Pathways to improve energy efficiency under carbon emission constraints in iron and steel sector: Using EBM, NCA and QCA approaches

Abstract: Improving environmental performance of energy- and carbon-intensive sectors represented by the iron and steel sector (IS) is of utmost importance to address the challenges of resource depletion and climate change worldwide. This article adopts a global-super-Epsilon-Based Measure (EBM) model with undesirable output for IS energy efficiency estimation, identifies efficiency determinants based on Technology-Organization-Environment (TOE) framework, and analyzes various pathways for efficiency improvement by grouping Necessary Condition Analysis (NCA) and fuzzy-set Qualitative Comparative Analysis (fsQCA). Empirical testing using statistical data of the G20 economies during 2010-2020 demonstrates that: 1) energy efficiency in the IS sector in G20 countries has risen amidst fluctuations, with developed countries performing more efficiently than developing countries; 2) individual factors do not constitute a compulsory condition to achieve high energy efficiency in the IS sector; 3) three different paths to achieve high energy performance are found, that is, technology-structure driven, regulation-economy-technology driven, and regulation-technology-production driven. Heterogenous policy recommendations for efficiency gains in the IS sector of different countries with divergent features are proposed accordingly.

Keywords: iron and steel (IS) sector, energy efficiency, Technology-Organization-Environment (TOE) framework, NCA, fsQCA

1. Introduction

Since the 1990s, governments around the globe have been concerned about climate change caused by the rise in greenhouse gas (GHG) emissions, most notably CO_2 from the burning of fossil fuels (Zhou et al., 2023). With the increasing conflict between the growth of energy demand and the shortage of fossil fuel resources, the transition to a low-carbon paradigm is the only sustainable route. It is undeniable that the iron and steel (IS) sector has been a critical foundation for urbanization and modernization, as well contributing highly to the economy (Chen et al., 2022). Although the world's IS sector has seen intensity improvement in terms of energy conservation and emission reduction, the energy- and carbon-intensive characteristics of the IS sector cannot be overlooked①. The sector currently accounts for about 8 percent of global energy-related CO_2 emissions②, and thus is still facing serious challenges of resource scarcity and emission control regulations. As the global IS demand grows, more efforts are needed to achieve the 2DS target (i.e., Paris 2 °C scenario) by 2050.

Considering that energy efficiency is a crucial way to manage energy security, boost economic advancement, and reduce greenhouse gas (GHG) emissions represented by CO_2 simultaneously, how to enhance IS sector efficiency gains has become a significant challenge to accelerate its low carbon development (Huang et al., 2022; Brodny & Tutak, 2022). Against this background, multiple levels of government have strategically incorporated energy efficiency goals and emission reduction programs into their national and specific sector agendas. However, regional disparities of energy intensity still significantly exist (Wang et al., 2022). In addition, pathways to achieve efficiency improvement and optimization can be quite different for various types of economies (Sharma et al., 2021). Therefore, it is very important to explore a low-carbon and efficient development path for the IS sector that is the most suitable for their national conditions.

Although some studies regarding the low-carbon development of the IS industry have been found using data from China, Germany, Japan or other countries, international comparative studies on the low-carbon development of the IS industry, especially for

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① According to IEA, the direct CO2 intensity of crude steel production has decreased slightly in the past few years, dropped from 1.46 t in 2010 to CO2/ t steel to 1.41 t CO_2/t steel in 2022. (https://www.iea.org/energy-system/industry/steel, accessed 2023-08-16)

② Worldsteel Association. World steel in figures 2020. 2020. https://www.worldsteel.org/en/dam/jcr:f7982217-cfde-4fdc-8ba0-795ed807f513/World%2520Steel%2520in%2520Figures%25202020i.pdf. [Accessed 21 July 2020].

different types of economies, are currently very scarce (Ren et al., 2023; Yu and Tan, 2022). Specifically, in terms of efficiency evaluation, energy efficiency with carbon emission constraints for cross-country analysis is rather limited. In terms of estimation methodology, most studies have failed to incorporate radial and non-radial characteristics of inputs, expected outputs, and unexpected outputs. In terms of influencing factors, regulatory quality and numerical levels are rarely discussed, while a systematic framework for the identification of efficiency determinants is missing. In addition, the synergistic effects of various factors on efficiency improvement have not been given much attention. In other words, the following research questions need to be answered: How to comprehensively evaluate the IS industry's energy efficiency level with carbon emission constraints of different countries? How to identify the key factors that may impact efficiency gains? What is/are the necessary and sufficient conditions to achieve high efficiency performance? And, what pathway(s) could a specific country follow to gain high efficiency performance?

To fill the above-mentioned research gaps, this paper first constructs a hybrid measure (i.e., a global super-EBM with undesirable outputs) for the group 20 (G20) countries - countries with various economic development levels and with great importance in both global economic development and steel production - to analyze energy efficiency under carbon emission constraints in the IS sector. The model can accurately estimate the efficiency level by simultaneously considering the radial/non-radial characteristics of the variables as well as the inter-period comparison and ranking of efficient decision-making units (DMUs). In addition, the technology-organization-environment (TOE) framework is used to identify the determinants for energy efficiency in the IS industry. The necessary condition analysis (NCA) and fuzzy set qualitative comparative analysis (fsQCA) techniques are combined to identify and reveal the possible pathways to achieve high efficiency performance. In accordance, the contributions of this study are threefold: first, a hybrid efficiency model with undeniable output is adjusted to provide a comprehensive technical foundation for cross-country comparison of energy efficiency with emission constraints. Second, a theoretical framework is introduced to identify key aspects of efficiency influencing factors. Last but not least, necessary condition(s) and divergent paths to achieve high efficiency performance are identified for countries under different situations.

The rest of this paper is structured as follows. Section 2 summarizes the existing relevant literature and presents the innovations of this thesis study. Section 3 presents the model, sample and data used. Section 4 conducts the empirical analysis. Section 5 is the discussion, and Section 6 presents the conclusion and proposes countermeasures.

2. Literature review

2.1 Energy efficiency measurement for the IS industry

The evaluation of energy efficiency in the IS sector is usually conducted from two dimensions, that is, single and total factor perspectives. For example, Lin et al. (2011) used energy usage per unit output value as an indicator to reflect the IS sector's energy intensity in China. This method is also used by Wiboonchutikula et al. (2014) and Wang (2022) to reflect the energy intensity of Thailand's and China's IS sectors, respectively. In addition to efficiency estimation using economic indicators, energy consumption to produce one unit of product (i.e., crude steel or pig iron) is also a widely used indicator to reflect energy intensity (Lu et al.,2016; He and Wang, 2020; Sun et al., 2021). As an approach to measure energy economic efficiency, energy intensity has the advantages of intuitiveness, conciseness, and operability. However, this type of measurement method is still limited as it overlooks other important production elements while unable to reflect the substitution relationship between factors (Liu et al., 2020).

On the other hand, total factor analysis based on Data Envelopment Analysis (DEA) approach that deals with multiple input and output variables has been widely used to estimate efficiency level in the current literature. For example, Morfeldt and Silveira (2014) estimated the dynamics of energy efficiency in the European IS sector during 2000-2010 using Malmquist index calculated based on slacks-based model (SBM). The inputs selected were solid fuels, electricity, and other energy resources, while pig iron, crude steel, and finished steel were selected as outputs. Wu and Lin (2022) also used DEA-based Malmquist index to estimate dynamic energy efficiency of China's IS industry, and capital, labor, and energy inputs were selected to produce the industrial economic output in the estimation model. In addition, two stage DEA and the combination of meta-frontier technique and the CCR (Charne, Cooper, and Rhodes) models are also utilized to estimate the total factor energy efficiency of China's IS industry (Wu et al., 2015; Feng et al., 2018).

2.2 Influencing factors of energy efficiency

Influencing factors of efficiency are various, depending on the analytical focuses or perspectives. Some studies focused on economic development or institutional factors when discussing the determinants of the IS sector's energy efficiency. Flues et al. (2015) investigated the energy consumption of steel production in five major EU steel countries (Germany, Italy, France, Spain, and the United Kingdom) by analyzing the proportion of capital stock to GDP, labor costs, and the price of raw materials. The findings suggested that GDP and investment climate exert the biggest influence on intensity reduction in the long run. Zhang and Huang (2017) found that the ownership reform due to changes in the regulatory framework helped to improve energy efficiency in China's IS industry, whereas fast market expansion due to market liberalization and regulation decentralization exerted negative impacts on intensity reduction.

Structural factors such as energy mix, technical structure, and product structure are also studied by researchers. One study by Liu et al. (2012) showed that due to technological differences in China's IS sector, electricity represented only 20% of the energy use of the sector. Decline in energy intensity of Swedish IS production may be attributed to increasing electricity usage, as well as consistent utilization of natural gas and other fuels (Morfeldt and Silveira, 2014). In terms of technical structure, blast furnace/ basic oxygen furnace (BF/BOF) and electric arc furnace (EAF) are two commonly used techniques in IS production. Studies have shown that the higher the share of EAF, the more helpful it is to decrease CO_2 intensity (Hasanbeigi et al.,2014; Rojas-Cardenas et al., 2017). Other efficiency influencing factors such as material or product prices, technology diffusion, innovative capability, waste recycling, and green supply chain construction were also discussed in the literature (Bhadbhade et al., 2019; Talaei et al.,2020; Devlin and Yang, 2022).

