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Research article

Assessing energy efficiency towards carbon emissions in Yangtze River Economic Belt from a configurational perspective

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Abstract: Green economy has been attracting attention around the world. The "dual carbon" policy has been proposed to emphasize the pursuit of high-quality economy in China, and improving energy efficiency is considered an effective way to achieve this strategic target. Moreover, the Yangtze River Economic Belt acts as the principal carrier for China's economic development; therefore, analyzing the energy efficiency is crucial. Three phases constituted the analysis in this paper: a) Using the LDA topic model to conduct the evaluation system of energy efficiency based on the "dual carbon" policy texts; b) using the SBM-Undesirable model to measure the energy efficiency of 11 provinces and cities in the Yangtze River Economic Belt between 2011 and 2020; and c) using the fsQCA method to further analyze the configurational impact of influential factors on the energy efficiency of the Yangtze River Economic Belt. Through systematic research, the evolving trends within the Yangtze River Economic Belt could be examined from two perspectives. Chronologically, energy efficiency within the region exhibited fluctuating development patterns. From a geographical perspective, overall energy efficiency exhibited a tiered distribution pattern of "downstream > midstream > upstream", indicating that the midstream and upstream sectors possessed greater potential for improvement compared to the downstream sector. Therefore, four configuration paths that affect energy efficiency were finally identified toward achieving the "dual carbon" target.

Keywords: energy efficiency; carbon emissions; fsQCA; SBM-Undesirable model; LDA

1. Introduction

With the rapid global economic development, the reliance on energy has been increasing [1,2]. In 2020, the Chinese government proposed the "dual carbon" target (national "Carbon Peaking and Carbon Neutrality Goals") with a series of related policies toward carbon emission [3], which indicates that improving energy efficiency has become a key issue of economic development [4,5]. In essence, advancing energy efficiency constitutes the primary market-based instrument for carbon mitigation. Efficiency gains reduce fossil fuel input per unit economic output and curb carbon emissions, while the energy rebound effect tends to partially counteract such decarbonization outcomes. To facilitate well-grounded low-carbon policy formulation, it is imperative to accurately evaluate regional energy efficiency performance, particularly within core economic zones. The Yangtze River Economic Belt acts as China's strategic growth hub and the backbone of national sustainable development [6]. Restricted by insufficient indigenous resource reserves, the Belt fails to realize full energy self-sufficiency, which renders energy efficiency enhancement an urgent and pivotal challenge. Nevertheless, two notable research gaps remain in the literature. First, few researchers have developed energy efficiency evaluation frameworks tailored to low-carbon policy orientations. Second, empirical evidence regarding how the Yangtze River Economic Belt can boost energy efficiency under the guidance of the "dual carbon" target remains insufficient and under-explored. In this paper, we address these shortages through targeted empirical analysis.

Numerous energy-intensive industries within the Yangtze River Basin remain incompatible with the principles of green development [7]. Relevant research falls into two categories: One quantifies the marginal carbon reduction contribution of energy efficiency via econometric regression with carbon emissions as a dependent variable; another adopts the SBM model to embed carbon emission as undesirable output to measure green total-factor energy efficiency. However, few researchers construct input-output indicator systems driven by dual-carbon policy text mining when evaluating regional green energy efficiency for the Yangtze River Economic Belt. Against this backdrop, analyzing energy efficiency from a spatio-temporal perspective not only provides a basis for differentiated low-carbon policy-making and promotes regional collaborative emission governance but also fills the above-mentioned research gap. This study makes several marginal contributions to the literature. First, different from the traditional data-blind indicator selection method, we combine LDA policy text mining results with Factor Allocation Theory and Porter Hypothesis to construct a more policy-oriented and theoretically grounded energy efficiency evaluation system, which improves the rationality and pertinence of indicator screening. Second, we incorporate carbon emissions and environmental pollution as undesirable outputs to evaluate green total-factor energy efficiency, effectively internalizing environmental and carbon reduction costs and forming a low-carbon-oriented efficiency assessment framework that fits the dual-carbon governance context. Third, based on the spatial heterogeneous characteristics of energy efficiency gradients in the Yangtze River Economic Belt, we further identify the configurational driving mechanisms of energy efficiency and provide differentiated sub-regional optimization paths, offering targeted empirical evidence and policy references for regional coordinated low-carbon development.

From the above, we construct a systematic analysis on the spatiotemporal differentiation and influencing factors of energy efficiency in the Yangtze River Economic Belt, which is of great significance for understanding the trend of energy efficiency in the economic belt. Moreover, the configurational analysis of influencing factors also helps indicate pathways of improving energy efficiency in the Yangtze River Economic Belt. Different from studies that set carbon emissions as standalone explained variables to decompose emission reduction contribution, we take carbon dioxide as an undesirable output to internalize carbon abatement cost into green energy efficiency assessments, matching our core objective of low-carbon-oriented efficiency measurement rather than quantitative attribution of carbon reduction drivers. Finally, targeted policy recommendations are proposed to facilitate regional sustainable development and carbon emission mitigation, while the quantitative measurement of energy efficiency's carbon reduction contribution is reserved as the direction of future follow-up research.

2. Related work

Improving energy efficiency is an effective approach for economic transformation and green development. Researchers have conducted analyses for various perspectives on the indicator selection, evaluation methods, and influencing factors of energy efficiency [8]. Regarding the indicator system, capital, labor, and energy are often selected as input indicators, and GDP is the output indicator to analyze the impact of energy prices on energy efficiency [9]. Regulatory policies are also regarded as a source of indicators for measuring variations in energy efficiency, serving to evaluate policy effectiveness and explore avenues for improvement [10–12].

