Energy R&D Trends And Sustainable Energy Strategies In IEA Countries: Efficiency, Dependency And Environmental Dynamics

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Abstract

Understanding the factors affecting R&D trends in the energy sector has a key role in overcoming environmental concerns such as combating climate change, as well as other economic and political problems related to energy. Based on such concerns, this study aims to analyze fundamental factors that determine the energy R&D trends of 29 International Energy Agency (IEA) countries. The data set, consisting of annual indicators for the period 1990-2015, is analyzed with the Driscoll-Kraay panel data estimator. Empirical findings for overall sample show that efficiency, import dependency, and the share of renewable energy use are positively related with R&D expenditure in energy sector. CO_2 intensity is found to be statistically insignificant. When countries are grouped considering their energy composition structures, the dynamics of energy R&D expenditures differ between groups. In overall evaluation, our findings illustrate efficiency and dependency to have greater priority compared to environmental dynamics on energy R&D expenditures for IEA countries during the period.

Introduction

The choices made regarding the acquisition and the use of energy in an economy are critical in terms of welfare effects, environmental quality, international security, and competitiveness. Therefore, countries are faced to developing strategies that serve multiple purposes to create an effective energy strategy. While designing such a strategy, countries must handle with various objectives related to economic, environmental, and political dimensions (Weijermars et al. 2012; Trutnevyte 2014).

Allowing the differentiation of the order of these objectives between economic actors in a country, economic objectives can be convened in three common points: (i) to provide energy at a level that can sustain economic activities without disruption; (ii) to provide cost-effective energy supply to economic actors; and (iii) to limit macroeconomic vulnerabilities arising from balance of payments deterioration which may occur because of external dependency in energy (Holdren 2006; Ren et. al. 2010).

Environmental objectives, on the other hand, are not likely to incorporate unanimity as economic ones in the short term (See, for instance, Valentine, Sovacool, and Matsuura 2011). Objectives of environmental concerns can be defined in two cohort. First one consists of alternatives to traditional energy resources, energy utilization, storage etc. and is related with environmental improvement. The other is related with environmental degradation and focuses on to limit negative externalities of energy processes.

When looking at the political dimension of a successful energy strategy, the objectives can be listed as reducing the risks of conflict related to oil and gas resources, prevention of nuclear armament, and security issues about energy production and transportation systems (Winzer 2012).

Economic and environmental returns of developing new energy technologies is the key factor in achieving energy goals regarding efficiency, environmental impact, and the security of supply (Costa-Campi et al. 2015). The size and composition of R&D expenditures in the sector are not distinct from energy related characteristics and strategies of the countries (Bergquist and Söderholm 2014). R&D expenditures, which enables innovative activities for the energy sector, can be seen as a part of the energy strategy.

Figure 1 shows the leading area of R&D expenditure in energy sector for IEA countries. Although renewable energy and energy efficiency are the rising fields in energy sector R&D activities, fossil fuels and nuclear energy are continuing to be the leading field in some countries. Considering resource structures, as having nuclear technology or not and the degree of fossil resource dependence, energy sector R&D specialization differ greatly among IEA countries. Therefore, it is foreseen that a *de facto* energy R&D strategy process will emerge in the energy sector coinciding with the structural priorities of the countries.

Our framework in this study comprises of several economic and environmental objectives. External dependency, energy efficiency, the use of renewable energy and carbon intensity are indicators that are thought to be effective on energy sector R&D strategies through various channels.

The motivation of the research is "What are the factors that determine the trend of R&D expenditures in energy sector?". Based on this formulation, it is thought that R&D activities in energy sector are conducted basically for reducing external dependency, increasing energy efficiency, improvement of environmental quality, and diminishing environmental degradation. In this framework, the effects of energy intensity, import dependency, the share of renewable energy and CO_2 intensity on the energy R&D expenditures of the IEA member countries are analyzed. Moreover, we grouped countries depending on their fossil resource use and nuclear energy. Based on econometric findings, we reevaluated significant factors of energy R&D through energy strategy perspective.

