Ref. Ares(2026)5644869 - 03/06/2026

iSteel-Expert

Deliverable 5.3

Guidelines for transferability and deployment of the system in the EU steel sector

	Name	Date
Prepared by:	Renato Girelli	30.04.2026
Checked by:	All the partners	14.05.2026
Approved by:	All the partners	14.05.2026

Project co-funded by the Research Fund for Coal and Steel (RFCS)

G.A. 101112102

Project details

Project Name	**Remote expert virtual system enhancing human management capabilities and favors preservation, transfer and continuous evolution of knowledge for steelmaking operation**		
Project Acronym	iSteel-Expert		
Project No.	101112102	Duration	36 months
Project Start Date	01.07.2023	Project End Date	30.06.2026

Document details

WP:	**5**	**WP Leader:**	**SIDER**
WP Title:	Field Tests and system assessment for exploitation and transferability analysis		
Task:	5.4	Task Leader:	TENOVA
Task Title:	Transferability analysis		
Deliverable No.	5.3		
Deliverable Title	Guidelines for transferability and deployment of the system in the EU steel sector		
Dissemination level	PU		
Written By	TENOVA		
Contributing beneficiary(ies)	All the partners		
Approved by	All the partners		
Status	Complete version		
Date	30.04.2026		

Document history

Vers	DATE	AUTHOR / REVIEWER	NOTES
0.1	26.03.2026	Renato Girelli	Initial version
0.2	30.04.2026	Renato Girelli	Draft complete version compiled for approval

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Executive Summary

The European steel industry is undergoing a major transformation driven by decarbonisation targets, increasing process complexity, and a rapid loss of experienced workforce. Electric Arc Furnace (EAF) steelmaking, while central to this transition, remains a highly dynamic and operator-dependent process, where variability in conditions, limited visibility of critical events, and reliance on tacit knowledge can affect performance, safety, and efficiency.

At the same time, the sector faces a structural challenge in preserving and transferring expertise, as a significant share of experienced personnel is leaving the workforce, while new operators require faster and more effective training solutions.

The iSteel-Expert project addresses these challenges through the development of a remote expert virtual system, integrating artificial intelligence, data analytics, and human-centric training tools into a unified digital platform. A key design principle is the integration of process intelligence with workforce support, enabling the system to augment operator capabilities rather than replace them.

The system has been demonstrated in industrial EAF environments, confirming its technical feasibility and industrial relevance. Key outcomes include:

- Improved anomaly detection capability, including identification of rare and critical process events;
- Transition from reactive to predictive process management, through data-driven insights;
- Enhanced operator support, particularly in complex and safety-critical conditions;
- Structured knowledge capture and transfer, reducing dependency on individual expertise.

The training component further enables the development of scalable, repeatable learning processes, addressing workforce skill gaps and supporting faster onboarding.

At sector level, the solution supports EU priorities related to industrial competitiveness, digitalisation, and skills development. Moreover, the project defines a structured pathway for deployment and replication across the EU steel sector. The modular architecture and adaptability of AI models, in principle, enable transferability however action is needed to scale these solutions across the EU steel sector to address operational challenges, workforce transformation, and sustainability objectives in steel plants with different digital maturity levels.

1. Introduction

The iSteel-Expert project aimed to implement and demonstrate a remote expert virtual system within an industrial environment. Designed and developed for EAF steelmaking plants, the system monitors events and suggests actions to minimize human presence in critical areas around the furnace. The system also features a multimodal training platform, offering EAF operators a combination of interactive learning, step-by-step instructions, and realistic simulations.

This document provides guidelines for the transferability (ability to replicate the system across plants), deployment (practical implementation in a specific plant) and exploitaion (commercialization and industrial use of the results) of the system within the EU steel industry. It also proposes strategies to overcome the key barriers that could hinder successful implementation in other EAF steelmaking plants, specifically related to:

- **Technical Integration:** challenges in integrating the system with existing automation and process control systems, as well as varying hardware and sensing configurations across EAF plants.
- **Process and Operational Heterogeneity:** variations in process control and operational practices that require system adaptation to achieve the necessary interoperability.
- **Organizational Resistance:** a lack of specialized digital skills among the workforce and internal inertia regarding the adoption of new automated processes.

