How to improve total factor energy efficiency under climate change: does export sophistication matter?

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Abstract
Climate change has a profound impact on human survival and development. Climate change is an energy and economic issue, which should be driven by technology. Total factor energy efficiency (TFEE) improvement is undoubtedly a breakthrough in solving energy problems. In this paper, the fixed effect model, impulse response function, and threshold regression model are used to test the complex relationship between export sophistication and TFEE. The results reveal that export sophistication improvement leads to higher TFEE. The impulse response results verify the existence of a phased and positive correlation between export sophistication and TFEE. Finally, the relationship between export sophistication and TFEE significantly varied across different threshold levels of regional corruption score, economic development, and openness. This article led the foundation for supporting China’s export sophistication promotion strategy and also provides a reference for energy efficiency improvement and energy crisis response in the post-pandemic era.

Keywords Export sophistication · Total factor energy efficiency · China · Threshold model

Introduction
Affected by the COVID-19 epidemic, energy exploration investment and other production activities were blocked, which aggravated the energy crisis (Chofreh et al. 2021). For example, China’s thermal power enterprises have fallen into a contradiction between power supply and demand recently (Xue et al. 2022; Ren et al. 2022). For the power demand side, the supply chains in various countries fail to return to normal during the epidemic. While China’s manufacturing orders surged due to effective epidemic prevention and control, and electricity demand soared (Wang et al. 2020). From January to August in 2021, China's electricity consumption totaled 5470.4 billion kWh, which is 13.8% more than last year. For the power supply side, the generation cost of power plants increased sharply due to the soaring price of coal, which led to production cuts and power brownouts. Many regions in China have implemented the policy of “switching off and power rationing” to deal with the problem of energy shortage, which affects regional economic development and brings inconvenience to people’s life. The TFEE improvement can provide countermeasures for the problem of energy shortage.
supply shortage (Xu et al. 2021; Rehman et al. 2021). The post epidemic era makes more stringent requirements for TFEE improvement. Energy efficiency optimization and energy structure transformation are imminent.

Technological progress is coupled with production instruments innovation, management mode change, and allocation efficiency improvement, which are crucial for TFEE improvement (Zhang et al. 2020; Hong et al. 2020). To some extent, export sophistication is a manifestation of technological progress, and it can improve TFEE through the “learning by exporting” effect (Findlay 1978; Gkypali et al. 2021; Wang et al. 2022a) and the upgrading of international division of labor. Specifically, on the one hand, export enterprises have been subject to various requirements in the long window of development (Lu et al. 2020), which will inevitably drive the continuous upgrading of enterprise product technology, the continuous optimization of product structure, and the continuous increase of product added value, resulting in the “learning by exporting” effect, so as to lift the simultaneous improvement of TFEE. On the other hand, with economic globalization deepening, developed countries will outsource low-cost and non-high-end technology links to other countries (Vu et al. 2021), and contractors can upgrade the original production technology (Liu et al. 2021). When the contracting country develops to a certain stage, it can be outsourced to other countries with relatively backward economy. With the gradual deepening of international division of labor in the world, countries have continuously integrated into the role of the international division of labor (Gryczka 2010). China’s early opening-up mainly produced resource-consuming products with low added value and relied on huge output to obtain income. The improvement of export sophistication is mainly to improve the machine production speed and output. With China’s increasing status in the international division of labor, the resource-consuming industries with low added value are gradually outsourced, the industrial division of labor with higher technical complexity is transformed, the export trade structure is upgraded to a higher stage, and more advanced technology production links are contracted in the global division of labor value chain. The increasing export sophistication, high-added value, and green production have also brought about the improvement of energy efficiency (Irfan et al. 2020a, b; Li and Du 2021). Generally speaking, the upgrading of international division of labor brings opportunities for company to continuously develop their energy efficiency. Does the complexity of export technology affect energy efficiency as expected? Is this effect nonlinear? Using data from China, the effect of export sophistication on energy efficiency is studied through empirical research, which effectively enriches the research in the field of ecological effects of export technology.

The possible contributions are as follows: First, many scholars discuss the relationship between technology and energy efficiency. We turn the perspective to export sophistication, and DEA software is used to measure TFEE. The two variables are put into a unified analysis framework to empirically analyze their relationship. This paper provides empirical evidence and literature supplement for the influence of export sophistication and the influencing factors of TFEE. Secondly, distinguish from the previous research on linear relationship, nonlinear relation between export sophistication and TFEE is revealed through threshold model under the three influencing mechanisms of economic growth, regional corruption, and openness. Further, targeted countermeasures and suggestions are put forward according to the corresponding results.

