Varied Characteristics of R&D Expenditure in Environmental and Energy Sectors

Shinano Hayashi

Faculty of Business Administration, Tokoha University, 6-1 Yayoi-cho, Suruga-ku, Shizuoka, Japan
Email: s-hayashi@sz.tokoha-u.ac.jp (S.H.)

Manuscript received June 28, 2025; revised July 17, 2025; accepted August 19, 2025; published January 19, 2026

***Abstract*—This study conducted a comprehensive analysis of the factors that influence environmental and energy-related Research and Development (R&D) expenditures. The analysis was based on panel data from 22 manufacturing industries from 2008 to 2023, which was obtained from the "Research and Development Trends Survey" published by the Ministry of Internal Affairs and Communications. The findings imply that discrepancies among various industries have a negligible effect on environmental R&D expenditure. Conversely, the results suggest that industry-specific characteristics may play a significant role in allocating resources for energy-related R&D expenditures. Although internal funding plays a major role in both the environmental and energy fields, determining whether it has a positive or negative impact on R&D expenditures requires consideration of the background of both the fixed and random effects models using panel data.**

***Keywords*—R&D investment, environmental R&D, energy R&D, panel data, internal and external funding, fixed and random effects models**

I. Introduction

Investing more in Research and Development (R&D) funds is widely regarded as a crucial strategy for fostering innovation [1]. However, the rationale behind companies' decisions to allocate resources to research in diverse domains remains unclear.

The Survey of Research Expenditures on Science and Technology, administered by the Ministry of Internal Affairs and Communications, is an ongoing survey that monitors trends in R&D expenditures. Specifically, data is collected in eight priority areas: life sciences, information and communications, materials, environment, energy, nanotechnology, space development, and ocean development [2].

The objective of this study is to examine the relationship between the various factors related to sustainable science and technology (such as the number of researchers, research funding amount, economic trends, and sustainability progress) and R&D funding in the environmental and energy fields. This paper aims to identify the similarities and differences between the factors that influence R&D spending in the environmental and energy sectors, as well as the parallels and divergences between these two domains. Additionally, this research examines the link between the global Coronavirus (COVID-19) pandemic and energy consumption in relation to R&D expenditure.

Furthermore, the study will determine whether the acceptance of external research funding encourages firms to increase their R&D expenditure (crowding-in) or whether it leads companies to provide their own funds (crowding-out), as indicated in previous studies [3–8].

II. Background and Methodology of the Study

Despite a recent decline due to the global financial crisis (2008–2013) and the spread of COVID-19, Japan's expenditures on scientific and technological research in the environmental and energy fields, including efforts to mitigate and adapt to climate change, have continued to increase (Fig. 1).

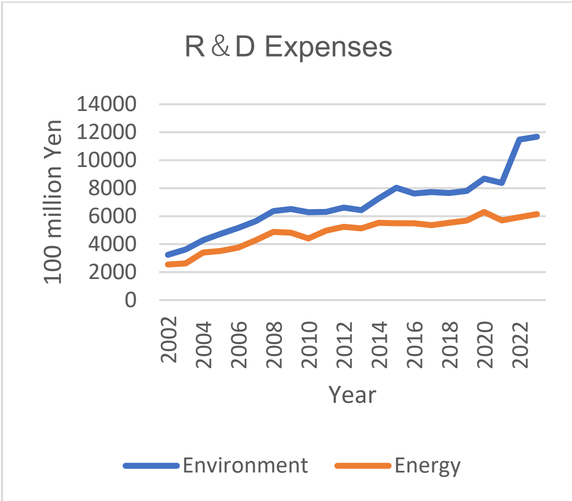

Fig. 1. Trends in R&D funding in Japan's environmental and energy fields.

As previously discussed in extant studies, it is challenging to ascertain the factors that contribute to increased R&D expenditures. For instance, a robust economy, augmented sales figures by the respective firms, and escalated public research expenditures by the government have been identified as contributing factors. This study employs a quantitative approach to examine the relationship between environment- and energy-related R&D expenditure and economic growth. This empirical research model incorporates sales by industry (past sales, considering the impact on this year's research expenditures), external funds, and internal funds of 22 classified manufacturing firms as explanatory variables. Research expenditures per firm and per researcher are also included as explanatory variables. Given the nominal nature of these values, this study employs the Producer Price Index (PPI) published by the Bank of Japan in 2005 to convert them into real values [9]. It is further hypothesized that R&D investment decisions are influenced by the perceptions of business managers regarding prevailing business conditions. Following this hypothesis, the Bank of Japan's Tankan (Diffusion Index) was incorporated into the model as an explanatory variable. It is widely regarded as a significant economic indicator, providing insights into the

doi: 10.18178/ijesd.2026.17.1.1560

current state and future prospects of the economy. This is based on the hypothesis that environmental and energy research expenditures are influenced by managers' sentiment toward the economy, which differs from industry to industry. Considering the widely acknowledged significant impact of sustainability on both the environmental and energy-related R&Ds, the model is expanded to include fossil fuel and renewable fuel consumption, thereby allowing for the observation of their impact on R&D expenditure.

