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The role of digital technologies in enhancing safety and competitiveness in the steel industry : A review of industry 4.0 applications

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Abstract

The steel sector is a fundamental industry in the global economy, facing challenges in both safety aspects and the need to increase competitiveness in response to growing environmental regulations and global market pressures. This article, based on information provided by various sources, reflects on the multifaceted role of digital technology (including technology related to Industry 4.0) in addressing these challenges. Digital tools result in safer environments. Digital technologies help make workplaces safer by enabling automated monitoring systems, such as Computer Vision, for detecting potential hazards and the use of robotics to keep workers away from dangerous situations. Moreover, solutions like AI-powered Predictive Maintenance enhance the reliability of your equipment, which is extremely important for security in high-risk environments and also to enhance operational efficiency. At the same time, digital innovations are important drivers of competitiveness by enabling more energy and resource-efficient production, incentivising decarbonisation, and improving supply chain management. Despite the promise, the implementation of such

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solutions will be contingent on research knowledge gaps regarding the use and application of solutions in practice, as well as the training of the workforce.

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Introduction

The steel industry is one of the key industries driving industrial development in both developed and developing countries. Worldwide, it supports numerous downstream industries, including infrastructure, automotive, energy, and construction sectors. Yet, steel making remains a fundamentally hazardous work environment, characterised by its heavy equipment, high-temperature operations, high energy consumption, and a significant environmental footprint, primarily in the form of carbon emissions. As of 2025, it represents almost 8% of the world's energy demand and generates significant quantities of greenhouse gases; decarbonising it is crucial in achieving global climate targets. Accordingly, the ongoing global trend of steel demand doubling between 2000 and 2025 makes a stronger case for the urgent need to move forward to a Circular Economy, fostering our practices in reuse and recycling.

The steel industry in India is an engine of economic growth and a trigger of environmental stress. As the world's third-largest producer of steel, India's steel industry accounts for ~25% of India's industrial energy consumption and 6.2% of its CO2 emissions. In addition to these environmental issues, Indian steelmakers are under increasing pressure to compete globally as production costs rise and regulations change. The volatile and dynamic steelmaking setting in India requires a strong safety management system, which must be more than just a legal compliance.

With this background, the steel industry globally, as well as in India, is adopting digitalisation and Industry 4.0 technologies for transformation. These technologies can provide scalable options to improve operational safety, reduce emissions, enhance resource utilisation, and boost economic competitiveness. Applications including AI-enabled predictive maintenance, computer vision for PPE compliance, robotics automation, Big Data analytics, and the Industrial Internet of Things (IIoT) are redefining how safety and efficiency are addressed on the shop floor. This article builds on the existing literature and aims to highlight how digital tools are being implemented, or rather, leveraged, to enhance safety and competitive advantage in the steel industry, both globally and in the Indian context.

Literature Review

With its status as one of the foundations of worldwide industrialisation, the steel industry has been under increasing pressure to be responsible for its economic importance while accounting for its significant environmental impact. In 2020, the industry was responsible for approximately 7–9% of the world's CO2 emissions and accounted for nearly 8% of global final energy consumption [1]. In this light, it is argued that the academic and policy debate has expanded to include innovation strategies that incorporate sustainability, specifically the Circular Economy (CE), Predictive Maintenance (PdM), and Green Technological Innovation.

Circular Economy and Steel Reuse in Construction

The shift towards a Circular Economy (CE) has become increasingly popular in the Architecture, Engineering, and Construction (AEC) sector, due to its reliance on finite resources and its significant contribution to the world's waste stream. Construction and demolition works are responsible for 40–50% of raw materials use and generate 600 to 700 million tonnes of waste annually [2]. Steel has excellent durability and mechanical strength, good reusability with slight quality degradation, and is thus a promising candidate for CE.

Stakeholders have been considered in a few studies for the reuse of steel in construction. From the stake holders interview it is found that, despite acknowledging the environmentally friendly characteristics and cost savings, there remain issues with certification, traceability, and compatibility with current design standards [3]. It had also strongly recommended that optimal protocols and supportive policy infrastructures be in place to mitigate these impediments [4]. Moreover, it is emphasised the importance of supply chain cooperation and information exchange in realising the large-scale recirculation of materials [5]. These results raise a dual requirement: to develop technical tools that facilitate the assessment of materials and to develop governance tools for quality control and liability management.