Literature review

Studies on export sophistication

Export sophistication reflects a country’s export commodity structure, trade quality, comparative advantage, and competitiveness (Gu and Guo 2013; Utomo et al. 2020). Michaely (1984) proposed the concept of export sophistication to judge the technical content of products produced by countries all over the world. Hausmann and Rodrik (2003) deepen the research in the field and deepened the concept of “sophistication”, that is, it is a comprehensive concept that integrates quality, technology, and productivity. And this concept has been gradually applied in the international field. For the calculation of export sophistication, the academia generally adopts the calculation method of Hausmann et al. (2007). This method assumes that the technical skills of export products are the related average per capita income in export regions. The weight of the export value of each product in the export area is the proportion of the total export value, and then multiplied by the actual per capita GDP excluding the price factor in the base period to calculate export sophistication. Ni (2017) has innovated the method of measuring export sophistication, which is measured from the perspective of the production process. At the same time, the difference in the technology involved product exported by different industries is also considered.

Export sophistication has many effects. The existing literature discusses the effect of export sophistication from regional and global perspectives. The regional influence mainly involves productivity, economic development (De-xue and Ye 2019), employment level, development quality of export trade (Lall 2000), and technological innovation. Specifically, De-xue and Ye (2019) pointed out that effectively evaluating the sophistication and combining it with different institutional environments can effectively promote a country’s productivity and economic development. Taglioni and Winkler (2016) hold that export sophistication
advancement can create jobs along with the improvement of product production links. Lall (2000) emphasized that the improvement of export sophistication should be combined with digital economy, and its positive effect will become a new boost to promote the high-quality progress of domestic export transaction in the new era. Globally, the increasing complexity of export technology has an impact on global sustainable development (Blohmke 2014) and global economic governance (Simai 2013).

Studies on energy efficiency

With climate change and the energy crisis, energy efficiency improvement has become a much-talked-about research topic (Zhang et al. 2010; Yao et al. 2021). The development of the new era needs to improve energy efficiency, uphold the concept of green development, and focus on sustainable development (Haley et al. 2020; Jia et al. 2022). Energy efficiency measurement methods include single-factor indicator and total-factor indicator (Zhang et al. 2011; Li et al. 2022). The calculation of single factor index is simple, and the substitution impact of other factors on energy is ignored (Cheng et al. 2020; Li et al. 2022). In order to make up for the shortcomings, scholars often use total-factor indicator to measure energy efficiency (Li and Hu 2012; Su et al. 2021). Many factors contribute to energy efficiency (Liao and He 2018). In terms of structural factors, Wang et al. (2017) indicated that energy consumption structure improvement can effectively promote the rational allocation of resources, thereby improving TFEE. For technical factors, technological progress can effectively improve TFEE (Cui et al. 2014; Khan et al. 2021). Fort scale factors, expanding production scale can produce scale effect, reduce resource waste, and improve resource utilization. At the same time, the expansion of enterprise scale is usually accompanied by the introduction of advanced equipment, thereby promoting energy efficiency (Lin and Long 2015; Wang et al. 2022b). There are other influencing factors, such as energy prices, which also affect TFEE (Cornillie and Fankhauser 2004; Irfan et al. 2019). For TFEE improvement, the most essential factor is the technical factor, among which export sophistication is one of the key criteria to measure the quality of technology.

Studies on export sophistication and TFEE

There are few literatures directly studying the relationship between export sophistication and TFEE. Roy and Yasar (2015) found export can reduce fuel use and has beneficial effects on TFEE. The author also found that some export stimulus policies of developing countries may bring additional environmental advantages. Bashir et al. (2020) further studied the relationship between export diversification and energy efficiency, and found that all three indicators have reduced energy power. Besides, the improvement of export quality and the adoption of clean technologies will achieve the goal of improving energy efficiency (Wang et al. 2021). Whether it is export diversification or the improvement of export quality, the essence is to improve the technical level. Waheed Rida et al. (2020) found that in the Gulf Cooperation Council countries, high-tech exports can help reduce total energy demand while reducing energy intensity, thereby achieving energy efficiency promotion.

