Circular Economy and Sustainability (2024) 4:1539–1558
https://doi.org/10.1007/s43615-023-00327-5

ORIGINAL PAPER

How Does Environmental Policy Stringency Affect Inefficiency of Firms? New Evidence from International Firm-Level Data

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Received: 28 June 2023 / Accepted: 13 November 2023 / Published online: 13 December 2023

Abstract
This paper examines the strong version of the Porter hypothesis (PH) using a huge international firm-level dataset of approximately 800,000 observations during 2010–2015. To examine the impacts of the environmental policy stringency (EPS) on firms' inefficiency, this paper applies the technical inefficiency effects model of stochastic frontier analysis to examine the nonlinear impacts from the total EPS index and four policy instruments of standards, tax, trading schemes, and research and development subsidies. To address potential endogeneity, predicted EPS indices are employed in the estimation. Empirical results indicate that the strong PH holds for both the aggregate total and all individual environmental policy instruments when EPS exceeds the threshold. The estimated results by policies and industries are qualitatively nearly the same. Empirical findings validate that the strong PH holds when environmental regulations are tightened beyond a certain level. Finally, the "appropriate mix of instruments" instead of "best instrument" is recommended by this paper.

Keywords Environmental policy stringency · Porter hypothesis · Stochastic frontier analysis

JEL Classification Q50 · Q58 · D24

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Introduction

Under the global movement of achieving net-zero emissions by 2050 [1], the environmental policy stringency (EPS) have becoming higher and higher in the global village. The EPS affects not only the environmental but also production performance of the firm. Although the environmental, social, and corporate governance (ESG) has become a central feature of policymaking [2], some industries contend that it has a negative impact on corporate profits due to compliance costs. In contrast, many researchers and policymakers assert that more environmental regulations are needed to achieve the ceiling of 2 °C temperature increase target encoded in the Paris Agreement [3, 4].

While stricter environmental regulation imposes compliance costs, it can also stimulate environmental innovation among regulated firms, and the benefits of such innovation may exceed its costs. The Porter hypothesis (PH) refers to the mutually beneficial state that arises between environmental policy and industrial performance [5, 6]. Specifically, the stricter the environmental regulation, the higher the compliance cost on regulated firms, which stimulates incentive toward environment-friendly innovation. When the benefits of the innovation exceed the costs, the regulation is then stricter, and innovation offset occurs [6]. Consequently, the relationship between EPS and economic performance could be nonlinear, and it should be examined when PH exists as well as when nonlinearity exists. Even though PH has been a famous hypothesis, the existing literature obtains different empirical findings about it, making it still a hypothesis instead of a theorem.

Various environmental policies have been implemented based on the political context in countries and regions since the end of World War II. The command-and-control approach was introduced in developed countries to mitigate air and water pollutants. With the growing recognition of global warming, northern European countries have introduced carbon taxes in the early 1990s, achieving some success [7]. Since its foundation in 2005, the European Union Emissions Trading Scheme (EU ETS) represents the largest greenhouse gas emissions trading scheme in the world. Subsidies have also been used in many countries to promote political accessibility. Differences in the effects of policy measures should be investigated in the context of the PH.

Many studies that will be reviewed in the next section examine the strong PH by measuring total factor productivity (TFP) in the first step, then regressing TFP on environmental policy stringency (EPS) and other control variables. Notably, this approach estimates the production frontier without considering the effects of EPS.

This research instead explores the relation between EPS and the firm's production inefficiency. Similar arguments can be drawn from the literature on the relation between EPS and TFP. A more rigorous EPS should first increase the firm's production inefficiency because the firm has to spend resources and efforts in adjusting its production in order to meet the upgraded EPS. However, as the EPS gets even higher, it can help the firm reduce production inefficiency because of more advanced production technology and processes.

This paper will examine the strong PH using the stochastic frontier analysis (SFA) and examine the nonlinear effects of the EPS on firms' inefficiency. The research questions of our study are as follows:

- How does EPS affect firm performance?
- Is the impact of EPS linear or nonlinear?
- How does the impact of EPS differ by policy instrument?
- What is the recommended policy direction for each country in the sample?

This study's contributions are fourfold. First, it estimates a production frontier, considering the influence of EPS. The technical inefficiency effects model capable of simultaneously estimation of both the production frontier and inefficiency factor [8] will be adopted.

Many studies measure economies' and firms' TFP change in an intertemporal direction in the first stage to analyze how TFP changes with ESP in the second stage, whereas this study measure firms' TFP in a cross-sectional direction within the same period, taking EPS as an explanatory variable. Our results provide alternative information for policymakers to strategically develop environmental policies. Second, we use a huge multinational dataset, which is obtained from the ORBIS of the Bureau Van Dijk. Third, we examine the nonlinear impacts of EPS on firms' inefficiency, incorporating the squared term of EPS into the model, which enables us to uncover the heterogeneous influences of EPS on firms' efficiency. Finally, we examine the impacts of EPS using the total stringency index as well as individual policy instruments, including standards, emission taxes, trading schemes, and research and development (R&D) subsidies.

The remainder of this paper is organized as follows. The "Literature Review" section presents a review of related empirical literature on the influence of environmental policy on firms' efficiency. The "Methology and Data" section describes our data and research methodology. The "Empirical Results" section presents the research findings, a discussion of the main results, and related policy implications. The "Concluding Remarks" section offers our conclusions.

Literature Review

The PH highlights the relationship between environmental policy and industrial performance [5, 6]. Jaffe and Palmer [9] distinguish three levels of the PH. The weak version implies that properly designed environmental policy stimulates innovation, wherein whether the innovation improves firms' performance does not matter. The strong version implies that tightening EPS improves overall economic performance, inducing innovation. The narrow version implies that flexible environmental policy encourages firms' innovation. This study specifically investigates the strong version of the PH.

