

Construction of environmental performance evaluation system for iron and steel enterprises under digital background

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Abstract. Against the backdrop of global climate warming and China's "dual carbon" goals, the steel industry, as a representative of high energy consumption and high emissions, has drawn widespread attention regarding its environmental performance. This paper takes steel enterprises as the research subject, analyzes the connotation of digital-green coordinated development, and constructs an environmental performance evaluation system for steel enterprises in the digital context by integrating policy requirements for the metallurgical industry outlined in the Implementation Guidelines for Digital-Green Coordinated Transformation Development. The paper briefly introduces data processing methods for evaluation indicators and subsequent scoring calculation approaches, providing concrete ideas on how to incorporate digital indicators into the environmental performance evaluation of steel enterprises.

Keywords: digitalization, steel enterprises, environmental performance, double transformation coordination.

1. Introduction

In September 2020, China clearly proposed the strategic goals of "carbon peaking and carbon neutrality". Subsequently, the 14th Five-Year Plan released in 2021 emphasized the importance of coordinated development between digitalization and green transformation, advocating that digitalization should lead the green process while green transformation drives digital development. The Implementation Guidelines for Digital-Green Synergistic Transformation, organized and compiled by ten departments including the Cyberspace Administration of China, National Development and Reform Commission, and Ministry of Industry and Information Technology over eight months in 2024, explicitly requires promoting deep integration of digitalization and green transformation. The steel industry exhibits characteristics of "high pollution, high energy consumption, and high emissions", accounting for 15% of China's total energy consumption, and its carbon emission intensity directly impacts the national emission reduction process. Therefore, this paper addresses the issue of neglecting digital-related indicators in current environmental performance evaluations of steel enterprises, aiming to establish a more comprehensive environmental performance evaluation system for steel enterprises to ensure that environmental performance assessments fully reflect their environmental protection measures and performance levels.

2. theoretical analysis

2.1. Synergy theory

The synergy theory proposed by German physicist Hartung emphasizes that systems form ordered structures through the coordination of their internal subsystems. The digital-green synergy system, being an open system far from equilibrium, contains nonlinear feedback mechanisms that self-organize into ordered states. As subsystems within socio-economic complex systems, digitalization and greening drive the system's evolution from "dual-wheel advancement" to an integrated architecture of "fusion symbiosis". Through element interpenetration, subject collaboration, and unified objectives, this synergy ultimately unleashes a "1+1>2" system efficiency, providing an innovation engine for high-quality development. The connotation of coordinated digital-green

development highlights the bidirectional interaction where digitalization empowers greening and greening drives digitalization. The application of digital technologies not only enhances resource utilization efficiency but also reduces environmental burdens and pollutant emissions for enterprises. Greening development imposes new demands on digital acquisition technologies, network transmission performance, and intelligent applications, thereby driving technological upgrades in digitalization. Cao Yu et al. [1] found that manufacturing digitization has undergone three leaps—evolving from tooling to online, intelligent, and ecological phases—which subsequently facilitated green transformation in manufacturing enterprises. Li Yixuan et al. [2] argue that the high alignment of digitalization and greening goals, deep integration of development elements, and significant overlap in development entities constitute the theoretical logic of dual-advancement synergy. In practice, the practical mechanism of the coordinated development of the two aspects includes three levels: digital empowerment, green traction and system adaptation, which are respectively reflected as the technology-driven green transformation process, the intensive low-carbon technology transformation direction and the symbiotic transformation form of integrated innovation.

The coordinated development of digitalization and green is an inevitable choice to achieve a "win-win" for economy, society and ecological environment protection. The inclusion of digital indicators into the environmental performance evaluation system can more comprehensively evaluate the environmental protection achievements of steel enterprises, and encourage steel enterprises to accelerate the promotion of digital transformation, so as to improve environmental performance.

2.2. The guiding theory of the digital and green coordinated transformation development implementation guide for the metallurgical industry

The "Implementation Guidelines for Digital-Green Synergy Transformation Development" [4], jointly issued by ten departments including the Cyberspace Administration of China, National Development and Reform Commission, and Ministry of Industry and Information Technology on August 24, 2024 (hereinafter referred to as the "Guidelines"), provides systematic and forward-looking theoretical guidance for the metallurgical industry's future development. These guidelines apply to regional governments, relevant departments, industry associations, higher education institutions, research institutes, enterprises, and related sectors. Their core mission is to promote deep integration of digitalization and green transformation, supporting the achievement of the "dual carbon" goals through technological empowerment. This approach drives the upgrading of traditional industries and fosters new productive forces, thereby facilitating comprehensive green transformation across society. The Guidelines conduct an in-depth analysis of how the metallurgical industry can leverage digital technologies to achieve green transformation pathways in production models, significantly enhancing corporate capabilities in digitalization and green development. It offers clear advisory suggestions for the industry's green transition, emphasizing that local governments and relevant departments should clarify implementation paths for dual-carbon synergy in the metallurgical sector. By collaborating with industry associations, the Guidelines advocate strengthening digital technology integration in production processes, improving environmental governance and energy consumption monitoring, and achieving full-process green transformation across the metallurgical industry. As outlined in Table 1, the Guidelines provide a theoretical foundation for incorporating digital indicators into the environmental performance evaluation system of steel enterprises.