A. Model

This study employs both fixed and random effects models as methodologies for the analysis of panel data. The fixed effects model posits the hypothesis that industry characteristics remain constant over time, consequently eliminating the impact of these industry-specific characteristics. Conversely, the random effects model conceptualizes industry-specific effects as "part of the random error." The Hausman test [1] is a methodological approach that is employed to ascertain the most suitable model for evaluating environmental and energy R&D behavior.

The regression model for panel data is shown below.

$$research\_dev\_exp\_ln_{(i,t)}=\beta_1\times sales\_ln_{(i,t-1)}+\beta_2\times extfunds\_ln_{(i,t)}+\beta_3\times ownfunds\_ln_{(i,t)}+\beta_4\times perorg\_funds\_ln_{(i,t)}+\beta_5\times perres\_funds\_ln_{(i,t)}+\beta_6\times res\_workers\_ln_{(i,t)}+\beta_7\times researchers\_ln_{(i,t)}+\beta_8\times BOJ\_DI_{(i,t)}+\beta_9\times fuel\_cons\_ln_{(i,t)}+\beta_{10}\times renewable\_cons\_ln_{(i,t)}+\beta_{11}\times covid\_dummy_{(i,t)}+\varepsilon_{(i,t)} \quad (1)$$

where

- $(research\_dev\_exp)_{i,t}$ is an industry i's environmental research expenditure at year t.
- $(sales)_{i,t-1}$ denotes an industry i's sales at year t-1.
- $(extfunds)_{i,t}$ represents funds an industry i received from other organizations, such as governments, universities, and other firms, at year t.
- $(ownfunds)_{i,t}$ is the amount of research funds that an industry i provided by itself at year t.
- $(perorg\_funds)_{i,t}$ is the amount of research expenditure per organization of industry i at year t.
- $(perres\_funds)_{i,t}$ is the amount of research expenditure per researcher of industry i at year t.
- $(res\_workers)_{i,t}$ denotes the number of researchers, research assistants, technicians, research administration, and other relevant personnel for industry i at year t.
- $(researchers)_{i,t}$ refers to employees whose professional activities are related to research. These individuals are classified according to the expertise they have accumulated in the context of their current research endeavors for industry i at year t.
- $(BOJ\ DI)_{i,t}$ is the Bank of Japan's Tankan Diffusion Index (Short-term Economic Survey of Enterprises in Japan) for industry i at year t. A positive (BOJ DI) indicates a favorable financial condition among numerous companies, suggesting an optimistic economic climate with expectations of growth. A negative (BOJ DI) signifies that a significant number of companies indicate that their financial condition is "poor," that there is a pervasive sense of pessimism about the economy, and that the economy is in recession.
- $(fuel\_cons)_{i,t}$ denotes the total consumption of fossil fuels and non-fossil energy, non-fossil fuels, and next generation biofuels for industry i at year t.
- $(renewable\_cons)_{i,t}$ denotes the total consumption of renewable energy sources for industry i at year t.
- $(covid\ dummy)_{i,t}$ is a dummy variable of the COVID epidemic (2020–2022).
- The extension (ln) at the end of variables indicates the value of the natural logarithm.

The panel data analysis adds total fuel expenditure (fuel_cons) and renewable energy expenditure (renewable_cons) for each industry and analyzes the impact on R&D investment in energy.

If the explanatory variable (extfunds) has a statistically significant positive impact on the dependent variable (research_dev_exp), it means that the external funds have a Crowd-in effect on research expenditure. In the same manner, when the coefficient of the external research funds is negative, one can conclude the presence of a Crowd-out impact. The effect of the explanatory variable (ownfunds) demonstrates the extent to which changes in a firm's internal funds allocated to entire research expenditures influence the corresponding increase or decrease in environmental/energy R&D expenditure, since a considerable number of substantial enterprises are involved in an array of research activities, which are not exclusively confined to the domain of environmental/energy science.

B. Data and Model

The study attempts to capture trends in corporate environment-related R&D based on the *Short-Term Economic Survey of Enterprises* of the Ministry of Internal Affairs and Communications in Japan. A panel data set of 22 manufacturing industries for the 15 years from 2008 to 2023 was analyzed, using data for all industries and industry subcategories. *The Statistical Survey of Energy Consumption* (2008–2023), prepared by the Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, was also used for this analysis [10].

The diffusion index of the Bank of Japan's National Survey on Manufacturers' Confidence (Tankan D.I.) was also included as an explanatory variable. The BOJ survey asks business managers at about 10,000 companies across Japan about the current state of the economy and their outlook for the future. The results of this survey are published every quarter as the BOJ Tankan Diffusion Index. To observe the continuity of managers' economic assessments, a moving average is utilized in this context. This is based on the hypothesis that environmental/energy research expenditures are influenced by managers' sentiment toward the economy, which differs from industry to industry.

