

Spatiotemporal Distribution and Efficiency Measurement of Major Global Electricity Export Countries

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Abstract With the continuous growth of global energy demand and increasing environmental concerns, electricity, as a critical energy carrier, has become increasingly vital in global economic and social development. This study systematically analyzed the spatiotemporal distribution characteristics and efficiency evolution of the top 50 global electricity-exporting countries from 2014 to 2023 using the DEA-BCC model and Malmquist index method. Key findings include: (1) Electricity exports exhibited significant regional agglomeration, with Europe maintaining dominance through its mature transnational grid systems, while China emerged as Asia's core driver, boosting regional export volumes. (2) Efficiency measurements revealed a decline in the number of DEA-strongly efficient countries (from 4 to 3) and an increase in weakly efficient countries (to 6), primarily due to insufficient scale efficiency. Major exporters such as the U.S. and Italy remained inefficient owing to suboptimal resource allocation. (3) Total factor productivity (TFP) showed an average annual growth of 7.7%, driven by technological progress, but scale efficiency stagnated (index: 0.899), indicating room for scaling optimization.

Keywords: Electricity, Spatiotemporal distribution, Efficiency, DEA-BCC, Malmquist index

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1. Introduction

With the continuous growth of global energy demand and the continuous transformation of energy structure, electricity, as a clean and efficient form of energy, is becoming increasingly important in international trade. According to data from the International Energy Agency, electricity production accounts for about 40% of the total global energy-related carbon dioxide emissions, a proportion that tops the list of all industries. The export trade in electricity not only reflects the differences in energy resource endowment and energy industry development among countries, but also, to a certain extent, influences the supply and demand balance and price fluctuations in the global energy market.

Current global electricity markets exhibit distinct regional characteristics, with production and exports increasingly concentrated. For instance, Germany, Norway, and China dominate exports due to abundant hydropower, thermal, and nuclear resources [1]. In recent years, research on global energy trade has gradually increased [2], but it mainly focuses on the traditional fossil energy sector, and there are relatively few studies on the export trade of electric power. For example, Ze He et al. [3] explored in detail the evolution characteristics of the

global energy trade network and the competitiveness of the international trade from the perspective of complex network, and pointed out that the world energy trade network has the characteristics of "small world". It is pointed out that the world energy trade network has the characteristics of "small world" and scale-free, and that the center of gravity of energy export has gradually shifted from East Asia, the Middle East, Australia and Europe to regions such as Eastern Europe, the Middle East, North America, Australia and West Africa. In addition, based on the fossil energy trade data of the countries along the route from 2000 to 2018, Xia and Du [4] studied the structure of the energy trade of the 21st Century Maritime Silk Road and the evolution of the trade relationship with China, and found that the scale of the trade along the route has been expanded in recent years, but the proportion of the export has declined as a whole. In terms of power trade efficiency measurement, relevant research mainly focuses on the field of renewable energy. Chong Zhao et al. [5] explained the trade situation of fossil energy and renewable energy through social network analysis, and found that the renewable energy trade dependence network showed a higher degree of overall dependence, and its dependence on fossil energy trade has a substitution effect. Wang Li et al. [6] studied the geo-factor-driven mechanism of Arctic energy development, pointing out that Arctic countries are mostly energy

exporters, while Arctic observer countries are mostly energy importers, and that China's energy imports from Arctic countries are relatively small, but with greater potential.

Although existing studies have provided important perspectives for understanding the global energy trade pattern, systematic studies on the spatial and temporal distribution and efficiency measurement of the world's major power export trade are still insufficient, and the relevant studies have focused on the hierarchical and spatial spheres of power linkages between China and other countries [7], along the "One Belt, One Road" route [8] and the European region [9]. and spatial domains. As a special energy product, the trade of electric power is affected by various factors such as technology, policy and geography, which requires further in-depth exploration of its distribution characteristics and efficiency performance on a global scale. Understanding the spatial and temporal distribution characteristics of foreign power import and export trade can find the center of gravity of international power trade, so that we can better optimize the allocation of power resources, improve the efficiency of energy use and promote the sustainable development of the economy.