Regarding the selection of energy efficiency measurement methods, the literature demonstrates that SFA and DEA are appropriate options under various scenarios in the literature [13–16]. For instance, scholars have employed SFA in analyzing energy consumption among Chinese households [17]. Li employed the 3S-DEA methodology to assess green technological innovations among Chinese industrial enterprises from 2013 to 2022 [18]. Researchers have also used the Modified Undesirable Dynamic SBM DEA Model to analyze and conduct a comprehensive assessment of economic efficiency, energy consumption efficiency, and greenhouse gas emission efficiency across 29 European countries during the period 2015–2019 [19]. With the increasing emphasis on environmental issues in recent years, many researchers have begun incorporating environmental factors into their indicator systems [20], while enhancing the efficiency of green energy has become particularly crucial. Research has indicated that economic development, technological investment, and innovation capacity significantly improve efficiency [21].

From the above, the literature has accumulated relevant research findings in two key areas: Energy efficiency evaluation and the construction of corresponding indicator systems. Nevertheless, most researchers have adopted regression analysis to examine the impact of individual variables on energy efficiency, with few attempts to explore the synergistic effects of multiple variables. Moreover, in the process of indicator identification, little consideration has been given to how the selected indicators could reflect or respond to policy orientations, even though energy efficiency is widely recognized to be closely tied to policy interventions. Hence, we aim to fill up this gap by conducting systematic analysis on the energy efficiency of the Yangtze River Economic Belt that integrates the text analysis technique and configuration analysis. Factors that are extracted from "dual carbon" policy texts are involved in the construction of an energy efficiency evaluation system, and, accordingly, the energy efficiency is analyzed with the combined effects of factors. Finally, practical advice is discussed for achieving the "dual carbon" target based on the analytical insights.

3. Methodology

To systematically analyze the energy efficiency of Yangtze River Economic Belt for the "dual carbon" target, we use the LDA (Latent Dirichlet Allocation) topic model to extract relevant texts on dual-carbon policies and construct an energy efficiency evaluation system accordingly. Moreover, the Slacks-Based Measure (SBM)-Undesirable model is applied to measure the energy efficiency of the Yangtze River Economic Belt from 2011 to 2020, and the configuration analysis is performed to explore the driving factors and their combined effect using Fuzzy-set Qualitative Comparative Analysis (fsQCA).

3.1. The LDA model based on the "dual carbon" policy

The principle of the LDA model is that each word in each document is obtained by selecting a certain topic with a certain probability, which could help us understand the key thematic areas of focus [22,23]. Its final model results generally do not overfit. The number of topics and the number of words contained in each topic can be selected through multiple experiments. The LDA method normally applies the guidance of adding prior parameters that is suitable for training the model with small data volume.

The Chinese "dual carbon" target was officially proposed in September 2020, and there are limited formal policies and notifications from governments of various areas. Therefore, the related policy data belong to small data samples. Moreover, considering that the topic classification results of policy texts are relatively clear, and the definition of topics is not easy for producing ambiguity, the LDA method is used to analyze the topics of "dual carbon" policy texts. Relevant factors could be identified subsequently to "dual carbon" and constitute an energy efficiency indicator system for further analysis.

3.2. The SBM-Undesirable model for measuring energy efficiency

Research on environmental efficiency has rarely integrated climate change into its analytical framework, and most researchers investigating greenhouse gas emission efficiency focus on carbon dioxide emissions, frequently overlooking other greenhouse gases [19]. Moreover, traditional efficiency measurement models often struggle to accurately reflect the asymmetric relationship between undesirable outputs (such as carbon and sulfur emissions) and desirable outputs (economic and environmental benefits) in energy consumption processes. To address this, we employ the SBM-Undesirable model, which incorporates slack variables and accounts for undesirable outputs, to conduct a more comprehensive assessment of energy efficiency along the Yangtze River Economic Belt [24–26].

Suppose there exist N decision units, each possessing m input indicators, s desired output indicators, and k undesired output indicators. The SBM-Undesirable model can be defined as follows:

$$\rho = \min \frac{1\text{-}\frac{1}{m}\sum_{i=1}^{m}\left(\frac{S_i^-}{x_{i0}}\right)}{1+\frac{1}{s+k}\left(\sum_{r=1}^{s}\frac{S_r^+}{y_{r0}}+\sum_{t=1}^{k}\frac{S_t^-}{z_{t0}}\right)} \tag{1}$$

St.

$$\sum_{n=1}^{N}\lambda_n x_{in} + S_i^- = x_{i0}, i = 1,2,3\ldots,m \tag{2}$$

$$\sum_{n=1}^{N} \lambda_n y_{rn} - S_r^+ = y_{r0}, r = 1,2,3\ldots, s \tag{3}$$

$$\sum_{n=1}^{N} \lambda_n z_{tn} + S_t^- = z_{t0}, t = 1,2,3\ldots, k \tag{4}$$

$$S_i^-, S_r^+, S_k^-, \lambda_n \geq 0 \tag{5}$$

In the equation, ρ denotes the efficiency value, with a range of [0,1]; S_i^-, S_r^+, and S_t^- represent the slack variables for input redundancy, shortfall in desired output, and excess in undesired output, respectively; and λn is the weighting coefficient. When ρ=1 and all slack variables are zero, the decision-making unit lies on the production frontier and is deemed DEA-efficient; conversely, it indicates efficiency losses requiring improvement through optimized resource allocation and reduced pollution emissions. Moreover, we employ the model to measure energy efficiency across 11 provinces and municipalities in the Yangtze River Economic Belt from 2011 to 2020. We systematically identify regional coordination levels between energy utilization, economic growth, and environmental protection, thereby providing empirical evidence and decision-making references for differentiated advancement of the dual carbon goals and enhanced regional green and low-carbon development.