Table 1. The implementation Guide on the use of digital technology to enable green transformation in the metallurgical industry

We will strengthen the integrated application of digital technologies in production processes	Build smart smelting plants	Industry enterprises are encouraged to implement digital and intelligent upgrading of smelting equipment
		We will accelerate the development of complete sets of domestically produced intelligent equipment applications
		Build a factory operation environment with pan-sense and interconnection
	Building a big data analysis platform for metallurgical smelting	Encourage the analysis and optimization of smelting process data
		Explore the establishment of product carbon footprint analysis model
We will improve the level of environmental protection and energy consumption monitoring in metallurgy	We will strengthen digital management of pollutants	Establish an intelligent control platform for environmental protection
		Comprehensive use of the Internet of things, data statistical analysis and other processes
		Improve the level of intelligent control of wastewater treatment
		For enterprises with noise-sensitive buildings around, promote automatic station construction to monitor noise emissions
	We will strengthen energy monitoring in the industry and optimize the energy use structure	Building an energy control system
		Support the use of intelligent energy-saving smelting, heat treatment and other equipment
		Use digital technology to achieve the optimal allocation of clean energy
		Energy in the steel industry with dynamic digital management system
We will promote digital, green and coordinated development across the metallurgical industry chain	Promote the construction of a smart cycle system in the industry	Building a resource recycling system and coupling development among industries
		The construction of intelligent logistics system covers the whole life cycle of the industry
	Explore the innovative application of digital enabling industry carbon emission trading	The national carbon emission trading preparation work is being accelerated to participate in the smelting of steel, copper, lead and zinc
		Improve the automatic collection and analysis of carbon emission data in the metallurgical industry, and improve the information management level of carbon emission data

3. Selection of environmental performance indicators for iron and steel enterprises in the digital context

Building upon the traditional Balanced Scorecard framework, this study introduces a five-dimensional Balanced Scorecard that comprehensively evaluates environmental performance in steel enterprises through financial, stakeholder, internal process, learning and growth, and resource & environmental dimensions. Furthermore, by integrating digital-related indicators into the environmental performance assessment of internal processes, this research addresses the limitations of traditional evaluation systems in incorporating digital metrics.

3.1. Financial dimension indicators

The financial dimension index of environmental performance needs to have both financial attributes and environmental attributes, which can not only reflect the input and effect of environmental protection in iron and steel enterprises, but also reflect the impact of these inputs on the financial status of enterprises.

Environmental protection investment refers to the amount of funds allocated by steel enterprises for environmental conservation within a specific accounting cycle. Generally, higher environmental investment indicates greater corporate commitment to ecological sustainability. The environmental investment cost ratio reflects the proportion of annual environmental protection expenditures in total operational costs. The comprehensive environmental return rate measures the ratio between an enterprise's annual net profit and its environmental protection investments, demonstrating the economic benefits generated by eco-friendly initiatives. The environmental penalty per ton of steel denotes the fine imposed for environmental violations within a fiscal period, with lower penalties reflecting better compliance with regulations and reduced non-compliance incidents. Environmental taxes per ton are levied based on pollutant emissions during production processes. Government environmental subsidies represent monetary or non-monetary assets provided by authorities to enterprises during accounting cycles. The fuel and power cost ratio indicates the proportion of such expenses in operating costs, where lower ratios correspond to reduced energy consumption per product and improved environmental performance.

3.2. Stakeholder dimension indicators

The development of stakeholder-oriented metrics is grounded in stakeholder theory, designed to address the diverse needs of various stakeholders including consumers, partners, regulatory bodies, and the general public. As these stakeholders' focus on corporate environmental performance continues to grow, it becomes imperative to carefully consider their expectations and demands when establishing such metrics.

The customer satisfaction score reflects the recognition and evaluation of steel enterprises' production of green products, other products, environmental protection measures, and their effectiveness. The number of green product categories refers to the total variety of eco-friendly products developed and produced annually by steel enterprises. Environmental information disclosure measures the transparency of environmental protection-related information disclosed through annual reports, social responsibility reports, and Environmental, Social, and Governance reports. The frequency of environmental incidents indicates the number of environmental issues caused by improper management during operations within a specific accounting cycle. Steel sales volume specifically denotes the total quantity of steel products sold within a fiscal period, measured in tons. Market share refers to the proportion of annual revenue from steel enterprises relative to the total annual revenue of the steel market. $\text{Market share} = (\text{Enterprise Revenue} \div \text{Market Size}) \times 100\%$.