Operational Efficiency and Predictive Maintenance

Meanwhile, as Artificial Intelligence (AI), Industrial Internet of Things (IIoT), and machine learning (ML) continue to advance, so too is the evolution of Predictive Maintenance (PdM), which is transforming the way maintenance is planned in heavy industries. PdM assists in the early identification of faults/dysfunctions, reduction of unplanned downtime, and extension of the valuable life of Capital Assets [6] [7]. This is especially true in an asset-intensive and high-temperature environment such as steel manufacturing.

Mengile & Nikolai reviewed and analysed their studies for the increasing penetration of PdM in steel-making sub-processes, such as sintering, hot rolling, and blast furnace operation [8]. The application of deep learning, including convolutional neural networks and recurrent neural networks, on anomaly detection and life prediction of critical components is promising [9]. Hosni also commented on the emergence of hybrid systems, which combine parametric and non-parametric diagnostic methods [10]. Also, the study proposes a flexible Industry 4.0 security framework that leverages fuzzy logic to enhance anomaly detection, threat mitigation, and incident response against evolving cyber threats [11]. However, despite the benefits, obstacles remain, primarily related to data interoperability, interaction with existing systems, and the generally significant cost of up-front infrastructure investment in sensors.

Energy Optimisation and Prediction

Energy management is also a key area in the sustainable manufacture of steel. Much of the energy intensity in the steel industry is attributed to blast furnaces, basic oxygen furnaces, and coking operations, which vary in energy demand during steelmaking. This variability in energy consumption is highly dependent on location and context, influenced by factors such as the quality of raw materials, furnace efficiency, and logistics.

Narkhede et al. [9] employed simulation-based optimisation for steel ladle logistics to minimise heat losses and idle times, which are the primary sources of energy wastage. Simulations integrated with live effective data have been used to optimise both scheduling and routing. In a similar vein, an article in the IISE Annual Conference,2023 employed linear regression and K-Nearest Neighbours (KNN) clustering to predict the energy use of steel plants [12]. In that analysis, CO_2 emissions had the most significant effects on performance, highlighting the strong connection between energy usage and environmental performance.

It is, therefore, reasonable to assume that the integration of analytics into operations can significantly improve the decision-making process.

However, the performance of these models has much to do with the quality of the historical data, data labelling practices, and model interpretability, all of which are still understudied vestiges.

Environmental Technologies and CO2 Emissions

Decarbonising the steel industry is a linchpin to global climate action. A plethora of technological advancements have been introduced, from Carbon Capture and Storage (CCS) to Hydrogen-based Direct Reduced Iron (DRI) processes. Study by Kumar and Mckensey referenced pilot European projects that substitute hydrogen for coke as a reducing agent, thereby reducing CO_2 emissions in mass [13] [14]. However, adoption is limited due to infrastructure and cost impediments, particularly in the developing world.

Post-combustion carbon capture (PostCCC) has been considered the most practical approach for carbon mitigation, given its retrofit potential in already existing plants. Qiu cited evidence from the Go4ECOPLANET project, which showed industrial-scale deployment and identified key variables, including capture efficiency, solvent degradation, and integration with power generation cycles [15]. Although such projects offer models that can be replicated at a larger scale, their scalability is questionable without policy and financial incentives.

Furthermore, recent policy pull-mechanisms, including the European Union's Green Claims Directive and Sustainable Finance Taxonomy, are prompting downstream sectors, particularly the automotive and construction industries, to source green-certified steel [16]. These measures are driving market development, yet to prevent greenwashing and trade distortion, there is a need for alignment across jurisdictions.

Case Studies of India and China

The Indian steel industry, with the employment of over 2.6 million people and accounting for 2% of the country's gross domestic product (GDP), is anticipated to witness growth under the National Steel Policy (2017) with a projected production capacity of 300 MT by 2030–31 [17]. Although the sector has rebounded post-COVID and experienced a 22% increase in its exports, it remains carbon-intensive, accounting for 6.2% of India's CO_2 emissions and 25% of the country's industrial energy [1]. This balance between accelerating economic growth and maintaining sustainability requires a concerted effort to drive technological advancements, facilitated by digital infrastructure, tax incentives, and public-private partnerships.