3.3. Configuration analysis with fsQCA

The fsQCA method combines qualitative and quantitative analysis from an overall research perspective. With this, we aim to find appropriate control objects in each individual case and comparatively analyze these cases to obtain the different combinations of influencing factors that could lead to the same consequence. The basic idea of the fsQCA method considers the interrelationships among variables based on set theory. The perspective of set theory is utilized to observe the overall relationship among variables. Thereafter, the case analysis and Boolean algebra calculations are used to explore whether there is a sufficient necessary connection between variables' combinations and corresponding research consequences. This enables causal judgments to be made, and reference solutions could be proposed accordingly for policy makers [27].

To explore the path of improving energy efficiency in 11 provinces and cities along the Yangtze River Economic Belt, fsQCA is chosen for the configuration analysis. The data sample size is relatively small, and the interaction among the variables of influencing energy efficiency is relatively obvious; hence, the regression analysis is unsuitable in this case. Nevertheless, fsQCA is suitable for studies with a small sample size. Moreover, we do not need to consider the interaction effects among variables when selecting variables, which enables us to further explore the joint effect of multiple influencing factors on energy efficiency.

4. Empirical analysis

4.1. Data description

Data sources include the China Energy Statistical Yearbook, China Environment Statistical Yearbook, China Statistical Yearbook, China Carbon Accounting Database, statistical yearbooks of various provinces and cities and statistical bulletins of provincial and municipal statistical bureaus. For data preprocessing, the interpolation method is mainly used to fill in missing data for some provinces. Due to the data availability, the energy efficiency of the Yangtze River Economic Belt during 2011-2020 is chosen as the research object.

4.2. Construction of the indicator system

The key words are mined and extracted from the policy texts published on the official websites of the 31 provinces, municipalities, and autonomous regions in China (except for Hong Kong, Macao, and Taiwan). First, the crawler technology is used to collect text policy data of the "dual carbon" target, and the text data is then preprocessed. Second, special characters, punctuation marks, and messy symbols such as noise from the text according to regular expressions are removed. Then, we perform Chinese word segmentation and stopword processing on the text. Finally, the word segmentation results are optimized by expanding the stopword list and customizing the domain word list.

We perform keyword extraction and clustering using TF-IDF on text corpora and control the number of topic classification results according to the topic consistency and topic confusion. Then, taking the topic clustering results obtained from keyword clustering as a reference, we consider the classification results of the LDA model and the keywords under the corresponding topic category to obtain the final topic extraction results through topic screening and merging. Furthermore, from a comprehensive perspective, the high topic consistency helps achieve better results, and we need to control the relatively small number of topics. The lower confusion is necessary for facilitating the subsequent topic summarization.

The confusion curves (upper) and topic consistency curves (lower) are depicted in Figure 1. It can be seen that the topic consistency reaches a small peak at "6", while the confusion degree gradually decreases. Therefore, the number of topics is determined as 6.

Using the visualization tool pyLDAvis, the keywords extracted from the LDA topic model are classified according to topic categories, and the plotted topic distribution is depicted in Figure 2. Therein, different circles represent different topics. The size of the circles represents the number of texts related to the topic, and the distance between circles represents the similarity between topics.

As can be seen from Figure 2, the similarity overlap of each topic is not high. Therefore, 6 topic classification results can be directly obtained for the specific "dual carbon" topic extraction after eliminating meaningless topic words such as "key" and "continuous" that are irrelevant to the indicator selection.

The extracted topics of the "dual carbon" policy texts are summarized and named as shown in Table 1.

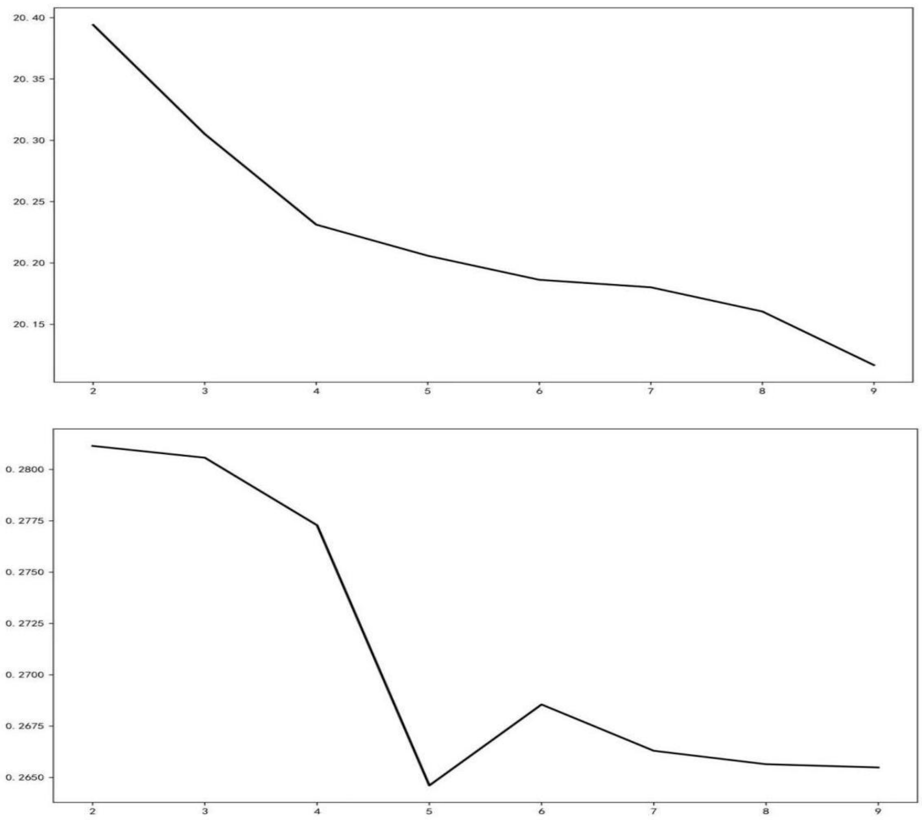

Figure 1. The confusion curves (upper) and topic consistency curves (lower).

