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Air Pollution and Enterprise Energy Efficiency: Evidence from Energy-Intensive Manufacturing Industries in China

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Abstract: This study aims to investigate the causal effect of air pollution on enterprise-level energy efficiency in the energy-intensive manufacturing industries of China. To address the potential endogenous problem, it employs thermal inversions as the instrumental variable. The study finds that air pollution would significantly decrease enterprise-level energy efficiency. It shows heterogeneous influences of air pollution on enterprise-level energy efficiency, varying with enterprise ownership, enterprise age, enterprise location, and regional energy resource endowment. This study further reveals that air pollution exerts a negative influence on enterprise-level energy efficiency through the mechanisms of decreasing enterprise productivity (both total factor productivity and labor productivity), increasing enterprise total energy consumption, and lowering enterprise exports. The findings of this study provide an economic rationale for enterprises to motivate themselves to reduce air pollution and have important implications for policymaking in China and other developing countries.

Keywords: air pollution; energy efficiency; energy-intensive manufacturing industries; instrument variable; thermal inversion; China

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1. Introduction

Energy has long been one of the most important issues in economic and social development. It is related to ecological environment development as well as national economic security and national strategic security. In the past few decades, economic growth has been highly dependent on energy and resource input in China. Although rapid economic growth has brought economic prosperity, it has also caused a series of problems such as the shortage of energy and resources and the ecological degradation of the environment [1]. Rapid economic growth is often accompanied by a large amount of energy consumption. On the one hand, with the declining energy reserves, energy security will threaten sustainable development; on the other hand, the greenhouse effect and air pollution caused by the use of fossil fuels are becoming increasingly serious. Thus, reducing carbon emissions and achieving carbon neutrality require improving energy efficiency as an important national strategy.

China overtook the U.S. as the world's largest energy consumer in 2009, according to the International Energy Agency. Since the reform and opening-up policies, although energy efficiency has improved, compared with other countries, energy consumption per unit GDP is still high in China, about twice the world average, three times that of America, and seven times that of Japan. The Central Government of China made it clear that the country should accelerate green and low-carbon development, continuously improve the quality of the environment, enhance the quality and stability of the ecosystem, and comprehensively improve the efficiency of resource utilization. The white paper titled "China's Energy Development in the New Era 2020" pointed out that energy efficiency in key areas should be improved. In 2021, the State Council of China issued the Action Plan for Achieving Carbon Peak before 2030, which put forward action requirements such as promoting energy conservation and energy efficiency of key energy-using equipment and accelerating the improvement of energy efficiency of buildings, and indicated that improving energy efficiency shall be an important task in the 14th and 15th Five-Year Plan periods.

Meanwhile, China's carbon emissions from fossil fuels are likely to continue rising for some time to come. Carbon emissions from energy use pose a severe threat to air quality and the environment. According to the BP Statistical Review of World Energy 2021, energy consumption in China increased by 2.1% in 2020, accounting for 26.1% of the total global energy consumption. The carbon dioxide (CO_2) emissions increased by 0.6% in the same year, accounting for 26.1% of the total global CO_2 emissions. The Chinese government has decided to achieve an emissions peak around 2030 or earlier and reduce carbon intensity (CO_2 emissions per unit of gross domestic product [GDP]) by 40% to 45% in 2020 and 60% to 65% in 2030, compared with 2005.

In the context of carbon peaking and carbon neutrality goals, enterprises should take actions to abate pollution and improve energy efficiency to satisfy the requirements of national strategy, especially for those in energy-intensive industries. The energy-intensive industries are those in which the consumption of energy occupies a relatively large proportion of the inputs during the production process; they are also called 'high energy-consuming industries' [2–5]. Six industries are designated as energy-intensive by the Chinese government. Among these, five are manufacturing industries: (The sixth energy-intensive industry is the production and supply of electric and heat power, which does not belong to the manufacturing industry and thus is excluded from the analysis in this study) (1) Processing of petroleum, coking, and nuclear fuel manufacturing; (2) raw chemical materials and chemical products manufacturing; (3) nonmetallic mineral products manufacturing; (4) smelting and pressing of ferrous metals manufacturing; and (5) smelting and pressing of nonferrous metals manufacturing. The National Bureau of Statistics of China shows that the above five energy-intensive manufacturing industries consumed 42.9% of China's total energy consumption in 2019. Further, they are primary fossil energy users. In 2019, the coal, fuel oil, and natural gas consumed by them accounted for 36.7%, 54.8%, and 31.2% (respectively) of the country's total consumption of the corresponding fossil energies (calculated by using information from http://www.stats.gov.cn/sj/, accessed on 17 January 2023). These energy-intensive manufacturing industries also generate massive air pollutants. Two industries—nonmetallic mineral products manufacturing and the smelting and pressing of ferrous metals manufacturing—generated 36.5% of sulfur dioxide (SO_2) and 49.6% of oxides of nitrogen (NO_x) emissions in 2020 [6]. Nationally, industrial coal burning contributes 10 $\mu g/m^3$ (17%) of fine particles ($PM_{2.5}$) on average [7]. Energy efficiency in energy-intensive manufacturing industries is strongly related to commercial and energy security, as well as to the environment and climate change [8]. Hence, an in-depth discussion on improving the energy efficiency of energy-intensive manufacturing industries is instructive for future sustainable development in China.

Improving energy efficiency has become one of the key ways to achieve green development in the process of transforming China's economy from high-speed growth to high-quality development [9], which has also become a highly concerning topic in academic circles. A long strand of literature has demonstrated the *proposition* that lowering energy efficiency causes increases in air pollution (e.g., [10–17]). However, its *converse proposition*—that a decrease in air pollution raises enterprise-level energy efficiency—has not been explored, either formally or directly. This study, therefore, attempts to explore the causal effect of air pollution on enterprise-level energy efficiency in the energy-intensive manufacturing industries of China. From a microeconomic perspective, the findings attempt to provide an economic rationale for those enterprises in energy-intensive manufacturing industries to motivate themselves to reduce air pollution, promote energy efficiency, and reduce costs.

The main obstacle to exploring the causal relationship between air pollution and enterprise-level energy efficiency is the potential endogenous problem caused by the apparent reverse causality. In addition, omitted variables can exacerbate the problem. To solve it, the study employs the annual number of thermal inversion days in the county as the instrumental variable (IV) (see the detail in Section 3.2). In general, the air temperature drops with increasing altitude. However, under certain weather conditions, the structure of the atmosphere above the ground shows an abnormal increase in temperature with altitude. It is called a thermal inversion. Thermal inversions are deviations caused by exogenous meteorological factors, which can trap air pollutants near the ground such as $PM_{2.5}$ and degrade air quality. There are plenty of studies about the impacts of air pollution on economic and social variables such as infant mortality, migration, productivity, and health. These studies have demonstrated that employing thermal inversions as an IV in two-stage least squares (2SLS) estimates is reliable for obtaining unbiased effects [18–21].

Relying on a valid IV strategy, the baseline results of this study demonstrate that air pollution decreases enterprise-level energy efficiency. This study finds further heterogeneous impacts of air pollution on enterprise energy efficiency. The effects vary with enterprise ownership, enterprise age, enterprise location, and regional energy resource endowment. The study also discusses the potential mechanisms that may explain why air pollution has an adverse effect on enterprise energy efficiency. It is found that air pollution can reduce enterprise productivity (both total factor productivity [TFP] and labor productivity), increase energy consumption, and lower enterprise export, thereby decreasing enterprise energy efficiency.

This study makes several contributions. First, to the best knowledge of the authors, this is the first attempt to explore the causal impacts of air pollution on enterprise-level energy efficiency. Previous studies discuss the influencing factors of energy efficiency, for example, energy-saving technology investment, energy management practice [22], energy policy [23–25], improvements in technology [15,26–28], population density [29–31], institutional quality [28,32], and trade openness and urbanization [31,33,34]. The findings of this study enrich the literature on the knowledge of energy efficiency, especially from a microeconomic perspective.