2.3 Pathways to improve energy efficiency

Pathways to improve the efficiency of the IS sector are usually discussed based on literature review, statistical estimation, or regression analysis. For example, Hasanbeigi et al. (2014), by analyzing historical data, proposed that newer equipment and higher EAF share might be helpful to decrease the energy intensity of the IS sector. Lee (2015) used a questionnaire to explore the driving forces of energy efficiency in the Korean IS sector, and found that cost saving, energy tax and energy price were important factors. Na et al. (2019) pointed out that energy efficiency can be enhanced by adjusting the energy and product structure of enterprises based on a systematic literature review analysis. This article also articulated that improving the level of science and technology and renewing equipment could contribute to the sustainable development of the IS industry. Wang et al. (2022) emphasized that global cooperation between different countries along the entire steel supply chain needs to be encouraged to facilitate the efficiency gains of the global steel sector, based on carbon and energy intensity statistics for major countries.

Regression approaches were employed to explain the impacts of different factors on efficiency gains from a quantitative perspective to reveal pathways to achieve high efficiency performance. For example, Flues et al. (2015) analyzed the pathways to achieve high energy efficiency performance of the IS sector in five countries using the generalized least squares method, and concluded that GDP and investment climate exert the biggest influence in the long run. Based on the results of truncated regression, Haider and Mishra (2021) argued that technology should be transferred from the best energy efficient firms of advanced countries to undeveloped economies' firms to narrow the efficiency gap. Wu and Lin (2022) utilized the TOBIT model to estimate the relationship between environmental regulations and energy-environmental performance of China's IS sector, and suggested that reasonable and diversified environmental regulations as well as innovative system construction should be promoted to gain high efficiency performance.

2.4 Review and contributions of this study

First, it can be seen that energy efficiency evaluation for the IS sector has gradually transited from single factor to total factor analysis. However, the current research mainly depends on either radial or non-radial techniques of DEA. Such methods have certain limitations that may lead to biased estimation (Wang et al., 2023). In addition, the single-stage DEA model used in the existing research uses different sets of technologies, which may bring about non-comparability of the efficiency values of DMUs in different periods. Therefore, this study uses the global-super-EBM model, taking unexpected output into account to eliminate the defects of the above models and enhance the comparability of the results.

Second, in terms of factors affecting the IS sector's energy efficiency, the selection of influencing factors is relatively random and little research has provided a theoretical framework for determinant identification. In addition, the discussion on the quality of regulation and the role of digitalization is rarely mentioned in previous studies. According to the theory of industrial competition, technology, policy, market, and economic environment are four important external factors affecting the competitive advantage of a sector (Peng et al., 2022). Therefore, this article first employs the TOE framework to discuss the key components of the IS sector's energy efficiency in several countries from the aspects of technical, organizational (i.e., policy), and environmental (i.e., market and economic) factors to solve the problems of disorder and dispersion in factor selection.

Third, prior studies mostly used regression methods to analyze the net effect of specific factors without considering the possibility of interaction of each antecedent variable. In other words, the coupling effect of the interdependence of influencing factors on the entire system has not been taken into consideration. In addition, endogenous problems among the variables often lead to spurious regressions (Wu et al., 2019). Therefore, this article utilizes the perspective of set theory to determine which conditions (configurations) are adequate or necessary for the outcome (configurations) to provide a new angle and implications for policy and decision making in the IS sector.

Finally, the current international comparison has relatively low coverage in samples of the global IS producing countries as they are mainly concentrated on geographical agglomeration (i.e., the European major steel producers) or individual countries with large IS production (i.e., China and the U.S.) (Lopze et al., 2023). In other words, international efficiency comparative analysis of the IS industry covering countries with different development levels is rather limited. Therefore, this article selects the G20 countries which are major IS producers, with various backgrounds, as the research sample for analysis. In so doing, efficiency gaps between industrialized and emerging countries as well as pathways to achieve high efficiency performance for countries with different backgrounds and characteristics will be revealed accordingly.

3. Model and data

3.1 Model construction

(1) global-super-EBM with undesirable output

In measuring energy efficiency, prior studies have used radial DEA models represented by CCR models or non-radial DEA models represented by SBM models. However, radial models usually overestimate the actual efficiency while non-radial models tend to underestimate the actual efficiency due to the neglect of non-zero inputs and output relaxation, leading to bias in efficiency assessment (Wang et al., 2020). The EBM model is a hybrid distance function combining the characteristics of radial and non-radial techniques that can effectively address the inherent shortcomings of the above two models and provide a new solution for energy efficiency measurement. In addition, previous studies usually consider that the production frontiers constructed in each period are independent of each other when measuring energy efficiency, which makes it impossible to compare the energy efficiency obtained from the study across different periods. Therefore, this study uses a global DEA approach to solve this problem. Moreover, to further rank the efficiency values among the effective decision units, the super-efficiency evaluation technique is also added to the model. In summary, an improved DEA model, i.e., global-super-EBM model with undesirable output is developed and used to evaluate the energy efficiency of the IS industry in G20 countries in order to obtain more accurate evaluation results (Wang et al.,2023).

Specifically, for a given DMUs at time $t(t = 1, \cdots, T)$, each DMU_k $(k = 1, \cdots, n)$ has m inputs $X = (x_1, x_2, \cdots x_n) \in R_+^{m\times n}$, s desirable outputs $Y = (y_1, y_2, \cdots, y_n \in R_+^{s\times n})$, and q undesirable outputs $B = (b_1, b_2, \cdots b_n)R_+^{q\times n}$. The global-super-EBM with undesirable outputs can be expressed as:

$$K^{*}=\min_{\theta,\eta,\lambda,s^{-},s^{+}}\frac{\theta-\varepsilon_{x}\sum_{i=1}^{m}\frac{w_{\mathrm{i}}^{-}s_{i}^{-}}{x_{ik}}}{\eta+\varepsilon_{y}\sum_{r=1}^{s}\frac{w_{r}^{+}s_{r}^{+}}{y_{rk}}+\varepsilon_{b}\sum_{q=1}^{p}\frac{w_{q}^{b-}s_{q}^{b-}}{b_{qk}}}$$

$$\text{s. t.}\ \sum_{t=1}^{T}\sum_{j=1,j\neq \mathrm{k}}^{n}x_{ij}^{t}\lambda_{j}^{t}-s_{i}^{-}=\theta x_{ik},i=1,\cdots,m$$

$$\sum_{t=1}^{T}\sum_{j=1,j\neq \mathrm{k}}^{n}y_{rj}^{t}\lambda_{j}^{t}+s_{r}^{+}=\eta y_{rk},r=1,\cdots,s$$

$$\sum_{i=1}^{T}\sum_{j=1,j\neq \mathrm{k}}^{n}b_{qj}^{i}\lambda_{j}^{i}-s_{q}^{b-}=\eta b_{qk},q=1,\cdots,p$$

$$\lambda\geqslant 0,s_{i}^{-}\geqslant 0,s_{r}^{+}\geqslant 0,s_{q}^{b-}\geqslant 0$$

where $K{*}$is the efficiency score ; x_{ik}, y_{rk}, and b_{qk} are the i-th input, r-th desirable output, and p-th undesirable output, respectively; θ is the planning parameter of the radial part; ε_x , ε_y and ε_b stand for the importance of the non-radial part of desirable inputs, desirable and undesirable outputs, respectively; ε is a core parameter that reflects the importance of non-radial parts whose value is between 0 and 1, if $\varepsilon = 1$, it is equivalent to SBM model; if $\varepsilon = 0$, it is equivalent to the CCR model; w_{i}^{-} , w_i^{+} and w_q^{b-} are the weight of inputs, desirable and undesirable outputs, respectively ; s_i^{-} , s_i^{+} and s_q^{b-} represent the non-zero slack term of inputs, desirable and undesirable outputs, respectively; λ is the linear combination coefficient of DMUs (Tone and Tsutsui, 2010).

(2) Necessary condition analysis model

Necessity and sufficiency both are emerging explanations of causation. A necessary cause is defined as an outcome that does not appear in the absence of an antecedent, while a sufficient cause means that the antecedent (combination) can sufficiently produce the outcome (Dul, 2016). Therefore, this article adopts the NCA approach as a complement to the QCA method, which is superior in sufficiency analysis. QCA can recognize necessary relationships, however, it simply expresses "whether a condition is necessary or unnecessary for a result “in terms of quality. On the contrary, NCA uses variable scores and linear algebra to allow for making in-degree statements of necessity. NCA plots an upper limit line on the top of the data in the XY scatter diagram, with a blank space in the upper left corner indicating that a higher Y value is not achievable for a lower X value. According to Dul (2016) and Torres and Godinho (2022), the effect size d is the percentage of the observed potential area that is above the ceiling line. D is equal to C/S, where C is the size of the ceiling area and S is the size of the potential area for the observed value.

The combination of NCA with QCA has a greater value due to the quantification of the necessary degree of NCA. Therefore, this article uses NCA to check if certain external conditions are required to achieve certain energy efficiency performance, and further utilizes QCA to test the robustness of the outcome of the necessity analysis.

(3) Qualitative comparative analysis approach

As a classic approach in configurations research, QCA uses a set-theoretic perspective to conduct comparative analysis across cases, identifying those divergent pathways which can lead to the same result (Furnari et al., 2021). QCA aims to identify sufficient or necessary subset relationships, combining the strengths of qualitative and quantitative analysis, answering the question of "generalizability" of qualitative analysis in a handful of instances, and making up for the lack of qualitative shift and phenomenological assessment in large samples (Ragin, 2009). Meanwhile, QCA makes use of Boolean algebra, which prevents omitted variable biasness. Hence, control variables are not included in the QCA method, which also excludes the endogeneity problem of traditional regression analysis. Depending on the data type, QCA methods can be further divided into multi-value qualitative comparative analysis (mvQCA), clear set qualitative comparative analysis (csQCA), and fuzzy set qualitative comparative analysis (fsQCA). Since fsQCA has the advantage of dealing with both category and degree problems, it is chosen as the model for energy efficiency influencing factors under the carbon emission constraint in the IS industry in this study (Schneider and Wagemann, 2012).