Over the past few decades, a considerable number of studies have tested the PH.[1] For the strong version, the empirical results are mixed, whereas [11–16] support the strong version of the PH, [17–22] do not.[2] Costantini and Mazzanti [23] and De Santis [24] also do not support the strong PH for export. Franco and Marin [25] test both strong and weak versions of the PH by using European countries' data, showing that environmental taxes have positive impacts on productivity.

Recent studies investigate the nonlinear and heterogeneous effects of environmental policies, including case studies of specific countries on the strong and weak forms of the PH. Xie et al. [26] test the strong PH for China's 30 provinces using a slack-based measure and the Luenberger productivity index, finding both market-based regulation and command-and-control to have nonlinear effects on TFP growth. Using SFA, van Leeuwena and Mohnen [27] use a Dutch manufacturing firm-level panel dataset to estimate the relative effect

[1] Cohen and Tubb [10] provide a meta-analysis of 103 publications regarding the PH.

[2] [12] support the strong version of the PH for Mexico but not for the USA. Lanoie et al. [14] support the PH for the lagged regulatory variable and a subgroup of industries that are more exposed to international competition.

of environmental regulations on eco-investment and eco-innovation. The authors determine that the weak-form PH is supported, whereas the strong version of PH is not supported. Shen et al. [28] investigate the heterogeneity of the influence of various environmental regulations on TFP in China's industries. Using the index of metafrontier Malmquist–Luenberger productivity and threshold model, the authors determine that the optimal interval of environmental regulation varies, depending on types of regulations, command-and-control, market, and types of industries.

Li et al. [29] also apply the Malmquist–Luenberger productivity index to China's iron and steel enterprises, finding that the relationship between market incentive environmental regulation and total factor environmental governance efficiency is an inverted U-shaped. However, no statistically significant relationship between command control environmental regulation and the efficiency is observed.

In a cross-country comparison, Albrizio et al. [30] test strong PH, examining industry- and firm-level productivity growth in OECD countries. The authors find stricter environmental policies to have a positive effect for the most productive firms, but a negative effect on less productive firms. Wang and Shao [31] also employ the panel threshold regression, finding a single structural breakpoint for market EPS and two breakpoints for nonmarket EPS in G20 countries. Examining the effects of environmental policy on productivity changes, Wang et al. [32] demonstrate that the strong PH holds for OECD countries when EPS is lower than a certain level. Lei et al. [16] also supported the strong PH using Chinese A-share listed companies' data. Analyzing the profitability of publicly held firms in the chemical manufacturing industry in the USA; Rassier and Earnhart [33] find that tighter water regulation meaningfully lowers profitability and does not support the strong PH. Rexhäuser and Rammer [19] used firm-level data from Germany, and although their empirical findings generally do not support the strong PH, the authors assert that the conclusion depends on the type of environmental innovation. Liu et al. [22] also do not support the strong PH in Chinese textile, printing, and dyeing firms, using a difference-in-differences regression model with propensity score matching. Recently, Shuai and Fan [34] construct the green economy efficiency using the super-efficient data envelopment analysis model in 30 provinces in China. They find a U-shaped relationship between the derived efficiency and environmental regulation. Besides, Wu and Lin [35] construct the energy environmental performance index of China's iron and steel industry using the data envelopment analysis method and present that it has a U-shaped relationship with the environmental regulation intensity.

As noted previously, while the nonlinear effects of EPS on productivity have been widely examined, the effects of policy measures, including taxes, standards, and R&D subsidies, have not yet been fully investigated, except by Wang et al. [32]. How each environmental policy affects firms' inefficiency is remains an open question. This paper hence fills the gaps in previous research by examining the PH under the non-linear relationships between enterprise inefficiency and EPS.

Methodology and Data

Methodology

We employ the technical inefficiency effects model [8] to examine how EPS affects firms' inefficiency, assuming the following translog production function:

$$\ln Y_{it} = \beta_0 + \beta_L \ln L_{it} + \beta_K \ln K_{it} + \frac{1}{2}\beta_{LL}\ln L_{it}^2 + \frac{1}{2}\beta_{KK}\ln K_{it}^2 + \beta_{LK}\ln L_{it}\ln K_{it} + \gamma_{\text{Country}}D_{\text{Country}} + \gamma_{\text{Industry}}D_{\text{Industry}} + \gamma_{\text{Year}}D_{\text{Year}} + v_{it} - u_{it} \quad (1)$$

where Y_{it} is the operating profit; L_{it} is labor employment; K_{it} is the amount of fixed assets as a proxy for capital stock; i indicates the firm; t indicates year; D_{Country}, D_{Industry}, and D_{Year} are dummy variables for country, industry, and year, respectively; and $v_{it} - u_{it}$ is the error component term of a stochastic frontier, in which v_{it} is the usual statistical noise and u_{it} is a non-negative inefficiency term. It is assumed that $v_{it} \sim N(0, \sigma_v^2)$ and $u_{it} \sim N^+(\mu, \sigma_u{}^2)$ with $\mu > 0$.

The determinants of firms' inefficiency are estimated by the following equation:

$$u_{it} = \delta_0 + \delta_1 EPS_{it} + \delta_2 EPS_{it}^2 + \omega_{it} \quad (2)$$

where EPS_{it} is the EPS index and ω_{it} is the stochastic noise ($\omega_{it} \sim N(0, \sigma_\omega^2)$). We estimate Eqs. (1) and (2) in one stage, using the maximum likelihood method.[3]

In a relationship between choosing EPS indices and firms' responses, potential endogeneity problems due to reverse causality or simultaneity could arise between EPS and firms' performance [30]. Countries with highly productive companies are more likely to lead strict regulations, and vice versa. For this problem, we construct the predicted EPS indices using seemingly unrelated regression (SUR) with exogenous variables, to estimate Eqs. (1) and (2) by using them instead of the actual EPS indices.