Second, the findings on specific energy-intensive industries can provide more elaborate, practice-based implications for policymakers. Recently, energy consumption, carbon emissions, and energy efficiency in Chinese energy-intensive industries have attracted much attention from researchers (e.g., [2,3,35,36]). According to the existing literature, improving energy efficiency can reduce air pollution. Our conclusions demonstrate that reducing air pollution could increase enterprise-level energy efficiency, thus reducing costs and improving firm-level performance. Reducing air pollution is not a burden, but it is good for enterprises themselves instead. Our findings provide an economic rationale for enterprises to motivate themselves to reduce air pollution. Thus, a virtuous circle could be generated if enterprises adopted pollution-reducing methods, especially in energy-intensive industries that are the primary users of fossil energy, as already noted.

Finally, this study on China is essential in and of itself. The government of China has established particular energy consumption reduction and energy intensity reduction goals for energy-intensive manufacturing industries. Specifically, the 13th Five-Year Plan has required that the energy consumption in the ferrous metals sector decline by at least 10% and the energy intensity in both nonferrous metals and petrochemical industries reduce by 18% [3]. Improving energy efficiency will be vital for achieving the above goals and benefiting sustainable development. The findings indicate that reducing air pollution itself could play a role in achieving the goal. For governments, it logically follows that, in order to reduce air pollution, it requires them to shrink coal and other fossil energy consumption and become climate neutral.

The remainder of the paper is organized as follows: Section 2 discusses the previous studies on enterprise-level energy efficiency and air pollution. Section 3 presents the econometric model, data sources, variables, and summary statistics. The empirical results are presented in Section 4. Section 5 is a discussion of the findings. The final section concludes the study.

2. Literature Review

2.1. Studies on Factors That Influence Enterprise Energy Efficiency

Studies on the factors that influence enterprise energy efficiency have grown rapidly; these involve various elements inside and outside an enterprise. Regarding enterprise characteristics, Hassen et al. [37] believe that as the size of an enterprise increases, it is more likely that the enterprise will use new energy-saving technologies, thus improving energy efficiency. Other scholars confirm this conclusion [38,39]. Ownership could also play an essential role in affecting enterprise energy efficiency. Studies show that state-owned enterprises (SOEs) have lower energy efficiency than private firms [39,40]. Regarding innovation, Liao and Xu [41] indicate that enterprise innovation in input and output can reduce energy intensity and that innovation in output has a greater effect on reducing energy intensity. Moreover, Backlund et al. [22] provide evidence that the increase in energy efficiency requires a combination of energy-saving technology investment and energy management practice. Perroni et al. [42] conclude that the effect of energy efficiency promotional practices on energy efficiency is positive when an enterprise operates with an increasing returns-to-scale (RTS). When an enterprise operates at a decreasing RTS, the effect of this practice on energy efficiency is negative.

Regarding the external factors influencing enterprise energy efficiency, Stern [26] shows that technological change is the key factor to reducing energy consumption. Qin et al. [15] find that technological progress plays a crucial role in increasing energy efficiency. Yuan et al. [43] illustrate that technological progress increases energy efficiency by changing the production frontier. Li and Lin [44] consider two types of technological progress and show that both Hicks-neutral technological progress and capital-embodied technological progress have contributed to energy efficiency. Song and Yu [27] observe that, aside from technological progress, market instruments are also important tools for energy efficiency improvement. In addition, Danquah [34] shows that the national energy efficiency of sub-Saharan Africa is related to trade openness, machinery imports, research, and economic development. Marin and Palma [33] note that the technology spillover from abroad has positive effects on domestic energy efficiency. Previous studies also show that energy prices and policies can affect energy efficiency. Lin and Long [38] find that energy prices provide support for improving energy efficiency. Lv et al. [45] further find that energy price, energy structure, railway transportation development, and research and development (R&D) stock affect energy efficiency significantly at the national level. Regarding energy policy, Thollander et al. [23] believe that the positive impacts of energy policy on energy efficiency cannot be ignored. Zhou et al. [24] and Lin et al. [25] reach the same conclusion.

Finally, governmental and regional characteristics could influence enterprise energy efficiency. Du et al. [32] validate that government-funded research programs can significantly increase Chinese energy efficiency. Sun et al. [28] provide evidence of the positive influence of institutional quality on energy efficiency. Moreover, Otsuka and Goto [29] indicate that increasing population density can improve energy efficiency. Jebali et al. [30] reveal that countries in the Mediterranean region with a higher population density and economic growth experience higher energy efficiency. Jiang et al. [31] show that population density and the foreign direct investment received by a province have positive effects on the energy efficiencies of the province and its neighboring provinces. Moreover, Liu et al. [46] and Tanaka and Managi [47] find that industrial agglomeration can affect energy efficiency with positive effects.

2.2. Studies Implicating the Effect of Air Pollution on Energy Efficiency

The previous literature connects energy efficiency with environmental pollution. There is a long strand of literature that investigates the *proposition* that lowering energy efficiency causes increases in air pollution [10–17].

Regarding the *converse proposition* that increases in air pollution cause the lowering of enterprise energy efficiency, previous studies suggest that a causal link between air pollution and enterprise energy efficiency may exist, although this has not been studied directly and formally. First, scholars have established that air pollution reduces enterprise TFP [20,48–50] and labor productivity [51–56]. Concurrently, studies find that TFP could improve energy efficiency. Stern [26] notes that countries with higher TFP have higher energy efficiency. Montalbano and Nenci [57] find that increased productivity would improve the energy efficiency of firms. Enterprise productivity is an indicator that illustrates the innovation capacity within technological progress. Bloom et al. [58] and Shapiro and Walker [59] find that a firm's production technology plays a negative role in emission intensity. This validates that technological progress can increase enterprise energy efficiency. As a result, air pollution may negatively influence enterprise energy efficiency by providing a risk to enterprise productivity.

Second, increasing foreign market access is associated with technological improvement. It is also associated with the enterprise innovations through which enterprises meet the pollution-control standards required by their trade partners, which generally results in energy savings [60–63]. In turn, this may encourage energy efficiency improvements [58,59]. Among the few firm-level discussions, that of Galdeano-Gómez [64] finds that environmental performance positively correlates with enterprise exports in Spain. Cole et al. [65] also reveal the positive impacts of exports on the environmental performance of firms in Japan. Thus, it may be deduced that air pollution reduces energy efficiency by reducing enterprise export activities.

Together, the above-mentioned existing studies suggest that air pollution has a negative effect on enterprise energy efficiency. Nevertheless, there is no direct and formal empirical evidence of this. This study tries to fill that gap.

3. Methodology, Data, and Variables

3.1. Econometric Methodology

The fundamental empirical strategy used in this study is to relate air pollution to enterprise-level energy efficiency by instrumenting air pollution by the yearly number of days in which thermal inversion occurs at least once in the county. The ordinary least squares (OLS) representation of this relationship is:

$$Log(Enterprise\ energy\ efficiency)_{irt} = \alpha_0 + \alpha_1 Air\ pollution_{rt} + \alpha_2 W_{rt} + \alpha_i + \rho_t + \varepsilon_{irt}, \quad (1)$$

where subscripts $i, r,$ and t denote enterprise (by enterprise identification code), county, and year, respectively. The explanatory variable $Log(Enterprise\ energy\ efficiency)$ represents the energy efficiency of energy-intensive manufacturing enterprises in logarithmic form; $Air\ pollution$ uses the county-level $PM_{2.5}$ concentration; and W is a set of county-level weather control variables. During the observation period of this study, there were very few enterprises (accounting for 1.7%, 666 observations out of 39,988 in total) that relocated to another county. There are just 271 enterprises (accounting for 0.7%) that switched from one industry to another. In the baseline analysis, the study excludes those observations that switched industries or relocated. Accordingly, the α_i represents the enterprise fixed effects, which control all the time-invariant characteristics of enterprises and can absorb time-invariant factors of industry and county affecting enterprise energy efficiency as well. The ρ_t indicates year-fixed effects. Finally, ε_{irt} is an error term. In the baseline estimation, the study clusters standard errors at the enterprise level to account for serial correlation within the enterprise.