To examine the impact on energy-related research, the study added two independent variables from data published

[1] The Hausman test is a statistical test used to determine whether a fixed effects model or a random effects model is more appropriate, and in the Hausman test, the hypothesis of the fixed effects model, that there is a time-independent unique effect on R&D expenditure in each industry, and that this effect is observed independent of the variable.

by the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry. One is the total consumption of fuels (including petroleum and non-petroleum fuels), and the other is the total consumption of renewable energy in each industry. For nominal values such as sales and research expenses, the 2005-based Producer Price Index was used as a deflator and adjusted to convert them to real values. Petroleum and other petroleum fuels, as well as renewable energy, were extracted from the Energy Consumption Statistics, which are governed by the Agency for Natural Resources and Energy, the Ministry of Economy, Trade and Industry, and added to the model (kiloliters of oil equivalent). Moreover, Eq. (1) categorizes research funding according to its source, distinguishing between externally and internally funded projects. Additionally, this research included research funding per organization and per researcher.

III. Analytical Results

This study employed panel data to execute regression analyses, aiming to ascertain the factors that influence environmental and energy R&D expenditures. Therefore, the Hausman test was utilized to assess the adaptability of the fixed and random effects models (Table 1) [11]. The outcomes were deemed to be statistically significant, with a p-value of 0.05 or higher for the environmental R&D, signifying the appropriateness of random effects analysis. Conversely, a p-value of less than 0.05 for the energy R&D indicated the suitability of fixed effects analysis.

The Hausman test outcomes indicated that the random effects model was suitable for R&D in the environmental field, whereas the fixed effects model was more appropriate for the energy field. This suggests that a statistically valid model selection was made in each field.

Table 1. Hausman test results

	Chi Square	p-Value
Environmental R&D	3.7206	0.9774
Energy R&D	2330.6	2.2e-16

These findings indicated that discrepancies among various industries had a negligible effect on environmental R&D expenditure. Instead, factors at the company level, such as sales and research funding received, proved to be significant. These variables appear to be the primary drivers of environmental R&D spending. Moreover, given the insignificance of the fixed effects for each industry, a meaningful comparison between companies in disparate industries is indeed feasible.

Conversely, conducting panel data analysis with energy-related R&D expenditure serving as the dependent variable notably reduced the p-value. Consequently, the results indicated that fixed effects analysis was the most suitable approach. This suggests that industry-specific characteristics may play a significant role in the allocation of resources for energy-related R&D expenditure.

R&D expenditure in the environmental and energy-related research fields suggests that the influence of industry-specific features varies accordingly. For instance, regarding environmental-related research expenditures, it is recommended that the focus be directed toward the impact of common variables encountered by each industry (e.g., sales and research expenditure) rather than "fixed factors that differ by industry" when formulating policy recommendations and decisions. To formulate a comprehensive R&D policy for environmental considerations, it is advisable to prioritize factors that are consistent across various industries, such as funding and market size.

When formulating R&D policies for energy research, it is imperative to acknowledge the heterogeneity among different industries and devise strategies and support measures tailored to the unique requirements of each field. For instance, a multifaceted approach is warranted, entailing the provision of distinct incentives for the renewable energy industry and the implementation of disparate regulations for the fossil fuel sector, with each requiring a customized approach.

A. Environmental R&D

Given the significance of the random effects analysis in the Hausman test, the following R&D expenditure characteristics were identified in the environmental field:

First, it was evident that fixed effects were negligible or could be disregarded. The influence of individual fixed effects for each industry was minimal. While distinct variations were evident by industry, these did not exhibit a statistically significant correlation with R&D expenditure differences in the environmental field.

Second, randomly distributed heterogeneity was evident between the industries, otherwise known as unobserved heterogeneity. The effect of each industry was randomly distributed and was not correlated with the explanatory variables. The fixed effects model considers all industry-specific effects. However, in this data, these effects may not be statistically significant.

Third, the impact of variables not incorporated within the model — that is, confounding factors — was minimal. The fixed-effects model is a statistical method that is employed to remove unobservable industry-specific influences. However, if the random-effects model is deemed acceptable, it suggests that unobserved factors do not have a significant impact.

Lastly, since the sample size was relatively large, the random-effects model was more efficient. The fixed-effects model incorporated industry-specific dummy variables, thereby reducing the degrees of freedom.

A random effects analysis was conducted employing the estimation method proposed by Swamy–Arora (1972) [12]. The study estimated the idiosyncratic error (intertemporal variation) within industries and the variance between them. These estimates were employed to derive the Generalized Least Squares (GLS) weights. For instance, in the context of pooled Ordinary Least Squares (OLS), the weight was set to 0 and to 1 during fixed effects analysis. The results of the GLS employing the weights derived via the "error structure transformation" were as follows:

Table 2 shows the variance composition of the random effects analysis.

Table 2. Variance composition

	Variance	Std Dev	Share
Idiosyncratic	0.274	0.523	19%
Individual	1.168	1.081	81%

As shown in Table 2, the individual effects (81%) substantially influenced environment-related R&D expenditure, surpassing the impact of idiosyncratic effects (i.e., constant differences between industries).

Conversely, although the share was negligible, a Breusch–Pagan test was conducted to examine the idiosyncratic effect [13, 14]. The p-value was exceedingly small at 2.22e-06, confirming that the idiosyncratic error variance was not uniform (heteroscedastic), requiring the implementation of a heteroscedasticity correction.