2. Research Methods

2.1. DEA-BCC Model

Data Envelopment Analysis (DEA), proposed by Charnes et al. [10] in 1978, evaluates efficiency under variable returns to scale (BCC model). The BCC model decomposes comprehensive efficiency into pure technical efficiency (PTE) and scale efficiency (SE), enabling precise identification of inefficiency sources. Given the diversified and scaling nature of renewable energy development, the BCC model was selected for this study.

The BCC model assumes n decision-making units (DMUs) with m inputs and s outputs. For DMU_j , inputs and outputs are denoted as x_{ij} and y_{rj} , respectively. The model is formulated as (1):

$$\begin{aligned} & \max \theta_0 \\ & \left\{ \begin{array}{l} \sum_{j=1}^n x_{ij} \lambda_j + S_i^- = \theta x_{ij}, \\ s.t. \sum_{j=1}^n y_{rj} \lambda_j - S_r^+ = y_{rj}, \\ \sum_{j=1}^n \lambda_j = 1, \quad \theta, \lambda_j, S_r^+, S_i^- \geq 0, \\ i \in (1, 2, \dots, m), r \in (1, 2, \dots, s), j \in (1, 2, \dots, n) \end{array} \right. \quad (1) \end{aligned}$$

In the formula, S_i^- and S_r^+ are relaxation variables, λ_j is then the weight of each DMU indicator, θ represents pure technical efficiency, if $\theta_0 = 1, S_i^- = 0, S_r^+ = 0$, this

decision unit is a valid DEA; if $\theta_0 = 1$, but one of the slack variables is not zero, or $\theta_0 \neq 1$, $SE = 1$, this decision unit DEA is weakly valid; otherwise it is DEA invalid.

2.2. Malmquist Index

The Malmquist index can be used to describe the change of total factor productivity of decision-making unit in the period before and after, and the reasons leading to this trend of change. When the data to be evaluated DMU is panel data containing observations at multiple time points, the Malmquist Total Factor Productivity Index can analyze the changes in the technical efficiency of decision-making units and the changes in production technology, so it can be used to vertically compare the efficiency values of different time periods from a dynamic point of view. Total factor productivity less than 1 indicates that total factor productivity declined compared with the previous year; total factor productivity greater than 1 indicates that total factor productivity increased compared with the previous year; total factor productivity equal to 1 indicates that there is no change in total factor productivity compared with the previous year. Total factor production index can be further decomposed into technical efficiency index and technical progress index, in which the technical efficiency index reflects the organizational management level of decision-making units, and the technical progress index reflects the level of technological innovation of decision-making units. The details are as in formula (2).

$$MPI = \sqrt{\frac{D_t(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)}} \times \sqrt{\frac{D_{t+1}(x_{t+1}, y_{t+1})}{D_{t+1}(x_t, y_t)}} \quad (2)$$

In the formula, MPI is Malmquist Index, D_t and D_{t+1} denote the distance function for periods t and $t+1$, respectively.

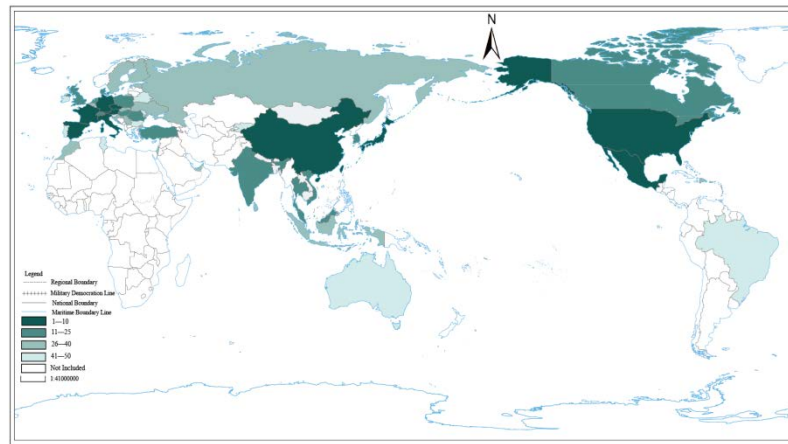
3. Empirical Research

3.1. Data Sources

Panel data for the top 50 electricity-exporting countries (2014–2023) were sourced from the World Bank and processed using Excel and DEAP 2.1.