The plan of this study is as follows. After the introduction, second section gives literature review on the dynamics of energy R&D activities. Third section presents dataset, econometric modelling, and estimation method. Findings of the econometric analysis are discussed in fourth section. Conclusion summarizes the findings of the study.

[1]Other IEA countries are as following: Australia and Canada in fossil fuels; South Korea and New Zealand in renewable energy; Japan in nuclear energy; and the US in other cross-cutting technologies in energy.

Literature Review

The literature on identifying the underlying dynamics of country-level energy R&D trends is relatively limited. The literature on energy R&D activities generally focus on various aspects of the phenomenon. The relation and contribution to economic growth, the impact on CO_2 emission reduction, and its effect on energy consumption are general themes in the literature. In addition to these, knowledge production in energy sector, government's role in energy R&D, are also further areas of concentration. In this context, we categorize related literature in three groups.

In the first group of studies, energy R&D expenditure is considered as a fact to be explained alone. Inglesi-Lotz (2019), for instance, examine energy R&D trends of Australia, Canada, Germany, the United Kingdom, and the United States over the 1981-2017 period. In the study, energy R&D trends are analyzed with the Logarithmic Average Divisia Index (LMDI), considering four different factors as explanatory variables. The findings show that energy R&D return, energy R&D priority, and GDP positively affects energy R&D expenditures in all five countries, while R&D intensity is found in inverse relation. Another study in this group is Bointner (2014). This study focuses on government's role in energy R&D activities. The study analyses the cumulative knowledge stock represented by public R&D expenditure and patents in the energy sector in 14 selected IEA countries during the 1974-2013 period, considering seven groups of energy technologies. Regression analysis findings indicate a linear relationship between GDP and cumulative information. In addition, it is found that there is a strong relationship between the knowledge stock arising from R&D expenditures and patent knowledge in renewable energy technologies.

Second and third group of the literature take energy R&D expenditure as explanatory factor. While second group is about the effect of energy R&D activities on macroeconomic indicators, third group is more specific, namely on environmental improvement. For the second group, Huang et al. (2017) and Saudi et al. (2019) consider energy sector R&D activities as a means of increasing energy efficiency. Both studies relate R&D with lower energy intensity in production in different country cases. Koçak, Kınacı and Shehzad (2021) investigated the environmental efficiency of R&D expenditures for various energy R&D fields in OECD countries with data envelopment analysis (DEA) in 2015. Estimation findings show that only the USA provides environmental efficiency through R&D activities. The article also proposes energy R&D policy recommendations for inefficient countries. Wang and Wang (2019) investigate same causality with Chinese regional data. Using data envelopment analysis and dynamic GMM methods, the study captures significant increase in total factor productivity because of energy R&D. Zhu et al. (2021) assess the relation between energy R&D and energy composition for 18 IEA countries. The findings indicate 40% decrease in carbon content of energy mix for 1980-2015 period. Lastly, Wong et al. (2013) and Jin et al. (2018) can be given as examples of the impact of energy R&D on energy consumption and economic growth. Although the factual link between R&D and economic growth is relatively weak, the long-run estimations reveal a bilateral correlation between energy consumption and energy R&D.