Because of the potential endogeneity from reverse causality and omitted variables, using OLS estimation in Equation (1) may obtain biased results, even if the study includes a rich set of controls for potential confounders. Meanwhile, controlling enterprise and year-fixed effects can only solve endogenous problems caused by time-invariant, unobservable factors. This study, therefore, adopts a 2SLS estimate by employing an IV to obtain an unbiased result. The two-stage models are specified as follows:

$$Air\ pollution_{rt} = \rho_0 + \rho_1 Thermal\ inversion_{rt} + \rho_2 W_{rt} + v_i + \delta_t + \xi_{irt}, \quad (2)$$

and

$$Log\ (Enterprise\ energy\ efficiency)_{irt} = \gamma_0 + \gamma_1 Air\ \widehat{pollution}_{rt} + \gamma_2 W_{rt} + \mu_i + \pi_t + \vartheta_{irt}, \quad (3)$$

where $Thermal\ inversion_{rt}$ is the IV; $Air\ \widehat{Pollution}_{rt}$ in Equation (3) is the predicted value of $Air\ pollution_{rt}$ in Equation (2); v_i and μ_i capture enterprise fixed effects; δ_t and π_t represent year-fixed effects; and ξ_{irt} and ϑ_{irt} are error terms. The definitions of the other variables are the same as in Equation (1).

3.2. Data Sources and Variables

The study uses the Annual Survey of Industrial Firms (ASIF) and Chinese Environmental Statistics (CES) as sources of enterprise-level data. It merges these two databases and obtains a panel from 1998 to 2007.

The enterprise-level data in the ASIF database came from annual surveys enforced by China's National Bureau of Statistics (NBS) from 1998 to 2007. The dataset contains basic characteristics of both Chinese non-state-owned industrial enterprises with an output value of more than CNY 5 million [around USD 0.8 million] and all state-owned enterprises, including enterprise age, address, telephone number, the net value of a fixed asset, and employees. The study follows Brandt et al. [66] to handle the missing data measurement error, convert industry codes, and conduct a matching process. Using the merged data set and detailed price deflators, this study calculates the real capital stock and ensures the consistency of variable definition during the observation period.

The CES database used for this study is another large administrative data set collected by China's Ministry of Environmental Protection. The dataset covers the most polluting industrial enterprises, which together contribute to approximately 85% of major pollutants (e.g., chemical oxygen demand, ammonia nitrogen, sulfur dioxide, industrial smoke, and dust, as well as solid waste) in China [25,39,67]. It is currently the most comprehensive environmental database in China, including basic information about enterprises, energy consumption, and pollutant emissions.

Regarding the dependent variable—enterprise energy efficiency—it is calculated with the following equation, as other studies did (see [8,25,39,44,68,69]):

$$Enterprise\ energy\ efficiency = \frac{Output}{Energy\ consumption}. \quad (4)$$

The calculation proceeds with the following steps: (1) The study obtains the enterprise's real output. The nominal total industrial output of enterprises from the ASIF database is adjusted by the GDP deflator to a constant price in 1998. (2) The study calculates total energy consumption. As discussed before, energy-intensive manufacturing enterprises heavily rely on fossil energy. Specifically, the study converts coal, diesel, fuel oil, and natural gas consumption in the CES database into standard coal and calculates the total energy consumption. (3) The study obtains the enterprise energy efficiency by dividing the real output by the total energy consumption. (4) To eliminate the influence of extreme values, the study winsorizes the upper and lower 5% of the data based on energy efficiency values. The final dataset consists of 39,128 firm-year observations.

$PM_{2.5}$ is one of the most serious air pollutants, and energy consumption is its dominant emission source. The study, therefore, employs it as the main variable to represent air pollution. It obtained $PM_{2.5}$ data from the satellite-based Aerosol Optical Depth (AOD) retrievals. Many scholars used monthly AOD data disclosed by the National Aeronautics and Space Administration of the United States (NASA) to predict and measure air pollution (e.g., [20,70–72]). Following the formula provided by Buchard et al. [73], the study calculates the monthly $PM_{2.5}$ concentration and aggregates them to the county level. The annual average of the county-level monthly $PM_{2.5}$ concentrations is the value of the variable of interest (the county-year $PM_{2.5}$ concentration).

This study adopts thermal inversions to instrument air pollution. The satellite-based NASA data report air temperature in a 50-by-60 km grid for 42 atmospheric layers, ranging from 110 m (the first layer) to 36,000 m. The data are available in 6-hour periods from 1980 onward. A thermal inversion is defined as the temperature of the second layer (320 m) being higher than that of the first layer (110 m) [18]. The used latitude is based on sea level. If layers are below a grid's latitude, missing values may exist. For example, the first (400 m) and second layers (110 and 320 m, respectively) will be missing if a grid's latitude is 500 m. Then, the two closest non-missing layers are adopted. As many other scholars did, the data were aggregated to the county level, and thermal inversions were calculated for each county over a six-hour period every day. A thermal inversion day is defined as a calendar day with at least one thermal inversion. To merge with the annual enterprise-level data, the number of thermal inversion days within a calendar year is used.

Finally, the values of daily county-level weather variables are from China's National Meteorological Information Center, including precipitation, temperature, wind speed, humidity, and air pressure. Following a widely accepted practice (e.g., [20,21]), this study turns daily weather data into annual county-level data as control variables. Table 1 provides all relevant variables and their definitions and descriptive statistics.

Table 1. Definition and summary statistics for relevant variables.

Variables	Definition	Observation	Mean	Std. Dev.	Min	Max
Log (Enterprise energy efficiency)	Enterprise energy efficiency in logarithm form	39,128	–2.192	1.755	–4.256	2.092
Air pollution	County-level $PM_{2.5}$ concentration (μg/m^3)	39,128	64.413	21.970	7.743	134.842
Thermal inversions	The annual number of days in which thermal inversion occurs at least once in the county	39,128	155.030	67.438	1	330
Precipitation	Measured as the average annual precipitation in each county (100 mm)	39,128	10,381.74	4102.811	1358.069	30,988.54
Temperature	Measured as the average annual temperature in each county (1 °C)	39,128	15.568	4.158	–0.946	25.247
Wind speed	Measured as the average annual wind speed in each county (1 m/s)	39,128	2.182	0.685	0.530	6.796
Humidity	Measured as the average annual relative humidity in each county (1%)	39,128	70.600	8.194	40.871	85.716
Air pressure	Measured as the average annual air pressure in each county (1 hPa)	39,128	976.840	51.182	742.982	1016.969

4. Empirical Results

4.1. Baseline Results

Table 2 shows the set of baseline estimates. The first-stage results in Equation (2) are reported in the first two columns of Table 2. In Columns (1) and (2) of Table 2, the coefficients of IV are statistically positive, without and with baseline controls, respectively. The Cragg–Donald F statistic is significantly higher than the critical value, indicating that the IV is not weak. The result of the endogeneity test reveals that an endogenous problem indeed exists, as the *p*-value is 0.094.

Table 2. Main results.

Variables	**Air Pollution**		**Log (Enterprise Energy Efficiency)**			
	First Stage		**Reduced Form**		**2SLS Estimate**	
	OLS	**OLS**	**OLS**	**OLS**	**2SLS**	**2SLS**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Thermal inversions	0.026 ***	0.037 ***	–0.001 ***	–0.001 ***		
	(0.002)	(0.002)	(0.0004)	(0.0004)		
Air pollution					–0.038 ***	–0.025 **
					(0.014)	(0.010)
Baseline controls	No	Yes	No	Yes	No	Yes
Enterprise FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cragg–Donald Wald F statistic	231.416	484.350				
Tests of endogeneity (*p*-value)					0.002	0.094
Observation	33,042	33,042	33,042	33,042	33,042	33,626

Note: All standard errors in parentheses are clustered at the enterprise level: ** $p < 0.05$, *** $p < 0.01$. Columns (1), (3), and (5) control for enterprise and year-fixed effects (FEs). Columns (2), (4), and (6) use all controls. See Table 1 for baseline controls.

Next, this study presents the influence of thermal inversions on enterprise energy efficiency and reports the results in Columns (3) and (4) of Table 2. The coefficients are both significantly negative. The results in a full setting indicate that one additional day with a thermal inversion annually reduces enterprise energy efficiency by 0.1% [= $\exp(-0.001)^{-1}$].