Most of the above-mentioned studies are solely on export sophistication or on energy efficiency and provide a certain theoretical basis for this article. First, the impact of export sophistication can involve domestic economic development, technological revolution, and even global sustainable development. Scholars research the influence of export sophistication on the economy, technology, environment, and society from different angles. Second, insufficient TFEE is a thorny problem in global countries, and exploring the factors of TFEE optimization is a topic worthy of study. The attention of scholars is also very high, and the related research results are also very rich. However, the existing research has the following gaps: First, there are few studies that directly research the relationship between export sophistication and energy efficiency, and most of the relevant studies are conducted separately. Second, most studies examine the connection between technology, trade, and energy efficiency, without considering the existence of non-linear relationships. Based on this, this article examines the linear and non-linear influence between export sophistication and total factor energy efficiency, enriching existing research.

Method and data

Model

Baseline model

According to the above analysis, following the research of Hao et al. (2022), the baseline model is constructed.

\[
g_{\text{ee}}_{it} = \alpha_0 + \alpha_1 \text{esp}_{it} + \alpha_k X_{it} + \mu_i + v_t + \epsilon_{it} \quad (1)
\]

In formula (1), subscripts \(i\) and \(t\) represent province and time, respectively; \(g_{\text{ee}}\) is TFEE; \(\text{esp}\) indicates export sophistication; \(X\) indicates control variables; \(\mu_i\) is province fixed effect; \(v_t\) indicates time fixed effect; and \(\epsilon_{it}\) is the error term.
Threshold model

For the purpose of studying the impact of export sophistication and GTEE, learning from Wu et al. (2019), this paper constructs a threshold model.

\[ g_{it} = \beta_0 + \beta_1 \text{esp}_{it} * I(q_{it} \leq \gamma) + \beta_2 \text{esp}_{it} * I(q_{it} > \gamma) + \beta_n x_{it} + e_{it} \]  

(2)

where \( q_{it} \) indicates threshold variables, including regional corruption, economic growth, and openness. \( I() \) represent the indicator function. \( \gamma \) is the specific threshold; \( \beta_0 \) and \( \beta_1, \beta_2, \beta_n \) denote the constant term and the parameters to be estimated, respectively.

Variables and data

Measurement of export sophistication

With reference to Hausmann et al. (2007), this article measures export technology complexity in various provinces. First, we calculate the export technical complexity of each type of product \( ps_{it} \):

\[ ps_{it} = \sum_i \frac{X_{ijt}/X_{it}}{\sum_i (X_{ijt}/X_{it})} Y_{it} \]  

(3)

Among them, \( X_{ijt} \) is the export value of products \( j \) of \( i \) in \( t \). \( X_{it} \) is the total export value. \( Y_{it} \) is the GDP per capita based on purchasing power parity.

Secondly, on the basis of formula (3), export technology complexity of various provinces \( esp_{it} \) is further measured:

\[ esp_{it} = \sum_j \frac{X_{ijt}}{X_{it}}ps_{jt} \]  

(4)

Measurement of TFEE

TFEE was measured by DEA-SBM, in which the selection of input and output indicators is the key (Ma et al. 2021). Referring to Wu et al. (2021) and Hao et al. (2022), the input–output indicators are selected as follows (Table 1):

Control variables

There are some control variables in this paper. The control variables of this paper mainly include R&D investment (rd), Internet development (internet), corruption (cor), industrial structure upgrading (ugg), and human capital (hum). Specifically, the ratio of regional R&D investment in GDP is utilized to represent rd (Chunxiang et al., 2022). Following the research of Ren et al. (2021), the internet is expressed by a comprehensive index system. The number of cases of corruption, bribery, and dereliction of duty per 100,000 people in each region is applied to represent corruption (Hao et al. 2022). The ratio of tertiary industry expresses the industrial structure. The years of education per capita expresses human capital (Wu et al. 2019).