Third group is a highly specialized category of literature on energy R&D. Studies in this group consider innovative activities in energy sector as a cause of environmental improvement. The share of renewable resources in energy production, carbon emissions, and ecological footprint indicators are general variables to be explained in these studies. Ndlovu and Lotz (2020), Wang et al. (2020), and Kılınç and Kılınç (2021) are studies that propose alternative models for renewable energy and R&D. The direction of causality is from energy R&D to renewables in general, which indicates dissemination of technological innovations in energy sector to renewables. However, studies with long-term perspective are more likely to set up a bilateral causality. The difference between these causality relationships is demand or supply side connections. While long-term causality from renewables to energy R&D can be entitled as demand pull explanation, the reverse is attached to supply side accessibility in energy sector. Garrone and Grilli (2010), Işık and Kılınç (2014), Gu and Wang (2018), Shahbaz, Nasir, and Roubaud (2018), and Kılınç (2021) are the examples of studies that conceive of energy R&D as facilitator of CO_2 or ecological footprint reduction. Since carbon emission targets or ecological concerns are generally policy oriented, these studies aim to assess sustainability of environmental policies in countries with various level of economic development. Bilgili et. al (2021) consider the impact of efficiency related, fossil fuel, and renewable energy R&D expenditures on carbon emissions. The study shows that energy efficiency related R&D expenditure is more effective on carbon emission reduction than the two others in 13 developed countries for 2003-2018 period. Koçak and Ulucak (2019) also analyzes the impact of disaggregated energy R&D expenditures on carbon emission for 19 high-income OECD countries for 2003-2015. According to the study, only power and storage R&D expenditures diminishes carbon emission, while efficiency and fossil fuel R&D are found to be positively related to carbon emission. Balsalobre-Lorente et. al (2019) finds a conditional impact of energy R&D on carbon emissions. According to the study, the degree of corruption diminishes positive impact of energy innovations on environmental quality.

Data And Econometric Model

Data and Variables

The empirical part of our study is based on the annual data set of 29 IEA countries for 1990-2015 period (See Appendix 1 for the IEA country list). Our dataset is in panel format with a cross section number (N) of 29 and a time dimension (T) of 26. The structure of the dataset is an unbalanced panel, as there are missing values in the data for some countries, especially in the period between 1990-1995. Although most of the data are available up to date until 2019, the empirical analysis is based on the period 1990-2015, since the data compiled by the IEA was discontinued from 2016 onwards. A time interval of this length provides sufficient prospect for medium and long-term analysis. Table 1 shows the variables and their definitions used in econometric analysis.

Table 1. Variables and Definitions

Variable	Definition	Unit	Source
rd_total	Total R&D expenditure; energy sector	2019 prices and exchange rates; million US dollar	IEA
imp_dep	Net energy imports; ratio to energy use	per cent ratio	IEA
renew_share	Renewable energy consumption; ratio to total energy consumption	per cent ratio	World Bank
e_int	Energy intensity of primary energy	million joule/2011 GDP PPP; ratio	World Bank
co2	Production related CO_2 intensity; per capita	Tons	World Bank

Energy sector R&D expenditures and energy imports data are compiled by the IEA (IEA 2021). The data for other variables were taken from the World Bank's *World Development Indicators* (World Bank 2021).

The selected variables represent the general dynamics that are thought to affect energy sector in terms of R&D trend and are discussed briefly in the introduction and the literature review section of this article.

Summary statistics of the level values of the variables are given in Table 2. When the number of observations of the variables in the second column is considered, it is seen that our panel data set is unbalanced due to the missing *rd_total* variable for some countries between 1990-1995. There are no missing values for other series. In addition, there is no high correlation between the variables that can cause multicollinearity (See Appendix 2).

Table 2: Summary Statistics

Variable	No of Obs.	Mean	St. dev.	Min.	Max.
id	754	-	-	1	29
year	754	-	-	1990	2015
rd_total	589	577.69	1227.32	0.89	11593.84
renew_share	754	14.19	13.41	0.44	61.38
imp_dep	754	17.04	136.54	-843.48	99.16
e_int	754	5.52	2.21	1.95	18.23
co2	754	9.37	4.37	2.39	29.09

imp_dep variable, which represents energy dependency, takes negative values for some countries. This means that these countries are net energy exporters. In order to prevent the measurement units of the variables to affect the magnitude of estimated coefficients, *rd_total* and *co2* were used in logarithmic form. In this way, all estimation coefficients can be interpreted as either percentage or proportional changes.