2. iSteel-Expert System overview and Value Proposition

The iSteel-Expert system is a digital solution designed to enhance operational awareness, decision-making, and knowledge transfer in Electric Arc Furnace (EAF) steelmaking. The system operates as a remote expert virtual platform, continuously monitoring process conditions, analysing multi-source data, and supporting operators with actionable insights. Its architecture is based on a modular structure integrating:

- Data acquisition (process, electrical, visual signals)
- Data analytics and AI models for anomaly detection and prediction
- Decision support functionalities
- Human–machine interfaces (dashboards, alerts)
- Training and knowledge management modules

This architecture enables integration with existing plant systems and adaptation to different levels of digital maturity.

2.1 Core Functionalities

The system provides three main functional capabilities:

- **Anomaly detection and monitoring**: identification of abnormal process conditions (e.g. slag and furnace reactions) through machine learning applied to industrial datasets.
- **AI-based decision support**: prediction of process deviations and recommendation of corrective actions through integrated optimization approaches.
- **Training and knowledge transfer**: simulation-based and AI-supported training environment enabling structured knowledge preservation and workforce upskilling.

Additional functionalities include visual monitoring of safety-critical areas through computer vision techniques (e.g. smoke detection, personnel tracking).

2.2 Value Proposition

The iSteel-Expert system delivers value across three main dimensions:

- **Operational performance**
  - Improved process stability through early anomaly detection
  - Enhanced decision-making through AI-supported insights
- **Safety and workforce**
  - Increased situational awareness in hazardous environments
  - Reduced dependence on tacit knowledge through structured digital support
- **Digital transformation**
  - Integration of AI, data analytics, and simulation tools
  - Standardization of practices across different plants

The system supports the transition towards more efficient, safer, and knowledge-driven steelmaking processes.

2.3 Industrial Relevance and Use Cases

The system has been designed and validated in industrial EAF environments, addressing key operational needs:

- Detection and classification of process anomalies using real plant data;
- Monitoring of safety-related conditions in the melting area;
- Simulation-based training for operator onboarding and skill development;
- Knowledge capture and transfer across workforce generations.

These use cases demonstrate the applicability of the system in real production contexts and its potential for replication across the EU steel sector.

2.4 Scalability and Transferability Potential

The system is designed for deployment across multiple steel plants due to:

- Modular and flexible architecture
- Adaptable AI models requiring site-specific tuning
- Generalized representation of EAF processes

These features enable the system to be deployed in plants with different configurations, supporting its scalability and transferability within the European steel sector.

3. iSteel-Expert Transferibility Framwork

Transferability of the iSteel-Expert system refers to its ability to be effectively replicated across different steel plants with limited redesign effort, while preserving its performance and value proposition. The assessment of transferability is structured along the following dimensions:

- **Technical dimension**: compatibility with existing process configurations, instrumentation, and automation systems.
- **Data and AI dimension:** availability and quality of process data required for training and adaptation of machine learning models. The system relies on heterogeneous datasets (process, electrical, chemical) aggregated at heat level.
- **IT/OT integration dimension:** capability to interface with plant-level control systems and data infrastructures, including communication protocols and cybersecurity constraints.
- **Operational dimension:** alignment with site-specific process practices, operating procedures, and control strategies.
- **Workforce and training dimension**: ability of operators to adopt and effectively use the system, including required training and digital literacy.

3.1 System Characteristics Enabling Transferability

The iSteel-Expert system incorporates design features that inherently support transferability:

- **Modular architecture**: the system is composed of independent modules (monitoring, AI models, DSS (Decision Support System), training platform), allowing selective deployment.
- **Parametric and adaptable AI models**: machine learning models can be retrained using site-specific data to accommodate process variability.
- **Generalized process representation**: the system is designed to capture core process logic rather than plant-specific configurations, enabling adaptation across multiple EAF plants.
- **Human-centric design**: the system augments operator capabilities rather than replacing decision-making, improving acceptance and usability.

3.2 Typology of Target Steel Plants

Transferability is assessed considering different plant configurations:

- **EAF configurations**: EAF charged with scrap and EAF/DRI
- **Digital maturity levels**
    - Low: limited sensorization and data availability
    - Medium: partial digital infrastructure

  - o High: advanced data acquisition and analytics capabilities
- **Plant scale and complexity**: variability in production volume, layout, and operational practices.

The following matrix provides a qualitative assessment of transferability across typical EAF configurations, highlighting the relationship between digital maturity, deployment effort, and expected value.