First, in our SUR estimation, EPS is predicted by using Eqs. (3) and (4):

$$EPS_{ct} = \lambda_0 + \lambda_1 \ln GDPPC_{ct} + \lambda_2 \ln Popden_{ct} + \lambda_3 Polity_{ct} + \xi_{ct} \quad (3)$$

$$\ln GDPPC_{ct} = \theta_0 + \theta_1 EPS_{ct} + \theta_2 \ln Popden_{ct} + \theta_3 GES_{ct} + \theta_4 TO_{ct} + \eta_{ct} \quad (4)$$

where $GDPPC_{ct}$ is GDP per capita, $Popden_{ct}$ is population density, $Polity_{ct}$ is the degree of democracy, GES_{ct} is the government expenditure share of GDP, and TO_{ct} is trade openness. Corresponding to the EPS being based on a 3-year average, these variables are also based on a 3-year average. The predicted EPS value $\widehat{EPS}_{ct}$ is used for the stochastic estimation for firm i in country c at year t.

Our study analyzes the nonlinear relationship between EPS and firms' inefficiency by using industry analysis, in order to estimate the effects of environmental policy instruments on coke, chemical, non-metallic, and metal industries which are energy-intensive. It then finds out how the impacts of EPS on firms' performance differ between energy-intensive and non-energy-intensive industries and among individual energy-intensive industries.

Data

All firm data are obtained from the ORBIS database provided by the Bureau Van Dijk. The data period covers 2010 to 2015. Thirty-three countries are selected based on the availability of data on the EPS.[4] All monetary values are expressed in the 2012 US dollars

[3] To capture the nonlinearity of the impacts of EPS, we also employ [36]'s model to examine non-monotonic efficiency effects; however, the maximum likelihood estimator in the model fails to converge. Hence, to investigate the influences of EPS in more detail, we adopt a traditional technical efficiency effects model [8].

[4] The countries in the dataset include Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, the

using the producer price index of the US Bureau of Economic Analysis. The industrial classification of the firm data follows the four-digit level of the Statistical Classification of Economic Activities in the European Community (NACE) Rev. 2. We include firms that are classified as manufacturing by NACE Rev. 2 from ORBIS. Our dataset includes approximately 800,000 observations of 216,000 manufacturing firms in 33 developed and developing countries.

The EPS index is obtained from the OECD.[5] There are two issues related to the examination of the strong PH. One is how to measure EPS, which was once difficult to measure; however, the OECD developed and released the EPS index. The OECD EPS is a new cross-country measure of environmental policy that allows for a multi-dimensional EPS comparison between countries by indexing the proxy variables in the range of zero (nonexistent) to six (most stringent). The scores are cardinal and constructed based on the information of each instrument, including the values of emissions limit, tax rate, price of one CO_2 allowance, and government R&D subsidy expenditure as a percentage of GDP.[6] The EPS index is widely employed in studies of the PH [30–32]. Here, we use five types of EPS indices, including total, standards, emissions taxes, trading schemes, and R&D subsidies. Following [30], we use 3-year average index values.

For the SUR estimation, GDP per capita, population density (person/km^2), proportion of government R&D subsidy expenditure to GDP, and trade openness are obtained from the OECD Stat. The Polity Index [38] is obtained from the Polity V project website.[7] We use the Polity2 score, which is a composite index measuring the degree of democracy ranging from − 10 (strong autocracy) to 10 (strong democracy). The above five related variables are used as exogenous in the SUR estimation and also calculated as 3-year average index values. A summary of the variables' statistics is presented in Table 1.

Empirical Results

Empirical Results for the Manufacturing Industry

Table 2 demonstrates how tightening environmental policies affect firms' efficiency by policy instruments, simultaneously estimating Eqs. (1) and (2) by using the maximum likelihood method. The actual and predicted EPS indices are calculated using Eqs. (3) and (4) are the efficiency determinant variables. We also estimate linear models without the quadratic term of EPS for each instrument. For each EPS index, the nonlinear model is preferred to the linear model using the likelihood ratio test at a 1% significance level; hence, we only present the results of the nonlinear models.

For the total, standards, and emissions taxes, as shown in columns (1)–(6), the estimated signs of δ_1 and δ_2 between the actual and predicted EPS indices are the same. The positive sign of δ_1 and the negative sign of δ_2 suggest that an inverse U-shaped relationship exists between EPS and firms' efficiency, implying that tightening environmental policy increases

Footnote 4 (continued)

Netherlands, Norway, Poland, Portugal, Russia, the Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, the UK, and the USA.

[5] OECD Stat, Environmental policy Stringency Index: https://stats.oecd.org/Index.aspx?DataSetCode=EPS

[6] For details, see [30, 37].

[7] The website address is http://www.systemicpeace.org/inscrdata.html.