Table 1. The result of six topic classification toward the "dual carbon" target

Cluster No.	Topic	Keywords
1	Ecological environment	ecology, construction, development, green, protection, industry, energy conservation, energy, ecological environment, governance, pollution, innovation, environment, low-carbon, restoration
2	Development and construction	construction, development, ecology, green, protection, energy, resources, ecological environment, industry, environment, capacity, governance, strengthening, emissions, mechanism
3	Energy resources	green, development, ecology, construction, energy, low-carbon, governance, energy conservation, protection, ecological environment, resources, industry, emissions, environment, industry
4	Ecological protection	green, development, construction, ecology, energy, energy conservation, emissions, strengthening, protection, environment, city, technology, industry, encouragement, low-carbon
5	Industry resources	green, development, construction, ecology, energy, industry, energy conservation, protection, resources, ecological environment, technology, governance, cleanliness, emissions, transformation
6	Production resources	development, construction, ecology, green, protection, industry, governance, ecological environment, environment, low-carbon, production, capacity, city, resources, industry

Figure 2. The visualization of plotted topic distribution.

According to the policy themes and core keywords extracted via the LDA topic model in Table 1, the policy formulation under the "dual carbon" target predominantly centers on high-quality economic development, green ecological governance, and clean energy utilization. On this basis, we further incorporate the Factor Allocation Theory and Porter Hypothesis to scientifically construct a rigorous energy efficiency evaluation index system [28]. From the perspective of Factor Allocation Theory, energy efficiency is essentially determined by the rational allocation and efficient combination of core production factors. Optimal matching of capital, labor, and energy input factors can effectively reduce resource redundancy and input waste, which lays a theoretical foundation for us to select labor, capital, and energy consumption as core input indicators for energy efficiency evaluation. In addition, the Porter Hypothesis clarifies the endogenous correlation between environmental constraints, technological progress, and efficiency improvement: Scientific environmental governance and low-carbon development policies can trigger innovation compensation effects, which can boost economic and ecological performance while curbing pollutant emissions. This theoretical perspective perfectly fits the multi-dimensional evaluation logic of green energy efficiency that balances economic growth, ecological improvement, and pollution reduction.

Combining the theoretical connotations of the two theories and the LDA policy topic extraction results, we determine the input-output indicator framework for energy efficiency evaluation. Guided by Themes 3, 5, and 6 identified by LDA analysis, energy efficiency evaluation focuses on resource input efficiency. In addition to core energy input, labor and capital inputs, as essential production factors supporting regional industrial operation and economic construction, are included in the input indicator system in accordance with Factor Allocation Theory to reflect the overall allocation level of production factors in energy utilization activities. Based on Themes 1, 2, and 4, and in line with the dual performance requirements of the Porter Hypothesis for economic development and environmental governance, we set two types of desirable outputs, namely economic benefits and ecological environmental benefits, to measure the high-quality output level of energy consumption. Moreover, undesirable outputs take typical environmental pollutants as core indicators, corresponding to the pollution emission constraints in the low-carbon green development concept implied by "dual carbon" policies. In summary, we construct a multi-dimensional energy efficiency evaluation index system for the Yangtze River Economic Belt covering factor inputs, desirable economic and ecological outputs, and undesirable pollutant outputs. The detailed indicator composition is presented in Table 2.

Table 2. The input-output indicators.

Category	Indicator	Indicator Definition	Unit
Input	Labor Input	year-end employment population	ten thousand people
	Energy Input	total energy consumption	ten thousand tons of standard coal
	Capital Input	capital stock	100 million RMB
Desired Output	Economic Benefits	gross regional production	100 million RMB
	Environmental Benefits	green coverage rate of built-up area	%
Undesirable Output	Environmental Pollution	carbon dioxide emissions	ten thousand tons
		sulfur dioxide emission	ton

A. Input indicators:

In terms of input indicators, we focus on three core elements, energy, labor, and capital, based on the analysis results of the LDA model applied to the "dual carbon" policy texts. Specifically: (1) Labor input is represented by the year-end employment figures for each province and municipality; (2) energy input is measured using total energy consumption (in ten thousand tons of standard coal equivalent); and (3) capital input is represented by capital stock. It should be noted that, as direct capital stock data is unavailable, we employ the perpetual inventory method referenced in the study by Ni et al.[29]. Using 2000 as the base year, fixed asset investments across 11 provinces and municipalities from 2011 to 2020 are estimated through conversion calculations.

B. Desired output indicators:

The output indicators sought in energy efficiency assessments are termed expected output indicators. Regarding economic benefits, following the approach adopted by most scholars, gross domestic product (GDP) is employed as the representative metric. For environmental benefits, we select the green coverage rate within built-up areas of each province and municipality as the environmental benefit indicator [30,31]. This choice is grounded in the energy-economy-environment theory, which mandates that society adhere to a sustainable development path to achieve equilibrium among energy, economic activity, and environmental protection. Concurrently, enhancing green coverage rates or forest coverage holds significant strategic importance for realizing carbon peak and carbon neutrality objectives.