Econometric Model and Estimation Method

Since our dataset consists of a sample of heterogeneous macro units, country-specific unobservable factors or the omitted variables that are not included in the model must be taken into consideration. A common way of estimation of this type of models is the fixed effects estimator. Consider general representation of a linear panel data model given in Equation 1.

$$y_{it} = \alpha + \beta x_{it} + \varepsilon_{it} \tag{1}$$

In the equation, subscripts i and t represent cross-section units and time respectively. y_{it} is the dependent variable and x_{it} represents explanatory variables. The disturbance term ε_{it} is composed of two distinct components, u_i and v_{it}. First part of the disturbance u_i represents time-invariant country-specific factors. The second part v_{it} is the remainder disturbance. We assume v_{it} to be uncorrelated with x_{it} and identically distributed with (0, σ_v^2). By subtracting time averages, country-specific parts of the equation are eliminated (Baltagi 2005). Equation 2 shows the fixed effects estimator.

$$\tilde{y}_{it} = \beta \tilde{x}_{it} + \tilde{\varepsilon}_{it} \qquad (2)$$

where $\tilde{y}_{it} = y_{it} - \overline{y}_i$, $\tilde{x}_{it} = x_{it} - \overline{x}_i$, and $\tilde{\varepsilon}_{it} = \varepsilon_{it} - \overline{\varepsilon}_i$.

The fixed effect estimator will yield standard errors that are consistent based on assumptions uncorrelated and homoscedastic disturbances. To check the first assumption, we applied Wooldridge autocorrelation test. With F test statistic value of 49.132, Wooldridge test rejects no-autocorrelation assumption and we accept AR(1) autocorrelation structure of error terms. For the second assumption, we applied Breusch-Pagan (1979) Lagrange multiplier (LM) test and White (1980) test. LM test statistic is 26.165 and White test statistic is 78.35. Both tests reject homoscedastic groupwise variances.

In addition to these two assumptions, it is shown in econometric literature that cross-sectional dependence (CD) is a serious problem and arises especially in macro panel data. CD causes estimation of covariance matrix to be biased (Pesaran 2004; Sarafidis and Wansbeek 2012). For problems of serial correlation and heteroscedasticity, we can get robust standard errors by Arellano (1987)'s clustering method. Yet, fixed effect estimation with robust standard errors must be tested for CD. So, we check spatial and temporal dependence with Pesaran (2015) CD test (See Appendix 3). The test is implemented to residuals of fixed effect estimation and the dependent variable (*lnrd_total*). The test rejects null hypothesis of cross-section independence with 28.163 test statistics and confirms correlation between the panel groups.

Under serial correlation, heteroscedasticity, and CD, fixed effects estimate of coefficients are still consistent, but clustered covariance matrix estimation is biased. Therefore, we employed Driscoll and Kraay (1998) estimation of covariance matrix which yields standard errors that are robust to CD as well as first order autocorrelation and heteroscedasticity (Driscoll and Kraay 1998; Hoechle 2007).

The main model used in econometric analysis is in a linear panel form and given by Equation 3. Subscripts *i* and *t* represent cross-section units (countries) and time (year) respectively.

$$\ln rd\_total_{it} = \beta_0 + \beta_1 e\_int_{it} + \beta_2 imp\_dep_{it} + \beta_3 renew\_share_{it} + \beta_4 \ln co2_{it} + \varepsilon_{it} \qquad (3)$$

In the model, logarithmic total R&D expenditure in the energy sector (*lnrd_total*) is dependent variable. The explanatory variables are energy intensity (*e_int*), import dependency (*imp_dep*), renewable energy consumption share (*renew_share*) and logarithmic CO_2 emissions (*lnco2*).

To check for robustness, after the estimation of Equation 3 for a sample of 29 IEA member countries, estimations were made for subgroups according to countries' status in nuclear energy and fossil resource use. Firstly, countries are divided into two groups as those that use nuclear energy and those that do not according to IEA (2021) data. This process divided the data set into two approximately equal groups and allowed the coefficients between the groups to be compared. In the other grouping, countries with less than 50% use of fossil resources in energy production are labeled as “low fossil”, countries with 50% to 80% as “medium fossil”, and countries with more than 80% as “high fossil”.