The process of exploring the pathways for generating high energy efficiency in the IS industry through the fsQCA approach in this study is as follows: first, a calibration process was performed to convert the qualitative conditions to quantitative values between 0.0 and 1.0. The selection of anchor points for the data calibration process was enlightened by earlier studies, including the full non-membership point (5%), the crossover point (50%), and the full membership point (95%) (Fiss, 2011). However, samples scoring 0.5 would be deleted from the truth table analysis. This problem was solved by adding a little constant (0.001) to recalibrate every participation score with 0.5 value (Fiss, 2011). Next, each condition was tested individually to see if it is necessary for the outcome. If the reliability level is above 0.9, then the requirement or set of requirements is "necessary" or "nearly always necessary" (Ding, 2022). In addition, by analyzing the truth table, a sufficiency test can be performed to get the possible configurations.

3.2 Research sample, variables, and data

In this study, G20 countries were selected as the research sample, for several reasons. First, G20 countries represent economies with extensive economic and trade contacts and frequent factor exchanges. Second, the G20 countries represent a diverse spectrum of economies, including both traditionally industrialized nations and growing countries like China and other significant developing nations, which have particular research significance. Third, the overall crude steel production of G20 countries in 2020 accounts for almost 90% of the global share, which has research typicality and practical significance for this study. Considering data availability and sample typicality, Spain was used to replace the EU, while Saudi Arabia and Indonesia were excluded as they had serious data missing.

(1) Inputs and outputs for energy efficiency estimation

For firm-level or region-level energy efficiency level analysis, more employee or economic related indicators are available, whereas cross-nation comparison for IS energy efficiency is quite constrained due to the limits on comparative indicators of the sector. Therefore, two important studies conducted by Morfeldt and Silveira (2014) and Nilsen (2017) are referenced when constructing the input-output analytical framework in this study. Specifically, coke, electricity, and other energy (i.e., natural gas, coal-related energy except coke, and other power carriers) resources are selected as the inputs to reflect the energy usage for iron and steel production. Because coke there is a clear distinction in the types of energy inputs between primary and secondary production of IS, where coke is the primary energy input for the former and electricity is for the latter, the energy input groupings in the model in this study provide a clear energy efficiency boundary that is more representative of the structural division of the sector.

In terms of output variable section, pig iron and crude steel production are both used as proxies for desirable outputs as they are the two main products of primary and secondary production of IS, respectively. In other word, these outputs can reflect the variations of energy inputs required along the process. In the meanwhile, fossil fuel-based energy mix and production process also make the IS sector one of the most carbon-intensive industry globally. Considering that carbon dioxide emissions is the most typical and influencing indicator among all the GHG emissions, it is therefore used as the by-product and the undesirable output for efficiency estimation in this study. Specifically, the CO_2 emission value for the IS industry is calculated using energy consumption data from the International Energy Agency (IEA) and conversion factors from Intergovernmental Panel on Climate Change (IPCC) for various energy sources. The observation period is chosen as 2010-2020, and the description of inputs, outputs and data sources are detailed in Table 1.

Table 1. Inputs and outputs of EBM model

Variable	Description	Sources
desirable outputs		
pig iron	annual pig iron production	Steel Statistical Yearbook of World Steel Association (WSA)
crude steel	annual crude steel production	
undesirable outputs		
CO2	carbon dioxide emissions from the IS production process	calculated by IEA Extended Energy Balances
inputs		
coke	coke use in IS production	IEA Extended Energy Balances
electricity	electricity in IS production	
others	other energy in IS production	

(2) Influencing factor identification

IS production, being an activity influenced by policy orientation, requires an elevated level of relevant organizational capacity and technology. To discuss the influencing factors in a more organized way, this study introduces the TOE framework. The properties of technology itself and other relevant technological variables are highlighted by Technology (*T*); Organization (*O*) emphasizes how the regulators, represented by the government, stimulate or constrain the behavior of the enterprises through the enactment and implementation of regulatory policies; and Environment (*E*) analyzes how resource constraints and economic development have an impact on growth of the sector to develop or hinder it.

Technology (*T*): As information and communication technology (ICT) advance, the digital economy enables firms to upgrade their products, create new value, and improve their allocative efficiency (Koch and Windsperger, 2017). In addition, ICT diffusion supports the dissemination of information, data creation and sharing across space and time, which can reduce unnecessary energy consumption, carbon emissions and enhance energy efficiency (Zhao et al., 2022). Therefore, this study uses the ICT index as one of the proxies of the technology dimension. It is also noted that the ICT indicator is determined by fixed telephone subscription, mobile cellular subscription, internet use, and fixed broadband subscription, and is calculated using principal component analysis (PCA) following the study of Dutta et al. (2019). PCA is a multivariate statistical method that is used to construct composite indexes based on different variables. It simplifies the complexity in high-dimensional data while maximumly containing the information reflected by the original variables, and this approach has been widely used to construct composite indexes including the ICT index in the literature (Khan et al., 2022). In addition, the share of EAF production can also reflect the technical structure of the sector (Hasanbeigi et al., 2014). The energy usage per ton of steel and the type of power carrier varies according to the production technology route. In general, BF/BOF consumes about 2.2-2.6 times more energy than EAF as more chemical energy is required for the conversion of iron ore to iron. Therefore, in this study, the EAF ratio is used as another proxy variable for the technology dimension.

Organization (*O*): The transformation of the IS sector to green development is a dynamic process in which the government "sets the stage" and the enterprises "sing". In fact, it is closely related to government support for enterprises to perform well. Under environmental regulations, enterprises need to invest more in green transformation to comply with government-set green manufacturing requirements, which in turn brings "legitimacy" to the enterprises, and this process stimulates green innovation behavior and promotes the green transformation of the IS sector (Xiao et al., 2022). Hence, this study chooses the regulatory quality (RQ) of the world governance index (WGI) as a proxy variable for the organizational dimension.

Environment (*E*): A significant element of the market environment is the resource constraint, which refers to the resource limitations on the development of the sector (Harris et al., 2019). The IS sector is among the heavy industries with a high dependence on fossil fuels such as coal, thus is facing serious resource constraints. Accordingly, this study uses the share of coal usage in overall energy consumption as one of the proxy variables for the environment. In addition, with the deepening of socio-economic growth and industrialization, the need for IS products and the corresponding demand for low carbon development will both increase. Therefore, the degree of economic development of an economy is closely related to efficiency in IS sector, and this work uses real value of GDP per capita to represent environmental dimension.

The description of outcome and condition indicators of NCA and fsQCA models as well as the data sources are detailed in Table 2.

Table 2. Outcome and conditions of NCA/fsQCA models

Outcome/ conditions	**Description**	**Sources**
outcome		
energy efficiency	energy efficiency score in IS sector of the G20 countries	Calculated from the global-super-EBM model
conditions		
T: ICT	ICT level	World Development Index (WDI) dataset
T: EAF	ratio of EAF steel in IS production	Steel Statistical Yearbook of WSA
O: RQ	regulatory quality	WGI dataset
E: PCE	proportion of coal usage in the energy use of IS sector	calculated by IEA Extended Energy Balances
E: GDP	GDP per capita (in constant PPP)	WDIdataset

4. Empirical tests

4.1 Energy efficiency analysis

Based on the global-super-EBM model with unexpected outcome presented in section 3.1, this study measures the energy efficiency scores under carbon emission constraint using statistical data of G20 countries (see Table 3 for details).

Table 3. Energy efficiency of G20 countries (2010-2020)

No	DMU	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Ave.
1	Argentina	0.676	0.692	0.703	0.706	0.721	0.729	0.706	0.842	0.982	1.068	0.780	0.773
2	Australia	1.027	0.901	0.811	0.851	0.832	0.861	0.931	0.936	0.900	0.916	0.918	0.897
3	Brazil	0.695	0.696	0.657	0.666	0.682	0.670	0.676	0.671	0.669	0.662	0.659	0.673
4	Canada	0.713	0.661	0.691	0.719	0.698	0.686	0.675	0.693	0.663	0.690	0.653	0.685
5	China	0.708	0.701	0.702	0.716	0.695	0.707	0.703	0.706	0.838	0.827	0.949	0.746
6	France	0.794	0.785	0.832	0.805	0.807	0.797	0.758	0.866	0.866	0.885	0.851	0.822
7	Germany	0.989	0.896	1.002	0.984	1.054	0.978	0.968	0.995	0.985	0.995	0.972	0.983
8	India	0.615	0.616	0.614	0.622	0.617	0.630	0.640	0.625	0.599	0.601	0.598	0.616
9	Italy	0.710	0.741	0.741	0.732	0.784	0.771	0.817	0.814	0.791	0.773	0.736	0.764
10	Japan	0.931	0.891	0.904	0.952	0.974	0.944	0.944	0.891	0.907	0.890	0.855	0.916
11	Korea	0.837	0.886	0.904	0.848	0.902	0.835	0.994	0.948	0.873	1.002	0.989	0.909
12	Mexico	0.890	0.929	0.896	0.935	0.965	0.962	0.970	1.005	0.973	0.899	1.013	0.948
13	Russia	0.581	0.579	0.585	0.590	0.588	0.587	0.584	0.587	0.584	0.577	0.580	0.584
14	South Africa	0.790	0.773	0.759	0.776	0.843	0.593	0.591	0.600	0.597	0.596	0.514	0.667
15	Spain	0.878	0.847	0.878	0.807	0.962	1.017	0.872	0.809	0.922	0.863	0.783	0.874
16	Turkey	0.884	0.921	1.001	1.000	1.007	0.994	0.915	0.894	0.895	0.861	0.872	0.930
17	UK	0.878	0.888	0.932	0.998	1.004	0.948	0.920	0.973	1.005	0.983	0.985	0.955
18	US	0.742	0.781	0.863	0.840	0.844	0.800	0.814	0.724	0.719	0.739	0.674	0.774
Developed ave.		0.850	0.828	0.856	0.853	0.886	0.864	0.869	0.865	0.863	0.873	0.842	0.859
Developing ave.		0.730	0.738	0.740	0.751	0.765	0.734	0.723	0.741	0.767	0.761	0.746	0.745
G20 ave.		0.797	0.788	0.804	0.808	0.832	0.806	0.804	0.810	0.820	0.824	0.799	0.808