3.2. Spatiotemporal Distribution

In order to have a clearer picture of the spatial and temporal changes in electricity export trade, so with the help of Adobe Illustrator 2021 software, the electricity trade volume of each country in 2014 and 2023 is divided into four echelons from deep to shallow, and plotted as a Lisa diagram, as shown in Figure 1.



(a) 2014



(b) 2023

Note: This map is based on the standard map GS(2016)2765 downloaded from the standard map service website of the National Administration of Surveying, Mapping and Geographic Information of China. The base map has not been modified.

Figure 1. Spatial distribution of trade volume of the world's top 50 electricity exporters in 2014 and 2023

As can be seen from Figure 1, the global major electricity export trade in 2014 showed a significant concentration trend, mainly concentrated in Europe, North America and Asia.

In 2014, there were 27 countries in Europe among the top 50 countries in the electricity export trade, and there were even 6 countries in Europe ranked in the top 10, which were Germany, Italy, France, Austria, the Czech Republic and Spain. Specifically, the power exports of European countries not only the number of dominant, and these countries have a certain representative of the power export trade model and development level. This stems from the relatively mature power market reforms in Europe, where cross-border power exchanges and grid interconnections have made intra-regional power supply more stable and efficient. Countries such as Germany, France, and Italy, represented by their strong power production capacity, advanced technological facilities, and well-established power networks, have driven the growth of their power exports.²⁰²³ Europe still occupies a dominant position in the global power export market and its power export capacity continues to grow. Although the top 10 countries have changed from 6 in 2014 to 5, the number of top 50 European countries has increased from 27 in 2014 to 30 in 2023, which also indicates a further

improvement in Europe's electricity production and export capacity.

In 2014, there were 15 Asian countries in the top 50 and two Asian countries in the top 10, namely China and Japan. Although the number of Asian countries is relatively inferior to that of Europe, China, as the world's top electricity exporter, exports almost as much as the entire European countries' exports combined, which gives Asia a significant advantage in the total electricity export trade.²⁰²³ Although the number of Asian countries ranked in the top 50 declines by only one, the number of countries in the top 10 changes from two to three, suggesting that, despite the global electricity market pattern in the changes, Asian countries still maintain a relatively stable position in electricity exports. In particular, China, as the world's largest exporter of electricity, continues to play an important role in promoting electricity exports in Asia. Despite the dominance of European countries in power exports, the Asian region's power export capacity remains highly competitive and has the potential for continued growth. Only a few countries have experienced a decline in power export capacity, while the performance of other countries has been relatively flat, demonstrating the stability and continuity of the Asian region's power exports.

Located in North America, the United States, Mexico and Canada are in the top 50, the first two are in the top 10, which shows that North America also occupies a certain position in the global electricity export market, but compared to Europe and Asia, its electricity export scale and market share is still relatively small, and there is still a lot of room for competitiveness to improve. The remaining continents account for a relatively small number of power exporters and trade volume, in the fourth echelon, indicating that these regions play a relatively weak role in the global power export trade, the market share of power exports is relatively low, and has not yet formed a strong competitiveness. 2023, the power exports of the other continents basically remained unchanged, with a relatively small volume of exports, indicating that these regions are still limited in the capacity of the power exports, and failed to form a strong competitive advantage in global electricity trade.

In summary, from 2014 to 2023, the center of gravity of electricity exports is in Europe, Asia and North America, with the dominant position of Europe further strengthened, while Asian electricity exports also perform more prominently, led by China, especially as its share in total global electricity exports continues to rise. Power

exporting countries in other continents have not changed significantly, but are still in a marginal position in global power exports, failing to realize an effective breakthrough.

3.3. Efficiency Evaluation

3.3.1. Data collection and Selection of Indicators

The electricity industry data used in this paper comes from the electricity trade data provided by the World Bank for all countries in the world, and the collected indicator data are organized through EXCEL tables. The decision unit of this paper is the world's top 50 electricity trade exporting countries, and the number of population, land area and GDP of each country's country are selected as input indicators, and the amount of electricity export trade of each country is an output indicator.