Because of the potential endogeneity, OLS produces biased estimates. The study uses a 2SLS estimate by introducing IV to instrument air pollution. The next two columns of Table 2 present the 2SLS estimates. The result in Column (5) is −0.038, which is statistically significant. Controlling for weather variables, the coefficient is −0.025, and this is statistically significant at a 5% confidence level. The findings indicate that air pollution would decrease enterprise energy efficiency.

4.2. Robustness Checks

To check the robustness of the results, this study conducts several tests. First, it uses the logarithms of the ratio of output over energy in the above baseline estimate. Instead, it uses the ratio of output to energy for a robustness check. Second, it uses the real industrial value added to construct enterprise energy efficiency [39,74]. The industrial value added of enterprises is also obtained from the ASIF database and adjusted by the GDP deflator to a constant price in 1998. Columns (1) and (2) of Table 3 reveal that the results are significantly negative. This is consistent with the baseline findings.

Third, this study includes the quadratic terms of each weather variable to account for possible non-linear effects. Fourth, this study adds more control variables from the enterprise and industry levels, including enterprise age, enterprise ownership, and the Herfindahl–Hirschman Index for the industries. The results are presented in Columns (3) and (4) of Table 3. The results are consistent with the baseline result.

Fifth, the standard errors are clustered at the enterprise level in the baseline estimation. This study checks robustness by clustering the standard errors differently, as below: (1) the standard errors are clustered by enterprise, county, and year; (2) the standard errors are clustered by enterprise and county year; (3) the standard errors are clustered by county year. The results are shown in Columns (1), (2), and (3) of Table 4, respectively. Compared with the baseline results in Column (6) of Table 2, the standard errors increase slightly, but the results remain significant statistically.

Table 3. Robustness with remeasured energy efficiency and additional controls.

Variables	**Enterprise Energy Efficiency**	**Log (Enterprise Energy Efficiency) (Measured with Value Added)**	**Log (Enterprise Energy Efficiency)**	**Log (Enterprise Energy Efficiency)**
	(1) 2SLS	**(2) 2SLS**	**(3) 2SLS**	**(4) 2SLS**
Air pollution	−0.023 *	−0.235 **	−0.028 **	−0.024 **
	(0.013)	(0.106)	(0.011)	(0.010)
Baseline controls	Yes	Yes	Yes	Yes
Quadratic terms of weather variables	No	No	Yes	No
Additional controls	No	No	No	Yes
Enterprise FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Cragg–Donald Wald F statistic	231.485	14.185	447.412	495.012
Observation	33,042	23,627	33,042	32,996

Note: All standard errors in parentheses are clustered at the enterprise level: * $p < 0.10$, ** $p < 0.05$,. Additional controls include enterprise age, enterprise ownership, and the Herfindahl–Hirschman Index for the industries.

Table 4. Robustness with various clustering of standard errors.

Variables	**Log (Enterprise Energy Efficiency)**		
	(1) 2SLS	**(2) 2SLS**	**(3) 2SLS**
Air pollution	–0.025 **	–0.025 *	–0.025 *
	(0.012)	(0.012)	(0.013)
Baseline controls	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Clustered by enterprise, county, and year	Yes	No	No
Clustered by enterprise and county-year	No	Yes	No
Clustered by county-year	No	No	Yes
Cragg–Donald Wald F statistic	484.423	484.350	331.508
Observation	33,042	33,042	33,042

Note: Standard errors are reported in parentheses: * $p < 0.10$, ** $p < 0.05$. Column (1) clusters the standard errors by enterprise, county, and year. Column (2) clusters the standard errors by enterprise and county year. Column (3) clusters the standard errors by county year.

4.3. Heterogeneous Effects

The effects of air pollution on energy-intensive manufacturing enterprise-level energy efficiency may be heterogeneous. Therefore, the study categorizes the observations according to enterprise ownership, enterprise age, enterprise location, and regional energy resource endowment. It divides the full sample into subsamples according to these characteristics and runs the regression model for the relevant subsamples to directly compare the differences in air pollution effects between subsamples.

First, the study focuses on the nature of the ownership and divides the full samples into two types: SOEs and non-state-owned enterprises (non-SOEs). These two types of enterprises may have different reactions to air pollution in terms of energy efficiency [39,40]. The results in Columns (1) and (2) of Table 5A show that the result for SOEs is not statistically significant. However, the result for non-SOEs is significant. One possible reason for this is that non-SOEs have fewer resources to improve energy efficiency than SOEs.

Table 5. (**A**) Heterogeneity analysis by ownership and age. (**B**) Heterogeneity analysis by location and regional resource endowment.

(A)				
Variables	**Log (Enterprise Energy Efficiency)**			
	Enterprise Ownership		**Enterprise Age**	
	SOE	**Non-SOE**	**Mature**	**Young**
	(1) 2SLS	**(2) 2SLS**	**(3) 2SLS**	**(4) 2SLS**
Air pollution	−0.029	−0.024 **	−0.040 **	−0.022
	(0.020)	(0.012)	(0.016)	(0.014)
Baseline controls	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Cragg–Donald Wald F statistic	77.263	407.893	184.093	343.486
Observation	6269	25,974	16,429	14,517
(B)				
Variables	**Log (Enterprise Energy Efficiency)**			
	Enterprise Location		**Region Energy Resource Endowment**	
	Eastern Region	**Middle and Western Region**	**High Coal Production Provinces**	**Low Coal Production Provinces**
	(1) 2SLS	**(2) 2SLS**	**(3) 2SLS**	**(4) 2SLS**
Air pollution	−0.018 *	−0.040 *	−0.053 **	−0.014
	(0.010)	(0.021)	(0.022)	(0.010)
Baseline controls	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Cragg–Donald Wald F statistic	599.580	121.917	105.999	570.022
Observation	17,121	15,921	16,424	16,617

Note: All standard errors in parentheses are clustered at the enterprise level: * $p < 0.10$, ** $p < 0.05$.

Second, start-up and growth enterprises have higher energy efficiency compared with mature companies. In the initial and growth stages, enterprises usually face greater competitive pressure and have a relatively stronger awareness of energy conservation, therefore adopting more advanced technology, machines, and equipment [75]. This study, therefore, considers the heterogeneous effects of enterprise ages and divides the sample into mature and young enterprises according to the median enterprise age. In Columns (3) and (4) of Table 5A, it can be found that air pollution causes a significant decline in the energy efficiency of mature enterprises. Generally, the large machinery and equipment of energy-intensive manufacturing industries are usually expensive to replace. Therefore, mature enterprises may have more production equipment using older and energy-inefficient technologies. Moreover, mature enterprises often prefer to rely on established market power, and their motivation to improve energy efficiency may be weaker.

Third, the study divides the sample according to the provinces where energy-intensive manufacturing enterprises are located, namely the eastern, central, and western regions. As shown in Columns (1) and (2) of Table 5B, air pollution in the eastern region has a smaller effect on an enterprise's energy efficiency compared with the central and western regions. One possible reason for this is that the eastern region's economic environment differs from that of the central and western regions. Energy-intensive manufacturing enterprises in the eastern region may benefit from the area's more advanced economic development. Thus, when facing a loss in energy efficiency due to air pollution, these enterprises have a better ability to counter this decline.

Finally, this study investigates whether air pollution has different effects on energy efficiency for enterprises located in provinces with different resource endowments. According to whether coal production in a province in any given year is greater than the median of the coal production outputs of all provinces in the same year, the study divides provinces as follows: those with high coal production and those with low coal production. The results are reported in Columns (3) and (4) of Table 5B. In terms of absolute value, the estimate in low coal production provinces is smaller and statistically insignificant, while that in high coal production provinces is larger and statistically significant. The regional energy resource endowment has a significant negative effect on enterprise energy efficiency [39,76]. According to the "resource curse" theory, an increase in energy resource endowment will weaken enterprises' awareness of energy conservation, thus reducing their energy efficiency [77]. Therefore, air pollution may bring about a greater decline in enterprises' energy efficiency in high-coal production provinces.