Table 3 shows that the energy efficiency of the IS sector in the G20 countries has slightly increased by about 0.25% during 2010-2020. In addition, the efficiency performance of industrialized economies is significantly higher than that of emerging countries. The advanced industrialization level of Japan, Korea, Western Europe, and the United States makes them able to support the development of the EAF route due to the accumulation of a certain scrap base (Talaei et al., 2020; Na et al., 2019). Research by Hasanbeigi et al. (2014) and Nielsen (2017) also supports the above conclusion. The development model of the IS sector in these countries has reflected intensive and qualitative growth. In contrast, developing countries have not yet completed industrialization (Zhang et al., 2017). It is also notable/worth mentioning that the low ranking of emerging economies, represented by the BRICS, may be related to their large-scale production of IS and insufficient product structure optimization and adjustment. A conventional BF/BOF route uses blast furnaces to turn iron ore, coke, and limestone into pig iron, which is then transformed into crude steel in alkaline oxygen furnaces. China, Russia, and Brazil produce most of their crude steel based on the BF/BOF process, and China is the world's largest producer of crude steel with 90% of its crude steel produced through the BF/BOF process. India, on the other hand, is lagging in its industrial sector despite the introduction of IS energy efficiency programs. Technical, financial, and regulatory constraints limit companies from investing in energy efficiency programs in emerging nations like India, which can lead to energy inefficiency (Haider and Mishra, 2021).

In order to distinguish the variations in the G20 group's average level of energy efficiency more clearly, this article also analyzes the disparities between the groups (i.e., developed and developing) using the Wilcoxon rank-sum test. The P-value of the annual average level difference test between developed and developing countries rejected the original hypothesis at a significant level of 1% ($P=0.0002<0.01$), indicating that the efficiency gap between developed and developing countries is still remarkable. Fortunately, it is also noteworthy that the gap between the average efficiency of developed and developing groups narrowed from 0.120 to 0.096 during the observation period, demonstrating that the efficiency gap in the IS sector between different groups is slowly narrowing down over the years. Therefore, how to further narrow down the differences across countries needs to be discussed. In other words, finding the most suitable pathways for a given country to achieve high energy efficiency performance will be helpful to facilitate the convergence of efficiency differences worldwide.

4.2 Necessary Condition Analysis

NCA can be used to determine if a particular circumstance is required for a specific outcome. It can also estimate the size of the necessary condition's influence. Ceiling Envelopment (CE) and Ceiling Regression (CR) techniques are both selected to generate functions for robustness purpose, and the results are presented in Table 4③.

The effect size (d) ranges from zero to one, which represents a low level when the effect size is less than 0.1, a medium level when the effect size is between 0.1 and 0.3, and a higher level when the effect size is closer to 1. The necessary conditions to be calculated by the NCA method must satisfy both statements: the effect size should not be less than 0.1, and the Monte Carlo simulation substitution test results of the effect size need to be significant (Dul et al., 2020).

Table 4. Necessary condition analysis Results

Condition	Method	Accuracy	Effect size (d)	P-value
ICT	CR-FDH	77.80%	0.252	0.012
	CE-FDH	100.00%	0.091	0.156
	CR-VRS	77.80%	0.252	0.008
	CE-VRS	100.00%	0.047	0.213
EAF	CR-FDH	83.30%	0.048	0.421
	CE-FDH	100.00%	0.042	0.533
	CR-VRS	83.30%	0.050	0.401
	CE-VRS	100.00%	0.021	0.568
RQ	CR-FDH	88.90%	0.165	0.099
	CE-FDH	100.00%	0.130	0.011
	CR-VRS	88.90%	0.165	0.087
	CE-VRS	100.00%	0.068	0.024
PCE	CR-FDH	88.90%	0.023	0.528
	CE-FDH	100.00%	0.015	0.659

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③ CE is commonly used for discrete data while CR is usually applied to continuous data or when a linear ceiling is assumed. However, the CE-FDH is preferred when a straight ceiling line drawn by CR-FDH does not properly represent the distribution of data around the roofline and reduces the size of the roof area (Dul, 2016).

	CR-VRS	88.90%	0.026	0.521
	CE-VRS	100.00%	0.009	0.674
GDP	CR-FDH	66.70%	0.264	0.003
	CE-FDH	100.00%	0.093	0.034
	CR-VRS	66.70%	0.244	0.004
	CE-VRS	100.00%	0.055	0.040

In Table 4, the effect sizes of ICT and GDP based on CR are greater than 0.1, but the accuracy values are lower than 80%. The effect sizes of EAF and ES under CE and CR are less than 0.1. The effect size of RQ under CE-FDH is larger than 0.1 yet the value is less than 0.1 under CE-VRS. In addition, some studies also suggest a significance level of $p<0.01$ as a standard (Chi et al., 2022; Bu et al., 2023). On this basis, fsQCA is further used to identify the necessary condition, and the result is shown in Table 5.

As can be seen in Table 5, the consistency of individual condition necessity is generally low (i.e., lower than 0.9), indicating that no necessary condition is found to generate high energy efficiency. QCA uses set membership scores and Boolean algebra to make statements of in-kind necessity ("the presence (or absence) of X is necessary for the presence (or absence) of Y"), whereas NCA uses variable scores and linear algebra to allow for making in-degree statements of necessity ("level A of X is necessary for level B of Y") (Tóth et al., 2019). Therefore, no single factor is considered necessary to achieve high energy efficiency performance in this study.

Table 5. Analysis of necessity for high energy efficiency using fsQCA

Condition	**Consistency**	**Coverage**
ICT	0.737	0.801
EAF	0.562	0.610
RQ	0.728	0.805
PCE	0.361	0.436
GDP	0.656	0.764
~ICT	0.512	0.550
~EAF	0.619	0.667
~RQ	0.466	0.492
~PCE	0.869	0.850
~GDP	0.536	0.541

Note: ~ indicates logical non

4.3 Configurations of high energy efficiency

Compared to NCA, fsQCA aims to figure out divergent combinations of conditions required to achieve the same result and can produce different solutions. Compared to complex solutions, parsimonious and intermediate solutions are easier to understand and can reveal required information, thus are mainly analyzed in this study. In the latter solution, both core and secondary conditions are obtained, while the secondary variables aid the core conditions (Fiss, 2011). This study performs an adequacy analysis by utilizing a frequency threshold ≥ 1, a raw consistency ≥ 0.80 and a proportional reduction in inconsistency (PRI) cutoff ≥ 0.60 for proportional reduction. Solution coverage measures the percentage of the result sample covered by all solutions and typically needs to exceed 0.3 (Svensson et al., 2021). Solution consistency indicates the degree of agreement between results and samples and typically needs to exceed 80% (Fiss, 2011). Table 6 reveals the results.

Table 6. Configurations with a high efficiency level

Conditions	**S1**	**S2**	**S3**
ICT	●	●	⊗
EAF	⊗	•	•
RQ	●	●	⊗
PCE		⨂	⨂
GDP	•	⨂	⨂
Consistency	0.932	0.991	0.895
Raw coverage	0.462	0.238	0.351
Unique coverage	0.310	0.010	0.188
Solution coverage	0.737		
Solution consistency	0.910		

Note: (•) shows that the condition variable exists, and (⊗) demonstrates that the condition variable does not exist. ● and ⨂ represents core conditions; and • and ⊗ are edge conditions. Spaces manifest that the results are not affected by the conditional variables.

Based on the literature analysis, it is evident that the presence of ICT, EAF, RQ, and GDP usually have positive impacts on efficiency gains, i.e., the presence of the condition shows that the corresponding values are higher and beneficial to efficiency improvement. On the contrary, the presence of PCE negatively influences efficiency, for example, the presence of the condition specifies that the corresponding values are higher and pose obstacles to efficiency improvement. Under the parsimonious solution, the consistency and coverage of the group analysis in this study are 0.910 and 0.737, respectively. The overall consistency is 0.910, indicating that the three configurations explained 91.0% of the high energy efficiency in the IS industry. This outcome demonstrates that there is a positive subset relationship between the three configurations and high energy efficiency performance. The overall coverage is 0.737, indicating that the research results can cover 73.7% of the cases (Xiong and Sun, 2022).

Meanwhile, the three configurations identified in this study show the impact of the presence or absence of each condition in different configurations on energy efficiency in the IS sector (Xiong and Sun, 2022). Among them, the configuration S1 reflects high ICT and high RQ as core conditions, complemented by non-high EAF and high GDP as marginal conditions; the configuration S2 has high ICT, high RQ, non-high PCE and non-high GDP as core conditions, complemented by high EAF as marginal conditions; the configuration S3 has non-high PCE and non-high GDP as core conditions, complemented by non-high ICT, high EAF and non-high RQ as marginal conditions.