Data

In this research, the Panel Data in the Chinese mainland except Hongkong, Macau, and Tibet from 2006 to 2018 were used to investigate the influence of export sophistication on GTEE. The data mainly come from China Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, Wind database, and China Internet Development Report. Table 2 is the data

### Table 1 Index description

| Index type       | Index            | Index explanation                                                                 |
|------------------|------------------|-----------------------------------------------------------------------------------|
| Input            | Capital          | Calculated by perpetual inventory method                                           |
|                  | Labor            | Employment population                                                             |
|                  | Energy           | Energy consumption                                                               |
| Expected output  | GDP              | Real GDP based on 2000                                                            |
| Unexpected output| Industrial wastewater discharge | Negative results of economic development                                         |
|                  | Industrial waste gas emission | Negative results of economic development                                         |
|                  | Output of industrial solid waste | Negative results of economic development                                         |
|                  | Urban domestic waste discharge | Negative results of economic development                                         |

### Table 2 Descriptive statistics

|                | Obs | Mean   | Std. Dev | Min   | Max  |
|----------------|-----|--------|----------|-------|------|
| TFEE           | 390 | 0.500  | 0.243    | 0.162 | 1.087|
| esp            | 390 | 2.825  | 0.957    | 0.973 | 5.457|
| rd             | 390 | 1.478  | 1.078    | 0.200 | 6.064|
| internet       | 390 | 0.171  | 0.148    | 0.024 | 0.688|
| cor            | 390 | 0.284  | 0.122    | 0.038 | 1.649|
| ugg            | 390 | 0.432  | 0.094    | 0.286 | 0.810|
| hum            | 390 | 8.966  | 0.969    | 6.594 | 12.555|
description. The descriptive statistical results of control variables are basically consistent with the existing literature, which indicate that the sample selection in this paper is representative.

In addition, by calculating the variance inflation factor (VIF), it is found that the average value of VIF among all variables is 2.47 (shown in Table 3), less than 10, which shows that there is no multicollinearity among the variables studied in this paper.

### Results and discussion

#### Baseline results

Table 4 is a regression analysis of model 1. No control variables are added in column 1, and columns 2–6 are the results of increasing control variables. The coefficients of esp are clearly greater than 0, which prove that with esp improvement, TFEE has been improved. The results show that the more complex the export commodity structure, the higher the degree of industrial structure optimization, in other words, the higher the technical complexity, the higher the energy utilization efficiency. The potential causes and theoretical analysis of this positive impact are as follows: The “learning in export” effect exists. It is easier for export enterprises to participate in the global value chain. They can often get in touch with foreign advanced technology, production equipment, and management experience first, and have the opportunity to share the dividends brought by global technological progress and upgrading of factor structure. Therefore, while the complexity of export technology is improving, the productivity of enterprises is also increasing, the domestic and international resources are cooperatively and optimally allocated, and the energy consumption per unit product of export is reduced, thus improving the total factor energy efficiency of our country.

With R&D investment improvement, the product structure will be optimized, and the added value of products will increase, resulting in the “export learning” effect and the corresponding improvement of energy efficiency. Internet has correspondingly promoted the export enterprises to realize technology integration and learning on a global scale, continuously promoted their position in the global industrial value chain. Gradually outsourcing the resource-consuming low-tech industries with low added value to the industrial division with higher technical complexity has improved the energy utilization efficiency of enterprises (Ren et al. 2021). There is a negative correlation

![Table 3 VIF results](image)

|   | VIF | 1/VIF |
|---|-----|-------|
| esp | 4.26 | 0.2345 |
| rd  | 2.78 | 0.3595 |
| internet | 2.74 | 0.3644 |
| cor  | 2.24 | 0.4466 |
| ugg  | 1.59 | 0.6295 |
| hum  | 1.18 | 0.8465 |
| Mean VIF | 2.47 | – |

![Table 4 Basic results](image)

|   | (1) | (2) | (3) | (4) | (5) | (6) |
|---|-----|-----|-----|-----|-----|-----|
| esp | 0.028** | 0.030** | 0.026* | 0.026* | 0.026* | 0.026* |
| | (0.014) | (0.014) | (0.014) | (0.014) | (0.013) | (0.013) |
| rd  | 0.028* | 0.031** | 0.030** | 0.033** | 0.033** | 0.033** |
| | (0.015) | (0.015) | (0.015) | (0.015) | (0.015) | (0.015) |
| internet | 0.392*** | 0.391*** | 0.380*** | 0.378*** | 0.376*** | 0.376*** |
| | (0.109) | (0.110) | (0.108) | (0.108) | (0.108) | (0.108) |
| cor | −0.009 | −0.012 | −0.012 | −0.012 | −0.012 | −0.012 |
| | (0.027) | (0.027) | (0.027) | (0.027) | (0.027) | (0.027) |
| ugg | −0.376*** | −0.371*** | −0.371*** | −0.371*** | −0.371*** | −0.371*** |
| | (0.104) | (0.104) | (0.104) | (0.104) | (0.104) | (0.104) |
| hum | 0.008 |  |  |  |  |  |
| |  |  |  |  |  |  |
| Constant | 0.989*** | 0.831*** | 0.573*** | 0.578*** | 0.844*** | 0.751*** |
| | (0.034) | (0.091) | (0.115) | (0.116) | (0.136) | (0.217) |
| Year FE | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Provincial FE | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Obs | 390 | 390 | 390 | 390 | 390 | 390 |
| Adjusted $R^2$ | 0.957 | 0.957 | 0.957 | 0.957 | 0.957 | 0.957 |