C. Undesirable output indicators:

Undesirable outputs primarily refer to environmental pollutants generated during energy consumption. Aligning with the regulatory focus on key emissions within the dual carbon policy, we select carbon dioxide emissions and sulfur dioxide emissions as indicators of undesirable outputs. These two pollutants are not only major sources of atmospheric pollution but also key targets under China's energy conservation and emission reduction policies, effectively reflecting the negative environmental impacts of energy consumption.

4.3. Measurement of the energy efficiency in the Yangtze River Economic Belt

Based on the constructed energy efficiency evaluation framework, we employ the SBM-Undesirable model to measure energy efficiency in the Yangtze River Economic Belt during the period 2011–2020. In this study, Shanghai, Jiangsu, Zhejiang, and Anhui are categorized as the downstream region; Jiangxi, Hubei, and Hunan as the midstream region; and Chongqing, Sichuan, Yunnan, and Guizhou as the upstream region. The measurement results are presented in Table 3. In the subsequent analysis, we will examine three dimensions: temporal evolution trends, spatial pattern characteristics, and the specific performance of each province and municipality. The measurement results obtained through the MaxDEA software is shown in Table 3:

Table 3. The measurement result of the energy efficiency in the Yangtze River Economic Belt.

Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Jiangsu	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.892	0.897	0.871	0.966
Zhejiang	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Anhui	1.000	1.000	0.718	0.701	0.675	0.659	0.659	0.695	0.701	0.711	0.752
Jiangxi	0.806	0.808	0.800	0.791	0.758	0.737	0.719	0.680	0.687	0.694	0.748
Hubei	0.699	0.708	0.740	0.728	0.732	0.714	0.705	0.697	0.706	0.663	0.709
Hunan	0.737	0.743	0.764	0.751	0.755	0.734	0.725	0.656	0.673	0.676	0.721
Chongqing	0.695	0.717	0.769	0.756	0.791	0.785	0.776	0.720	0.734	0.787	0.753
Sichuan	0.661	0.678	0.689	0.676	0.676	0.658	0.673	0.653	0.659	0.714	0.674
Guizhou	0.497	0.521	0.542	0.542	0.551	0.528	0.536	0.497	0.498	0.511	0.522
Yunnan	0.521	0.524	0.535	0.510	0.489	0.461	0.455	0.478	0.488	0.481	0.494
Downstream	1.000	1.000	0.929	0.925	0.919	0.915	0.915	0.897	0.899	0.896	0.929
Midstream	0.747	0.753	0.768	0.757	0.748	0.728	0.716	0.678	0.689	0.677	0.726
Upstream	0.594	0.610	0.634	0.621	0.627	0.608	0.610	0.587	0.595	0.623	0.611
Average	0.783	0.791	0.778	0.769	0.766	0.752	0.750	0.724	0.731	0.737	0.758

From a historical perspective, the average energy efficiency of the 11 provinces and municipalities along the Yangtze River Economic Belt between 2011 and 2020 stood at 0.758, representing merely 75.8% of the optimal level. This indicates substantial room for improvement in their energy efficiency. During this period, overall energy efficiency exhibited a fluctuating downward trend, declining from 0.783 in 2011 to 0.737 in 2020. The peak efficiency of 0.791 was reached in 2012, primarily attributable to enhanced energy efficiency levels in most provinces along the middle and upper reaches. This improvement was closely linked to energy-saving policies implemented during the Twelfth Five-Year Plan period, notably the National Development and Reform Commission's Implementation Plan for the Energy Conservation and Emission Reduction Action in Ten Thousand Enterprises. However, efficiency levels subsequently declined, reaching a low point of 0.724 in 2018 during the study period. This may be linked to imbalances between economic development and environmental carrying capacity, alongside persistent smog issues in certain regions. By 2020, energy efficiency levels rebounded to 0.737, indicating a degree of recovery.

From a spatial perspective, the average energy efficiency levels in the lower, middle, and upper reaches of the Yangtze River Economic Belt stood at 0.929, 0.726, and 0.611, respectively, none of which reached the efficient production frontier. This presents an overall gradient pattern of decreasing efficiency: lower reaches > middle reaches > upper reaches. The downstream region, leveraging their unique geographical advantages, exhibited higher levels of economic development, greater openness, and a transition toward a more environmentally sustainable tertiary sector dominated by service industries. Consequently, this area possesses significant advantages in energy-saving and emission-reduction technologies and energy utilization, with energy efficiency levels substantially exceeding those of the mid- and upstream regions. The middle and upstream regions, constrained by their inland locations, heavy industrial structures, weaker capabilities in energy-saving and emission-reduction technologies, and greater environmental pollution pressures, generally demonstrated lower energy efficiency.

At the provincial and municipal levels, Shanghai and Zhejiang maintained full energy efficiency throughout the study period, demonstrating outstanding performance in per capita GDP and environmental pollution control. Jiangsu occupied the efficiency frontier between 2011 and 2017, experiencing a slight decline thereafter to 0.871 by 2020. Anhui achieved efficiency between 2011 and 2012 before gradually declining to 0.711 by 2020. The three provinces in the central region, Jiangxi, Hubei, and Hunan, all exhibited fluctuating declines in energy efficiency. Despite relatively rapid economic development, coordination between environmental protection and energy efficiency improvements remained inadequate. In the upstream region, while Chongqing (average 0.753) recorded relatively high efficiency, Yunnan (0.494) and Guizhou (0.522) averaged below 0.6. This reflects constraints on energy efficiency stemming from later economic development and lower technological levels. During the study period, none of the provinces in the middle and upper reaches achieved the average energy efficiency level. Consequently, most provinces failed to attain an energy efficiency score of 1 during the sample study period, indicating that their DEA analysis was ineffective and that significant room for improvement exists.