Table 1 Summary of variable statistics

Variable	Unit	Obs	Mean	SD	Min	Max
Economic variables						
Labor	Person	1,407,804	260.2	3,284.7	0.000	399,381
Fixed asset	USD	1,988,582	22,383.4	893,806.4	− 1,165.545	2.44E + 08
Operating income	USD	2,055,089	5,479.4	221,640.7	− 3.04E + 07	6.81E + 07
Environmental stringency index						
Total	0–6	2,515,047	1.987	1.001	0.375	4.028
Standards	0–6	2,519,480	3.246	1.685	0.500	6.000
Emissions taxes	0–6	2,519,480	1.613	0.535	0.000	3.917
Trading schemes	0–6	2,515,047	0.917	1.149	0.000	4.733
R&D subsidies	0–6	2,519,480	1.755	1.060	0.000	6.000
Variables for SUR						
GDP per capita	USD	198	32,552.290	13,657.180	3,789.940	66,170.500
Polity Index	− 10 to + 10	198	8.901	3.072	–7.000	10.000
Population density	person/km^2	198	82.559	42.468	22.938	193.920
Government expenditure share of GDP	%	198	42.229	22.730	11.100	106.014
Trade openness	%	198	147.548	136.823	2.767	518.113

firms' inefficiency in the early stage, and then reduces it in a later stage. Note that a positive (negative) sign of the coefficients in the inefficiency equations signals that such variables indicate an inefficiency (efficiency-)-enhancing factor in the technical inefficiency model. The results imply a U-shaped relationship between EPS indices and firms' productivity for total, standard, and emissions taxes. For trading schemes and R&D subsidies, the signs of δ_1 and δ_2 in columns (8) and (10) are also positive and negative, respectively, when the predicted EPS indices are the explained variables, also implying a U-shaped relationship.

Accordingly, a strong PH holds when regulation is stricter than the threshold in total and individual EPS indices. Although the strong PH holds, each differs among the five indices. The thresholds can be calculated by $-\delta_1/(2\delta_2)$, using the estimated coefficients, presented in Table 2. The threshold of the EPS is 1.449 for the total. Among the four individual policy instruments, the thresholds of EPS, in descending order, are 0.381 for trading schemes, 0.774 for emission taxes, 1.067 for R&D subsidies, and 2.110 for standards. The smaller the threshold, the more likely the strong PH will hold; hence, as the government tightens environmental regulations, trading schemes will reach the threshold in which average policy impact changes from negative to positive sooner than other policy instruments. Among the four instruments, from the perspective of reducing of greenhouse gas and air pollutant emissions, emissions taxes and trading schemes are determined to be key market-based measures, which we will feature in our discussion of proposed policy implications in the "Policy Recommendations" section.

In summary, the strong PH holds for both the total and all individual environmental policy instruments when each of the EPS indices exceeds the threshold. The domain in which the strong PH holds depends on the policy instruments, as threshold values vary.

Table 2 Stochastic frontier estimates of the impact of environmental policy stringency on firms' inefficiency by policies

EPS	Total		Standards		Emissions taxes		Trading schemes		R&D subsidies	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Production function										
β_0	3.407***	3.370***	3.484***	3.359***	3.636***	3.354***	3.414***	3.372***	3.345***	3.348***
	[0.129]	[0.125]	[0.132]	[0.125]	[0.136]	[0.125]	[0.131]	[0.125]	[0.127]	[0.125]
β_L	0.497***	0.503***	0.492***	0.503***	0.483***	0.502***	0.490***	0.504***	0.495***	0.502***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]
β_K	0.062***	0.056***	0.065***	0.056***	0.070***	0.057***	0.067***	0.055***	0.064***	0.058***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]
β_{LL}	−0.009***	−0.008***	−0.010***	−0.008***	−0.010***	−0.008***	−0.011***	−0.008***	−0.008***	−0.008***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
β_{KK}	0.058***	0.059***	0.058***	0.058***	0.056***	0.058***	0.057***	0.059***	0.058***	0.058***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
β_{LK}	−0.008***	−0.009***	−0.007***	−0.009***	−0.006***	−0.009***	−0.007***	−0.009***	−0.008***	−0.009***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Inefficiency equation										
δ_0	−45.334***	−18.625***	−79.536***	−17.229***	−70.843***	−16.470***	−96.184***	−8.843***	−13.136***	−13.156***
	[6.017]	[1.178]	[9.714]	[0.631]	[2.115]	[1.430]	[13.739]	[0.583]	[2.417]	[0.725]
δ_1	6.794***	14.175***	4.531***	7.990***	68.220***	18.212***	−35.785***	3.672***	−16.610***	6.414***
	[1.266]	[0.789]	[0.998]	[0.284]	[2.237]	[1.338]	[4.983]	[0.211]	[2.298]	[0.314]
δ_2	−5.015***	−4.892***	−2.357***	−1.893***	−24.774***	−11.760***	6.884***	−4.817***	1.735***	−3.006***
	[0.665]	[0.265]	[0.309]	[0.063]	[0.779]	[0.849]	[0.967]	[0.236]	[0.247]	[0.137]
Inverse logit of σ_u/σ_v	3.707***	2.417***	4.217***	2.463***	3.098***	2.517***	4.358***	2.397***	3.251***	2.546***
	[0.123]	[0.054]	[0.117]	[0.030]	[0.025]	[0.074]	[0.139]	[0.049]	[0.142]	[0.045]

Table 2 (continued)

EPS	Total		Standards		Emissions taxes		Trading schemes		R&D subsidies	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\ln(\sigma^2_u+\sigma^2_v)$	3.798***	2.559***	4.303***	2.602***	3.222***	2.654***	4.454***	2.540***	3.349***	2.681***
	[0.121]	[0.051]	[0.116]	[0.028]	[0.024]	[0.069]	[0.137]	[0.046]	[0.138]	[0.042]
Log likelihood	−1,292,799	−1,291,125	−1,297,632	−1,295,071	−1,296,942	−1,295,122	−1,293,959	−1,291,113	−1,296,413	−1,295,202
$-\delta_1/2\delta_2$	0.677	1.449	0.961	2.110	1.377	0.774	2.599	0.381	4.787	1.067
LR chi(1)	406.34***	3750.82***	282.05***	3847.05***	3323.95***	3844.92***	1183.08***	3794.52***	317.21***	3851.5***
p value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Obs	786,370	786,370	788,878	788,878	788,878	788,878	786,370	786,370	788,878	788,878