3.3.2. Evaluation Results

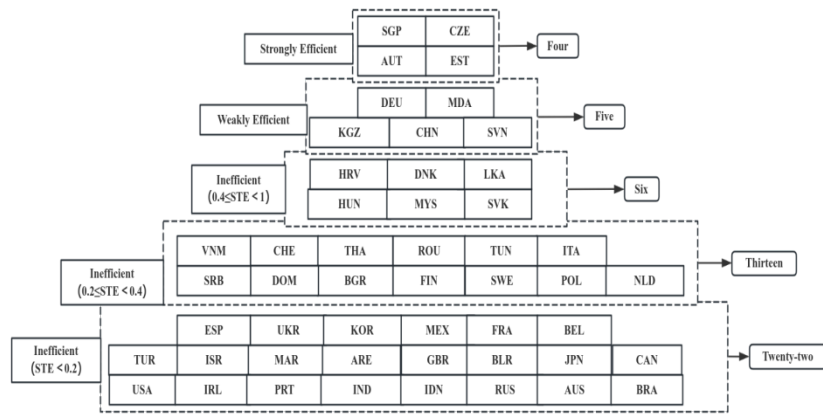
Using DEAP 2.1 software, this paper evaluated the total factor productivity of electricity exports of the top 50 countries in the world for the period 2014-2023 using equation (1), as shown in [Table 1](#).

Table 1. Evaluation of Total Factor Efficiency in Electricity Export Trade in 2014 and 2023

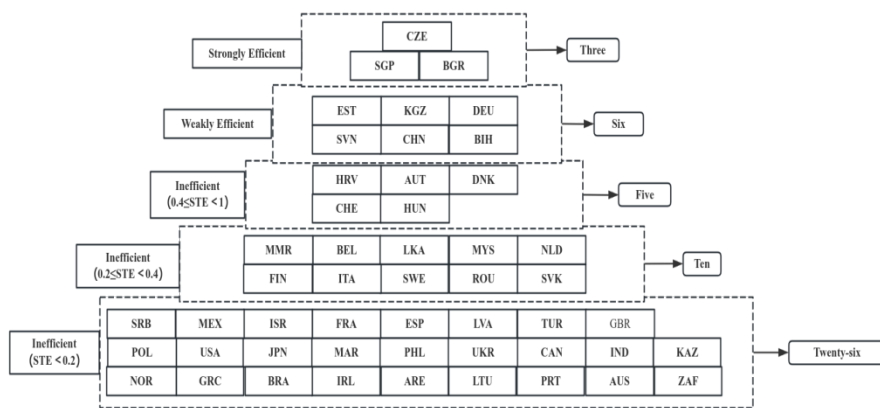
2014						2023					
		TE	PTE	SE				TE	PTE	SE	
1	CEZ	1	1	1	-	1	CEZ	1	1	1	-
2	SGP	1	1	1	-	2	SGP	1	1	1	-
3	BRA	0.005	0.009	0.569	irs	3	BRA	0.005	0.014	0.365	irs
4	USA	0.078	0.117	0.664	drs	4	USA	0.09	0.171	0.523	drs
5	ITA	0.252	0.299	0.842	drs	5	ITA	0.259	0.317	0.816	drs
6	MEX	0.168	0.268	0.625	drs	6	MEX	0.171	0.697	0.245	drs
7	TUR	0.143	0.15	0.954	drs	7	TUR	0.125	0.127	0.988	irs
8	GBR	0.1	0.1	0.994	irs	8	GBR	0.112	0.117	0.957	irs
9	BUL	0.218	0.321	0.679	irs	9	BUL	1	1	1	-
10	NED	0.337	0.34	0.991	irs	10	NED	0.362	0.382	0.948	irs
11	CHE	0.322	0.427	0.754	irs	11	CHE	0.452	0.515	0.878	irs
12	IND	0.036	0.04	0.906	drs	12	IND	0.062	0.112	0.554	drs
13	SWE	0.201	0.213	0.941	irs	13	SWE	0.254	0.257	0.988	irs
14	BEL	0.148	0.342	0.433	irs	14	BEL	0.362	0.474	0.764	irs
15	ISR	0.12	0.533	0.225	irs	15	ISR	0.152	0.521	0.292	irs
16	SLO	0.198	1	0.198	irs	16	SLO	0.253	1	0.253	irs
17	IRL	0.048	0.394	0.121	irs	17	IRL	0.053	0.369	0.144	irs
18	CHN	0.322	1	0.322	drs	18	CHN	0.195	1	0.195	drs
19	GER	0.76	1	0.76	drs	19	GER	0.557	1	0.557	drs
20	FRA	0.161	0.172	0.937	drs	20	FRA	0.15	0.15	1	-
21	AUT	1	1	1	-	21	AUT	0.681	0.694	0.982	irs
22	JPN	0.086	0.101	0.851	drs	22	JPN	0.082	0.087	0.943	irs
23	ESP	0.187	0.19	0.985	drs	23	ESP	0.15	0.15	0.998	-
24	MAS	0.466	0.501	0.93	drs	24	MAS	0.278	0.287	0.97	irs
25	POL	0.201	0.202	0.996	drs	25	POL	0.1	0.136	0.732	irs
26	DEN	0.759	0.829	0.915	irs	26	DEN	0.528	0.647	0.816	irs
27	ROU	0.261	0.269	0.969	drs	27	ROU	0.234	0.274	0.854	irs
28	HUN	0.529	0.545	0.97	irs	28	HUN	0.432	0.536	0.806	irs
29	CAN	0.082	0.085	0.968	irs	29	CAN	0.063	0.064	0.987	irs
30	CRO	0.768	0.8	0.96	irs	30	CRO	0.752	0.935	0.804	irs
31	LKA	0.575	0.658	0.874	irs	31	LKA	0.345	0.632	0.546	irs
32	FIN	0.209	0.241	0.867	irs	32	FIN	0.268	0.275	0.976	irs
33	SVK	0.443	0.697	0.635	irs	33	SVK	0.208	0.542	0.384	irs
34	EST	1	1	1	-	34	EST	0.976	1	0.976	irs