4.4. Configuration impact analysis of the energy efficiency in the Yangtze River Economic Belt

The improvement of energy efficiency in the Yangtze River Economic Belt is a comprehensive "configuration" effect that results from the concurrent influence of multiple factors, and conventional regression analysis methods are difficult to use for analyzing the synergistic effect of multiple variables. Therefore, fsQCA is further used to analyze the influencing factors of energy efficiency in the Yangtze River Economic Belt, and then we explore the implementation paths for improving energy efficiency in the regions of Yangtze River Economic Belt.

4.4.1. Variable design

A. Result Variable:

Energy efficiency of various provinces and cities in the Yangtze River Economic Belt is used as the result variable to indicate the development status of energy use in each province and city.

B. Conditional Variables:

The selection of variables could have a significant impact on research outcomes in the empirical analysis. According to the characteristics of the fsQCA method, in the case that the number of conditional variables increases, the number of conditional combinations for the result variable would increase exponentially. Therefore, for a sample size of 10-50, 3-8 conditional variables are normally selected. Based on a related study in the literature, factors are selected to investigate the configurational impacts on energy efficiency in the Yangtze River Economic Belt, including economic development level, industrial structure, government regulation, degree of openness, technological level, and environmental protection investment. The selected factors are specified in Table 4.

Table 4. Specifications of the selected factors for the configuration impact analysis.

Conditional Variable	Variable Explanation
Economic Development	GDP Per Capita
Industrial Structure	Added value of the tertiary industry /GDP
Government Regulation	Local fiscal expenditure /GDP
Openness Degree	Total export-import volume /GDP
Technological Level	R&D expenditure/GDP
Environmental Investment	Total investment in industrial pollution /GDP

4.4.2. Data calibration

Before using the Qualitative Comparative Analysis (QCA) method [32], it is crucial to calibrate the data of the result variable and the conditional variables, and the Ragin's direct method is adopted for the data calibration [33]. The 95%, 50%, and 25% quantile values of the conditional variables are used as the anchor points for the complete membership point, cross point, and incomplete membership point, respectively. The fsQCA3.0 software is then used to calibrate the variables. The membership degree ranges from 0 to 1, and the higher values indicate a higher degree of membership; conversely, the lower values indicate a lower degree of membership. Results of the data calibration are illustrated in Table 5.

Table 5. Results of the data calibration for variables.

Variables	Complete Membership	Cross Point	Incomplete Membership	Unit
Energy Efficiency	1.000	0.748	0.508	-
Economic Development	107425	44513	33561	RMB
Industrial Structure	61.57	47.79	43.61	%
Government Regulation	34.55	22.22	13.50	%
Openness Degree	12.66	2.00	0.79	‰
Technological Level	31.42	16.82	7.53	‰
Environmental Investment	12.02	7.29	4.06	‱

4.4.3. Necessity test

After the data calibration, the necessity of individual conditional variables is needed to test the result variable. The necessity test primarily examines the consistency and coverage between the conditional variables and the result variable. The consistency refers to the sufficiency of a conditional variable for the result variable, and the coverage refers to the necessity of a conditional variable for the result variable [34]. If the consistency of a certain conditional variable exceeds the threshold of

0.9, then this conditional variable is a necessary condition for the result variable [33]. Table 6 lists the necessity analysis results of the influencing factors for energy efficiency in the Yangtze River Economic Belt. More specifically, the consistency of each conditional variable was below the necessary threshold of 0.9. This result indicates that all conditional variables have passed the consistency test, revealing the complexity of the configuration path for energy efficiency in the Yangtze River Economic Belt. Hence, the conditional variables need to be interconnected and matched to jointly influence the energy efficiency of the regions in the Yangtze River Economic Belt.

Table 6. The necessity test result of each influencing factor.

Variables		Energy Efficiency	
		Consistency	Coverage
Economic Development	ED	0.893	0.906
~ Economic Development	~ED	0.506	0.515
Industrial Structure	IS	0.696	0.743
~ Industrial Structure	~IS	0.626	0.595
Government Regulation	GR	0.530	0.563
~ Government Regulation	~GR	0.873	0.834
Openness Degree	OP	0.854	0.906
~ Openness Degree	~OP	0.519	0.496
Technological Level	TL	0.888	0.889
~ Technological Level	~TL	0.532	0.537
Environmental Investment	EI	0.613	0.615
~ Environmental Investment	~EI	0.627	0.632

4.4.4. Configuration path analysis

Using the fsQCA3.0 software, a specific configuration analysis is further conducted by setting the original consistency, PRI consistency, and case frequency thresholds as 0.8, 0.5, and 1 respectively. In accordance with practice, the results of the intermediate solution with universality and guidance are used to explain the research problem [33]. Under the premise of satisfying consistency and coverage, four configuration paths are identified, which are depicted in Table 7. More specifically, "●" indicates the presence of a core condition; "•" indicates the presence of a peripheral condition; "⊗" indicates the absence of a core condition; "⊗" indicates the absence of a peripheral condition; and a blank space indicates that presence or absence is acceptable.

Regarding the configuration table, the consistency and coverage corresponding to the overall solution and each individual path need to be further analyzed. A higher consistency indicates a more sufficient analysis result, and a higher coverage indicates a more reliable analysis result. Overall, the consistency was 0.963, indicating that all conditional variables ensure a high degree of explanation for the energy efficiency in the Yangtze River Economic Belt. Moreover, the coverage of the overall solution was 0.723, indicating that the four configuration paths could cover 72.3% of the sample cases in the regions of the Yangtze River Economic Belt.