4.4. Mechanisms

Previous research is concerned with the *proposition* that lowering energy efficiency causes increases in air pollution [10–17]. This study is pioneering in its attempt to investigate the *converse proposition* of air pollution on energy-intensive manufacturing enterprises' energy efficiency in China from 1998 to 2007. To obtain a casual effect, it employs the 2SLS method with thermal inversion as the IV, accounting for the potential endogenous problem. The main results validate that air pollution has significant negative effects on enterprise energy efficiency.

This research furthers a discussion about how air pollution may have an influence on enterprise energy efficiency. As mentioned in Section 2, enterprise productivity positively influences energy efficiency [26,57–59]. This study first considers the relationship between air pollution, enterprise TFP, and labor productivity. From the estimated results in Columns (1) and (2) of Table 6, the coefficients of –0.002 and –0.006 are negative and statistically significant. The findings are consistent with previous studies [20,48–56]. The results indicate that enterprise productivity will be reduced because of air pollution. A decline in productivity can decrease enterprise energy efficiency, as previous studies demonstrate [57]. Therefore, it can be concluded that air pollution may adversely affect the energy efficiency of enterprises by reducing productivity (both TFP and labor productivity).

Table 6. The 2SLS estimates of mechanism analysis.

Variables	**Enterprise Total Factor Productivity**	**Enterprise Labor Productivity**	**Enterprise Total Energy Consumption**	**Enterprise Export**
	(1) 2SLS	**(2) 2SLS**	**(3) 2SLS**	**(4) 2SLS**
Air pollution	−0.002 **	−0.006 **	0.023 **	−0.016 ***
	(0.001)	(0.003)	(0.010)	(0.005)
Baseline controls	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Cragg–Donald Wald F statistic	463.514	842.806	484.350	713.595
Observation	15,737	30,732	33,042	5868

Note: All standard errors in parentheses are clustered at the enterprise level: ** $p < 0.05$, *** $p < 0.01$.

Second, Eom et al. [78] find that air pollution can increase household electricity consumption. A similar situation may take place in industrial sectors. Therefore, the study discusses whether air pollution would increase enterprises' energy consumption and further decrease energy efficiency. The coefficient is 0.023 and statistically significant, as shown in Column (3) of Table 6, demonstrating that air pollution increases the energy consumption of enterprises. As discussed above, air pollution would bring a decline in enterprise productivity and thus a decrease in enterprise output. With the decrease in enterprise output and increase in total energy consumption, air pollution may therefore decrease enterprise energy efficiency.

Finally, the study discusses whether air pollution would lower enterprise export, which could potentially lead to a decline in energy efficiency. Some exporters may be required by their trade partners to improve energy efficiency. Thus, export has a significant promoting effect on enterprise energy efficiency [39,60,79]. It can be shown that air pollution has a significantly negative influence on enterprise exports, as shown in Column (4) of Table 6. The finding suggests that air pollution may affect enterprise energy efficiency negatively by lowering exports.

5. Discussion

The problem of energy utilization has become the bottleneck of China's high-quality economic development. Due to the scarcity and high emission of fossil energy, scholars have gradually realized the importance of energy conservation, emission reduction, and energy efficiency improvement. Therefore, related research on energy efficiency has rapidly developed, mostly from a macroeconomic perspective. The vast majority of studies agree that the improvement of energy efficiency can, directly and indirectly, promote economic growth [80,81]. Whether economic growth has an impact on energy efficiency or not, most studies believe that economic growth does not necessarily affect energy efficiency and needs to be a concern based on the development stage [82,83]. Meanwhile, the fact that industrial structure adjustment is beneficial to the improvement of energy efficiency has been proven by many previous studies. Zhang and Pu [84] agree that the goals of industrial structure upgrading and energy efficiency improvement are strategically consistent and feasible. Lv and Chen [85] believe that the evolution of industrial structure has a significant impact on energy efficiency, and the improvement of energy efficiency mainly comes from the contribution of industrial structure upgrading. Li and Cheng [86] argue that the overall level of energy efficiency in China is still very low, which is mainly determined by the energy-intensive manufacturing industrial structure and its production technology structure. However, research on energy efficiency is still scarce using enterprise-level data [37,87–89]. Different from previous studies, this paper explores the causal impact of air pollution on the energy-level (micro-level) efficiency of energy-intensive manufacturing enterprises. Further, we analyze the heterogeneous effects and influencing mechanisms. Our findings may further enrich the understanding of energy efficiency improvement from a micro-perspective and thus complement the literature on the effect of air pollution on energy utilization and economic growth.

Additionally, most previous studies believe that the improvement in energy efficiency will reduce environmental pollution. Li et al. [90] suppose that there is a long-term equilibrium relationship between total factor energy efficiency and economic losses from environmental pollution in China, and the former has a more obvious effect on the latter, which means that the improvement of total factor energy efficiency plays an important role in reducing the environmental pollution. Energy efficiency is found to be the main driving factor for the decrease in carbon emissions [91,92]. At present, with the carbon peaking and carbon neutrality goals established and new energy regulations stipulated, enterprises have to reduce carbon emissions and promote energy efficiency, especially for those in energy-intensive manufacturing industries. Though this study uses observations of energy-intensive manufacturing enterprises from the period 1997 to 2007, our main result that reducing air population could improve enterprise-level energy efficiency and thus reduce costs still has important policy implications. Since energy-intensive manufacturing industries were and still are the primary fossil energy users, our findings provide an economic rationale for those enterprises in energy-intensive manufacturing industries to motivate themselves to reduce air pollution by employing effective green technology and adopting innovation activities.

This study tries to quantitatively investigate the impact of air pollution on enterprise energy efficiency. The finding enriches our understanding of air pollution's effect on energy consumption and sustainable development. However, because of data limitations, the data on enterprise electricity consumption are not available. This is one of the reasons that the analysis of the study is limited to energy-intensive manufacturing industries, apart from the importance of these industries, which mainly rely on fossil energy and are crucial in terms of energy conservation and pollution reduction. In the future, if electricity consumption data are available, it would be necessary to extend the investigation to other industries. Furthermore, though the findings using the observations from 1997 to 2007 still have important implications, we will update when the latest data are available and try different measurements of energy efficiency apart from the one calculated by Equation (4) [93].

6. Conclusions and Policy Implications

The findings show that air pollution causes a significant loss in the enterprise-level energy efficiency of energy-intensive manufacturing industries. This indicates that there is a significant potential benefit to increasing energy efficiency through improved air quality. It offers an economic rationale for enterprises to motivate themselves to control pollution and has significant implications for policymaking in China and other developing countries. Governments should attach greater importance to mechanisms that can combat air pollution.

Additionally, the findings of the study shed new light on energy policy formulation. The formulation of energy policy should be adapted to enterprise characteristics. The analyses of the heterogenous effects of the study indicate that, facing severe air pollution issues, governments should provide incentives to those enterprises with greater declines in energy efficiency, such as non-SOEs and mature enterprises, as well as those enterprises in central and eastern provinces, to increase the adoption of technological upgrades.

Meanwhile, because of the divergent economic development and resource endowment, the implementation of energy policies should be tailored to local conditions. For example, to undercut the negative effects of the "resource curse", in energy-rich regions, governments should adopt more powerful penalties for those enterprises whose pollution levels are higher than those stipulated.

The governments should strengthen overseas trade and integrate into the international market so as to improve the efficiency of resource allocation and energy efficiency. Moreover, the higher the level of opening to the outside world, the higher the degree of technology spillover, and the higher the efficiency of energy utilization.

Finally, enterprises should strengthen the accumulation of human capital, pay attention to the improvement of labor skills, increase investment in research and development (R&D) and innovation, further improve the utilization rate of enterprise energy, and realize the "win-win" of energy conservation, emission reduction, and economic growth.