3.3. Internal process dimension indicators

In establishing metrics for internal process dimensions, this study analyzes the "Implementation Guidelines" that propose digital-green synergy strategies across three critical operational phases: integration of digital technologies in metallurgical production, environmental governance and energy consumption monitoring, as well as industrial chain digitization and green transformation. Based on these recommendations, corresponding evaluation indicators were identified. When assessing these key processes, the research evaluates the duration of technology/system implementation. While extended application periods demonstrate technical maturity and corporate commitment, this metric alone lacks comprehensiveness. A multi-dimensional approach should consider implementation depth, integration level, intelligent capabilities, and business value. However, obtaining detailed data on technological integration and AI sophistication proves challenging. Ultimately, application duration remains the primary evaluation metric for assessing steel enterprises' operational performance, guided by cost-effectiveness principles.

The number of municipal-level or higher intelligent manufacturing demonstration units refers to the quantity of steel enterprises that have obtained municipal-level or higher certification titles in the field of intelligent manufacturing, including national-level smart demonstration production bases, National 5G factories, provincial-level intelligent manufacturing demonstration factories, provincial-level intelligent demonstration workshops, municipal-level intelligent demonstration factories, and

municipal-level intelligent demonstration workshops. The number of TSP monitoring stations indicates the total number of particulate matter micro-monitoring stations installed by steel enterprises as of the statistical cut-off date. The application duration of industrial internet platforms, ultra-low emission centralized control systems, energy and power management centers, logistics control integration platforms, and carbon emission data management platforms refers to the number of years since these platforms were initially implemented by steel enterprises up to the statistical cut-off date.

3.4. Learning and development dimension indicators

The learning and growth dimension measures evaluate an organization's performance in cultivating environmental awareness, enhancing eco-friendly competencies, and fostering a corporate culture of sustainability. Designed to highlight the pivotal role of human resources in driving environmental performance improvements, this dimension underscores HR's strategic importance in sustainable development initiatives.

The number of environmental protection awards refers to the quantity of honors and awards received by steel enterprises within a specific period. The number of technical transformation projects specifically denotes the number of technological innovation activities implemented by steel enterprises during a particular timeframe. Patent quantity indicates the number of patents obtained by steel enterprises within a given period. The proportion of R&D personnel serves as a key indicator measuring an enterprise's emphasis on investment in environmental technology research and development. A higher proportion of R&D personnel signifies stronger capabilities and potential in environmental technology innovation, enabling continuous technological advancement to provide sustained momentum for green development. The proportion of highly educated talents refers to the percentage of employees with bachelor's degrees or higher among the total workforce in steel enterprises. The R&D expenditure ratio indicates the proportion of funds invested in R&D activities relative to operating revenue during an accounting period. $\text{R\&D expenditure ratio} = (\text{R\&D investment} \div \text{Operating revenue}) \times 100\%$.

3.5. Resource and environmental dimension indicators

When selecting indicators for resource and environmental dimensions, we considered both resource consumption and pollutant emissions. For resource consumption metrics, specific indicators such as energy consumption per unit of output value and water recycling rate were selected. Regarding pollutant emission metrics, key indicators like sulfur dioxide emissions per ton of steel and nitrogen oxide emissions per ton of steel were chosen to quantify environmental impacts.

New water consumption per ton of steel refers to the weight of fresh water consumed per ton of steel product. The water recycling rate further demonstrates a company's water reuse capacity. By improving this ratio, enterprises can significantly reduce reliance on new water resources, lower production costs, and contribute to environmental protection. Operational photovoltaic installed capacity represents the total maximum output power of all solar panels under standard testing conditions in photovoltaic systems, serving as a key indicator of green energy utilization in steel manufacturing. More photovoltaic facilities mean greater clean energy production from solar power, leading to better environmental performance. Energy consumption per unit output measures the energy used per unit of steel produced. Lower energy consumption per unit output indicates higher energy efficiency. Particulate matter emissions per ton of steel quantify total particulate emissions generated per ton of product throughout the entire production process. Sulfur dioxide emissions per ton of steel measure total sulfur dioxide emissions per ton of product across the entire operational cycle. Nitrogen oxide emissions per ton of steel account for total nitrogen oxide emissions per ton of product in the entire production chain.

4. Construction of environmental performance evaluation system for iron and steel enterprises in digital environment

4.1. Construction of environmental performance evaluation system

The environmental performance evaluation system for steel enterprises has been developed across five dimensions: financial, stakeholder, internal processes, learning and growth, and resource environment. The indicator framework comprises 33 metrics, including 20 positive indicators, 9 negative indicators, and 4 moderate indicators. Specific indicators are detailed in Table 2.