Standard error in ()
between the degree of corruption and the complexity of export technology. The increase in the degree of corruption may affect the R&D investment of company to some extent, and the corresponding technological innovation and application promotion may be delayed, which will affect the increase of the complexity of export technology of enterprises, and finally reduce the energy utilization efficiency. In addition, industrial structure advancement, human capital, and other factors are positively correlated with TFEE enhancement. All of these verify that export sophistication can significantly improve TFEE.

Robustness test

The independent variable and dependent variable are mutually causal. Export sophistication can not only promote the improvement of total factor energy efficiency but also be the result of the increase of total factor energy efficiency, which leads to the existence of endogenous problems. In order to solve this problem, this paper adopts the instrumental variable method to solve the endogenous problem. Therefore, on the basis of benchmark regression, this paper further uses instrumental variable method to correct the estimation deviation of the model caused by potential endogenous problems. As for the choice of the instrumental variable, the shortest distance between provinces and coastal ports as the instrumental variable of export sophistication. First, the closer a province is to the port, the more favorable it is for foreign technology and knowledge to spill over to the region, and the higher the complexity of export technology in the region. Second, physical distance is not related to total factor production efficiency. Table 5 shows the estimation results of instrumental variable. In columns 1 and 3, the estimation results of the first stage show that the estimation coefficients of instrumental variable (distant) are all significantly negative at the level of 1% whether or not the control variable is added, and the goodness of fit is above 80%, so it has a good explanation for export sophistication. In column 2 and column 4, the second stage regression show that the estimated coefficients of esp are 0.881 and 1.298, respectively. The robustness of the benchmark regression results is verified.

### Impulse response analysis

Impulse response trend is observed to further analyze the time-varying shock and influence of export sophistication on TFEE. Based on the principle of stationary variables and optimal order lag selection, the PVAR model is estimated. The model can analyze the impact of one variable on other variables and describes the corresponding change of response degree of variables with the passage of time through the trend chart. As shown in Fig. 1, the horizontal axis indicates the number of lagging periods. In this paper, 10 consecutive periods are selected for impulse response analysis. The vertical axis indicates the direction and intensity of impact response. The upper and lower lines of the trend graph are 95% confidence interval boundaries. By observing the solid line in the middle of the trend graph, the impact of impulse response tends to zero with the passage of time, which demonstrated that the PVAR model is stable.

In Fig. 1, TFEE has a positive effect on itself, and with the passage of time, the effect fluctuates and declines gradually. Specifically, the effect is largest at the beginning of the period, and then it drops to the lowest point in the third period, with a small fluctuation in the third to tenth periods. The influence of export sophistication on TFEE is generally positive. At the beginning of the period, the impact was the greatest, with a significant decline in the period 0–2, a large fluctuation in the period 2–4, the highest point in the later periods in the period 3, and then a downward trend. This trend shows that export sophistication brought about by improving the product structure at the beginning can obviously improve the optimization of TFEE. Subsequently, the spillover effect brought by the increase of export sophistication will gradually weaken.

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1 The calculation is based on China Coastal Port Layout Plan and Google Maps.
effect on the improvement of total factor energy efficiency. In the middle and late stages of export, China gradually got rid of the low-end processing role in the global value chain, and China shifted from technology introduction to technological innovation and breakthrough. The benefits of technology innovation need time and cannot be revealed immediately, so the effect of export sophistication gradually slows down at this stage.