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References

1. Xu, G.Q.; Deng, X.; Chen, X.Y. Transformation and upgrading of manufacturing and high-quality economic development: A Research based on total factor energy efficiency. *Econ. Theory Bus. Manag.* **2020**, *360*, 100–110. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErAMS82w2u8ncrRENPc-9g7JzB7FW7rk9jC_0rtydDGps3R8TJigiPqxGjpeWNpHDGQ9HTcVcIUs05O00_gI65m5rajk8mQv_QsRNx9reX6nuN8FvrCiDENo&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
2. Tan, R.; Lin, B. What factors lead to the decline of energy intensity in China's energy intensive industries? *Energy Econ.* **2018**, *71*, 213–221. [CrossRef]
3. Wang, J.; Hu, M.; Tukker, A.; Rodrigues, J.F. The impact of regional convergence in energy-intensive industries on China's CO2 emissions and emission goals. *Energy Econ.* **2019**, *80*, 512–523. [CrossRef]
4. Yuan, H.; Feng, Y.; Lee, C.C.; Cen, Y. How does manufacturing agglomeration affect green economic efficiency? *Energy Econ.* **2020**, *92*, 104944. [CrossRef]
5. Zhang, T. Which policy is more effective, carbon reduction in all industries or in high energy-consuming industries? From dual perspectives of welfare effects and economic effects. *J. Clean. Prod.* **2019**, *216*, 184–196. [CrossRef]
6. Ministry of Ecology and Environment of the People's Republic of China. *China Ecological and Environmental Statistical Annual Report*; Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2020.
7. Ma, Q.; Cai, S.; Wang, S.; Zhao, B.; Martin, R.V.; Brauer, M.; Cohen, A.; Jiang, J.; Zhou, W.; Hao, J.; et al. Impacts of coal burning on ambient PM2.5 pollution in China, Atmos. *Chem. Phys.* **2017**, *17*, 4477–4491. [CrossRef]
8. Li, M.J.; Tao, W.Q. Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. *Appl. Energy* **2017**, *187*, 203–215. [CrossRef]
9. Shi, D.; Li, S.L. Emissions trading system and energy use efficiency: Measurements and empirical evidence for cities at and above the prefecture level. *China Ind. Econ.* **2020**, *390*, 23. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErD-OreruYm5oCgQ7-YtMynq3SKqfJ7NCIjKUzDDBryw-0nWYALzfeaISrWbgGsTgrlIU3v3kBFXRBivaF14QcCR7ArXe8-tgpq8_9kHjbavsGDGCoFfnkWn&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
10. National Research Council. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*; The National Academies Press: Washington, DC, USA, 2010. [CrossRef]
11. Hasanbeigi, A.; Morrow, W.; Masanet, E.; Sathaye, J.; Xu, T. Energy efficiency improvement and CO2 emission reduction opportunities in the cement industry in China. *Energy Policy* **2013**, *57*, 287–297. [CrossRef]
12. Zhang, S.; Worrell, E.; Crijns-Graus, W.; Wagner, F.; Cofala, J. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. *Energy* **2014**, *78*, 333–345. [CrossRef]
13. Zhang, S.; Worrell, E.; Crijns-Graus, W. Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry. *Appl. Energy* **2015**, *147*, 192–213. [CrossRef]
14. Cui, J.; Lapan, H.; Moschini, G. Productivity, export, and environmental performance: Air pollutants in the United States. *Am. J. Agric. Econ.* **2016**, *98*, 447–467. [CrossRef]
15. Qin, Q.; Li, X.; Li, L.; Zhen, W.; Wei, Y.M. Air emissions perspective on energy efficiency: An empirical analysis of China's coastal areas. *Appl. Energy* **2017**, *185*, 604–614. [CrossRef]
16. Forslid, R.; Okubo, T.; Ulltveit-Moe, K.H. Why are firms that export cleaner? International trade, abatement and environmental emissions. *J. Environ. Econ. Manag.* **2018**, *91*, 166–183. [CrossRef]
17. Yang, C.; Li, T.; Albitar, K. Does energy efficiency affect ambient PM2.5? The moderating role of energy investment. *Front. Environ. Sci.* **2021**, *9*, 707751. [CrossRef]
18. Arceo, E.; Hanna, R.; Oliva, P. Does the effect of pollution on infant mortality differ between developing and developed countries? Evidence from Mexico City. *Econ J.* **2016**, *126*, 257–280. [CrossRef]
19. Jans, J.; Johansson, P.; Nilsson, J.P. Economic status, air quality, and child health: Evidence from inversion episodes. *J. Health Econ.* **2018**, *61*, 220–232. [CrossRef]
20. Fu, S.H.; Viard, V.B.; Zhang, P. Air pollution and manufacturing firm productivity: Nationwide estimates for China. *Econ. J.* **2021**, *131*, 3241–3273. [CrossRef]
21. Chen, S.; Oliva, P.; Zhang, P. The effect of air pollution on migration: Evidence from China. *J. Dev. Econ.* **2022**, *156*, 102833. [CrossRef]
22. Backlund, S.; Thollander, P.; Palm, J.; Ottosson, M. Extending the energy efficiency gap. *Energy Policy* **2012**, *51*, 392–396. [CrossRef]
23. Thollander, P.; Danestig, M.; Rohdin, P. Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs. *Energy Policy* **2007**, *35*, 5774–5783. [CrossRef]
24. Zhou, N.; Levine, M.D.; Price, L. Overview of current energy-efficiency policies in China. *Energy Policy* **2010**, *38*, 6439–6452. [CrossRef]
25. Lin, B.Q.; Wang, X.Z.; Du, Z.L. Impact of environmental regulation on China's industrial energy efficiency: An empirical study based on the data of micro-enterprises. *J. Xiamen Univ. Arts Soc. Sci.* **2021**, *4*, 30–42. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=XMDS202104004&DbName=CJFQ2021 (accessed on 17 January 2023).
26. Stern, D.I. Modeling international trends in energy efficiency. *Energy Econ.* **2012**, *34*, 2200–2208. [CrossRef]
27. Song, F.; Yu, Y. Modelling energy efficiency in China: A fixed-effects panel stochastic frontier approach. *Econo. Polit. Stud.* **2018**, *6*, 158–175. [CrossRef]