Plant Configuration	Typical Data Availability	Integration Effort	Customisation Level	Main Gaps	Mitigation Actions	Expected Benefits
EAF – Traditional scrap-based with low automation	Limited sensors, fragmented historical data	**High**	**High**	- Missing signals - Poor data quality - Limited IT/OT integration - Low digital skills	- Install additional sensors - Data structuring - Training programs - Basic model calibration	Moderate: safety improvement, basic anomaly detection
EAF Standard scrap-based plant	Core process data available (electrical, operational)	**Medium**	**Medium**	- Partial data gaps - Heterogeneous systems - Limited anomaly dataset	- Model retraining - Middleware integration (OPC) - Data cleaning	High: improved process stability and decision support
EAF – Advanced digital plant (smart steelworks)	High-quality structured datasets + real-time monitoring	**Low**	**Low**	- Integration optimization - Cybersecurity alignment	- Fast integration - Model fine-tuning - KPI monitoring	Very high: predictive operations, full DSS value
EAF with DRI/HBI integration	Mixed data (scrap + DRI variability)	**Medium–High**	**Medium–High**	- Process variability - New anomaly patterns	- Model retraining - Extended datasets - Operator training	High: better control of process variability
EAF in multi-site steel group	Variable across sites	**Medium (per site)**	**Low–Medium**	- Standardization gap - Organizational differences	- Replication templates - Centralized data models - Standard training	Very high: scalability and standardization
Greenfield EAF (new plant)	Full design control of data and sensors	**Low**	**Low**	- Initial configuration only	- Native integration - Optimized architecture design	Maximum: full system potential from start

This matrix supports decision-making by identifying the expected implementation effort and potential value for different plant categories: transferability increases non-linearly with digital maturity, while customization effort is primarily driven by data availability and process variability.

4. iSteel-Expert Deployment Guideline

The deployment of the iSteel-Expert system in the EU steel sector requires a structured and phased approach, ensuring effective integration into heterogeneous industrial environments while minimizing operational risks.

The deployment strategy is based on three key principles:

- **Modularity**: the system can be implemented progressively through independent functional modules (monitoring, AI models, decision support, training)
- **Adaptability**: AI models and system configurations can be tuned to plant-specific conditions
- **Scalability**: solutions can be replicated across multiple plants within industrial groups

This approach enables deployment across steel plants with different process configurations and levels of digital maturity.

4.1 Deployment Phases

Deployment should not be considered as a one-step activity, but as a progressive maturity-driven pathway strongly dependent on plant characteristics. The implementation of the system follows a structured five-phase methodology:

- **Pre-assessment phase to evaluate plant readiness:**
    - Analysis of process configuration (EAF type, operating practices)
    - Assessment of available sensors and instrumentation
    - Evaluation of IT/OT systems and data infrastructure
    - Identification of data availability and quality

- **System adaptation phase to align the system with plant-specific conditions:**
    - Configuration of data acquisition interfaces
    - Adaptation of AI models using site-specific datasets
    - Definition of local parameters and thresholds

- **Pilot deployment phase to validate the system in real operating conditions:**
    - Installation in selected plant areas
    - Integration with automation and data systems
    - Initial testing of monitoring and DSS functionalities

- **Industrial validation phase to verify system performance and usability:**
    - Evaluation against operational KPIs
    - Validation of anomaly detection and decision support performance
    - User feedback collection (operators, engineers)

- **Scale-up and replication phase to extend deployment across the plant or to additional sites:**

- Standardization of deployment configurations
- Replication to other process areas or plants
- Integration into routine operations

4.2 Deployment Architecture

The deployment architecture is based on a hybrid digital infrastructure combining edge and cloud components:

- **Data acquisition layer**: collection of real-time process, electrical, and visual signals
- **Edge computing layer**: local data preprocessing and integration with plant control systems
- **Cloud analytics layer**: execution of AI models, anomaly detection, and decision support algorithms
- **User interface layer**: dashboards, alerts, and training interfaces supporting operator interaction
- **Training and knowledge layer**: simulation-based environment for workforce development

This architecture ensures flexibility, scalability, and compatibility with different plant infrastructures.

4.3 Data Requirements for Deployment

The effectiveness of the system strongly depends on the availability and quality of data. Key data requirements include:

- **Real-time process data**: electrical signals, operational parameters, and sensor outputs
- **Historical datasets**; required for training and validation of AI models
- **Event and anomaly records**; necessary for supervised machine learning approaches
- **Visual data (where available)**: camera feeds for safety monitoring and computer vision applications

Data quality must be assessed in terms of completeness, consistency, sampling frequency, reliability.