*1) Random effects model applying robust standard errors (heteroskedasticity-*consistent *standard errors)*

As mentioned previously, concerns have been raised regarding "bias in standard errors due to heteroscedasticity." To address this issue, robust standard errors, also known as Heteroskedasticity-Consistent Standard Errors (HCSE) [15, 16], were employed to rectify the impact of heteroscedasticity, shown in Table 3. In this case, the data was grouped by industry, which introduced the possibility of correlation between the error terms.

Therefore, the utilization of clustered industry-specific standard errors was imperative, as it enabled the consideration of the covariance of errors within the same group and facilitated the execution of appropriate estimations.

a) The res_workers_ln variable indicated the number of employees

The natural logarithm of the number of employees (res_workers_ln) demonstrated a strong degree of significance (p-value = 0.0004513) and positively affected R&D expenditure in the environmental field. Companies with a greater number of employees tended to increase their investment in R&D in the environmental field. As companies expanded in scale, they could leverage a greater number of human resources and assets. This likely increased funding for R&D.

b) BOJ_DI

The p-value for the BOJ_DI (Bank of Japan Tankan Survey) was 0.0541, which was significant at the 10% level of confidence. This finding indicated that managers' economic forecasts might adversely affect R&D investment.

c) In this case, the fuel consumption was measured using the fuel_cons_ln variable

The p-value for the fuel_cons_ln (natural logarithm of fuel consumption) was 0.0548, which was significant at the 10% level. Higher fuel consumption led to increased R&D investment in the environmental field. Additionally, elevated fuel consumption intensified the environmental impact, prompting companies to consider investments in technological development to mitigate this impact. For instance, advancements in energy efficiency and the emergence of renewable energy technologies are encouraged, leading to the estimation of a favorable impact on this variable.

d) Own funds (ownfunds_def_ln)

The p-value of ownfunds_def_ln (natural logarithm of own funds) was 0.0708, which was significant at the 10% level. An augmentation in own funds encouraged investment in R&D in the environmental sciences. Companies with sufficient own funds can conduct R&D independently, without reliance on external funds, which may increase investment in the environmental field. It is anticipated that companies with a high degree of flexibility in their fundraising activities will experience augmented R&D expenditure.

Table 3. Results of the heteroscedasticity-corrected random effect model

	Estimate	t value
(Intercept)	-5.6228249	-1.8997.
sales_lag1_Def_Ln	0.2082704	1.6139
res_workers_ln	0.1430563	3.5488***
extfunds_def_ln	0.1107158	1.524
ownfunds_def_ln	0.3280421	1.8135.
perres_funds_def_ln	0.6927701	1.4877
BOJ_DI	-0.0053873	-1.9338.
corona	-0.1642541	-1.2121
fuel_cons_ln	0.0913669	1.9281.
renewable_ln	-0.008372	-0.7336

Note: In the context of statistical analysis, the following symbols were used to denote the significance of p-values: ***: p-value less than 0.001, indicating a highly statistically significant result.. .: p-value less than 0.1, indicating a marginal or weak statistical significance.

The consideration of non-significant variables was warranted.

a) External funds (extfunds_def_ln)

Statistical analysis showed that the extfunds_def_ln (natural logarithm of external funds) variable was insignificant, with a p-value of 0.1286. It is conceivable that an augmentation in extraneous financial resources does not directly influence R&D expenditure in environmental sciences.

b) Renewable energy (renewable_ln)

The natural logarithm of renewable energy (Renewable_LN) did not demonstrate statistical significance (p-value = 0.4638). Once renewable energy technologies reach a state of technological maturity, R&D investments may be constrained or directed toward the refinement of existing technologies. Furthermore, R&D in renewable energy studies is influenced by multiple factors, including policies, regulations, and energy market demand.

2) Stepwise method based on the AIC

Given the paucity of significant coefficients in the calculation results of the random effects model applying the robust HCSE previously mentioned, the analysis of the environmental R&D expenses will be conducted using the stepwise method based on the Akaike Information Criterion (AIC). This analysis constitutes a methodological framework employed for the selection of statistical models, encompassing the process of selecting and deleting explanatory variables to explore the model with the lowest AIC. AIC penalizes models with elevated degrees of freedom, thereby circumventing the development of overly complex models. The criterion for determining the optimal model is predicated on two factors: the model's high likelihood of fitting the data and its parsimony, or the absence of overfitting. In essence, the stepwise method based on the AIC evaluates the overall superiority of a model, as opposed to determining its statistical significance based on the information criterion of the entire model. This approach effectively mitigates the risk of overfitting, thereby facilitating the acquisition of a model that exhibits a high degree of versatility.

The following variables were selected using the stepwise method with AIC:

The p-value for the number of R&D personnel was 0.066, indicating a marginal level of significance.

The impact of internal financing on R&D expenditure in the environmental field displayed statistical significance, with a p-value of 0.0018 (Table 4).