China, the world's biggest steelmaker, is using production curtailment, efficiency improvements and carbon pricing as levers to shrink its carbon footprint. Li et al. utilise the Long-range Energy Alternatives Planning (LEAP) model to model emissions constructs, and argue that reduced production has the most significant influence [3]. However, Lan, Awolusi, and Cai [18] and Hu et al. [19] stressed that efficiency improvements and carbon pricing are even more cost-effective in the short run. Gu et al. [20] emphasised the need to implement policy packages that combine innovation subsidies with the deepening of the carbon market and financial penalties for non-compliance.

Applications of digitalisation and Industry 4.0

Industry 4.0 technologies are being integrated into the steel industry, changing how supply chains, logistics, and process control are managed. Gajdzik, Wolniak, and Grebski [21] stated that in Poland, 75% of steelmakers recognise automation, smart warehousing and real-time analytics as principal competitiveness levers. Digital twins and AI-based decision support systems are providing more granular visibility into operations, reducing bottlenecks and improving responsiveness.

In China, Yang et al. [22] developed a green technology evaluation index for energy technologies in steel plants based on entropy weighting and grey relational analysis. They found that they were optimal for gas cycle generation, but were inconsistent with other indicators, such as cost, scale, and environmental impact.

The steel industry is also moving towards Industry 4.0, where the convergence of cyber-physical systems, IoT, and data analytics is transforming operational paradigms across the value chain. Digital transformation in this area is considered not only a lever to increase competitiveness but also an enabler to meet sustainability objectives through optimised energy, predictive maintenance, and improved process control.

IoT and IIoT solutions have become a key enabler of collecting real-time data from equipment, assets and manufacturing processes. Sensors in machines enable the monitoring of parameters such as temperature, pressure, vibration, or energy consumption, which is the best way to implement predictive maintenance and some process optimisation. Not least, the IIoT enables machinery to communicate and share data across various operational domains, leading to, for instance, "smart" steel plants that can make adaptive decisions [23].

Gadzik et al. [21] found that approximately 75% of steel manufacturers considered automation, real-time analytics, and IoT-enabled asset tracking technologies to be among the leading tools for enhancing operational flexibility in the European context. These technologies support supply chain visibility, shorten lead times, and can be environmentally friendly by minimising waste of resources. Likewise, in steel production in China, the implementation of the IIoT has allowed advanced process control, fault diagnosis and energy management, where sensors provide real-time data to a centralised control room [24].

Big Data analytics serves as the analytical engine of Industry 4.0, facilitating the processing of vast and rapidly generated datasets (from steel plant processes) across steel operations. The application of ML and AI on these datasets has been found to improve forecasting, anomaly detection and quality control. Iriakuma, Ukela, and Ajuru [25] for example, used AI-enabled load forecasting in steel plants and found that electricity cost and energy consumption were significantly reduced. At the same time, digital twins, virtual simulations of physical assets, are helping to simulate and optimise operations of plants in real-time based on Big Data inputs.

Leveraging IIoT and Big Data, digital twin models will provide a dynamic, advanced model of the entire production line, enabling proactive actions to optimise throughput and energy usage. These models can consider not only operational data but also contextual information on supply chains and market dynamics, allowing for more holistic decision-making [26].

AI and computer vision applications have also helped keep workers safe. Lan et al. utilised the YOLOv9c algorithm for hard hat detection in construction and industrial settings, achieving high accuracy rates, which demonstrates how AI-enabled visual systems can contribute to enhancing occupational safety in heavy industries [27].

There are, however, several unresolved issues. The realisation of IoT and Big Data also requires solid data governance, communication protocols that comply with standards, and cyber resilience in an era when industrial control systems are increasingly fragile. Additionally, the legacy machinery from previous steel plants poses integration challenges, necessitating considerable retrofitting and reskilling of personnel to fully leverage digital technologies [20].

However, the overlapping points of IoT, IIoT, Big Data, AI, and digital twinning within the framework of Industry 4.0 also provide a remarkable opportunity for the steel sector. When combined with sustainability and decarbonisation objectives, digitalisation has the potential to reduce the energy intensity of steelmaking by multiples, by enhancing process efficiency and making SCF counterfactual across the steel value chain.