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively. Standard errors are in brackets. To save space, we do not report the coefficients of year, industry, or country dummies in the production function equation. Each of the threshold values is derived by $-\delta_1/2\delta_2$ using the coefficients. LR chi-squared(1) and *p* value present the likelihood ratio test results with and without the EPS quadratic term

Table 3 Stochastic frontier analysis estimates of the impact of environmental policy stringency on firms' inefficiency by policies and sectors

	Energy-intensive industry												Non-energy-intensive industry	
	Manufacturing		Paper		Coke		Chemical		Non-metallic		Metal			
EPS	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(a) Total														
δ_1	−0.126	18.015***	22.238	11.020*	−12.468***	27.997***	−3.154	59.241***	−1.695*	10.805***	−2.183	12.928**	17.683***	14.956***
	[1.443]	[1.756]	[14.125]	[5.771]	[4.179]	[6.417]	[7.636]	[12.358]	[1.002]	[1.403]	[1.797]	[5.201]	[3.581]	[0.802]
δ_2	−2.402***	−5.966***	−7.997	−4.100*	0.768	−8.705***	−4.859	−18.917***	−0.510*	−3.481***	−1.047*	−4.767**	−14.175***	−5.193***
	[0.395]	[0.570]	[4.936]	[2.128]	[0.809]	[1.999]	[3.439]	[3.874]	[0.267]	[0.447]	[0.569]	[1.861]	[1.211]	[0.264]
Log L	−341,221	−340,862	−40,873	−40,824	−15,358	−15,279	−122,676	−122,588	−112,592	−112,421	−48,250	−48,242	−948,815	−947,766
Obs	202,180	202,180	24,544	24,544	8,877	8,877	72,161	72,161	66,971	66,971	29,627	29,627	584,190	584,190
(b) Standards														
δ_1	−7.352**	10.467***	27.110**	6.09	−10.595	15.576***	−2.875	31.720***	−2.463**	6.055***	−7.462	8.101***	4.353***	8.637***
	[2.906]	[1.901]	[10.991]	[3.794]	[7.123]	[3.696]	[3.151]	[4.519]	[0.975]	[0.766]	[4.644]	[2.288]	[1.096]	[0.581]
δ_2	−1.381***	−2.371***	−7.021***	−1.57	0.324	−3.269***	−0.668	−6.904***	−0.024	−1.328***	0.106	−2.084***	−2.214***	−2.059***
	[0.492]	[0.428]	[1.984]	[0.971]	[0.526]	[0.776]	[0.558]	[0.939]	[0.128]	[0.166]	[0.382]	[0.551]	[0.299]	[0.134]
Log L	−342,043	−341,458	−41,017	−40,932	−15,398	−15,289	−122,843	−122,700	−112,924	−112,682	−48,404	−48,346	−952,700	−951,107
Obs	202,548	202,548	24,616	24,616	8,879	8,879	72,230	72,230	67,137	67,137	29,686	29,686	586,330	586,330
(c) Emissions taxes														
δ_1	68.353***	21.707***	59.189***	13.298***	221.304	34.781***	80.037***	56.202**	23.886***	13.431***	57.862*	18.544**	69.800***	18.990***
	[12.372]	[3.052]	[12.038]	[4.471]	[228.266]	[8.391]	[24.684]	[26.379]	[6.063]	[1.743]	[34.371]	[7.288]	[2.769]	[1.958]
δ_2	−26.662***	−13.351***	−20.877***	−9.455***	−96.04	−19.593***	−30.339***	−33.099**	−9.693***	−7.957***	−23.303*	−13.238***	−25.238***	−12.358***
	[4.778]	[1.857]	[4.187]	[3.048]	[98.839]	[4.723]	[9.251]	[15.495]	[2.383]	[1.019]	[13.740]	[4.978]	[0.950]	[1.253]
Log L	−341,745	−341,475	−40,955	−40,933	−15,408	−15,293	−122,750	−122,704	−112,852	−112,686	−48,377	−48,351	−952,460	−951,137
Obs	202,548	202,548	24,616	24,616	8,879	8,879	72,230	72,230	67,137	67,137	29,686	29,686	586,330	586,330
(d) Trading schemes														
δ_1	−61.410***	4.882***	−28.085	2.293**	−95.916	9.431***	−40.109***	16.024*	−12.633***	3.372***	−68.593	2.685***	−33.304***	3.890***

Table 3 (continued)

	Energy-intensive industry												Non-energy-intensive industry	
	Manufacturing		Paper		Coke		Chemical		Non-metallic		Metal			
EPS	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	[4.622]	[0.339]	[21.851]	[0.997]	[119.186]	[2.165]	[5.650]	[8.924]	[1.528]	[0.443]	[53.714]	[0.865]	[4.598]	[0.336]
δ_2	11.740***	−5.518***	4.452	−4.142***	16.896	−8.748***	7.566***	−16.091*	2.614***	−3.484***	14.766	−4.642***	6.488***	−5.230***
	[1.051]	[0.291]	[3.598]	[1.474]	[21.132]	[1.998]	[1.349]	[8.897]	[0.360]	[0.428]	[11.630]	[0.947]	[0.906]	[0.395]
Log L	−341,587	−340,858	−40,908	−40,824	−15,432	−15,278	−122,750	−122,587	−112,685	−112,421	−48,423	−48,241	−949,580	−947,759
Obs	202,180	202,180	24,544	24,544	8,877	8,877	72,161	72,161	66,971	66,971	29,627	29,627	584,190	584,190
(e) R&D subsidy														
δ_1	−6.879**	8.765***	−6.168***	4.535**	3.861*	13.110***	−18.272***	26.676	−4.283***	4.908***	−5.017***	6.947***	−31.441***	7.081***
	[2.797]	[0.973]	[2.062]	[2.023]	[2.263]	[3.342]	[4.244]	[16.819]	[0.698]	[0.467]	[1.245]	[1.860]	[6.963]	[0.504]
δ_2	0.149	−3.827***	−0.031	−2.443**	−3.473***	−5.047***	0.169	−10.973	0.233**	−2.030***	0.275*	−3.816***	3.674***	−3.348***
	[0.143]	[0.411]	[0.445]	[1.048]	[0.932]	[1.282]	[0.865]	[6.903]	[0.119]	[0.183]	[0.159]	[0.857]	[0.822]	[0.225]
Log L	−341,513	−341,500	−40,949	−40,933	−15,354	−15,300	−122,703	−122,709	−112,760	−112,693	−48,297	−48,359	−952,114	−951,186
Obs	202,548	202,548	24,616	24,616	8,879	8,879	72,230	72,230	67,137	67,137	29,686	29,686	586,330	586,330