2014						2023					
35	UKR	0.187	0.189	0.993	irs	35	UKR	0.064	0.156	0.413	irs
36	SRB	0.377	0.432	0.874	irs	36	SRB	0.191	0.516	0.37	irs
37	UAE	0.111	0.278	0.399	irs	37	UAE	0.049	0.259	0.189	irs
38	MAR	0.114	0.13	0.882	irs	38	MAR	0.077	0.197	0.394	irs
39	POR	0.041	0.219	0.187	irs	39	POR	0.018	0.232	0.077	irs
40	AUS	0.013	0.056	0.23	irs	40	AUS	0.012	0.051	0.228	irs
41	KGZ	0.673	1	0.673	irs	41	KGZ	0.689	1	0.689	irs
42	TUN	0.26	0.299	0.869	irs	42	NOR	0.06	0.248	0.243	irs
43	BLR	0.086	0.224	0.382	irs	43	RSA	0.005	0.028	0.174	irs
44	MDA	0.68	1	0.68	irs	44	LAT	0.132	0.884	0.149	irs
45	KOR	0.173	0.18	0.96	irs	45	BIH	0.097	1	0.097	irs
46	DOM	0.25	0.589	0.424	irs	46	LTU	0.049	0.6	0.081	irs
47	THA	0.274	0.301	0.909	drs	47	KAZ	0.007	0.124	0.057	irs
48	VIE	0.366	0.402	0.911	drs	48	PHI	0.065	0.125	0.517	irs
49	INA	0.034	0.034	0.978	drs	49	MYA	0.215	0.283	0.758	irs
50	RUS	0.02	0.021	0.936	drs	50	GRE	0.059	0.233	0.252	irs

Note: 1) Country names are abbreviated, the same below; 2) TE is the integrated efficiency with variable returns to scale, i.e., total factor carbon efficiency; PTE is the pure technical efficiency, which is the SE scale efficiency; TE=PTE×SE. 3) irs, -, drs represent that the decision unit is in the stage of increasing returns to scale, constant returns to scale, and diminishing returns to scale, respectively.



(a) 2014



(b) 2023

Figure 2. Electricity export efficiency of the world's major electricity exporting countries in 2014 and 2023

3.3.3. Analysis of Evaluation Results

① Cross-sectional data analysis

In order to make the display of evaluation results more intuitive, so the results will be drawn pyramid diagram, in which the gradient division by efficiency evaluation

results, divided into strong effective, weakly effective, ineffective (ineffective but comprehensive efficiency ≥ 0.4) ineffective (ineffective but the comprehensive efficiency in the range of 0.2 to 0.4) very ineffective (ineffective and the comprehensive efficiency < 0.2) five gradients, as shown in Figure 2.