5. iSteel-Expert Barriers and Mitigation Strategies

The deployment of the iSteel-Expert system across the EU steel sector is subject to a set of technical, organizational, and economic barriers that must be explicitly addressed and that, generally, are not independent. They typically co-exist and reinforce each other, particularly in low digital maturity environment:

- Technical Barriers
  - **Heterogeneity of IT/OT systems**: variability in automation architectures and communication protocols across plants complicates integration.

  - **Sensor and instrumentation limitations:** differences in available measurement technologies can affect system performance.
  - **Scalability constraints**: integration of AI-based models in real-time industrial environments requires careful validation.

- Data and AI Barriers

  - **Limited availability of labelled data**: anomaly detection models depend on rare events, leading to strongly imbalanced datasets.
  - **Data quality issues**: inconsistencies, missing data, and low sampling frequency can affect model reliability.
  - **Model generalization limitations**: AI models trained on a specific plant may require adaptation before deployment elsewhere.

- Organizational Barriers
  - **Resistance to change**: introduction of AI-based decision support systems may face resistance from operators.
  - **Skill gap**: insufficient digital competencies among plant personnel may limit effective adoption.
  - **Knowledge transfer challenges**: existing expertise is often tacit and not formalized.

- Economic Barriers
  - **Initial investment costs**: deployment requires investment in sensors, integration, and infrastructure.
  - **Uncertainty in return on investment (ROI)**: benefits may depend on plant-specific conditions and maturity level.

To overcome the identified barriers and to ensure the successful rollout of the system across diverse steelworks, the following mitigation strategies will be implemented:

Modular deployment approach:
- Modular Architecture: Developing a "hardware-agnostic" software layer and universal middleware (e.g., OPC UA gateways) to bridge the gap between various legacy automation systems.
- Adaptive Sensor Kits: Designing flexible mounting and protection solutions (universal housings) that can be adjusted to different EAF physical layouts and environmental constraints.

Addressing Process and Operational Heterogeneity:
- Self-Learning Algorithms: utilizing machine learning models that can be "fine-tuned" using site-specific historical data, allowing the system to adapt to local operational variations without requiring a full redesign.
- Interoperability Standards: Establishing a "Core Process Logic" that remains constant, while allowing for "Local Parameter Sets" to accommodate site-specific operational variations.

Mitigating Organizational Resistance:

- User-Centric Design: Focusing on intuitive Human-Machine Interfaces (HMI) that clearly demonstrate "immediate value" to the operator.
- Incentivized Training & Gamification: Leveraging the training platform to provide micro-learning modules and certifications, turning digital adoption into a clear path for professional growth.

6. iSteel-Expert System exploitation

The exploitation of iSteel-Expert results aims at ensuring the effective industrial uptake of the developed system, supporting: commercialization of the digital expert system, deployment in industrial EAF environments, replication across multiple sites and industrial contexts extension of the approach to other industrial sectors.

The exploitation strategy is closely connected to the transferability and deployment framework defined in this document, ensuring alignment between technical deployment feasibility and industrial value generation.

6.1 Target Stakeholders and Value Proposition

The targeted stakeholders and the correspondent added values are:

• **Steel producers**: after the project completion, SIDER steel company will be in the position to exploit and extend the system to other plants belonging to PITTINI Group, thanks to the general validity of the approach and the developed guidelines.

• **Technology providers**: TENOVA intends to industrialize and commercialize the iSteel-Expert to batch and continuous EAF processes. It is expected that in the 5 years following the end of the project, iSteel-Expert system approach will be applied at multiple industrial deployments across Europe. Moreover the application of the iSteel-Expert approach can be evaluated for the Minining Division in Tenova.

• **RTOs and spin-off**: SSSA, UNICL, UNIRIO and SIM4 have consolidated their know-how and presence in the scientific and industrial community especially in activities focused on bridging the gap between Research and Innovation in the frame of training and safety. Moreover, there are many possibilities to transpose the iSteel-Expert approach to other industrial sectors by considering the well-being at work at the heart. UNICL, UNIRIO and SIM4 intend to use the experience gained during the project in relation to the game-based training framework in other domains.

• **Process engineers, technicians and operators (workers)**: new competence, knowledge and awareness in process engineering within and beyond the EU.