Table 2. Environmental performance evaluation system of iron and steel enterprises in the context of digitalization

Target layer	The guidelines layer	Indicator layer	direction
Environmental performance evaluation system for iron and steel enterprises	A. Financial dimension indicators	A1. Environmental protection investment (in billion yuan)	forward
		A2. Environmental investment cost ratio (%)	appropriate
		A3. Comprehensive environmental benefit level (%)	forward
		A4. Environmental fine per ton of steel (yuan)	negative
		A5. Environmental protection tax per ton of steel (yuan)	negative
		A6. Government environmental protection subsidy (10,000 yuan)	forward
		A7. Fuel power cost ratio (%)	negative
	B. Stakeholder dimension indicators	B1. Customer satisfaction (points)	forward
		B2. Number of green product categories (species)	forward
		B3. Environmental information disclosure (word)	forward
		B4. Number of environmental problems (times)	negative
		B5. Steel sales (ton)	forward
		B6. Market share (%)	forward
	C. Internal process dimension indicators	C1. Number of intelligent manufacturing demonstration units above municipal level (number)	forward
		C2. Application duration of industrial Internet platform (years)	forward
		C3. Application duration of ultra-low emission centralized control system (years)	forward
		C4. TSP Number of monitoring stations (units)	forward
		C5. Application duration of energy power control center (years)	forward
		C6. Application duration of logistics control and management integration platform (years)	forward
		C7. Application duration of carbon emission data information management platform (years)	forward
	D. Learning and growth indicators	D1. Environmental honors and awards (items)	forward
		D2. Number of technical transformation projects	forward
		D3. Number of authorized patents	forward
		D4. Number of R& D personnel	appropriate
		D5. The proportion of highly educated talents (%)	appropriate
		D6. R&D investment as a percentage of operating revenue (%)	appropriate
	E. Resource and environmental dimension indicators	E1. New water consumption per ton of steel (ton)	negative
		E2. Water recycling rate (%)	forward
		E3. Installed photovoltaic power generation capacity (MW) put into operation	forward
		E4. Energy consumption per unit output value (kgce)	negative
		E5. Tons of particulate matter emissions per ton of steel (kg)	negative
		E6. Tons of sulfur dioxide emissions per ton of steel (kg)	negative
		E7. Nitrogen oxide emissions per ton of steel (kg)	negative

4.2. Implementation of environmental performance evaluation system

4.2.1. Determination of index weight

First, applying the Analytic Hierarchy Process, we constructed a hierarchical analysis structure model and corresponding pairwise comparison judgment matrices based on the indicator hierarchy classification shown in Table 2. Next, for the weight calculation process of the environmental performance evaluation system developed in this study, we utilized the expert scoring method by selecting executives from evaluated enterprises, industry experts specializing in steel research, and professors in environmental performance evaluation as review experts. Participants were distributed judgment matrix questionnaires for scoring. Subsequently, weights for each indicator were statistically calculated based on questionnaire results, followed by consistency checks.

4.2.2. Standardization of index data

To enable cross-dimensional data comparison, this study employs dimensionless transformation to standardize quantitative indicators. The methodology begins with positive transformation of four moderation indicators using the formula $X_i = \frac{Q_i - K}{Q_{max} - K}$, where K denotes the reference value and Q_i represents the original moderation indicator values. The transformed indicators are then used for subsequent calculations. When applying this evaluation system to longitudinal comparisons of environmental performance across multiple years in steel enterprises, the range variation method is employed for dimensionless processing. The formulas for calculating both positive and inverse indicators under the range transformation method are as follows:

$$\text{The positive quantization value } X_i = \frac{X_i - X_{mix}}{X_{max} - X_{mix}} \quad (1)$$

$$\text{The inverse quantization value } X_i = \frac{X_{max} - X_i}{X_{max} - X_{mix}} \quad (2)$$

Here, i is the year, X_{max} and X_{mix} are respectively the maximum value and minimum value, and 0 is taken when the formula is meaningless.

4.2.3. Score calculation

The environmental performance score of each criterion layer $= \sum Y_i \cdot \text{the weight of the index in that criterion layer}$, where $Y = A, B, C, D, E, i = 1, 2, 3, \dots$

Comprehensive environmental performance score $= \sum \text{environmental performance score of each criterion layer} \cdot \text{weight of each criterion layer}$

By comparing the environmental performance index scores of each criterion layer, the environmental performance scores of each criterion layer and the comprehensive environmental performance index scores, the change of environmental performance of iron and steel enterprises is analyzed.

5. Conclusion

This paper provides some ideas for the construction of environmental performance evaluation system of steel enterprises in the digital background, so as to promote the coordinated development of digital green development while evaluating their own environmental performance and energy saving and emission reduction level.

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