As can be seen from Figure 2, the DEA strongly effective countries change from four in 2014 to three in 2023, of which Singapore and the Czech Republic's electricity export efficiency are both in the strong effective, indicating that they have a greater advantage in the utilization of resources and technical efficiency; Estonia and Austria change from strongly effective to weakly effective and ineffective, respectively, mainly by the impact of the purely technical efficiency, indicating that the ratio of its input factors has become irrational. Bulgaria has changed from ineffective to strong effective, and the efficiency of electricity export has improved significantly, indicating that its resource factor ratio and management level have reached a high level, which can provide a reference for other ineffective countries.

Weakly effective countries have changed from 5 to 6, and the reason why these countries are in weakly effective is affected by scale efficiency. Among them, the world's top 2 electricity exports of China and Germany are in the stage of diminishing returns to scale, the comprehensive efficiency in 2023 have declined, are caused by scale efficiency reduction, the reason may be that the scale of electricity exports increased, in the management of negligence, resulting in scale efficiency is low; the rest of the countries are in the stage of diminishing returns to scale, these countries if the increase in the scale of the inputs can increase the total factor productivity of their electricity exports. The number of ineffective countries is 41 in both 2014 and 2023, with the vast majority of ineffective countries in the increasing returns to scale stage.

The top 10 electricity exporting countries, including the

United States, Italy, Japan, Spain, Mexico and France, are all ineffective and in the stage of diminishing returns to scale, and the reason for their ineffectiveness is that they are affected by purely technical efficiency, which indicates that the input factor ratios of these countries are irrational and that there is redundancy of input factors. Among the bottom 10 countries, Slovenia, Kyrgyzstan, Ireland and other countries have been in a weakly efficient state, resulting in their failure to achieve strong efficiency due to the influence of scale efficiency; Tunisia, Brazil, Portugal and other countries have been in an ineffective state, which is mainly due to the influence of pure technical efficiency.

② Analysis of changes in time dynamics

Among all the research subjects, 41 countries have been ranked in the top 50 in the world, in order to further understand the sources that affect the changes in the efficiency of each country, so this paper is analyzed with the help of the Malmquist index, and the results of the index for 41 countries, as shown in Table 2.

As can be seen in Table 1, the overall total factor productivity of the world's major electricity exporters grows by about 7.7% between 2014 and 2023, thanks to slight technological advances and improvements in technical efficiency. In particular, the average pure technical efficiency change index reaches 1.146. However, it is worth noting that the change in scale efficiency is not satisfactory, with an average sech of only 0.899, suggesting that most countries have failed to effectively improve their efficiency when expanding their scales, which suggests that more attention should be paid to the rationality of resource allocation and management efficiency.

Table 2. Malmquist Index

Country	effch	techch	pech	sech	tfpch	Country	effch	techch	pech	sech	tfpch
CHN	0.606	1.11	1	0.606	0.672	ROU	0.897	1.189	1.018	0.881	1.067
GER	0.733	0.987	1	0.733	0.724	SWE	1.265	0.929	1.205	1.05	1.175
USA	1.154	0.929	1.466	0.787	1.072	LKA	0.599	1.138	0.959	0.624	0.682
ITA	1.027	1.006	1.059	0.969	1.033	CRO	0.979	1.173	1.169	0.838	1.149
MEX	1.021	1.286	2.601	0.392	1.313	SVK	0.47	1.014	0.777	0.604	0.476
FRA	0.928	1.024	0.869	1.067	0.95	FIN	1.284	0.931	1.141	1.126	1.196
AUT	0.681	0.938	0.694	0.982	0.639	EST	0.976	0.99	1	0.976	0.967
CZE	1	1.027	1	1	1.027	BEL	2.442	0.852	1.385	1.764	2.08
JPN	0.948	0.873	0.856	1.107	0.828	UKR	0.343	1.23	0.825	0.416	0.422
ESP	0.8	1.087	0.79	1.013	0.87	UAE	0.441	1.002	0.931	0.474	0.442
MAS	0.597	1.222	0.572	1.042	0.729	SRB	0.506	1.269	1.195	0.423	0.642
TUR	0.873	1.143	0.844	1.035	0.999	ISR	1.27	0.835	0.979	1.298	1.06
GBR	1.125	0.932	1.168	0.963	1.048	MAR	0.676	1.23	1.514	0.446	0.831
NED	1.075	0.836	1.124	0.957	0.898	BUL	4.586	1.272	3.113	1.473	5.835
POL	0.496	1.011	0.676	0.735	0.502	BRA	1.031	1.23	1.605	0.643	1.269
DEN	0.696	1.004	0.78	0.892	0.699	POR	0.435	1.053	1.059	0.411	0.458
SGP	1	0.798	1	1	0.798	SLO	1.279	1.081	1	1.279	1.383
IND	1.723	1.222	2.815	0.612	2.106	KGZ	1.024	1.23	1	1.024	1.26
HUN	0.817	1.052	0.984	0.831	0.86	AUS	0.907	0.929	0.916	0.991	0.843
CAN	0.767	0.93	0.752	1.02	0.713	IRL	1.118	0.929	0.937	1.193	1.038
CHE	1.405	0.984	1.206	1.165	1.383	Mean	1.024	1.047	1.146	0.899	1.077