From the perspective of examining individual configuration paths, there are four factor condition configuration paths with a significant impact on the energy efficiency. The original coverages of the four configuration paths were 0.280, 0.452, 0.398, and 0.255, which covered a considerable number of sample cases. Moreover, the consistency of these four configuration paths was above 0.9, indicating a strong degree of explanation for the energy efficiency.

Table 7. The configuration table of energy efficiency in the Yangtze River Economic Belt.

Conditional Variables		Configuration Analysis Results			
		CP.A.	CP.B.	CP.C.	CP.D.
Economic Development	ED		●	●	●
Industrial Structure	IS	⊗	•	⊗	•
Government Regulation	GR	⊗	•	⊗	•
Openness Degree	OP	⊗		⊗	•
Technological Level	TL	●	●	⊗	⊗
Environmental Investment	EI	●	●	●	⊗
Original Coverage		0.280	0.280	0.280	0.452
Unique Coverage		0.014	0.014	0.014	0.235
Consistency Level		0.969	0.969	0.969	0.992
Overall Consistency		0.963			
Overall Coverage		0.723			

A. Configuration path A (CP.A.) – environmental-technology oriented

In CP.A. (~IS~GR~OP*TL*EI), the original coverage was 0.280, the unique coverage was 0.014, and the consistency level was 0.969, covering one case. The CP.A. features the presence of technological level (TL) and environmental protection investment (EI) as core conditions, with the absence of industrial structure (~IS), government regulation (~GR), and openness degree (~OP) serving as peripheral conditions. These five variables work together to enhance the energy efficiency. The typical characteristic of this factor combination is that the high technological level and the substantial environmental investment jointly and dominantly drive the improvement of regional energy efficiency. In other words, if a region has reached a certain level of technological advancement and sufficiently invests in environmental protection, the energy efficiency could likely be improved. Taking Anhui as an example, in this configuration path CP.A., Anhui is in the downstream region of the Yangtze River Economic Belt with relatively developed economy; if Anhui is coupled with a senior technological level and sufficient environmental investments, the emission reduction could be effectively and potentially enhanced, thus further improving its energy efficiency.

B. Configuration path B (CP.B.) – economy driven enabled by environmental technology

In CP.B. (ED*IS*OP*TL*EI), the original coverage was 0.452, the unique coverage was 0.235, and the consistency level was 0.992, covering three cases. The CP.B. features the presence of economic openness (ED), technological level (TL), and environmental protection investment (EI) as core conditions, with industrial structure (IS) and government regulation (GR) serving as peripheral conditions. These five variables jointly enhance energy efficiency. The typical characteristic of this factor combination is the further development of economic levels based on improved technological advancements and increased environmental investments. Moreover, sound governmental regulations positively influence the energy market, and reasonable planning of industrial structures lead to the rational energy usage, thereby jointly enhancing the regional energy efficiency. This suggests that if a region has reached a certain level of environmental investments and technological development, coupled with the strong economic strength, its energy efficiency could likely be improved. In this configuration path CP.B., Shanghai, Jiangsu, and Zhejiang are taken as examples, which are in the downstream of the Yangtze River Economic Belt, with certain economic advantages due to their proximity to the sea in the east. Moreover, during the economic development, Shanghai, Jiangsu, and Zhejiang focus on "environment + technology" policies with a strong awareness of energy conservation and environmental protection. Under the guidance of the government, green industrial clusters are vigorously cultivated, and pollutant emissions are reduced. Hence, jointly promoting the green and low-carbon development of the region provides an effective path for improving the energy efficiency.

C. Configuration path C (CP.C.) - environmental-friendly led by the economy

In CP.C. (ED~IS~GR~OP~TL*EI), the original coverage level was 0.398, the unique coverage level was 0.089, and the consistency level was 0.952, covering one case. The CP.C. features the presence of economic development level (ED), absence of technological level (~TL), and environmental protection investment (EI) as core conditions, with the absence of industrial structure (~IS), government regulation (~GR), and openness degree (~OP) serving as peripheral conditions. These six variables jointly enhance the energy efficiency. The typical characteristic of this factor combination is the further increase in environmental investments based on the economic development, which jointly enhances the energy efficiency. In other words, if a region sufficiently invests in environmental protection, with a good momentum of economic development, the energy efficiency is likely improved. In this configuration path CP.C., Hunan could be explained as a case that belongs to the midstream region, which indicates that focusing on environmental protection and increasing environmental investments on the basis of a high level of economic development are conducive to the improvement of local energy efficiency.

D. Configuration path D (CP.D.) – economy development oriented

In CP.D. (ED*IS*GR*OP~TL~EI), the original coverage level was 0.255, the unique coverage rate was 0.027, and the consistency level was 0.979, covering one case. The CP.D. takes the level of economic development (ED) and the absence of technological level (~TL) as the core conditions, with the industrial structure (IS), government regulation (GR), openness degree (OP), and absence of environmental protection investment (~EI) as marginal conditions. These six variables simultaneously play a role in improving the energy efficiency. The typical characteristic of this factor combination is the dominance of a high level of economic development, and with a reasonable industrial structure (IS), government regulation (GR), and the openness degree (OP) as the supplement, help raise of regional energy efficiency level. In other words, if a region has a strong economic development momentum, a reasonable industrial structure, appropriate government intervention for markets, and a high degree of openness, the energy efficiency would likely be improved. In this configuration path CP.D., taking Chongqing in the upstream region of the Yangtze River Economic Belt as an example, based on a high level of economic development and the virtuous governmental guidance of the energy market, increasing the share of the tertiary industry to optimize the industrial structure and increasing foreign trade to enhance the openness could further improve the energy efficiency of the region.