Empirical Findings

All Panel Estimation Results

The estimation results of panel data regression models (Pooled OLS, Fixed Effects, Driscoll Kraay) in which total R&D expenditure in energy sector is the dependent variable are given in Table 3. Pooled OLS and Fixed Effects estimators are included for comparison purpose. The coefficients obtained with the Driscoll and Kraay estimator have standard errors corrected for cross-section dependence, heteroskedasticity and autocorrelation. Therefore, coefficient estimates of the Driscoll Kraay estimator are the ones that we interpret in Table 3 and in the following estimation tables.

Table 3: Regression Results for Energy Sector R&D Expenditures

Variable	Pooled OLS	FE (Robust)	FE (DK)
e_int	-0.074	-0.390***	-0.390***
	(0.055)	(0.044)	(0.050)
renew_share	-0.022***	0.039***	0.039***
	(0.007)	(0.011)	(0.010)
imp_dep	-0.001***	0.005***	0.005***
	(0.0006)	(0.0009)	(0.001)
lnco2	2.160***	0.604*	0.604
	(0.246)	(0.337)	(0.389)
constant	1.080**	4.870***	4.870***
	(0.463)	(0.905)	(0.764)
N	589	589	589
F	51.39	51.50	24.51
R^2	0.26	0.27	0.27

Note: Dependent variable is *lnrd_total* in each regression. Values in parentheses show standard errors in pooled OLS, robust standard errors in FE(Robust), and Driscoll and Kraay standard errors in FE(DK). *, **, and *** indicate 10%, 5% and 1% significance levels, respectively.

Comparing three estimation results in the table, both coefficients and standard errors in pooled OLS are found to be different from the other two methods. However, these findings are biased. One must consider time-invariant characteristics of cross section units. Therefore, unbiased estimates are fixed effects coefficients.

The last two column show fixed effect coefficients. The difference between the two is the computation of standard errors, and hence probability values. Both are robust to heteroskedastic and auto-correlated errors, while only Driscoll and Kraay has standard errors that are robust to cross sectional dependency. According to overall group estimation results, only CO_2 intensity is found to be statistically insignificant. The share of renewable energy and import dependency in IEA member countries have statistically significant and positive effect on energy R&D expenditures. Energy intensity has a negative and statistically significant effect on energy R&D expenditures.

Sub-Group Estimation Results

After overall group estimation of 29 IEA member countries, the member countries are grouped according to whether they use nuclear energy and their fossil energy use levels. The results in Table 4 show the results for nuclear energy sub-groups. Second column in the table gives coefficients for the sub-group of countries that have nuclear energy use, third column for the subgroup that have not nuclear energy and the last column for the overall IEA countries.

Table 4: Regression Results- Nuclear Energy Subgroups

Variables	Nuclear	Non-Nuclear	All
e_int	-0.173**	-0.977***	-0.390***
	(0.069)	(0.086)	(0.050)
renew_share	0.0372	0.0328*	0.039***
	(0.0247)	(0.0187)	(0.010)
imp_dep	0.0102***	0.00635***	0.005***
	(0.003)	(0.0008)	(0.001)
lnco2	-0.429	0.979	0.604
	(0.383)	(0.71)	(0.389)
constant	6.69***	5.37***	4.870***
	(1.3)	(1.75)	(0.764)
N	348	241	589
F	10.93	89.89	24.51
R^2	0.2775	0.4255	0.2703

Note: Dependent variable is *lnrd_total* in each regression. Values in parentheses show Driscoll and Kraay standard errors. *, **, and *** indicate 10%, 5% and 1% significance levels, respectively.