• **European Commission and policy makers**: will benefit from the industrial scale showcase for the significant efforts in digitalization of the production system, improving working conditions and process reliability, implementing training procedures by achieving benefits in terms of workers' satisfaction and upskilling and increasing higher capability to attract skilled personnel and young talents.

6.2 Exploitation strategy

iSteel-Expert has been successfully implemented and put into practice within a real-world production environment, marking the starting point of its exploitation strategy.

In fact, the opportunity of the system's application in a real-world production environment allows to demonstrate the concepts reported in several theoretical publication or communication. This holds true even though there are certain unfavorable conditions during the execution of the project. In primarily discontinuous production due to low market demand, which resulted in a smaller dataset for AI training. This in general slowed down or, in some cases, prevented the full achievement of the target performance in spite of full functionality of the system.

Nevertheless, customization efforts have been identified for the deployment of the system across the European steel sector.

First of all, transferring the system to other electric steelworks requires a comprehensive investigation to collect the proper information regarding IT/OT and automation systems, data, indicators, process concepts, performance, and operating instructions.

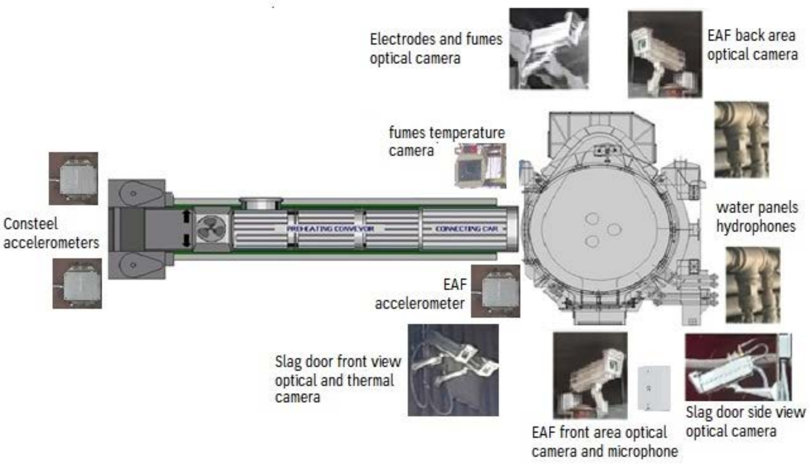
In detail, with reference to the process signals and data that need to be collected in real time for later analysis and integration with the "digital expert system," and, generically, the working environment the system will have to be integrated in, the following areas are to be investigated:

- **Sensors and measurement technologies**: current instrumentation in the EAF shop and its compatibility with the digital system.
- **Historical and real-time data**: existing datasets on process parameters, equipment status, and operational control.
- **IT/OT Connectivity and Communication Protocols**: assessment of existing protocol compatibility to ensure the data exchange required by the system.
- **Data Quality and Sampling Frequency**: accuracy, consistency, and refresh rates of signals to ensure reliable inputs for the expert system.
- **Digital Infrastructure**: requirements for local (Edge) and Cloud-based computing to support analytical models.
- **HMI and User Competency**: digital literacy of local operators and identification of specific training needs.
- **Cybersecurity and Data Governance**: security protocols to protect sensitive process data and definition of data ownership policies.

Instead, relevant for the training platform, the following are to be investigated:

- **Standard Operating Procedures**: currently applied operational instructions and best practices to ensure the training platform is aligned with site-specific procedures.
- **Operator Competency and Skill Gap Analysis**: to tailor the training modules to the specific digital and technical profile of the workforce.

Particularly demanding is the investigation into the housing, installation, and protection of the system's sensor suite. Here below the suite composition for the case of Consteel EAF:



Existing engineering drawings must be analyzed to obtain comprehensive information on the mechanical, electrical, and environmental requirements for installation. Furthermore, the required protection measures must be carefully evaluated based on the criticality of potential cable routing, considering the history of severe events occurred in the area.

6.3 Data collection forms

To ensure that the verification process and information gathering are conducted in a systematic and organized manner, standardized forms will be developed (ANNEX 1). These forms will outline the specific data and information to be collected for each area and aspect under investigation.