4.4 Pathway Analysis

The above configurations show three pathways to promote energy efficiency with carbon emission constraint.

(1) Regulation, economic and technology-driven pathway

Configuration S1 shows that despite the poor production technology structure of IS companies, high energy efficiency can still be generated under conditions of high socio-economic level, science and technology, and high governmental governance. The representative countries of S1 are Germany and Japan. As developed countries, these two countries have a good accumulation of economic development, a strong level of science and technology and a matching material base, and a high level of economic development. In 2020, the two countries ranked 15 and 23 on the global RQ index, respectively, with better governmental governance and advanced awareness and efficient means for policy formulation in the field of low-carbon environmental protection. Germany is traditionally a typical IS country where the production equipment is relatively outdated and it is hard to achieve low-carbon performance at the level of new plants (Hasanbeigi et al., 2016), which makes Germany lag in the technological and energy structural transformation. In Germany, traditional production lines dominate IS production, with BF/BOF accounting for almost 70% of total production and the rest produced by electric arc furnaces (Koasidis et al., 2020). The share of natural gas use in German EAF plants is lower than it is in Mexico, and the EAF ratio is lower than it is in the United States (Hasanbeigi et al., 2016). In addition, long expected payback periods and technology risks are obstacles for German IS companies to make a proactive transition to energy-efficient technology routes (Haider and Mishram, 2012). Faced with such dilemmas, the German IS industry is actively promoting digital transformation to improve productivity, quality, and flexibility. ThyssenKrupp Steel, a leading German IS company who is working to be climate-neutral, uses big data, artificial intelligence (AI) and internet of things (IoT) technologies to provide customized material and surface solutions as well as optimized processing technologies to ensure greater efficiency and resource-saving production④.

Moreover, the German government has been actively addressing the challenge of climate change, and since the 1990s, Germany has passed a series of laws to achieve its energy transition targets in order to become carbon neutral by 2045. In 2015, Germany signed the Paris Agreement to reduce carbon dioxide emissions and global temperature rise (Hansen et al., 2019). Germany has also set a target in the Kyoto Protocol to reduce greenhouse gas emissions by 40% by 2020, compared to 1990 levels. Under the "energy transition" target, Germany plans to achieve an 80-95% reduction in CO_2 emissions by 2050 compared to 1990. At the same time, Germany aims to increase the share of renewable energy in the final energy source to at least 60% by 2050. In addition, Germany has set targets for reducing primary energy demand for heating and transport. In line with this, Germany's approved coal phase-out law requires all coal and lignite power plants to be closed by 2038 (Hansen et al., 2019). At the same time, the establishment of a circular

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④ https://www.thyssenkrupp.com/en/stories/sustainability-and-climate-protection/the-steel-of-the-future:-digital-and-climate-neutral (accessed: 23-08-18) economy is also one of the goals of the German packaging bill (Abdelshafy and Walther, 2022). As a result, Germany's energy and industrial sectors will also continue to advance far-reaching transformation processes. Countries with a better economic level usually have good infrastructure, abundant human resources, advanced technology, and rich management experience, allowing greater capacity and more opportunities for efficient resource allocation and energy efficiency (Liu et al., 2020). Moreover, Germany plays an important role in the world IS market as it ranked third and fourth globally in terms of import and export of semi-finished and finished steel products in 2020⑤.

Another repetitive country is Japan. With the aim of fostering new industrial and social transformations by ensuring the penetration of scientific and technological achievements into various fields and regions, Japan's *Fifth Science and Technology Basic Plan* demonstrates its efforts to realize the world's first "super smart society" as "Society 5.0." In the IS sector, all major integrated IS manufacturers are applying AI (Artificial Intelligence) technologies in their efforts to solve problems in operations and equipment maintenance, R&D, and production development at the production site (ISIJ, 2022). For example, Nippon Steel, the largest IS manufacture in Japan, identifies ICT and digital technology as a critical element for corporate completeness. Digital transformation is being strongly promoted to make Nippon a digitally advanced company in the IS sector. In order to innovate production and business processes by making full use of data and digital technology, a series of measures have been taken to facilitate the development of digitalization⑥. First, ICT System Planning Departments were integrated to promote digital innovation as advocated in the management strategy. Second, AI (i.e., artificial intelligence) Solution Section was established to expand and improve AI and optimization technologies. Third, AI, IoT and other digital technologies are used to develop smarter manufacturing to optimize achieving advanced stability in production⑦.

At the same time, the Japanese government has advanced awareness and efficient tools for policy development in the field of low-carbon development. In 2017, the *Basic Hydrogen Strategy* was developed by the Japanese government. It outlines a vision for

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⑤ https://worldsteel.org/steel-topics/statistics/annual-production-steel-data/?ind=T_imports_sf_f_total_pub/USA/DEU [accessed 2023-08-19]

⑥ NIPPON STEEL. Promotion of Digital Transformation Strategy, https://www.nipponsteel.com/en/company/dx/ [accessed: 23-08-16]

⑦ NIPPON STEEL. Use of ICT, https://www.nipponsteel.com/en/company/dx/ict.html [accessed: 23-08-16]

Japan's future low-carbon energy society and the role of hydrogen energy in achieving that vision. The strategy acknowledges that Japan's energy system faces two key structural challenges: heavy reliance on imported fossil fuels and geopolitical risks, with the requirement to swiftly cut greenhouse gas emissions representing another barrier. Japan seeks to address these issues by innovating and diversifying its energy system in order to address the fundamental tenets of its strategic energy strategy, including environmental improvement, economic efficiency, energy security, and safety (Nagashima, 2018). In response to the government's call to control emissions, and to achieve carbon neutrality by 2050, in its *Long-Term Strategy Under the Paris Agreement as a Growth Strategy*, Japan has set a goal to cut greenhouse gas emissions by 46% from 2013 levels by fiscal year 2030. It has outlined a long-term growth vision that takes the energy and industrial sectors into account. The Japanese IS sector has also announced that it will accept the challenge of "Zero Carbon Steel" as a separate country for decarbonization, and has already taken various measures (ISIJ, 2022). Thus, although Japan produces about 3/4 of its crude steel through the BF/BOF process, its well-developed governmental regulations exert good supervision for IS producers (He and Wang, 2020).

(2) Regulation, technology, and structure driven pathway

The representative country of S2 is Spain. Despite its relatively uncompetitive economic strength, Spain ranks high in terms of RQ due to its strong government environmental regulations and its participation in relevant EU carbon reduction schemes, including the EU emission trading scheme (ETS). Environmental regulation has a catalytic effect on the improvement of energy efficiency and a constraining effect on the low-carbon development of IS. In addition to this, Spain developed its *Energy Efficiency Strategy 2004-2012*, which included two action plans for the years 2005-2007 and 2008-2012, respectively. The latter was submitted to the National Energy Efficiency Action Plan (NEEAP) of the EU under the Energy Services Directive with a 2% annual improvement in energy efficiency as the main goal. In the period 2011-2020, Spain submitted its second *National Energy Efficiency Action Plan* to the EU, in which the industrial sector is set as the main area to achieve green and low-carbon development (Travezan et al., 2013).

In addition, the Spanish government has introduced a series of policies targeting digital transformation, such as its Spain 2025 plan launched in 2020, which is expected to invest 140 billion euros over five years, all of which will be used to promote the building of digital transformation and drive economic relaunch and recovery. These policies encourage companies to adopt digital technologies and smart manufacturing, providing policy support for digital transformation. The Spanish government is also investing in smart manufacturing and digital transformation research and development, such as supporting digital manufacturing research centers.

Another reason for the high energy efficiency of the Spanish IS industry is the high proportion of electric arc furnace production (Sharma et al., 2021). In recent decades, the Spanish IS industry has been transformed, with electric arc furnaces replacing blast furnaces and converters to a large extent. Compared to other European countries such as Germany, where the BF/BOF production route is widely used, Spain has a favorable geographical location and the ease of shipping makes the transportation of steel scrap, one of the main inputs to the EAF, cheaper. In the case of the Celsa Steel Group, a leading Spanish IS company, sustainability and circular economy are its main development goals. Currently, the group recycles 8 million tons of scrap per year, making it the largest recycler in Spain and the second largest in Europe. Celsa is committed to minimizing the impact of its industrial activities, thus improving energy and environmental efficiency by reducing energy consumption⑧. As a result, Spain has lower constraints in terms of availability and cost of scrap, which has contributed to the high energy efficiency of the Spanish IS industry.

(3) Technology and energy mix-driven pathway

Configuration S3 shows that high energy efficiency can be generated under conditions of high technological structure and low coal dependence, even with insufficient levels of ICT, regulatory quality, or economic development.

The representative country of S3 is Mexico. Mexico is a developing country and belongs to the MINT group (i.e., Mexico, Indonesia, Nigeria, and Turkey). It ranked 84th in the world in terms of GDP per capita in 2020. Among the 18 sample countries studied in this paper, Mexico ranks 14th in terms of ICT level and is a relative laggard in terms of digital economy level. However, Mexico has a low dependence on coal in the IS production process and a technology structure more inclined to EAF. Despite attempts at the

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⑧https://www.celsagroup.com/en/services/recycling/#:~:text=Recycling%20CELSA%20Group%E2%84%A2%2C%20with%20eight%20million%20tons%20of,the%20second%20largest%20ferrous%20scrap%20recycler%20in%20Europe. (Accessed 2023-08-19) governmental level to eradicate poverty, the number of people living in poverty within Mexico has increased. Such uneven and unstable economic development also posts a constraint in the development of ICT within Mexico. In Mexico, about 50% of households do not have access to Internet services, and rural areas are at a clear disadvantage in terms of Internet access (Mora-Rivera and García-Mora, 2021). The geographical, technological, economic, social, and cultural inequalities and heterogeneity that still exist in Mexico act as barriers to the dissemination of the Internet within its borders (Martínez-Domínguez and Fierros-González, 2022).