Note: "effch" is the index of technical efficiency change; "techch" is the index of technical progress; "pech" is the index of pure technical efficiency change; "sech" is the index of scale efficiency change; "tfpch" is the index of total factor productivity change. "sech" is the scale efficiency change index; "tfpch" is the total factor productivity change index.

Many countries have realized significant improvements in pure technical efficiency by improving internal management and operational processes. For example, the change indices of pure technical efficiency of Bulgaria and Belgium are 3.113 and 1.385 respectively, which are much higher than the average level, showing the great progress in the level of organizational management in these countries. On the contrary, some countries such as Austria and Ukraine are facing the problem of declining pure technical efficiency, which indicates their shortcomings in resource utilization and technology application.

Changes in scale efficiency reveal differences in the effectiveness of scale expansion strategies in different countries. Bulgaria and Belgium not only excel in technical efficiency, but also make significant breakthroughs in scale efficiency, reaching 1.473 and 1.764, respectively. This shows that they successfully combine scale expansion with efficiency improvement. In contrast, large electricity exporters such as China and Germany, despite having large volumes of electricity exports, have experienced challenges in managing scale growth, resulting in lower scale efficiencies. In addition, countries such as Slovakia and Portugal have experienced a marked decline in scale efficiency, reflecting the fact that these countries may have neglected to make the appropriate managerial adjustments and technical support when scaling up.

4. Conclusions

(1) The trend of regional concentration has increased significantly. Global electricity exports show a significant trend of regional concentration. European countries continue to dominate the global power market, thanks to their highly efficient power systems and cross-border grid interconnections, which have boosted the growth of their power exports. Asia has realized a significant increase in total electricity exports, led by China, which plays an important role in the region as the world's largest electricity exporter. In contrast, power exports from North America and other regions, while also in a position to do so, have a small market share and need to improve their competitiveness. Other regions still have limited power export capacity and have failed to develop strong competitiveness in the global market.

(2) In terms of electricity export efficiency, the DEA strongly effective countries change from four in 2014 to three in 2023, and weakly effective countries change from five to six, and these countries are in weakly effective because they are all affected by scale efficiency. There are 41 ineffective countries in both 2014 and 2023, and the vast majority of the ineffective countries are in the stage of incremental scale compensation. The top 10 electricity-exporting countries, including the United States, Italy, Japan, Spain, Mexico and France, are all ineffective and in

the stage of diminishing returns to scale, and the reasons for their ineffectiveness are all affected by purely technical efficiency, which suggests that the input factor ratios of these countries are irrational and that there is redundancy of input factors. Ranked in the bottom 10 countries, Slovenia, Kyrgyzstan, Ireland and other countries have been in a weakly effective state, resulting in its failure to reach a strong effective because of the impact of scale efficiency; Tunisia, Brazil, Portugal and other countries have been in an ineffective state, mainly by the impact of pure technical efficiency.

(3) The world's major electricity exporters as a whole have achieved total factor productivity growth, which is largely attributable to technological advances and internal management optimization. However, scale efficiency gains have not kept pace, which is a pressing issue especially for those countries that are trying to increase their electricity exports by scaling up. In order to remain competitive in the global electricity market, countries should focus on the rationalization of resource allocation and the simultaneous improvement of management efficiency, while continuing to promote technological innovation to ensure the sustainable development of electricity exports.

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