Results of threshold effect

Using stata17.0 software and taking export sophistication as the independent variable, this paper tests the threshold effects of regional corruption, economic growth, and openness under the assumptions of single threshold, double threshold, and triple threshold. In Table 6, the regional corruption variable passed the significance test of the double threshold effect,

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**Table 6 Results of threshold affects**

| Threshold variable | Threshold | \( F \)-value | \( p \)-value | BS | 1%  | 5%  | 10%  |
|--------------------|-----------|----------------|---------------|----|-----|-----|------|
| Regional corruption| Singled   | 35.116         | 0.133         | 300| 41.191 | 38.408 | 36.630 |
|                    | Double    | 9.162***       | 0.000         | 300| 6.205 | 2.520 | 0.174 |
|                    | Triple    | 0.000          | 0.240         | 300| 0.000 | 0.000 | 0.000 |
| Economic growth    | Singled   | 16.018         | 0.477         | 300| 21.166 | 19.713 | 18.679 |
|                    | Double    | 6.724          | 0.560         | 300| 10.235 | 9.135  | 8.604 |
|                    | Triple    | 0.000***       | 0.000         | 300| 0.000 | 0.000 | 0.000 |
| Openness           | Singled   | 117.431        | 0.023         | 300| 119.299 | 116.34 | 113.33 |
|                    | Double    | 35.991         | 0.003         | 300| 33.829 | 31.692 | 29.154 |
|                    | Triple    | -30.854        | 0.043         | 300| -26.565 | -31.39 | -33.84 |

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Fig. 1 Impulse response

Errors are 5% on each side generated by Monte-Carlo with 1000 reps
and the double threshold estimation is selected. The threshold variables of economic growth and openness have passed the significance test of the triple threshold effect, and the triple threshold estimation is selected. Table 7 reports its threshold estimates and their confidence intervals.

In Table 8, columns 1, 3, and 5 respectively represent the estimation results with export sophistication as the independent variable and regional corruption, economic growth, and openness as the threshold variable.

(1) Regional corruption threshold. According to Tables 6, 7, the effect of export sophistication on TFEE has a significant double threshold effect of regional corruption. When regional corruption level is less than 0.244, export sophistication’s coefficient is 0.069. When regional corruption level is greater than 0.244 and less than 0.399, the contribution of export sophistication to energy efficiency decreases to 0.037. The reason may be that the upgrading of product structure usually requires a lot of R&D investment and innovative integration of product technology. Generally, the expenditure incurred in the research stage of technological innovation will be expensed and included in the current profit and loss. It will be capitalized only when it enters the development stage and meets the capitalization conditions. Many regions with high degrees of corruption have less support for enterprise innovation policies (Ren et al. 2021). Enterprises are usually unwilling to bear the risk burden and corresponding costs in the research stage. More enterprises only focus on short-term operating interests, ignore the technological innovation required for long-term development, and use more funds for short-term profit projects such as corruption and bribery. As for R&D investment, the capital investment in the technical upgrading of export products will be reduced, and the corresponding export technology complexity will be reduced (Liu and Xia 2018). As corruption in the region worsened, the technical complexity of export products decreases, which weakens the promotion of energy efficiency.

(2) Economic growth threshold. The effect of export sophistication on TFEE has a significant triple threshold effect of economic growth. When economic growth is lower than 21.487, the coefficient of export sophistication is 0.060. When economic growth level is greater than 21.487 and less than 21.995, the elasticity coefficient increases, expressing that the improvement of economic growth makes the promotion of export technology complexity on energy efficiency more significant. When economic growth level is greater than 21.995 and less than 72.678, the coefficient increases to 0.138, indicating that with the economic growth, the
to the complexity of export technology has increased, and more advanced high value-added and green production have also brought about a large proportion in China. More advanced technological innovation of export companies. Meanwhile, economic growth is accompanied by the improvement of social expectations, and enterprises need to assume more social responsibilities to obtain rationality, such as environmental protection and green production (Zhou et al. 2019). The promotion of social responsibility requires enterprises to optimize their technical level, continuously improve their market status, continuously transform to the production of products with high technical content, and continuously improve energy efficiency and green production. Therefore, with the economic growth, the technical complexity of export products will continue to promote energy efficiency.