28. Sun, H.; Edziah, B.K.; Sun, C.; Kporsu, A.K. Institutional quality, green innovation and energy efficiency. *Energy Policy* **2019**, *135*, 111002. [CrossRef]
29. Otsuka, A.; Goto, M. Estimation and determinants of energy efficiency in Japanese regional economies. *Reg. Sci. Policy Pract.* **2015**, *7*, 89–101. [CrossRef]
30. Jebali, E.; Essid, H.; Khraief, N. The analysis of energy efficiency of the Mediterranean countries: A two-stage double bootstrap DEA approach. *Energy* **2017**, *134*, 991–1000. [CrossRef]
31. Jiang, L.; Folmer, H.; Ji, M.; Tang, J. Energy efficiency in the Chinese provinces: A fixed effects stochastic frontier spatial Durbin error panel analysis. *Ann. Reg. Sci.* **2017**, *58*, 301–319. [CrossRef]
32. Du, M.; Wang, B.; Zhang, N. National research funding and energy efficiency: Evidence from the National Science Foundation of China. *Energy Policy* **2018**, *120*, 335–346. [CrossRef]
33. Marin, G.; Palma, A. Technology invention and diffusion in residential energy consumption. A stochastic frontier approach. *A Stoch. Front. Approach* **2015**, *9*, 2662362. [CrossRef]
34. Danquah, M. Technology transfer, adoption of technology and the efficiency of nations: Empirical evidence from sub Saharan Africa. *Technol. Forecast. Soc.* **2018**, *131*, 175–182. [CrossRef]
35. Chen, W.; Yin, X.; Ma, D. A bottom-up analysis of China's iron and steel industrial energy consumption and CO2 emissions. *Appl. Energy* **2014**, *136*, 1174–1183. [CrossRef]
36. Lin, B.; Tan, R. Ecological total-factor energy efficiency of China's energy intensive industries. *Ecol. Indic.* **2016**, *70*, 480–497. [CrossRef]
37. Hassen, S.; Gebrehiwot, T.; Arega, T. Determinants of enterprises use of energy efficient technologies: Evidence from urban Ethiopia. *Energy Policy* **2018**, *119*, 388–395. [CrossRef]
38. Lin, B.; Long, H. A stochastic frontier analysis of energy efficiency of China's chemical industry. *J. Clean. Prod.* **2015**, *87*, 235–244. [CrossRef]
39. Chen, Z.; Chen, Z.; Chen, Q.Y. Energy Efficiency of Chinese Firms: Heterogeneity, Influencing Factors and Policy Implications. *Chin. Ind. Econ.* **2019**, *12*, 78–95. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErCrjG8fanJsDZCjuopa3sqVtK4Fs2623zb7r7z24iAe6evkqdBSL3Piq9BQ02mkVzl9lYBWaB-eBL3Cx87IXE6Mb9cAWg_BHezjs5pHRJiWhlarmZBFKBSv&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
40. Wei, C.; Shen, M.H. Can structural adjustment improve energy efficiency: A study based on Chinese provincial data. *J. World Econ.* **2008**, *11*, 77–85. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErAT38Xc3oA3l8unMoSJ3_s-loIcPy6X7oUIvHoXcgflFmWOqep6qN9lpjYPcDuJVlmDs68DGkrCbcgo7bD3wLMoERGSzDsArgL35TEh9eytLA==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
41. Liao, J.Q.; Xu, J.T. Enterprise Innovation and Energy Intensity. *Contemp. Financ. Econ.* **2019**, *1*, 108–118. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErANioCoR3II8V2Z3MAas2Ay6aZFBaj5Ms9Faz4UbWtsY6m3untOxCb7hGBgwa0aaNOvnjeRUniMLZ2KO2YXmK2HphedXl132aHP9E_EEyFfwKAWCPvosAMg&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
42. Perroni, M.G.; da Costa, S.E.G.; de Lima, E.P.; da Silva, W.V. The relationship between enterprise efficiency in resource use and energy efficiency practices adoption. *Int. J. Prod. Econ.* **2017**, *190*, 108–119. [CrossRef]
43. Yuan, Y.J.; Guo, L.L.; Sun, J. Structure, technology, management and energy Efficiency: Stochastic frontier approach based on provincial panel data during 2000—2010. *China Ind. Econ.* **2012**, *2*, 18–30. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErBfMdk83lfdVwg-qaiH97zcpRnZsQ0OOnsFAebHu8NFe_iTNInpkEMe5VgB3b1b7EiydGjCltEYotbzCM8kRXKBRHhuNnUFwOzfOJQ5mfNJsQ==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
44. Li, K.; Lin, B.Q. How to promote energy efficiency through technological progress in China? *Energy* **2018**, *143*, 812–821. [CrossRef]
45. Lv, K.; Yu, A.; Bian, Y. Regional energy efficiency and its determinants in China during 2001–2010: A slacks-based measure and spatial econometric analysis. *J. Prod. Anal.* **2017**, *47*, 65–81. [CrossRef]
46. Liu, J.; Cheng, Z.H.; Zhang, H.M. Does industrial agglomeration promote the increase of energy efficiency in China? *J. Clean. Prod.* **2017**, *164*, 30–37. [CrossRef]
47. Tanaka, K.; Managi, S. Industrial agglomeration effect for energy efficiency in Japanese production plants. *Energy Policy* **2021**, *156*, 112442. [CrossRef]
48. Li, W.B.; Zhang, K.X. The impact of air pollution on enterprise productivity: Evidence from Chinese industrial firms. *Manag. World.* **2019**, *10*, 95–119. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErB7BZvGCOMhu5Rn9gjE_cPJU5-DE7NrSDShE33VPTOW1ZnGrByUDZVh57OC6XyGxzMoscLWYGtOUoT0HyXhL-wFci3OVIq8ee4rgMnB-FpQuBjj-0HJVnr_&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
49. Li, B.; Shi, S.; Zeng, Y. The impact of haze pollution on firm-level TFP in China: Test of a mediation model of labor productivity. *Sustainability* **2020**, *12*, 8446. [CrossRef]
50. Cao, Y.; Wang, Q.; Zhou, D. Does air pollution inhibit manufacturing productivity in Yangtze River Delta, China? Moderating effects of temperature. *J. Environ. Manag.* **2022**, *306*, 114492. [CrossRef]
51. Zivin, J.G.; Neidell, M. The impact of pollution on worker productivity. *Am. Econ. Rev.* **2012**, *102*, 3652–3673. [CrossRef]
52. Lichter, A.; Pestel, N.; Sommer, E. Productivity effects of air pollution: Evidence from professional soccer. *Labour Econ.* **2017**, *48*, 54–66. [CrossRef]

53. Archsmith, J.; Heyes, A.; Saberian, S. Air quality and error quantity: Pollution and performance in a high-skilled, quality-focused occupation. *J. Assoc. Environ. Reso.* **2018**, *5*, 827–863. [CrossRef]
54. Chang, T.Y.; Zivin, J.G.; Gross, T.; Neidell, M. The effect of pollution on worker productivity: Evidence from call center workers in China. *Am. Econ. J.-Appl. Econ.* **2019**, *11*, 151–172. [CrossRef]
55. He, J.X.; Liu, H.M.; Salvo, A. Severe air pollution and labor productivity: Evidence from industrial towns in China. *Am. Econ. J.-Appl. Econ.* **2019**, *11*, 173–201. [CrossRef]
56. Wang, F.; Wu, M. Does air pollution affect the accumulation of technological innovative human capital? Empirical evidence from China and India. *J. Clean. Prod.* **2021**, *285*, 124818. [CrossRef]
57. Montalbano, P.; Nenci, S. Energy efficiency, productivity and exporting: Firm-Level evidence in Latin America. *Energy Econ.* **2019**, *79*, 97–110. [CrossRef]
58. Bloom, N.; Mahajan, A.; McKenzie, D.; Roberts, J. Why do firms in developing countries have low productivity? *Am. Econ. Rev.* **2010**, *100*, 619–623. [CrossRef]
59. Shapiro, J.S.; Walker, R. Why is pollution from US manufacturing declining? The roles of environmental regulation, productivity, and trade. *Am. Econ. Rev.* **2018**, *108*, 3814–3854. [CrossRef]
60. Blalock, G.; Gertler, P.J. Learning from exporting revisited in a less developed setting. *J. Dev. Econ.* **2004**, *75*, 397–416. [CrossRef]
61. Bustos, P. Trade liberalization, exports, and technology upgrading: Evidence on the impact of MERCOSUR on Argentinian firms. *Am. Econ. Rev.* **2011**, *101*, 304–340. [CrossRef]
62. Lileeva, A.; Trefler, D. Improved access to foreign markets raises plant-level productivity for some plants. *Q. J. Econ.* **2010**, *125*, 1051–1099. [CrossRef]
63. Roy, J.; Yasar, M. Energy efficiency and exporting: Evidence from firm-level data. *Energy Econ.* **2015**, *52*, 127–135. [CrossRef]
64. Galdeano-Gómez, E. Exporting and environmental performance: A firm-level productivity analysis. *World Econ.* **2010**, *33*, 60–88. [CrossRef]
65. Cole, M.A.; Elliott, R.J.; Shimamoto, K. Globalization, firm-level characteristics and environmental management: A study of Japan. *Ecol. Econ.* **2006**, *59*, 312–323. [CrossRef]
66. Brandt, L.; Biesebroeck, J.V.; Zhang, Y.F. Challenges of working with the Chinese NBS firm-level data. *China Econ. Rev.* **2014**, *30*, 339–352. [CrossRef]
67. Zhang, B.; Chen, X.; Guo, H. Does central supervision enhance local environmental enforcement? Quasi-experimental evidence from China. *J. Public Econ.* **2018**, *164*, 70–90. [CrossRef]
68. Lyubich, E.; Shapiro, J.; Walker, R. Regulating mismeasured pollution: Implications of firm heterogeneity for environmental policy. *AEA Pap. Proc.* **2018**, *108*, 136–142. [CrossRef]
69. Kumar, S.; Russell, R.R. Technological change, technological catch-up, and capital deepening: Relative contributions growth and convergence. *Am. Econ. Rev.* **2002**, *92*, 527–548. [CrossRef]
70. Gupta, P.; Christopher, S.A.; Wang, J.; Gehrig, R.; Lee, Y.C.; Kumar, N. Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmos. Environ.* **2006**, *40*, 5880–5892. [CrossRef]
71. Kumar, N.; Chu, A.D.; Foster, A.D.; Peters, T.; Willis, R. Satellite remote sensing for developing time and space resolved estimates of ambient particulate in Cleveland, OH. *Aerosol. Sci. Tech.* **2011**, *45*, 1090–1108. [CrossRef]
72. Van Donkelaar, A.; Martin, R.V.; Brauer, M.; Kahn, R.; Levy, R.; Verduzco, C.; Villeneuve, P.J. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Development and application. Environ. *Health Persp.* **2010**, *118*, 847–855. [CrossRef]
73. Buchard, V.; Da Silva, A.M.; Randles, C.A.; Colarco, P.; Ferrare, R.; Hair, J.; Hostetler, C.; Tackettde, J.; Winker, D. Evaluation of the surface PM2. 5 in Version 1 of the NASA MERRA Aerosol Reanalysis over the United States. *Atmos. Environ.* **2016**, *125*, 100–111. [CrossRef]
74. Dong, F.; Li, Y.; Zhang, X.; Zhu, J.; Zheng, L. How does industrial convergence affect the energy efficiency of manufacturing in newly industrialized countries? Fresh evidence from China. *J. Clean. Prod.* **2021**, *316*, 128316. [CrossRef]
75. Zhang, S.F.; Wei, X.H. Whether ICT reduces firm energy consumption: Evidence from Chinese manufacturing firm survey data. *Chin. Ind. Econ.* **2019**, *2*, 155–173. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=GGYY201902010&DbName=CJFQ2019 (accessed on 17 January 2023).
76. Wang, Q.S. Energy Efficiency and Industrial Structure Optimization and Upgrading: An Empirical Study Based on Inter-Provincial Panel Data from 2000 to 2006. *Quant. Tech. Econ.* **2010**, *10*, 49–63. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=SLJY201010006&DbName=CJFQ2010 (accessed on 17 January 2023).
77. Pan, X.F.; Peng, X.X.; Li, B. Market distortions, technological progress, and energy efficiency: Policy choices based on inter-provincial heterogeneity. *J. World Econ.* **2017**, *1*, 91–115. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=SJJJ201701006&DbName=CJFQ2017 (accessed on 17 January 2023).
78. Eom, J.; Hyun, M.; Lee, J.; Lee, H. Increase in household energy consumption due to ambient air pollution. *Nat. Energy* **2020**, *5*, 976–984. Available online: https://www.nature.com/articles/s41560-020-00697-27 (accessed on 17 January 2023). [CrossRef]
79. Hübler, M. Carbon tariffs on Chinese exports: Emissions reduction, threat, or farce? *Energy Policy* **2012**, *50*, 315–327. [CrossRef]
80. Warr, B.S.; Ayres, R.U. Evidence of causality between the quantity and quality of energy consumption and economic growth. *Energy* **2010**, *35*, 1688–1693. [CrossRef]
81. Bernard, C.B. On the methodology of energy-GDP Granger causality tests. *Energy* **2010**, *35*, 3535–3539. [CrossRef]