Regarding the above, the conditional variables of energy efficiency in the Yangtze River Economic Belt could be combined into multiple paths. Different provinces and cities need to find suitable development strategies according to their own advantages to promote the improvement of energy efficiency.

5. Conclusion and advice

In this study, we first extracted key words from "dual carbon" policy texts using the LDA topic model, and an evaluation index system for energy efficiency is then constructed scientifically. Second, the SBM-Undesirable model is employed to measure the energy efficiency of 11 provinces and cities in the Yangtze River Economic Belt from 2011 to 2020. Based on the measurement, the influence of multiple factors on energy efficiency are analyzed. The research insights include:

Overall, the Yangtze River Economic Belt shows a gentle downward trend during the study period, indicating room to improve on energy efficiency.

From the perspective of the three major regions, the average energy efficiency of the Yangtze River Economic Belt exhibits a development pattern of "downstream > midstream > upstream". At the provincial and municipal level, the average energy efficiency of 11 provinces and cities fail to reach an efficient state.

Four configuration paths that affect energy efficiency are identified and analyzed, which facilitate the improvement of energy efficiency in diverse regions of the Yangtze River Economic Belt under distinct combination modes.

Based on the above analysis, the following advice for the development of energy efficiency is proposed:

Optimizing resource allocation and strengthening information exchange between provinces and cities could help, while promoting sustainable development for the economy. According to the configuration analysis results, as a core condition for high energy efficiency, the level of regional economic development plays a significant role in promoting the energy efficiency in the Yangtze River Economic Belt. First, the analysis indicates that the Yangtze River Economic Belt has tremendous potential for energy conservation and emission reduction. Therefore, in the process of economic development, rational allocation of resources, input-output structure optimization, actively usage of clean energy, low-carbon economy development, and sustained economic growth should receive attention in the Yangtze River Economic Belt to achieve the "dual carbon" target. Second, the analysis further reveals developmental imbalance and excessive polarization within the Yangtze River Economic Belt, which is mainly reflected in the development pattern of "high downstream, medium midstream, and low upstream." Therefore, local governments should gradually relieve administrative controls in the Yangtze River Economic Belt and strengthen information exchange between provinces and cities. If the geographical restrictions could be broken, and energy industries could transfer between provinces, energy factors would be able to flow rapidly, and the distortions in the market prices of energy factors would be reduced. Hence, the local advantages of downstream areas could be utilized for leading the common development of midstream and upstream areas to achieve the overall sustained growth in the regional economy of the Yangtze River Economic Belt. For differentiated implementation: Downstream focuses on phasing out backward high-energy industries and outputting capital and management experience; midstream strictly sets industry access thresholds for incoming industrial transfers and smoothes cross-provincial factor flow; and upstream gives priority to developing clean hydropower and constraining blind expansions of high-carbon heavy industries.

Strengthening scientific research efforts and innovation capabilities could help, promoting the improvement of environmental technology. According to the configuration analysis results, as a core condition for high energy efficiency, the technological level plays a significant role in promoting the energy efficiency in the Yangtze River Economic Belt. Therefore, specific measures should be employed in the Yangtze River Economic Belt, which include: First, it is necessary to strengthen scientific research efforts by increasing financial investments in scientific research institutions to promote technological innovation. Second, it is necessary to formulate relevant policies to attract high-quality scientific research talents and prevent the loss of scientific research talents, thereby ensuring the stable and continuous outputs of novel scientific research outcomes. Third, based on strengthening scientific research innovation capabilities and stimulating the innovation vitality and capabilities of enterprises, a scientific innovation mechanism should be established to enhance a close collaboration between enterprises and scientific research institutions that further drive the continuous development of technological advancements in energy conservation, emission reduction, and environmental pollutant treatment. Thus, innovative technologies could be applied to actual production to continuously improve the energy efficiency in the Yangtze River Economic Belt. For differentiated implementation: Downstream devotes fiscal funds to cutting-edge low-carbon technology R&D; midstream mostly introduces mature energy-saving technologies and professional talents; and upstream popularizes proven environmental protection technologies and builds technical cooperation channels with downstream research institutes.

Formulating environmental policies and strengthening environmental awareness could help, which is based on increasing investments in environmental protection. According to the configuration analysis results, as a core condition for high energy efficiency, the variable of environmental investments plays a significant role in promoting the energy efficiency development in the Yangtze River Economic Belt. Great potential for energy conservation and emission reduction exist in the Yangtze River Economic Belt, indicating that the concept of green environmental protection is fully accepted and fulfilled. Therefore, governments should continuously optimize the design and supervision of energy policies and improve the emission standards for enterprises. Moreover, enterprises should raise awareness about how "lucid waters and lush mountains are invaluable assets", and put this into practical actions. Environmental awareness can serve as a key supporting mechanism linking the "soft environment" and the "hard environment", enabling sustained investment in environmental technology and comprehensive improvement in energy efficiency. For differentiated implementation: Downstream adopts market-based tools such as carbon trading and stricter emission standards; midstream tightens daily environmental supervision and rectifies scattered polluting firms; and upstream increases fiscal ecological transfer payment and develops eco-friendly characteristic industries.

6. Limitations and future perspectives

This research has limitations in data coverage and analytical depth. Going forward, we will extend the research period with updated data. On this basis, we will apply Super-SBM to rank fully efficient provinces, supplement convergence and Dagum Gini decomposition for spatial disparity analysis, and implement more robustness checks for fsQCA by adjusting relevant calibration parameters.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflicts of Interest

The authors declare no conflicts of interest.

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