The high energy efficiency of the Mexican IS industry is mainly driven by the technological structure of it IS production and cleaner energy consumption, in the context of both economic and digital development disadvantages. In the IS production process, Mexico uses EAF to produce a large proportion of IS, a proportion even higher than Germany’s, and the intensity of CO2 emissions from electric furnace steel is lower than the BF/BOF route, which means that when producing of the same amount of IS, Mexico's EAF route can produce less CO2 by reducing undesired output to improve energy efficiency. At the same time, 98% of the fossil fuels used in Mexican EAF plants are natural gas, which has a lower emission factor compared to other coal-based fossil energy sources, which leads to a lower average emission factor for Mexican fuels, further contributing to the energy efficiency of the Mexican IS industry (Hasanbeigi et al., 2016).

4.5 Robustness test

Referring to the ideas of Schneider and Wagemann (2012), this study raises the consistency threshold by 0.05, i.e., 0.85 instead of 0.80, and starts the analysis again using a more stringent threshold (see Table 7). The outcome in Table 7 shows that the new grouping is consistent with the analytical outcome listed in Table 6, validating that the applied methodology is suitable in this study.

Table 7. Results of robustness tests for configuration analysis

Conditions	S1	S2	S3
ICT	●	●	⊗
EAF	⊗	•	•
RQ	●	●	⊗

PCE		⊗	⊗
GDP	●	⊗	⊗
Consistency	0.932	0.991	0.895
Raw coverage	0.462	0.238	0.351
Unique coverage	0.310	0.010	0.188
Solution coverage	0.737		
Solution consistency	0.910		

5. Discussion

In addition, although there are discrepancies with the results of some studies, the outcomes of this study are in line with the findings of related studies to some extent, as shown in Table 8.

Table 8. Conclusion comparison between this article and other relevant literature

Theme	Conclusion of this article	Conclusion of relevant literature
Energy efficiency of IS sector	The energy efficiency performance of the IS sector in developed countries is generally better than that in developing countries.	China's IS production energy intensity was about 1.5 times higher than that of the US (Hasanbeigi et al., 2014). IS production efficiency of market economy countries being generally higher than that of planned economies (Nielsen, 2017).
	The energy efficiency performance of the IS sector in Mexico is better than US and China.	The Mexican IS industry was more energy efficient and less carbon intense than US and China (Rojas-Cardenas et al., 2017).
Determinants of energy efficiency	Improvement of digital economy is conducive to improving the energy efficiency of the IS sector.	Digitization is a key topic in R&D of the European steel industry especially in Belgium, Germany, Italy and Sweden (Arens, 2019). Combining a digital technology application with a management strategy for behaviour modification would benefit energy efficiency gains in

		Germany, Norway and the UK (Stroud et al., 2020)
	Developing countries can enhance the share of clean energy in IS production by increasing the EAF ratio, thus improving energy efficiency.	Structural changes in the IS sector may help to significantly reduce energy and carbon intensity (Hasanbeigi et al., 2014; Hasanbeigi et al., 2016).
	Higher regulatory quality is conducive to the improvement of energy efficiency in the IS sector.	The European steel industry has significant concerns over energy efficiency and compliance with EU environmental regulations (Stroud et al., 2020).
	In the process of IS production, excessive reliance on coal poses obstacles for efficiency gains.	Substitution of coke with pelletized biocarbon can be an interesting option for low-carbon development of the steel industrial in Europe and China (Gul et al., 2021).
	The economic level enhances energy efficiency of IS production.	GDP and investment climate exert the biggest influence on energy efficiency in the long run (Flues, 2015).

Specifically, in terms of national-level energy efficiency comparison, most studies found that advanced economies usually had better performance compared to developing countries or emerging markets. For example. Hasanbeigi et al. (2014) found that for the whole iron and steel production process, the final energy intensity in China was about 1.5 times that of the U.S. in the base-case analysis. Nielsen (2017) selected 14 market countries represented by Japan, Spain, the U.S. and the U.K. and 7 planned economies represented by China to compare the productive efficiency in the IS sector. This study found that the efficiency level of market countries was remarkably higher than it was in planned economies, however, a convergence pattern of efficiency value was observed across the countries.

In terms of determinants of efficiency gains, both Arens (2019) and Stroud et al. (2020) demonstrated that all major actors of the European steel industry, especially Germany, are active in the field of digitizing this industry to facilitate resource efficiency, energy efficiency and low carbon transformation. Hasanbeigi et al. (2016) found that the higher share of EAF contributed greatly to low-carbon development of IS in Mexico, making the country have lower carbon dioxide emissions intensity of steel production than China, Germany, and the US. The study of Gul et al. (2021) pointed out that solid product of biomass pyrolysis can facilitate industrial decarbonization and energy efficiency gains for Europe and China because they both still have a significant percentage of BF-BOF plants. In addition, Stroud et al. (2020) noticed that steel plants in Germany and Norway, which are subject to several layers of environmental legislation and compliance, usually have strong motivations for innovation to improve energy efficiency.

However, our conclusion is not always consisting with the conclusions of studies on similar topics, due the differences in research sample, focus, observation period, and method used. For example, Flues (2015) found that GDP and investment climate exert the biggest influence on energy efficiency in the major steel producing European countries, namely Germany, Italy, Spain, France and the UK. This conclusion is supported by pathway S1 but not pathway S2 in our research. The possible reason is that our analysis uses configuration analysis that emphasizes the combination effects of different factors as opposed to estimating the net effect of a given indicator.

Moreover, as can be seen in Table 8, in terms of evaluation technique, most studies used single factor analysis or basic radial DEA approaches to estimate the energy efficiency level of the IS sector. However, this study utilizes a hybrid measure while considering byproducts of IS production as well as inter-period comparison and further ranks efficient countries to obtain more accurate efficiency values. In terms of analytical perspective, most research selected the determinants for efficiency improvement by logical reasoning based on literature review. In accordance, this study constructs a theoretical framework to select the key influencing technological, organizational, and environmental factors. In terms of pathway identification, few studies paid attention to the possible interaction among determinants, whereas this study adopts systematic thinking and uses qualitative comparative analysis techniques to observe various configurations to achieve efficiency improvement and to avoid shortcomings of traditional regression analyses.

6. Conclusion and implications

6.1 Conclusion

This study estimates energy efficiency with carbon emission constraints of the IS industry in G20 countries using the method of global super EBM with undesirable output, and further explores the heterogeneous factor configurations of high-energy-efficient performance combining NCA and fsQCA techniques. In so doing, differentiated profiles of low-carbon development model of the IS industry with different national conditions and development states are uncovered and discussed accordingly.

Specifically, the following research findings are based on the empirical tests.

(1) The low-carbon development level of the IS industry in G20 countries showed an upward trend in fluctuation and increased by 0.25% during the observation period. The efficiency performance of developed countries is generally higher than that of developing countries. Fortunately, the efficiency gap between these two groups is narrowing down over the years, indicating that a catching-up effect for the developing countries, represented by China, is contributing to energy conservation and emission reduction of the global IS sector. As the largest crude steel producer worldwide, China ranks 13th-15th among G20 countries in terms of energy efficiency in the IS industry due to its lack of steel scrap, which not only causes significant environmental impacts but also directly affects the EAF share in IS production (Zhang et al., 2023).

(2) The result of NCA analysis demonstrates that no individual factor constitutes a necessary condition for energy efficiency in the IS industry, and the results of fsQCA also confirm this conclusion. The configuration analysis shows that there are three pathways to achieve high energy efficiency for countries with different backgrounds, that is, the regulation-economic-technology driven path (i.e., S1: high ICT and high RQ as core conditions with non-high EAF and high GDP as marginal conditions), the regulation-technology-production driven path (i.e., S2: high ICT, high RQ, non-high PCE and non-high GDP as core conditions with high EAF as marginal condition) , and the technology-energy structure driven path (i.e., S3: non-high PCE and non-high GDP as core conditions, complemented by non-high ICT, high EAF and non-high RQ as marginal conditions). This outcome indicates that there is no one-size-fits-all solution for countries to achieve

efficiency gains in the IS industry. In other word, specific paths and measures need to be selected for a given country to adapt to its own conditions and utilize its resources.

(3) Typical countries of S1 are Germany and Japan. Their high level of economic development, comprehensive government regulations, as well as advantages in infrastructure, abundant human resources, and rich management experiences, provide effective guidance and supervision for IS enterprises to improve energy efficiency. A typical country of S2 is Spain. This type of country is relatively less competitive in terms of economic level, but has higher regulation quality, digital level and production structure. In addition to implementing environmental tax policies and encouraging the use of green energy to improve energy efficiency, such countries usually have higher EAF share and digital level. A typical country of S3 is Mexico. For this category of countries, although they don't have advantages in science and technology, economic level, or governance quality, they usually have EAF-based production technology and more environmentally friendly energy input systems.

6.2 Policy implications and limitations

The following policy implications are posited for the low-carbon development of the IS industry based on the research findings and discussion presented above.