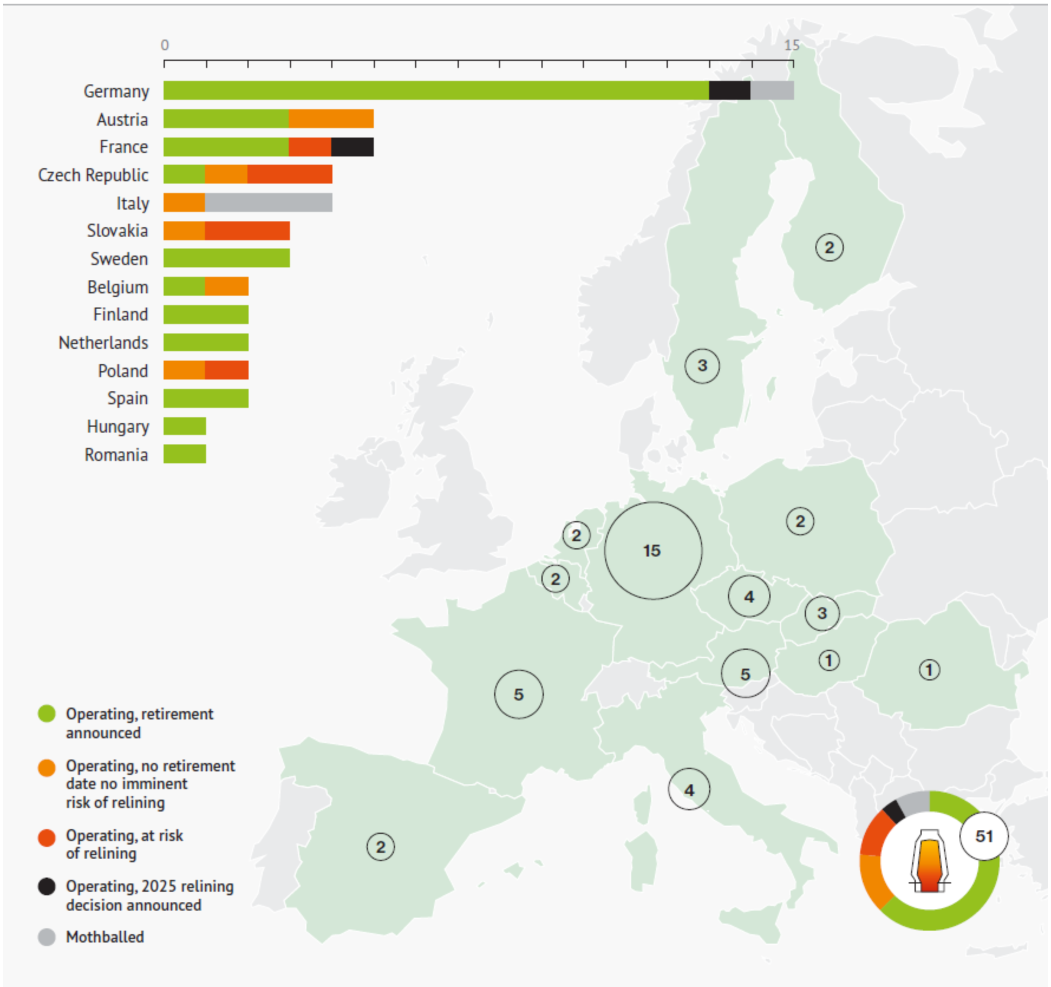
7. iSteel-Expert System as service

TENOVA is also considering leveraging the expert system, or specific modules thereof, to provide remote servicing and support to both existing and new clients. As demonstrated during the COVID-19 pandemic, technology suppliers must be equipped to support their customers even when on-site presence is not possible. iSteel-Expert will enable the delivery of high-level technical support across different geographical locations and time zones.

Furthermore, TENOVA is confident that the system’s training module will represent a breakthrough for the continuous development and certification of the workforce. TENOVA intends to exploit this service to drive continuous improvement and innovation within the steel industry.

8. iSteel-Expert as a facilitator in EU green transition

Published in March 2025 by the climate change think tank E3G, the 'State of the European Steel Transition' report provides a detailed overview of the EU's planned green transition for the next few years.



As shown in the above figure, of the 47 BFs (Blast Furnace) that are currently operating, 32 have announced retirement dates, the time at which the coal-based BF will end production. Of these, 24 are scheduled to retire by 2035, while the remaining 6 are set to run beyond 2035.