There have also been more advanced AI applications in the field of worker safety. Lan et al. utilised YOLOv9c for hard hat detection in construction, achieving good recognition performance, while also highlighting limitations, such as an unbalanced dataset and application-specific issues [18]. On the energy side, Wang et al. indicated that AI load forecast-based scheduling could potentially save electricity costs in both the steel plant (23-24%) and the grid (18-19%), leading to energy and financial savings [28].

Lack of available scrap steel and stresses in the supply chain are expected to boost demand for electric arc furnaces. The world's move to Electric Arc Furnaces (EAFs), which produce electric steel powered by renewable electricity, offers one of the most significant decarbonisation opportunities for the steel industry [29]. EAFs consume between 10% and 20% of the energy required by a blast furnace and can be used to process scrap steel in addition to smelting ore. However, Watari & McLellan warned that demand is expected to double by 2050 based on current trends, thus leading to an estimated 30% supply gap by 2050 if the same trend continues [30]. Therefore, demand must be moderated, and scrap collection systems need to be improved.

Such material transitions will require more than technological readiness; they will also depend on circular business models and international collaboration to ensure equal access to resources, particularly for developing economies that lack strong recycling capabilities. At the same time, study examines the impact of Industry 4.0 on the human workforce through a systematic literature review, with a focus on understanding key concepts and addressing the challenges faced by employees in this evolving industrial era [31].

Integration and Its Policy, Organisational and Future Fit

Foggia and Beccarello [30] noted that the organisation's strategy influences the paths of each reduction. Their modelling found that companies with high-carbon baselines and little ambition would not even be likely to meet modest reduction targets. In contrast, companies that embedded their decarbonisation targets within national and global policy frameworks enjoyed a significantly higher likelihood of success [32] [33].

Country-specific studies, which focuses on Libya, have shown that the transition from heavy oil to natural gas in steel plants could lower CO2 emissions by 25%, reiterating the importance of localised fuel-switching mechanisms [34]. In China, Qiao & Wang observed a very low level of coordination between the Chinese steel industry and the government and thus recommended increasing alignment between the Chinese government and the steel industry by defining clear dual-carbon reduction strategies, enhancing the relationship with academia, and incentivising a focus on developing new technologies [34] [35].

Methodology

The present work draws upon a meta-synthesis qualitative research approach to investigate the impact of digital and green technologies on sustainability and competitiveness from the perspective of the global steel industry. The literature review is based on scientific research articles, government policy papers, industry reports, and conference papers published between 2017 and 2024. In total, 60 papers were identified from academic databases, including Scopus, Web of Science, and Google Scholar, based on the following keywords: metal Industry, Industry 4.0, predictive maintenance, circular economy, carbon capture, and green steel.

The selected literature was analysed by theme according to subjects: (1) Circular Economy and Reuse, (2) Predictive Maintenance and Operational Efficiency, (3) Energy Forecasting and Optimisation, (4) Green Technologies and Emissions Reduction and (5) Industry 4.0 and Competitiveness. Quantitative case studies were analysed in terms of criteria and modelling employing regression, clustering, simulation, and entropy-based techniques where applicable.

Second, stakeholder perspectives were included through secondary sources, which were recorded from interviews based on relevant studies. These were used to situate the technical results within practical industry considerations, particularly in terms of viability, policy rollout, and market issues.

The review encompasses global steel production, and case-wise comparisons are made with leading steel-producing countries, including India, China, and the European Union. The research, therefore, provides a cross-regional study of the changing technological, regulatory, and economic environments that influence sustainable steel production.

Results

A literature review and case study analysis have shown a twofold impact of digitalisation in the steel examples considered: safety and competitiveness. Key findings are synthesised within these two sections:

Safety-Oriented Digital Technologies

Computer Vision (CV): AGI models, such as YOLOv5m, YOLOv8m, and YOLOv9c, have demonstrated high accuracy in safety-critical functions (e.g., hard hat detection). These provide real-time, objective monitoring of safety, whose utility can be supplemental to, or in some instances, a substitute for, manual oversight. Further research is needed to apply these approaches more broadly across various safety situations.

Robots: The roboticisation of a high-hazard activity, such as slide gate maintenance, demonstrates how robotics can be utilised as an engineering control to isolate workers from hazards. This enhances safety and alleviates shortages in the most hazardous job categories.