Table 4. Results of the stepwise method

	Estimate	Std. Error	t value	Pr(>|t|)	Interpretation
(Intercept)	-5.53052	0.97486	-5.673	3.35e-08 ***	--
res_workers_ln	0.19471	0.10589	1.839	0.06695.	Larger research teams tend to increase environmental R&D spending, although the significance is marginal.
researchers_ln	0.96207	0.23277	4.133	4.67e-05 ***	An increase in the number of researchers significantly increases environmental R&D spending. Core human resources are crucial.
extfunds_def_ln	0.33153	0.05391	6.15	2.52e-09 ***	More external funding from the government or other organizations substantially increases environmental R&D spending.
ownfunds_def_ln	-0.78149	0.24856	-3.144	0.00184 **	Greater internal funding is associated with a decrease in environmental R&D spending, suggesting reliance on external funds.
perres_funds_def_ln	3.4321	0.29901	11.478	< 2e-16 ***	Higher per-researcher investment significantly increases environmental R&D spending, indicating efficient fund allocation.
renewable_ln	0.07077	0.0165	4.288	2.45e-05 ***	Increased activity in renewable energy sectors is associated with higher environmental R&D spending, reflecting decarbonization efforts.

Note: In the context of statistical analysis, the following symbols were used to denote the significance of p-values: ***: p-value less than 0.001, indicating a highly statistically significant result. **: p-value less than 0.01, indicating a statistically significant result.

The p-values for the number of researchers, external funding, funding per researcher, and renewable energy-related investment were all less than 0.001, indicating high significance. Furthermore, an evaluation of the analysis results led to the exclusion of "sales lag" and "Bank of Japan Tankan" from the final model, as their impact on R&D expenses in the environmental field was deemed negligible.

In the present model, the factors influencing R&D expenses in the environmental field were as follows:

An increase in external funding corresponded to a rise in environmental R&D spending. The augmentation of a corporation's internal financial resources potentially curtails the R&D expenditure pertaining to environmental concerns. This phenomenon may be attributed to the influence of funding allocation priorities. A positive correlation is evident between the number of researchers and the R&D expenditure amount in the environmental field. That is, a higher number of researchers tends to increase the R&D expenditure in the environmental field.

Moreover, greater investment in R&D in the environmental sciences is associated with increased funding for individual researchers. In addition, as investment in renewable energy sources experiences growth, concomitant increases are observed in R&D expenditure in the environmental sciences. While the correlation may be considered modest, a positive relationship was observed between the number of R&D workers and the amount of R&D spending.

B. *Energy R&D*

The Hausman test results indicated that the implementation of a fixed effects analysis was appropriate for examining R&D expenditure in the energy field utilizing panel data. Therefore, to verify the characteristic differences between industries, the study directly specified specific coefficients and industry dummy cross terms in the stepwise method model to analyze their impact and capture the features of each sector.

As illustrated in Table 5, the factors that influence R&D expenditure in the energy sector were compared to those that influence spending in the environmental industry, as presented in Table 4. In a manner consistent with the findings in the environmental sciences, it was determined that corporate self-research funds and renewable energy consumption exerted a statistically significant influence on energy-related outcomes. However, in the domain of energy, the utilization of internal research funds has been shown to have a substantially positive influence. Conversely, external research funds, the number of research staff, the number of researchers, and the research funding per researcher were not associated with R&D expenditure in the energy field. As will be discussed later, the overall model demonstrated that the COVID-19 pandemic had a statistically significant positive influence on the allocation of financial R&D resources.

1) *The effect of internal funds by industry*

Regression analysis was conducted using a stepwise method with cross terms to examine the impact of internal corporate funds on energy-related R&D expenses. The results consistently demonstrated that internal corporate funds (ownfunds_def_ln) exhibited a remarkably robust and statistically significant positive impact ($p < 0.001$) on R&D spending. This indicated that internal corporate funds, including retained earnings and profits, played a substantial role in R&D investment.

The data in Table 6 revealed that in many industries, internal funding positively impacted R&D. However, a significant number of sectors, such as those involving rubber, printing, and general machinery, showed a negative effect. This heterogeneity underscores the need for sector-specific policy design.

Table 5. Selected variables for Energy R&D (with industry interactions)

Variable or Interaction Term	Estimate Direction	Interpretation
ownfunds_def_ln	+++	Strong positive overall effect
renewable_ln	+	Positive base effect
covid dummy	+	Positive base effect
sales_lag1_Def	+	Weak effect, weakly significant
extfunds_def_ln	+	Insignificant
res_workers_ln	Negligible	Insignificant
researchers_ln	Negligible	Insignificant
perres_funds_def_ln	Negligible	Insignificant

Table 6. Effect of Internal Funds by Industry

Industry	Net Effect (Coefficient)	p-Value (Significance)
Information & Communication Electronics Equipment	2.5902	0.0147 *
Petroleum & Coal Products	2.5015	0.0108 *
Iron and Steel	1.8051	0.0206 *
Textile Mill Products	1.7435	0.0054 **
Non-Ferrous Metals	1.0371	0.0041 **
Transportation Equipment	0.8075	0.0156 *
Chemical Products	0.2923	0.0017 **
Plastic Products	0.1775	0.0189 *
Electronic Devices & Circuits	-0.6485	0.0074 **
Printing & Allied Industries	-0.6926	0.0045 **
General-purpose Machinery	-1.1678	0.0371 *
Ceramic, Stone & Clay Products	-1.1894	0.0032 **
Miscellaneous Manufacturing	-1.7793	0.0011 **
Rubber Products	-4.5846	0.0027 **

Note: In the context of statistical analysis, the following symbols were used to denote the significance of p-values: ***: p-value less than 0.001, indicating a highly statistically significant result. **: p-value less than 0.01, indicating a statistically significant result. *: p-value less than 0.05, indicating a weak statistical significance.