Most of this retiring BF capacity is expected to be replaced by Electric Arc Furnace (EAF) steelmaking. As EAF steelmaking replaces retiring BF capacity, operators currently working the BF-BOF route (Blast Furnace-Bottom Oxygen Furnace) will need to be upskilled and transitioned into EAF-based production staff. In this emerging scenario, iSteel-Expert system has the potential to act as transition facilitator. In fact it can accelerate the training and upskilling of new EAF operators by providing immersive simulation and guidance, allowing staff transitioning from BF-BOF routes to gain hands-on experience with EAF technology more efficiently.

At the same time, it also provides 24/7 virtual expert assistance during operations. This support helps maintain operational stability during the critical ramp-up phases of new green steel projects, reducing the risk of errors and downtime, while ensuring continuous guidance for sustained high performance

9. Conclusions and Recommendations

The iSteel-Expert project demonstrates that AI-driven, human-centric solutions can be effectively deployed in Electric Arc Furnace (EAF) steelmaking to enhance operational awareness, decision-making, and knowledge transfer. The results show that **transferability is feasible**, thanks to modular architecture and adaptable AI models. However, **deployment effort and achievable benefits are strongly dependent on plant characteristics**, in particular: digital maturity, data availability and quality, integration complexity, workforce readiness.

Main recommendations for Industrial Deployment are:

- Adopt a phased deployment approach (pilot → scale-up)
- Prioritize data readiness and data quality
- Address IT/OT integration early
- Deploy modular solutions starting from high-value use cases
- Invest in training and workforce upskilling
- Use high-maturity plants as early deployment cases

Main recommendations for Policy Makers and EU Stakeholders are:

- Support digitalisation and data infrastructure investments;
- Promote workforce reskilling and transition to EAF technologies;
- Encourage standardisation and interoperability frameworks;
- Strengthen links between R&D projects and industrial deployment.

ANNEX 1 Data collection forms

Sensor Suite Installation

1. Area & Location Details

- Sub-area: (e.g., EAF Shell, Off-gas duct, Transformer room)
- Reference Drawings: (List of mechanical/electrical drawings analyzed)
- Physical Constraints: (Space availability, accessibility for maintenance)

2. Environmental & Operational Conditions

- Operating Temperature (Avg/Peak): [ ] °C
- Dust/Fumes Level: [ ] Low [ ] Medium [ ] High
- Vibrations/Mechanical Stress: [ ] Critical [ ] Managed
- History of Severe Events: (Note any previous meltdowns, breakouts, or cable fires in this specific area)

3. Electrical & Mechanical Requirements

- Power Supply Availability: (e.g., 230V AC, 24V DC)
- Cable Routing Path: (Length, protection needed, proximity to high-heat sources)
- Signal Interference (EMI): (Proximity to high-voltage cables/transformers)

4. IT/OT Connectivity

- Current Signal Protocol: (e.g., Profibus, Ethernet)
- Interface Point: (Local Junction Box ID / PLC Rack)
- Sampling Frequency Required: [ ] Hz / [ ] ms

5. Safety & Protection Measures

- Required Housing/Shielding: (e.g., Water-cooled jacket, Heat shields)
- ATEX/Hazardous Zone: [ ] Yes [ ] No

Training Platform & Workforce Competency

1. Operational Standards

- Process Area: (e.g., EAF Melting, Slag Foaming, Refining, Ladle Treatment)
- Current Instruction IDs: (List official manuals or best practice documents)
- Process Deviations: (Are there informal practices not in the manuals?) [ ] Yes [ ] No
- Safety Protocols: (Key safety steps that must be integrated into the training modules)

2. Workforce Profile (Skill Gap Analysis)

- Target Group: [ ] Operators [ ] Shift Supervisors [ ] Maintenance Techs
- Average Digital Literacy: [ ] Basic (Traditional HMI) [ ] Intermediate [ ] Advanced (Data-driven)
- Previous System Experience: (List any digital tools or "expert systems" used in the past)
- Language Requirements: (Local language only or technical English needed?)

3. Training Delivery Requirements

- Shift Scheduling Constraints: (When can operators train? During downtime / dedicated hours?)
- Interactive Needs: [ ] Video Tutorials [ ] Real-time Simulations [ ] Quiz/Assessment

4. Key Performance Indicators (KPIs) for Training

- Target Competency Level: (Define the "passing grade" for system certification)
- Error Rate Reduction Goal: (e.g., -10% manual overrides after training)
- Feedback Mechanism: [ ] Digital Survey [ ] Practical Test [ ] Supervisor Review