AI-enabled Predictive Maintenance (PdM): Although initially deployed with a focus on optimising production, PdM indirectly improves safety by minimising the risk of equipment failure in hazardous environments such as blast furnaces and hot rolling mills. This safety benefit is a primary spin-off of improved operating reliability.

Digital Applications for Competitiveness:

Adoption of Industry 4.0: There is a growing realisation that digital technologies, specifically IIoT, Big Data, AI, mobile systems, and automation, will be pivotal for the steel industry to stay relevant moving forward. They allow transitions from conventional to intelligent operations…they are the "evolution" in process control and possibly a "revolution" in business models and customer value creation.

AI and Big Data: These are widely used, including for example to maximise the realisation of production parameters, quality monitoring, defect detection, and production scheduling. They decrease the variance and increase the precision, leading to improvements in yield, throughput, and, consequently, the cost of ownership.

Automation & Robotics: Implemented systems increase accuracy and uniformity, in turn, significantly increasing quality and yield while minimising dependence on manual labour. Automated warehouses and Wi-Fi-enabled logistics systems enhance inventory management and speed up turnaround times.

Decarbonisation Enablers: Digital will be a driving force behind low-carbon manufacturing. Green strategies, such as increased scrap recycling and short process smelting, are enhanced with real-time monitoring, energy analytics, and material tracking. These result in lower carbon intensity and better utilisation of resources.

Digital SCM: Computer systems, mobile apps, and blockchain integrated to improve logistics, transparency and traceability. These solutions enhance just-in-time manufacturing, aid in warehouse management, and enable end-to-end visibility across complex and extensive global supply chains.

The evolving "twin transition" digitalisation, together with low-carbon sustainability, has also become a decisive factor in competitiveness for the European steel industry. Digitalise to accomplish more. Companies that embrace digital applications to advance circular economy objectives will be able to comply with regulatory requirements and market standards more easily.

The workforce readiness stands out as an enabling factor. The success of these digital actions relies on preparing our labour force in technical and soft (transversal) competencies, and on strategic investment in human capital as a complement to investment in technology.

Discussion

This apprehension reveals that the digitalisation of the steel industry is no longer confined to operational upgrades alone, but has become critical to the safety, sustainability, and long-term viability of the industry. The combination of AI, IIoT, Big Data, and robotics is delivering tangible results across safety and business performance measures.

Safety improvements are especially remarkable in high-risk operating environments. Computer vision, robotics, and predictive maintenance are redefining the way safety is observed and managed. These are proactive safety programs, rather than reactive, which lower human exposure to danger and enhance safety compliance. The knowledge base on this topic is, however, still developing, especially for CV applications and deserves further elaboration and standardisation.

Meanwhile, digital technologies are redefining competitiveness in several ways. The enablers of Industry 4.0 are enhancing operational capability, cost effectiveness, and product quality, a critical factor for global success in a highly cost-sensitive industry. This results in less variability through automated processes, as well as improved data-driven predictive production planning and a reduction in defects through the use of AI and data analytics. These benefits are significant as the sector faces increasing environmental regulations and growing demand for low-carbon materials.

Crucially, the potential for decarbonisation through digital technology is increasing. They provide a decision-making tool to maximise the use of back-fractions, minimise energy intensity and maximise resource recovery. In this sense, digitalisation not only serves as a tool for internal optimisation but can also be a driver for sectoral sustainability transitions.

Legacy systems, security concerns, and a lack of skills hinder the adoption of these technologies. Without that alignment between technology investment and the reskilling and upskilling of the workforce, digital transformation will fail to meet its potential.

The reviewed literature overall reveals that digital technologies are increasingly underpinning the steel sector in its quest to improve safety and long-term business competitiveness. The evolution of the sector, driven by Industry 4.0 concepts, is based on the use of tools such as computer vision (CV), robotics, artificial intelligence (AI), Big Data, automation, and Industrial Internet of Things (IIoT). These solutions enable not just operational efficiency but also tackle important challenges such as workplace safety, environmental compliance, and supply chain efficiency.