First, although a catching-up effect is observed, the efficiency gap in the IS industry across countries with different economic levels is still significant. Therefore, international industrial cooperation, especially technical exchange, and cooperation in energy conservation and emission reduction represented by hydrogen metallurgy, the use of biomass as a reducing agent, and CO_2 capture and storage technologies need to be strongly advocated. In addition, how to further exert the spillover effects of technology, management, and environmental governance of advanced countries in low carbon IS development and narrow down the efficiency gap between nations need to be carefully considered.

Second, the exploration of high energy efficiency in the IS sector reveals reference paths for countries with divergent backgrounds and conditions. Specifically, for countries lacking competitiveness in economic and technological levels, the technical structure of domestic IS production can be adjusted to change from BF/BOF to a more energy-efficient EAF route. It can drive production through the economic and technological level of society.

At the same time, government supervision should be supplemented to restrict the standardization of enterprises' production and pollution discharge through forced regulation and persuade them to transform their production input into clean energy. For example, the IS production route and energy structure cannot be completely changed temporarily due to the actual demand. However, extensive market demand, advanced technologies, and rich human resources as well as managerial experiences provided by strong economic strength can also effectively promote efficiency gains.

Finally, as the world's largest crude steel producer, China's transformation from using a BF/BOF to an EAF route cannot be fully realized in the near future due to its development stage of industrialization. However, this technical direction is still a focal point in the long run. Although China has made progress in terms of regulatory quality and digital development, it still lags behind compared to advanced economies worldwide⑨. Therefore, China also needs to further strengthen environmental regulations, supply-side structural reform, dual economic cycle, technological innovation and digitalization of the IS sector. In addition, China's IS sector needs to make more efforts in developing clean energy such as hydrogen energy to replace coal-based energy, reducing the by-products of IS production process from the root, and advocating for the low-carbon transition of the sector.

In terms of research limitation, first, this study does not incorporate spatial relations into the analytical framework yet. However, spatial correlations across countries with shorter economic, cultural, and/or geographical distance may represent similar trends in development paths. Moreover, spill-over effects of efficiency gains may also occur due to geographical impacts. Therefore, future studies are encouraged to incorporate spatial factors into the analyses to reveal more in-depth and comprehensive pathways for the low-carbon transition of the IS sector. Second, different types of environmental regulations such as public participation, voluntary, and information-based measures can be incorporated into the framework to reveal the combination effects of regulatory tools. Last but not least, future studies could expand the sample to cover more countries and regions in the steel

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⑨ In 2020, the digitization rate of enterprises in China's IS industry is only 30% (source: Head Leopard Research Institute. 2021 China's Iron Industry Digital Transformation Brief Report, https://pdf.dfcfw.com/pdf/H3_AP202104071481758230_1.pdf. Accessed: 2023-08-19) industry, especially the "Belt and Road" countries to identify more realization paths of low carbon development in the IS industry.

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Appendix

The abbreviations used in this article are listed in Table A1.

Table A1 Abbreviations

No.	Full name	Abbreviation	No.	Full name	Abbreviation
1	iron and steel	IS	15	group 20	G20
2	greenhouse gas	GHG	16	Mexico, Indonesia, Nigeria and Turkey	MINT
3	data envelopment analysis	DEA	17	Brail, Russia, India, China, and South Africa	BRICS
4	epsilon-based measure	EBM	18	Intergovernmental Panel on Climate Change	IPCC
5	necessary condition analysis	NCA	19	International Energy Agency	IEA
6	fuzzy-set qualitative comparative analysis	fsQCA	20	World Steel Association	WSA
7	information and communication technology	ICT	21	principal component analysis	PCA
8	electrical arc furnace	EAF	22	world governance index	WGI
9	blast furnace/ basic oxygen furnace	BF/BOF	23	regulatory quality	RQ
10	ceiling envelopment with a free disposal hull	CE-FDH	24	technology-organization-environment	TOE
11	ceiling regression with a free disposal hull	CR-FDH	25	proportional reduction in inconsistency	PRI
12	Ceiling envelopment with varying return to scale	CE-VRS	26	world development index	WDI

13	ceiling regression with varying return to scale	CR-VRS	27	purchasing power parity	PPP
14	European Union-Emission trading Scheme	EU-ETS	28	National Energy Efficiency Action Plan	NEEAP

References

Abdelshafy, A., Walther, G., 2022. Exploring the effects of energy transition on the industrial value chains and alternative resources: A case study from the German federal state of North Rhine-Westphalia (NRW). Resour. Conserv. Recy. 177, 105992.

Arens, M., 2019. Policy support for and R&D activities on digitising the European steel industry. Resour. Conserv. Recy. 143, 244-250.

Bhadbhade, N., Zuberi, M. J. S., Patel, M. K., 2019. A bottom-up analysis of energy efficiency improvement and CO_2 emission reduction potentials for the Swiss metals sector. Energy. 181, 173-186.

Brodny, J., Tutak, M., 2022. Analysis of the efficiency and structure of energy consumption in the industrial sector in the European Union countries between 1995 and 2019. Sci. Total Environ, 808, 152052.

Bu, Y., Li, S., Huang, Y., 2023. Research on the influencing factors of Chinese college students' entrepreneurial intention from the perspective of resource endowment. Int. J. Manag. Educ-Ox. f21(3), 100832.

Chen, W., Zhang, Q., Wang, C., Li, Z., Geng, Y., Hong, J., Cheng, Y., 2022. Environmental sustainability challenges of China's steel production: Impact-oriented water, carbon and fossil energy footprints assessment. Ecol. Indic. 136, 108660.

Chi M., Wang J., Wang W., 2022. Research on the influencing mechanism of firms' innovation performance in the context of digital transformation: A mixed method study. Stud. Sci. Sci. 40(2):319-331 (In Chinese).

Devlin, A., Yang, A., 2022. Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation. Energ. Convers. Manage. 254, 115268.

Ding, H., 2022. What kinds of countries have better innovation performance? –A country-level fsQCA and NCA study. J. Innov. Knowl. 7(4), 100215.

Dul, J., 2016. Necessary condition analysis (NCA) logic and methodology of “necessary but not sufficient” causality. Organ. Res. Methods. 19(1), 10-52.

Dul, J., Van der Laan, E., Kuik, R., 2020. A statistical significance test for necessary condition analysis. Organ. Res. Methods. 23(2), 385-395.

Dutta, U. P., Gupta, H., Sengupta, P. P., 2019. ICT and health outcome nexus in 30 selected Asian countries: Fresh evidence from panel data analysis. Technol. Soc. 59, 101184.

Feng, C., Wang, M., Zhang, Y., Liu, G. C., 2018. Decomposition of energy efficiency and energy-saving potential in China: A three-hierarchy meta-frontier approach. J. Clean. Prod. 176, 1054-1064.

Fiss, P. C., 2011. Building better causal theories: A fuzzy set approach to typologies in organization research. Acad. Manage. J. 54(2), 393-420.

Flues, F., Rübbelke, D., Vögele, S., 2015. An analysis of the economic determinants of energy efficiency in the European iron and steel sector. J. Clean. Prod. 104, 250-263.

Furnari, S., Crilly, D., Misangyi, V. F., Greckhamer, T., Fiss, P. C., Aguilera, R. V., 2021. Capturing causal complexity: Heuristics for configurational theorizing. Acad. Manage. Rev. 46(4), 778-799.

Gul, E., Riva, L., Nielsen, H. K., Yang, H., Zhou, H., Yang, Q., ... Fantozzi, F., 2021. Substitution of coke with pelletized biocarbon in the European and Chinese steel industries: An LCA analysis. Appl. Energ. 304, 117644.

Haider, S., Mishra, P. P., 2021. Does innovative capability enhance the energy efficiency of Indian Iron and Steel firms? A Bayesian stochastic frontier analysis. Energ. Econ. 95, 105128.

Hansen, K., Mathiesen, B. V., Skov, I. R., 2019. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew. Sust. Energ. Rev. 102, 1-13.

Harris, R., Moffat, J., Evenhuis, E., Martin, R., Pike, A., Sunley, P., 2019. Does spatial proximity raise firm productivity? Evidence from British manufacturing. Camb. J. Reg. Econ. Soc. 12(3), 467-487.

Hasanbeigi, A., Arens, M., Cardenas, J. C. R., Price, L., Triolo, R., 2016. Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States. Resour. Conserv. Recy. 113, 127-139.

Hasanbeigi, A., Price, L., Chunxia, Z., Aden, N., Xiuping, L., Fangqin, S., 2014.

Comparison of iron and steel production energy use and energy intensity in China and the US. J. Clean. Prod. 65, 108-119.

He, K., Wang, L., 2020. Time to change the energy conservation direction of China's steel sector: From upgrading the technology level to increasing scrap ratio. Sci. China Technol. Sc. 63(1), 128-139.

Huang, D., Dinga, C. D., Wen, Z., Razmadze, D., 2022. Industrial-environmental management in China's iron and steel sector under multiple objectives and uncertainties. J. Environ. Manage. 310, 114785.

Khan, H., Weili, L., Khan, I., 2022. Examining the effect of information and communication technology, innovations, and renewable energy consumption on CO2 emission: evidence from BRICS countries. Environ. Sci. Pollut. R. 29(31), 47696-47712.

Koasidis, K., Nikas, A., Neofytou, H., Karamaneas, A., Gambhir, A., Wachsmuth, J., Doukas, H., 2020. The UK and German low-carbon industry transitions from a sectoral innovation and system failures perspective. Energies. 13(19), 4994.

Koch, T., Windsperger, J., 2017. Seeing through the network: Competitive advantage in the digital economy. J. O. Design. 6(1), 1-30.