In addition, analysis of the cross terms indicated that the impact of internal funding exhibited substantial variation across different industries. In many industries, the cross terms were statistically significant. Particularly, in certain industries (e.g., manufacturing of textile mill products, pulp, paper, and paper products), internal funding had a substantial negative impact on R&D expenses. This suggests that, in comparison to the industry standard, an increase in internal funding tends to decrease energy-related R&D expenditure within these industries.

These findings indicated that industrial structures, funding allocation policies, and R&D characteristics exhibited substantial variation across different sectors. This underscores the necessity of an approach that considers the unique characteristics of each industry, as opposed to a universally applicable policy or investment strategy.

Fig. 2 visualizes the diverse impact of internal corporate funds on R&D expenditure by industry. Notably, some sectors, such as electronics and petroleum, showed highly positive effects, while others, such as rubber and ceramic products, demonstrated strong negative correlations, indicating divergent financial strategies or priorities.

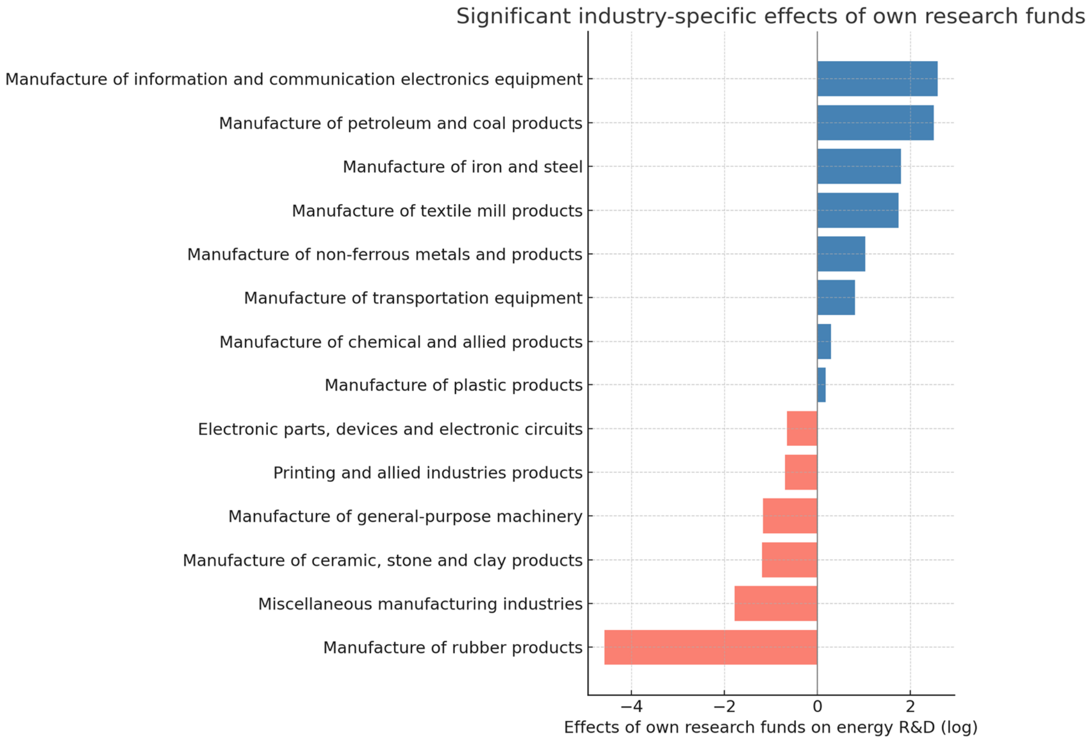

Fig. 2. The effect of internal funds by industry.

In terms of model evaluation, the model selected using the stepwise method demonstrated an exceedingly high coefficient of determination (R-squared = 0.9265) and extremely high statistical significance (p < 2.2e-16). This could be attributed to the elimination of variables with minimal significance, suggesting that the selected variables, particularly those pertaining to internal financing, industry dummies, and their cross terms, effectively elucidated the fluctuations in R&D expenses.

The analysis indicated that a company's energy-related R&D expenses were predominantly influenced by its equity capital, with industry characteristics significantly impacting this relationship.

2) The effect of renewable energy consumption by industry

The process of constructing the optimal model using the stepwise method demonstrated that efforts to promote renewable energy tended to stimulate R&D investment in the energy field as a whole. However, the impact of renewable energy is not straightforward. Analysis of cross terms revealed that their nature varied significantly depending on the industry. While the primary effect of renewable_ln positively affected R&D expenditure, the cross term between renewable energy and industry (industry x renewable_ln) exhibited statistically significant negative values in numerous sectors. A pronounced negative impact was observed in specific industrial sectors, including printing, chemical manufacturing, plastic manufacturing, electrical machinery production, and miscellaneous manufacturing.