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively. Standard errors are in brackets. The row of $-\delta_1/2\delta_2$ denotes the turning point value if the relationship between EPS and firms' inefficiency is nonlinear. To save space, we do not report the coefficients of the production functions and the constants of the inefficiency equations

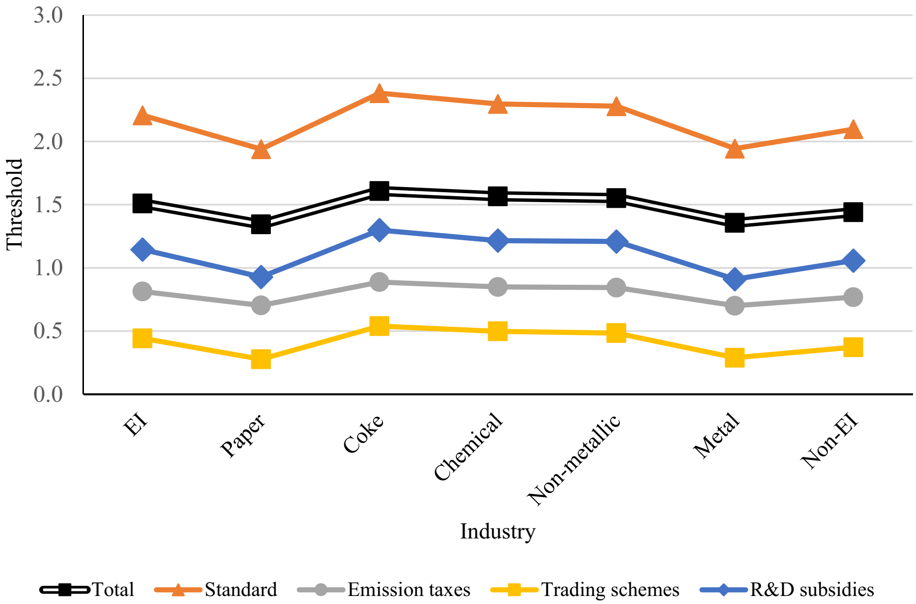

Fig. 1 The estimated thresholds by environmental policy instruments and industries. Note: The thresholds for each environmental policy instrument are derived from the estimated coefficients in Table 3 (parts a–e) as $-\delta_1/2\delta_2$

Empirical Results by Environmental Policy Instruments and Industries

Table 3 (parts a–e) presents the results of Eqs. (1) and (2) by environmental policy instruments and industries. Surprisingly, the positive sign of δ_1 and the negative sign of δ_2 are observed for all the predicted EPS estimates and are statistically significant at least at the 10% (and 1% or 5% levels in most models), except standards for paper industry in column (4) of Table 3 (part b) and R&D subsidies for the chemical industry in column (8) of Table 3 (part e). These results suggest that a strong PH holds for energy-intensive industries as well as non-energy-intensive industries when each of the EPS indices exceeds its threshold.

Figure 1 illustrates the estimated thresholds by industries, which are calculated as $-\delta_1/2\delta_2$ using the estimated parameters in Table 3 (parts a–e). The line for standards is higher than others, implying that standards must be considerably tightened to reach the circumstance in which the strong PH hypothesis holds. Among the four kinds of policy instruments, the strong PH is more likely to hold for each industry in descending order of trading scheme, emissions tax, R&D subsidy, and standards. The impact of strengthened environmental policies may vary depending on industries, even among energy-intensive industries. Relatively lower thresholds for the paper and metal industries imply that they are more likely to hold the strong PH than the coke, chemical, and non-metallic industries for each of the four instruments.

Policy Recommendations

Emission tax and trading scheme are undoubtedly efficient policy instruments among environmental policy instruments [39]. There is no consensus on whether emission taxes and trading schemes are preferable in the recent carbon pricing argument. Stavins [40] compare these two instruments in details. Emission trading requires more administrative costs than environmental taxes; however, it should also be noted that a simple environmental tax can be complicated by legislation. Transaction costs, monitoring, and enforcement should also be considered. As is well known as the Weitzman theorem, under uncertainty, an emission tax can offer higher efficiency gains than an emission trading if and only if marginal abatement costs are steeper than marginal emission damage curve [41].