Openness threshold. The effect of export sophistication on energy efficiency has a significant triple threshold effect of openness. When the openness is lower than 83.205, the export technology complexity coefficient is $-0.008$, indicating that the impact of export sophistication on TFEE is still negative, but the inhibitory effect is weakened. When the openness is greater than 83.205 and less than 172.114, the coefficient increases to $-0.008$, indicating that the impact of export sophistication on TFEE is still negative, but the inhibitory effect is weakened. When the openness is greater than 172.114 and less than 296.124, export sophistication coefficient turns from negative to positive, proving that with the continuous expansion of openness, export sophistication results in the enhancement of TFEE. China’s early opening-up was relatively low, mainly as a foundry to produce products with low added value and rely on huge output to obtain income. And the improvement of technical complexity of export products mainly focused on improving machine production speed and output and mainly exported resource consuming industrial products. With the continuous improvement of openness, China continues to rise, and the export trade structure has been upgraded to a higher stage. Some resource-intensive industries have been abandoned and some have turned to technology-intensive products. As the technology-intensive industries are still in the early stage, the improvement effect for TFEE is not significant (Yu 2020). In recent years, with the further improvement of openness, export technology-intensive industries account for a large proportion in China. More advanced technological production links have been contracted, the complexity of export technology has increased, and high value-added and green production have also brought about the improvement of energy efficiency (Li and Du 2021). Therefore, it is concluded that when the degree of openness reaches a certain scale, the upgrading effect of international division of labor makes the export technology complex and promotes the optimization of energy efficiency.

Conclusion and policy implications

Promoting energy efficiency is the way out to solve the current energy crisis, and it is also an important direction for the continuous improvement of the modern energy system. Using data from China, the effect of export sophistication on TFEE is uncovered under impulse response and threshold effect. The following is the conclusion of the article and the corresponding policy recommendations.

First, the improvement of export sophistication can enhance TFEE. The improvement of technological complexity is expected to optimize the rational allocation of energy resources, thus exerting the important role of scientific and technological input in energy efficiency optimization. Countries should guide enterprises to constantly improve the quality and structure of export products, enhance the application of scientific and technological achievements in practice, and attach importance to the results of energy conservation and utility maximization in energy science. Specifically, in export, countries should actively introduce and popularize advanced clean energy technologies at home and abroad; develop mature bioenergy technology; introduce engineering recycling equipment applied to new energy. Generally speaking, China and the developing countries should promote their total factor energy efficiency through “export middle schools.”

Second, the impulse response of export sophistication to energy efficiency is time-varying, and the overall impact is positive, with the greatest impact at the beginning of the period, followed by a downward trend of fluctuation. In the early export period, China’s innovation mode was the introduction, digestion, imitation, and innovation. By digesting and absorbing these advanced technologies, although China has gained some energy efficiency technologies and experiences in a short time, China has also become dependent on key technologies and equipment of developed countries. The promotion effect of “learning from export” strategy on total factor energy efficiency gradually decreases. Therefore, China should continue to adhere to the “innovation-driven development” strategy, increase its independent research and development capabilities, and provide a continuous impetus for the improvement of total factor energy efficiency in China.

Third, the degree of regional corruption, economic growth, and economic openness are momentous thresholds...
in the process of export sophistication affecting TFEE. First, for regions with a high degree of regional corruption, it is necessary to unwaveringly fight corruption, strengthen the construction of incorrupt government culture and create a good political and institutional environment. The government should introduce relevant policies to curb corruption and reduce the costs and risks of technological innovation of enterprises and give more tax incentives to enterprises with technological innovation. Thus, stimulate the enthusiasm of enterprise for research and promote investment increase in R&D of enterprises. Encourage export enterprises to adhere to independent innovation, optimize the product structure of export enterprises, continuously improve the production links and stages, enhance the technical complexity and accelerate TFEE enhancement. In addition, with the deepening of openness, facing the further adjustment and upgrading of international division of labor, countries need to constantly adapt to and blend in international cooperation. Countries are required to improve the transformation and optimization of export trade structure, improve the technical merit of export products and enhance the additional benefits of the product.

Fourth, since 2019, the new crown epidemic has continued to spread, and the global economy has been hit hard and the recovery pace is slow. In addition, the USA blocked the import and export of high-tech products in China, and China's exports was blocked. Under the background of many unfavorable factors, China's export enterprises need to continuously increase their independent research and development efforts to seek a breakthrough, and further increase the complexity of export technology, so as to climb up the global value chain.

Although this paper has made some positive explorations on the linear and nonlinear effects of export sophistication on TFEE, there exists deficiency in some aspects, which provides some paths for future research direction. First, we use provincial macro data and the number of samples used is small. In the subsequent research, we can consider using micro-level data for further testing. Second, there are still endogenous problems in this paper, and further research can make a breakthrough in endogenous treatment.

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Data availability All data generated or analyzed during this study are included in this article.

Declarations

Ethics approval and consent to participate Not applicable.

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