opinion, what's the most exciting development in steel today?

It's not a particular technology, but I think that the most exciting part for me is probably two things. First is what we can call process integration, which is that we are combining many processes into one. When I started in the steel industry, we were developing, or rather, one of the companies in U.S., Nucor, was putting in practice thin-slab casting direct rolling for hot-rolled coil production. This has evolved significantly. Now we are seeing that in long products rolling also and overcoming the challenges that we have of combining many processes to act as one continuous unit. That is really where the industry is moving.

The other part, in a way, is simplification, although it's not really simplification, but it's the move toward electric arc furnaces. And the U.S. has been the country that has grown electric arc furnace technology. But now we can see globally electric arc furnaces coming in and the size of these reactors is becoming larger and larger. And what is really transformational for me here is the fact that it is allowing us to simplify the front end of our steelmaking processes from what we have for the integrated side to an electric arc furnace–based side. So those are really the two conceptual or technological directions that I see being truly exciting and transformational for us in the coming years.

How has AIST impacted your career?

When I was a grad student, my advisor strongly recommended that I immediately join the professional societies. And at that time, because of the projects I was working on, I joined one of the sister society of AIST, The Minerals, Metals & Materials Society. Then when I started working in the steel industry, it was natural to join the Iron & Steel Society (ISS), now AIST. And the big benefit that you get from joining these societies is that you start to interact with not only your peers, but also people who have been there in the industry for a while, learning from their experience. What is amazing to me is that AIST has always encouraged the newcomers, the youngsters, to become very active. And being very active in the society — I was quite active in the early stages — allowed me to reach out, develop my network, develop contacts which I can draw upon, and even draw upon them today. It's a very core part of my professional, and in fact, in some ways, my personal growth also. So I strongly recommend all youngsters to join the societies as soon as possible and take active interests and participate there. ✦