In this subsection, we present policy recommendations for the sample countries. As mentioned above, emissions taxes and trading schemes are two major environmental instruments. We focus on these two policies among the five instruments examined in our study and suggest the policy directions for them. For this purpose, Fig. 2 illustrates the mean EPS for the two policies of the sample countries are mapped into Fig. 2, with four regimes based on the thresholds of these two policies for the manufacturing industry presented in Table 2. The vertical red line presents the threshold value of emission taxes (0.774), and the horizontal red line presents that of trading schemes (0.381), which are obtained from the estimated parameters for the predicted EPSs in Table 2. The two lines divide the figure into four regions. Our discussion of the policy implications of each region follows below. The mean shares of energy-intensive industries to the total manufacturing industry from 2010 to 2014 are presented in the size of bubbles,[8] which are also presented with country codes. The bubbles for developed and developing countries are drawn in blue and white, respectively. The definitions of developed and developing countries follow the classification of the International Monetary Fund.[9]

We next consider the policy recommendations for each of the four domains (Appendix, Table 4).

(1) Policy recommendations for the countries in Regime I

Out of the 33 sample countries, 21 are located in Regime I. Although most of them are developed countries, the three developing countries, Hungary (HU), Poland (PL), and Slovakia (SK), are also located there. For the countries plotted in Regime I, strengthening both emissions taxes and trading schemes would enhance firms' productivity. It is clear that the strong PH fully holds in these nations. The policy recommendation for the countries in Regime I is that further strengthening both emissions taxes and trading schemes should be encouraged, as represented by the green arrow in the figure.

(2) Policy recommendations for the countries in Regime II

Regime II has only two countries, Greece (GR) and India (IN), for which EPS indices for emissions taxes are smaller than the threshold, and the opposite result for trading schemes. The policy recommendation for these two countries is to raise emissions tax rates

[8] Data is unavailable for the year 2015. (See Fig. 2 note.).

[9] The IMF classification of developed and developing countries are sourced from https://www.imf.org/en/Publications/WEO/weo-database/2021/April/select-countries?grp=110&sg=All-countries/Advanced-economies

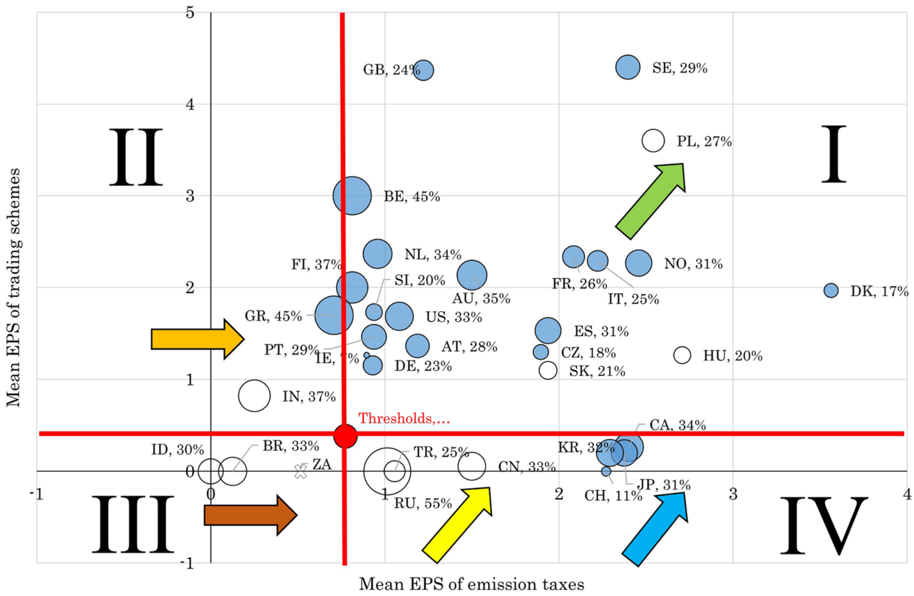

Fig. 2 Current policy positions of market-based environmental policies and recommended policy directions. Note: The mean actual EPS indices concerning emissions taxes and trading schemes in the sample period are plotted for the sample countries. The size of bubbles represents the mean shares of energy-intensive industries to the total manufacturing industry from 2010 to 2014, which are calculated using the data from the World Input–Output Database (WIOD). Because data on 2015 are unavailable in the latest WIOD, the mean shares are taken from 2010 to 2014. Data on South Africa were unavailable in the WOID; therefore, its energy-intensive industry share is not shown in the figure. The bubbles for developed and developing countries are drawn in blue and white, respectively. See Appendix for the country codes and regions.

rather than strengthening trading schemes, as represented by the orange arrow, as stricter trading schemes would increase inefficiency in the early stage due to inverse U-shaped characteristics.

(3) Policy recommendations for the countries in Regime III

Regime III includes three developing countries: Brazil (BR), Indonesia (ID), and South Africa (ZR). They have zero EPS for trading schemes. Furthermore, India has zero EPS not only for trading schemes but also for emission taxes. Environmental regulation should be strengthened in the three countries. Considering that the establishment of a well-designed and operational emissions trading system is difficult, the policy indicated for the above three developing countries is not to establish a new emissions trading system but to levy environmental taxes and to raise rates, as indicated by the brown arrow.

(4) Policy recommendations for the countries in Regime IV

Regime IV involves seven countries with EPS indices for trading schemes that are smaller than the threshold, and the opposite result for emissions taxes. These countries can be divided into two groups. The first group includes three developing countries, China (CN), the Russian Federation (RU), and Turkey (TR), which are located on the left side in

Regime IV, for which emissions tax rates are higher than the threshold, but are relatively low. In general, emissions taxes more directly affect a wider range of economic activities than emissions trading. The policy recommendation for the three countries is that emissions tax rates should be raised at first, followed by the arrangement of operational emissions trading markets, as indicated by the yellow arrow. The second group in Regime IV includes four developed countries, Canada (CA), Japan (JP), South Korea (KR), and Switzerland (CH), which are located on the right side in Regime IV. These countries have considerably laxer regulations concerning trading schemes, despite being developed nations. For example, Japan has no nationwide market for emissions trading schemes, and cap-and-trade programs are only implemented in Tokyo metropolitan area and Saitama prefecture. The policy recommendation for these four countries is to expediently establish emissions trading markets, as suggested by the blue arrow in Fig. 2.