Lee, K. H., 2015. Drivers and barriers to energy efficiency management for sustainable development. Sustain. Dev. 23(1), 16-25.

Lin, B., Wu, Y., Zhang, L., 2011. Estimates of the potential for energy conservation in the Chinese steel sector. Energ. Policy. 39(6), 3680-3689.

Liu, J. Y., Cai, J. J., Yang, J. H., 2012. Research and application of power nodes network in iron & steel factory. Chin. Metall. 22(7), 40-46.

Lopez, G., Galimova, T., Fasihi, M., Bogdanov, D., Breyer, C., 2023. Towards defossilised steel: Supply chain options for a green European steel industry. Energy, 273, 127236.Manso, J. M., Polanco, J. A., Losañez, M., González, J. J., 2006. Durability of concrete made with EAF slag as aggregate. Cement. Concrete Comp. 28(6), 528-534.

Lu, B., Chen, G., Chen, D., Yu, W., 2016. An energy intensity optimization model for production system in iron and steel industry. Appl. Therm. Eng. 100, 285-295.

Martínez-Domínguez, M., Fierros-González, I., 2022. Determinants of internet use by school-age children: The challenges for Mexico during the COVID-19 pandemic. Telecommun. Policy. 46(1), 102241.

Mora-Rivera, J., García-Mora, F., 2021. Internet access and poverty reduction: Evidence from rural and urban Mexico. Telecommun. Policy. 45(2), 102076.

Morfeldt, J., Silveira, S., 2014. Capturing energy efficiency in European iron and steel production-comparing specific energy consumption and Malmquist productivity index. Energ. Effic. 7(6), 955-972.

Na, H., Du, T., Sun, W., He, J., Sun, J., Yuan, Y., Qiu, Z., 2019. Review of evaluation methodologies and influencing factors for energy efficiency of the iron and steel sector. Int. J. Energ. Res. 43(11), 5659-5677.

Nagashima, M., 2018. Japan's hydrogen strategy and its economic and geopolitical implications (pp. 12-75). Paris, France: Ifri.

Nielsen, H., 2017. Productive efficiency in the iron and steel sector under state planning: The case of China and former Czechoslovakia in a comparative perspective. Appl. Energ. 185, 1732-1743.

Peng, Y. T., Hou, Y. C., Luo, J. Q., Li, Y. Y., 2022. Research on configuration of integration of equipment manufacturing sector and modern service sector based on TOE framework. Chin. J. Manage. 03, 333-341. [In Chinese]

Ragin, C. C., 2009. Qualitative comparative analysis using fuzzy sets (fsQCA). Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques. SAGE Publications.

Ren, L., Zhou, S., Ou, X., 2023. The carbon reduction potential of hydrogen in the low carbon transition of the iron and steel industry: The case of China. Renew. Sust. Energ. Rev. 171, 113026.

Rojas-Cardenas, J. C., Hasanbeigi, A., Sheinbaum-Pardo, C., Price, L., 2017. Energy efficiency in the Mexican iron and steel sector from an international perspective. J. Clean. Prod. 158, 335-348.

Santamaría, A., Linares, P., Pintos, P., 2014. The effects of carbon prices and anti-leakage policies on selected industrial sectors in Spain–Cement, steel, and oil refining. Energ. Policy. 65, 708-717.

Schneider, C. Q., Wagemann, C., 2012. Set-theoretic methods for the social sciences: A guide to qualitative comparative analysis. Cambridge University Press.

Sharma, G. D., Shah, M. I., Shahzad, U., Jain, M., Chopra, R., 2021. Exploring the nexus between agriculture and greenhouse gas emissions in BIMSTEC region: The role of renewable energy and human capital as moderators. J. Environ. Manage. 297, 113316.

Stroud, D., Evans, C., Weinel, M., 2020. Innovating for energy efficiency: Digital gamification in the European steel industry. Eur. J. Ind. Relat. 26(4), 419-437.

Sun, J., Na, H., Yan, T., Qiu, Z., Yuan, Y., He, J., Li, Y., Wang, Y., Du, T., 2021. A comprehensive assessment on material, exergy and emission networks for the integrated iron and steel industry. Energy. 235, 121429.

Svensson, J., Wang, Y., Garrick, D., Dai, X., 2021. How does hybrid environmental governance work? Examining water rights trading in China (2000–2019). J. Environ. Manage. 288, 112333.

Talaei, A., Ahiduzzaman, M., Davis, M., Gemechu, E., Kumar, A., 2020. Potential for energy efficiency improvement and greenhouse gas mitigation in Canada's iron and steel sector. Energ. Effic. 13(6), 1213-1243.

The Iron and Steel Institute of Japan., 2022. Production and Technology of Iron and Steel in Japan during 2021. Isij. Int. 62(6), 1027-1048.

Tone, K., Tsutsui, M., 2010. An epsilon-based measure of efficiency in DEA–a third pole of technical efficiency. Eur. J. Oper. Res. 207(3), 1554-1563.

Torres, P., Godinho, P., 2022. Levels of necessity of entrepreneurial ecosystems elements. Small Bus. Econ. 59(1), 29-45.

Tóth, Z., Dul, J., Li, C., 2019. Necessary condition analysis in tourism research. Ann. Tourism Res. 79.

Travezan, J. Y., Harmsen, R., van Toledo, G., 2013. Policy analysis for energy efficiency in the built environment in Spain. Energ. Policy. 61, 317-326.

Usman, A., Ozturk, I., Hassan, A., Zafar, S. M., Ullah, S., 2021. The effect of ICT on energy consumption and economic growth in South Asian economies: an empirical analysis. Telemat. Inform. 58, 101537.

Vögele, S., Rübbelke, D., Govorukha, K., Grajewski, M., 2020. Socio-technical scenarios for energy-intensive industries: the future of steel production in Germany. Climatic Change. 162(4), 1763-1778.

Wang, K. L., Pang, S. Q., Ding, L. L., Miao, Z., 2020. Combining the biennial Malmquist–

Luenberger index and panel quantile regression to analyze the green total factor productivity of the industrial sector in China. Sci. Total Environ. 739, 140280.

Wang, K. L., Zhang, F. Q., Xu, R. Y., Miao, Z., Cheng, Y. H., Sun, H. P., 2023. Spatiotemporal pattern evolution and influencing factors of green innovation efficiency: A China's city level analysis. Ecol. Indic. 146, 109901.

Wang, L., 2022. Role of FDI and energy intensity in mitigating the environmental pollution in the Chinese steel industry: does technological innovation makes a difference? Environ. Sci. Pollut. R. 29(19), 28127-28138.

Wang, P., Zhao, S., Dai, T., Peng, K., Zhang, Q., Li, J., Chen, W. Q., 2022. Regional disparities in steel production and restrictions to progress on global decarbonization: A cross-national analysis. Renew. Sust. Energ. Rev. 161, 112367.

Wang, X., Zhang, T., Nathwani, J., Yang, F., Shao, Q., 2022. Environmental regulation, technology innovation, and low carbon development: Revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel sector. Technol. Forecast. Soc. 176, 121471.

Wiboonchutikula, P., Chaivichayachat, B., Chontanawat, J., 2014. Sources of energy intensity change of Thailand's Steel industry in the decade of global turbulent time. Singap. Econ. Rev. 59(03), 1450027.

Wu, J., Zhu, Q., Chu, J., Liang, L., 2015. Two-stage network structures with undesirable intermediate outputs reused: a DEA based approach. Comput. Econ. 46, 455-477.

Wu, R., Lin, B., 2022. Environmental regulation and its influence on energy-environmental performance: evidence on the Porter Hypothesis from China's iron and steel industry. Resour. Conserv. Recy. 176, 105954.

Wu, Y., Su, J., Li, K., Sun, C., 2019. Comparative study on power efficiency of China's provincial steel industry and its influencing factors. Energy, 175, 1009-1020.Xiao, J., Zeng, P., Ren, G., 2022. How to improve the green transformation performance of manufacturing sector? --TOE framework-based configuration study. Stud. Sci. Sci. 12, 2162-2172. [In Chinese]

Xiong, Q., Sun, D., 2022. Influence analysis of green finance development impact on carbon emissions: an exploratory study based on fsQCA. Environ. Sci. Pollut. R. 1-12.

Yu, X., Tan, C., 2022. China's pathway to carbon neutrality for the iron and steel industry.

Global Environ. Chang. 76, 102574.

Zhang, C., He, W., Hao, R., 2017. Comparative analysis of Asian main iron and steel countries' total factor energy efficiency. Curr. Sci. India. 2226-2233.

Zhang, F., Huang, K., 2017. The role of government in industrial energy conservation in China: Lessons from the iron and steel industry. Energy Sustain. Dev. 39, 101-114.

Zhang, J., Shen, J., Xu, L., Zhang, Q., 2023. The CO2 emission reduction path towards carbon neutrality in the Chinese steel industry: A review. Environ. Impact Asses. 99, 107017.

Zhang, W., Liu, X., Wang, D., Zhou, J., 2022. Digital economy and carbon emission performance: Evidence at China's city level. Energ. Policy. 165, 112927.

Zhao, S., Hafeez, M., Faisal, C. M. N., 2022. Does ICT diffusion lead to energy efficiency and environmental sustainability in emerging Asian economies? Environ. Sci. Pollut. R. 29(8), 12198-12207.

Zhou, X., Niu, A., Lin, C., 2023. Optimizing carbon emission forecast for modelling China's 2030 provincial carbon emission quota allocation. J. Environ. Manage. 325, 116523.