Fig. 3 illustrates the estimated effects of firm-owned research funds on energy R&D (in logarithmic terms) across various manufacturing industries in Japan. Industries involving the manufacture of information and communication electronics equipment, petroleum and coal products, and iron and steel exhibit strong positive effects, suggesting that an increase in internal research funding is associated with higher energy R&D investment in these sectors. Conversely, industries involving rubber products, miscellaneous manufacturing, and ceramic, stone, and clay products show negative effects, indicating that internal research funding does not translate into increased energy R&D in these areas, and may even crowd out other sources.

Fig. 3. The effect of renewable energy consumption by industry.

Note: This graph shows the "cross-term coefficient" and "total effect (1.0305+coefficient)." Blue: Cross-term coefficient with renewable energy (interaction effect), Orange: Total effect of renewable energy (base effect 1.0305 added). The ★ mark indicates that the cross-term is significant at the 1% level.

3) The effect of COVID-19 by industry

This study examined the impact of the COVID-19 pandemic on corporate energy-related R&D expenditure while considering the differences between industries. The analysis indicated that the pandemic exerted a statistically significant and positive influence (estimated value 3.3097, $p < 2\text{e-}16$) on energy-related R&D spending.

However, the impact was not uniform across industries. A thorough examination of the cross-term between the pandemic and industry (corona x industry) yielded statistically significant negative coefficients in numerous industries. For instance, in multiple industries, including the manufacturing of general-purpose machinery and information and communication electronics equipment, the pandemic substantially reduced R&D spending. This indicated that these specific industries experienced significant repercussions from the pandemic, including supply chain disruptions and diminished demand, compelling them to curtail their R&D investment.

This result, which initially appears contradictory, may be interpreted consistently within the econometric model. The positive value indicated by the main effect of corona merely shows the "average" direction of the impact across all industries. Conversely, the negative values predicted by the cross-terms demonstrated the extent to which each sector deviated from the average trend. In summary, this analysis captures the duality of the impact, demonstrating that "the pandemic brought about an overall upward trend in R&D spending, but many manufacturing industries experienced a strong negative impact, which offset the positive effects, resulting in an overall negative impact of COVID-19 on R&D spending."

Table 7 shows how COVID-19 affects different industries, ranked by the size of their interaction. Some industries, such as those involving the manufacturing of electrical machinery, equipment, and supplies, as well as chemical and allied products, were positively affected, while others, including those involving the manufacturing of information and communication electronics equipment and general-purpose machinery, experienced stronger negative impacts. The results are based on a fixed effects regression model with notable statistical significance.

Table 7. The effect of COVID-19 by industry

Industry	Net effect (Coefficient)	Statistical significance of deviation from the benchmark industry
Benchmark Industry (food manufacturing industry)	3.386	--
Manufacture of electrical machinery, equipment, and supplies	1.439	***
Manufacture of chemical and allied products	0.373	***
Manufacture of iron and steel	0.331	***
Manufacture of textile mill products	0.249	***
Manufacture of transportation equipment	0.21	***
Manufacture of plastic products	0.177	***
Manufacture of petroleum and coal products	0.037	***
Manufacture of pulp, paper, and paper products	-0.006	***
Manufacture of production machinery	-0.1	***
Manufacture of ceramic, stone, and clay products	-0.184	***
Manufacture of non-ferrous metals and products	-0.205	***
Miscellaneous manufacturing industries	-0.376	***
Electronic parts, devices, and electronic circuits	-0.424	***
Manufacture of fabricated metal products	-0.551	***
Manufacture of general-purpose machinery	-0.602	***
Manufacture of information and communication electronics equipment	-0.772	***

The model's R-squared (0.9356) and adjusted R-squared (0.9253) values are both notably high, suggesting that it adequately captured the R&D expenditure variability.

Consequently, the COVID-19 pandemic had a multifaceted impact on energy-related R&D expenditure. While it generally promoted investment, it also significantly restrained investment in certain industrial fields, and its impact varied considerably depending on the characteristics of the industry.

IV. Conclusion

This study comprehensively analyzed the factors that influenced environmental and energy-related R&D expenditure. The analysis was based on panel data from 22 manufacturing industries from 2008 to 2023, which was obtained from the "Research and Development Trends Survey" published by the Ministry of Internal Affairs and Communications.

The findings indicated that an increase in the number of researchers and external funding sources was associated with a concomitant rise in environmental R&D spending. Specifically, external funding increased R&D expenditure in the environmental field (crowd-in effect). Conversely, regarding internal corporate funding, while both the heteroscedasticity corrected random effect model and the stepwise method yielded significant coefficients, a contradictory relationship was observed between the signs of these coefficients. In addition, the number of researchers, funding for individual researchers, and investment in renewable energy also tended to increase the R&D expenditure in the environmental field.

The results also showed that internal corporate funding (ownfunds_def_ln) and renewable energy (renewable_ln) significantly influenced R&D investment in the energy field as a whole. However, the impact was not straightforward, and the effects on individual industries varied. While these two factors generally had a positive impact on the energy-related R&D expenses, the net effect at the industry level varied between industries, with some showing positive effects and others negative correlations. The analysis indicated that a company's energy-related R&D expenses were predominantly influenced by its equity capital (but not external funds), with industry characteristics substantially impacting this relationship. Consequently, when formulating policies to promote R&D investment for energy, it is imperative to thoroughly assess the disparities in funding structures and investment behavior across various industries. This analysis should result in the development of customized strategies to address the unique needs of each research field.