82. Rajbhandari, A.; Zhang, F. Does energy efficiency promote economic growth? Evidence from a multicountry and multisectoral panel dataset. *Energy Econ.* **2018**, *69*, 128–139. [CrossRef]
83. Zhao, X.G.; Liu, P.K. Economic growth and energy intensity: An empirical research based on panel smooth transition regression. *Chin. J. Manag. Sci.* **2014**, *22*, 103–113. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErDQ2299g6Y48W4YsqQtvn_3OxWhUkPC7mp9YLAL42DH5YTwHGy1JFMfo5HkjMetAJH46CSVGl-idntc6D-Qds1ChWVpLkq1ytMhD3Gs_zdUcw==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
84. Zhang, Y.; Pu, Y.J. Industrial structure change and its influence on energy intensity. *Ind. Econ. Res.* **2015**, *75*, 15–67. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErCrptWkv7hAvIzEMFVDxW5rlk1m0nIwfotAcCHhxFBxS_za3JTc2LLIXifQ7f4ZGb4nJBTlJI5rKKPxVIL3VxkdjoOG_Vh_DZFVBsVmOD6QM23JA_tqG-ph&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
85. Lv, M.Y.; Chen, W.X. The impact of industrial structure upgrading on energy efficiency in China: Based on 1978–2013 data. *Resour. Sci.* **2016**, *38*, 1350–1362. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErAbMDvzOkSgIDJIZxUZfGY39p8gWWN5qv0L2-JdwmHAqJe4xaWCGEWom_V4rvDiuKamP3PlFgJgi_XZgtMwrKT1n-7ffzjIBJ8oJf0lgw3_29nQo1nabolc&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
86. Li, S.X.; Cheng, J.H. Evaluation of energy efficiency in China and analysis of its influencing factors. *Stat. Res.* **2008**, *204*, 18–27. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErCMdGjvkYuoH4kNLUDaihVdEJYWXVA6dwZzdQaq79v_zYR8LnaW3JY9dDZwiM38WVHmjf82SpunYA61_vbyGS9DthKnmiqfMsOHkemI9-N9XQ==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
87. Fisher-Vanden, K.; Jefferson, G.H.; Liu, H.; Tao, Q. What is driving China's decline in energy intensity? *Resour. Energy. Econ.* **2004**, *26*, 77–97. [CrossRef]
88. Li, S.H. Industrial agglomeration, human capital and enterprise Energy efficiency: A case study of high-tech enterprises. *Financ. Trade Econ.* **2011**, *358*, 128–134. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErBB6q-XqhjSEcqc5yoqteoEzNENjyvBTSEE0d03dzsNXLDoJfGdxBe3shDtwP-z3BGB9_ejrRzEReqoVCkCG7shX5TEKjAHibh7VZ3vkwgKxQ==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
89. Yin, Z.H.; Lei, M.; Yu, X.W. Energy and environmental efficiency analysis of China's iron and Steel industry: Based on microdata of industrial enterprises. *Chin. J. Manag. Sci.* **2014**, *22*, 691–697. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErCowFkGLg2Q9FECDdeiko5zGm545_CKjlyAi-uFpDZBQTvH1CZNScuovTieG51I-PVWssgMqKvVyhfehxBh0afu7NAysFN8iPT0pY3rAYOPqV1wDiaVEhbe&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
90. Li, G.Z.; Jiang, J.R.; Zhou, C.Y. Study on the relationship between total factor energy efficiency and environmental pollution. *China Popul. Resour. Environ.* **2010**, *20*, 50–56. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErBikANBJgp7Wt7v2pyPTiJS_1vyeAxAOlEInU1w9XirIZdgeDZ2ESMxa_tBc0vLmneMBJnl2O62m5C6HC_KJdUdneh6qkTQ0NtE86HZ0K07pw==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
91. Jin, L.Q.; Wu, H.Y. The trajectory and path of low-carbon economic transformation: Comparison and enlightenment between China, Japan and South Korea. *Economist* **2013**, *169*, 93–99. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErB6YeU7wzylqYitNmsFvjEH4RRHasjRWnc2pcSOQWCz3BwcUxuXaQtD0NDek2GjuM1gJ910OyIphgMuYZpDK-aq79dYi-c6krJJQuqLLigO4Q==&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
92. Wang, F.; Feng, G.F.; Wu, L.H. Decomposition of Provincial Contribution to Carbon Intensity Reduction in China's Economic Growth. *Econ. Res.* **2013**, *48*, 143–155. Available online: https://kns.cnki.net/kcms2/article/abstract?v=6uDTENTNErAVmyFKOuBfVygqxsHWB3ZCAekzBLgpH9nmy--7JkVBFqubypfHQbTbBWK4yLmiFYBimRjfXAO5BNuV1-obMj4d4Wz_yNZ8Pa-8Oc1v2JUWFKFlGYWaY_PD&uniplatform=NZKPT&language=CHS (accessed on 17 January 2023).
93. Patterson, M.G. What is energy efficiency: Concepts, indicators and methodological issues. *Energy Policy* **1996**, *24*, 377–390. [CrossRef]