Digitally Enabled Safety Improvement

The transfer from the subjective, human-dependent safety analysis to objective, automated systems is one of the most encouraging developments. Computer vision systems, such as those employing models like YOLOv5m and YOLOv9c, provide highly accurate real-time monitoring of PPE compliance and other safety-related behaviours. This automation is particularly relevant in the inherently hazardous conditions of steel-making, where even the slightest oversight can lead to catastrophic accidents.

Robotic systems for high-risk maintenance activities represent a shift in focus away from administrative and PPE control towards engineering controls, which physically remove workers from hazardous environments. These robotic applications enhance both safety and operational consistency.

Additionally, AI-based Predictive Maintenance (PdM), even when used primarily to enhance asset performance and reduce machine downtime, contributes to safety by decreasing the risk of machinery-related accidents. Such preventive capability minimises unscheduled failures in key systems (for example, blast furnaces or hot rolling mills), reducing risk exposure.

However, there is a considerable lack of research focused on the use of computer vision for safety management. This is an area ripe for continued exploration, especially in meshing CV with larger factory safety analytics systems or pairing CV with wearables and IIoT devices to deliver on holistic risk analysis strategies.

Advantages of Competitiveness Due to the Integration of Industry 4.0

In terms of competitiveness, applying Industry 4.0 technologies is considered advantageous and indispensable for the future of the steel industry. These are digital instruments that have a wide range of potential applications, from optimisation of processes to strategic projects. Big data analytics and AI enable more intelligent decision-making through the exposure of inefficiencies, prediction of process outcomes, and optimisation of production parameters. Automation and robotics increase throughput, decrease variance, and enhance product quality through accuracy and uniformity.

Digitalisation is also a key enabler for environmental sustainability, which is now an essential element of industrial competitiveness. Sensors for controlling energy consumption, emissions, and circular material technologies (utilising more scrap) are being increasingly employed in production. Digital techniques, such as sensor-based monitoring and real-time analytics, help work toward decarbonisation goals by identifying energy savings and reducing the carbon intensity of a process.

It is also evident that digital technologies are being utilised in logistics and supply chain management through mobile apps, blockchain, and robotics-enhanced warehouse automation, which enhance traceability, minimise delays, and reduce inventory oversight. These enhancements result in higher service levels and leaner operations, key elements to making money in a competitive world market.

However, the literature also emphasises a "lack of comprehensive, quantitative assessments of business value" due to advanced digital technologies themselves, and AI for predictive maintenance appears to be no exception. This implies that although the anticipated return on these technologies is high, the actual ROI has yet to be well-documented, indicating a need for longitudinal studies and standard metrics.

The twin transition and the human factor

A dominant integrative thread throughout all of the findings is the steel industry's fit with the European "twin transition" aiming for concurrent digitalisation and decarbonisation. Digital technologies are not only enablers of internal processes but also strategic levers for achieving the environmental performance required by current regulations and market demands. So, both sustainability and digital transformation are intertwined rather than divergent paths.

And then one has the human element as a vital driver of success. The challenges faced in implementing and supporting smart digital systems require a workforce that is not only digitally literate but also capable of working across multiple technical domains. The digital-enabled steel industry transition requires significant investment in reskilling and upskilling the labour force. Multidisciplinary teams, with knowledge in data science, integration and CPS, are necessary to capitalise on the use of these technologies and the sustainable implementation.

Conclusion

The digitalisation of the steel industry, led by industry 4.0 technologies such as IoT, IIoT, Big Data, AI, robotics and computer vision, is helping to drive tangible progress in both worker safety and organisational performance. These technologies provide twofold value by reducing hazardous operating conditions and increasing process efficiency, cost economics, product quality, and environmental compatibility.

From optional to essential, digital becomes a competitive differentiator. Today's Edelman Trust Barometer already shows that 77% of companies must digitalise to remain globally competitive, achieve low-carbon operations, and implement intelligent automation. The successful future steel company will be one that successfully balances these twin transitions, riding the digitalised change, to create sustainability combined with productivity.

However, making this vision a reality will require addressing integration issues, workforce shortages, and the cybersecurity implications of hyper-connected networks. Future research and policy should further focus on scaling up the deployment of digital safety tools, stimulating interdisciplinary innovation, and building an ecosystem that enables sustainable digital growth in the heavy industry sector.

Disclosure and Conflict of Interest

It is to confirm that there is no financial or other substantive conflict of interest that might be construed to influence the results or interpretation of their manuscript.

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