In sum up, the policy recommendations are (i) strengthening emission taxes and trading schemes for the countries in Regime I, (ii) raising the emission tax rates for the countries in Regime II, (iii) imposing emission taxes and raising the rates for the countries in Regime III, and (iv) raising emission tax rates or establishing trading schemes. Needless to say, the above policy recommendations should be implemented according to the actual situation in each country. Many of the countries plotted in Regime II and III are developing countries. It is important to note that how political instability and bribery influence the formation of environmental policy. Fredriksson and Svensson [42] show that corruption has a negative impact on the stringency of environmental policies; however, this impact is reduced as political instability increases due to the effect where incentives for corruption decrease as the probability of the government remains in office drops.

Because EPS thresholds for energy-intensive industries for emissions taxes and trading schemes (0.813 and 0.442) are very close to those in the manufacturing industry, with 0.774 and 0.442, respectively, the above policy recommendations are applicable not only for the entire manufacturing industry but for all energy-intensive industries.

Although previous studies indicate the effective interval of EPS [26, 28, 31, 32], and distinctions between policy instruments only consider two types of market and nonmarket [29, 30, 32], our results reveal shapes of the impact on inefficiency for each EPS index, allowing us to propose policy directions for each of major developed and developing countries. An important contribution of this paper is to demonstrate the nonlinearity of the policy effect for each policy measure. This made it possible to present specific prescriptions based on each country's actual policy position.

Concluding Remarks

If the strong PH that posits that tightening EPS leads to improved economic performance holds, a mutually beneficial relationship between environmental protection and firm competitiveness is established. It is crucial to examine whether the hypothesis is valid in terms of the feasibility of sustainable growth. Accordingly, a significant amount of research has been conducted on the development of the PH.

The previous studies have different empirical results of the famous Porter hypothesis. This study examines the strong version of the PH under nonlinear relationships by using huge panel microdata with approximately 800,000 observations of 33 developed and developing countries during the period of 2010–2015. For this purpose, stochastic frontier models are employed to estimate the nonlinear effects of EPS on firms' efficiency. The strong PH for both total EPS and each policy measure are empirically tested. To address potential endogeneity problems, the predicted EPS indices which are generated by the SUR model are used as the explanatory variables in the estimation.

Our results reveal that the relationship between EPS and firms' inefficiency (productivity) are inverse U-shaped (U-shaped) at total and individual environmental policy instrumental levels. This implies that the strong PH holds for an instrument when its stringency is stricter than a certain level. The thresholds vary among the four individual policy instruments, with 0.381 for trading schemes, 0.774 for emissions taxes, 1.067 for R&D schemes, and 2.110 for standards, in descending order. Accordingly, among the four environmental policy instruments examined, the strong PH is more likely to hold in this order for each industry. Since threshold values vary depending on the policy instrument and type of industry, the extent of the EPS where the strong PH holds also varies. Among energy-intensive industries, the paper and metal industry is more likely to hold the strong PH than coke and chemical industries for each of the four instruments.

In summary, we emphasize that the impact of environmental policies on firms' inefficiency depends on the policy instruments applied, their magnitude, and time periods. Consequently, governments should strategically choose policies based on their long-term effect. A reasonable arrangement of environmental policy instruments establishes a mutually beneficial scenario [31]. To achieve green economic growth, the appropriate "mix of instruments" should be pursued rather than the "best instrument" [43].

This study provides a useful reference for environmental policy instrumental choices in developed and developing countries at various stages of economic development. However, the following limitations exist here: (1) A combination of heterogeneous policy instruments should be examined in future research. (2) The weak and narrow PHs should also be verified, using data on innovation and green R&D expenditure. (3) The long-term effects of environmental policies on firm productivity must be identified. These three limitations can be relaxed by future research.

Appendix

Table 4 List of countries

No	Country	Code	Regime
1	Poland	PL	I
2	Sweden	SE	I
3	Belgium	BE	II
4	UK	GB	II
5	Austria	AT	III
6	Brazil	BR	III
7	Finland	FI	III
8	Germany	DE	III
9	Greece	GR	III
10	India	IN	III
11	Indonesia	ID	III
12	Ireland	IE	III
13	Netherlands	NL	III
14	Portugal	PT	III
15	Russian Federation	RU	III
16	Slovenia	SI	III
17	South Africa	ZA	III
18	Turkey	TR	III
19	USA	US	III
20	Australia	AU	IV
21	Canada	CA	IV
22	China	CN	IV
23	Czech Republic	CZ	IV
24	Denmark	DK	IV
25	France	FR	IV
26	Hungary	HU	IV
27	Italy	IT	IV
28	Japan	JP	IV
29	Norway	NO	IV
30	Slovakia	SK	IV
31	South Korea	KR	IV
32	Spain	ES	IV
33	Switzerland	CH	IV

Regimes I–IV of each country reflect on Fig. 2

Acknowledgements The authors thank to an anonymous referee of this journal and the participants of the 2020 Taiwan Economic Association Annual Conference for their valuable comments.

Author Contribution S.H: project initiation, data collection, analysis, first draft, writing, and editing. J-L.H: discussion, writing, and editing.

Funding The first author acknowledges financial support from the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number 19K01659. The second author acknowledges financial support from Taiwan's National Science and Technology Council (NSTC110-2410-H-A49-051).

Data Availability The data that support the findings of this study are available from Bureau van Dijk, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Bureau van Dijk.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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