Furthermore, the results also suggest the presence of a multifaceted structure regarding renewable energy consumption, indicating that "while endeavors directed toward renewable energy often stimulate energy R&D in numerous specific industries, these efforts may concurrently impede R&D expenditure on other energy-related technologies." This may be attributed to the strategic realignment of corporate investment priorities, with enterprises reallocating funds from conventional energy technologies to renewable energy sources. Alternatively, the observed trend could indicate the suppression of additional R&D investments in renewable energy technologies as their adoption and integration into the energy landscape become more prevalent. This phenomenon was also observed in relation to the impact of the COVID-19 pandemic. While the presence of the novel coronavirus encouraged overall energy R&D investment, certain industries substantially reduced R&D expenditure, resulting in adverse consequences. In the event of future pandemics, industry-specific policy responses will be required.

In subsequent research, the author intends to conduct similar analyses for six key development areas outside the environmental and energy domains (life sciences, information and communications, materials, nanotechnology, space development, and marine development). Furthermore, by accessing the Ministry of Internal Affairs and Communications' company-specific survey data, the author plans to perform a more detailed analysis of the factors that influence R&D expenditure. Access to this data is contingent upon the allocation of Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology. The application for funding is currently under review. Additionally, the author is contemplating the incorporation of additional data points, including the number of female researchers, into the panel dataset. This approach is designed to enhance the precision of the analysis by elucidating the correlation with R&D expenditure. In the future, the author intends to utilize firm-level survey data to enhance our capacity to comprehend alterations in research activities subsequent to companies (particularly those that receive public funds) acquiring external funding. Furthermore, the objective is to accurately ascertain the "crowding-in" and "crowding-out" behavior of each company's R&D expenditure after obtaining external funding.

CONFLICT OF INTEREST

The author declares no conflict of interest.

REFERENCES

[1] Economic Insights Limited, What Is the Relationship Between Public and Private Investment in Science, Research and Innovation? A Report commissioned by the Department for Business, Innovation, and Skills, London, U.K., 2015.

[2] Ministry of Internal Affairs and Communications, The Survey of Research and Development, The Statistics Bureau and the Director-General for Policy Planning of Japan.

[3] A. Alfonso and E. Rodrigues, "Is public investment in construction and in R&D, growth enhancing? A PVAR approach," *Applied Economics*, vol. 56, no. 24, pp. 2875–2899, 2023. https://doi.org/10.1080/00036846.2023.2203455

[4] B. Ito and S. Nakano, "The impact of Public R&D subsidies on firm's R&D activities: Evidence from Japanese firm-level data," *ESRI Discussion Paper Series*, no. 222, Economic and Social Research Institute, Japan, 2009.

[5] C. Giovanna, M. Deleidi, and M. Mazzucato, "Measuring the macroeconomic responses to public investment in innovation: Evidence from OECD countries," *Industrial and Corporate Change*, vol. 33, no. 2, pp. 363–382, Apr. 2024. https://doi.org/10.1093/icc/dtae005

[6] E. Duguest, "Are R&D subsidies a substitute or a complement to privately funded R&D? Evidence from France using propensity score methods for non-experimental data," *Revue d'Economie Politique*, vol. 114, pp. 245–274, 2004.

[7] H. Görg and E. Strobl, "The effect of R&D subsidies on private R&D," *Economica*, vol. 74, no. 294, pp. 215–234, 2007.

[8] L. A. Rocha, D. V. Sarmento, C. Almeida, and N. Silva, "Spillover, public investment and innovation: The impact of public investment in R&D on business innovation," *Economics Bulletin*, vol. 40, no. 3, pp. 2344–2360, 2020.

[9] Bank of Japan, The Short-Term Economic Survey of Enterprises in Japan (BOJ Tankan). [Online]. Available: https://www.boj.or.jp/en/statistics/tk/index.htm

[10] Agency of Natural Resources and Energy, Ministry of Economic, Trade and Industry, Energy Supply and Demand Report 2008–2023. [Online]. Available: https://www.enecho.meti.go.jp/statistics/energy_consumption/ec001/index.html

[11] J. Kmenta, Elements of Econometrics, 2nd ed. University of Michigan Press, 1997.

[12] P. A. V. B. Swamy and S. S. Arora, "The exact finite sample properties of the estimators of coefficients in the error components regression models," *Econometrica*, vol. 40, no. 2, pp. 261–275, 1972.

[13] G. Judge, W. E. Griffiths, R. C. Hill, H. Lutkepohl, and T. C. Lee, *The Theory and Practice of Econometrics*, 2nd ed. John Wiley and Sons, 1985.

[14] J. M. Wooldridge, *Econometric Analysis of Cross Section and Panel Data*, 2nd ed. The MIT Press, 2010.

[15] H. White, "A heteroskedasticity consistent covariance matrix estimator and a direct test of heteroskedasticity," *Econometrica*, vol. 48, pp. 817–838, 1980.

[16] J. G. MacKinnon and H. White, "Some heteroskedasticity-consistent covariance matrix estimators with improved finite sample properties," *Journal of Econometrics*, vol. 29, pp. 305–325, 1985.