According to the results in Table 4, import dependency has a statistically significant and positive effect on energy R&D expenditures in both subgroups. Energy intensity also has a statistically significant but negative effect in the subgroups. CO_2 intensity do not have a statistically significant effect on energy R&D expenditures. The coefficient and probability value of renewable energy share differ between nuclear and non-nuclear countries. In the nuclear countries, renewable energy share has a positive and statistically significant effect on energy R&D expenditures. In the non-nuclear group, it is insignificant. The impact of energy intensity on R&D tendency is lower in nuclear group since the nuclear technology countries have a higher overall R&D level compared to the other group.

In addition, since nuclear energy and renewable energy sources are alternative to each other, the coefficient of the renewable share does not have a significant effect in the country group with nuclear energy use. This finding shows that nuclear and renewable technology development activities are considered as alternatives to each other in these countries. The coefficient of the *imp_dep* variable is larger in the group of countries with nuclear technology. Therefore, it can be said that the sensitivity to import dependency is higher in R&D expenditures in countries using nuclear energy.

Table 5 shows the findings for the country groups classified according to the level of fossil resource use. According to table, CO_2 intensity does not have a significant effect on energy R&D expenditures the three subgroups. Energy intensity is statistically significant and has a negative effect in “Low Fossil” IEA member countries where fossil fuel use is below 50% in total energy use. Import dependency, share of renewable energy, and carbon intensity variables do not have a statistically significant effect on energy R&D expenditures for this group. The share of renewable energy and import dependency have a statistically significant and positive effect on energy R&D expenditures in “Medium Fossil” countries where fossil fuel use is between 50%-80%. Energy intensity, on the other hand, has a statistically significant but negative effect.

Table 5: Regression Results - Subgroups of Fossil Resource Use

Variable	Low Fossil	Medium Fossil	High Fossil	All
e_int	-0.277**	-0.497***	-0.385***	-0.390***
	(0.080)	(0.052)	(0.0985)	(0.050)
renew_share	0.00506	0.0375*	0.00505	0.039***
	(0.0168)	(0.0181)	(0.051)	(0.010)
imp_dep	-0.0516	0.00489***	0.00787***	0.005***
	(0.0239)	(0.0011)	(0.002)	(0.001)
lnco2	0.735	0.214	0.669	0.604
	(0.582)	(0.553)	(0.663)	(0.389)
constant	7.74***	5.65***	5.45**	4.870***
	(1.34)	(1.44)	(2.01)	(0.764)
N	83	307	199	589
F	*37.24*	24.55	10.43	24.51
R^2	*0.4389*	0.3196	0.2155	0.2703

Note: Dependent variable is *lnrd_total* in each regression. Values in parentheses show Driscoll and Kraay standard errors. *, **, and *** indicate 10%, 5% and 1% significance levels, respectively.

In “High Fossil” IEA member countries with more than 80% fossil fuel use in total energy, import dependency has a statistically significant and positive effect on energy R&D expenditures, while energy intensity has a statistically significant and negative effect. CO_2 intensity and the share of renewable energy do not have a significant effect on energy R&D expenditures in this group. In “Low Fossil” countries, import dependency is not effective on energy R&D expenditures compared to the other two groups. One explanation for this distinction between “Low Fossil” and the other groups can be interpreted as higher levels of fossil resource use call for the need for technologies that reduce import dependency.

e_int variable has the highest effect in “Medium Fossil” country group. As fossil resource utilization rate increases, the negative effect of energy density on the R&D tendency also increases. Since high energy density indicates low energy efficiency, it is seen that energy efficiency is more effective in R&D expenditures in countries with high fossil resource use. The variable *renew_share* does not have a significant effect in “Low Fossil” and “High Fossil” groups. In the “Medium Fossil” group, it has a positive and significant effect. This disparity points to the difficulties in changing the energy composition in the two extreme group of countries.

Energy R&D Strategy Implications

Our findings have economic and environmental implications for energy R&D strategy for the different groupings. Table 6 summarizes the empirical findings based on four indicators in three energy R&D strategy dimensions for the member countries in 1990-2015 period. Energy efficiency is found to be positively related with R&D expenditures in all groups. Dependency has positive effect on energy R&D expenditures in all groups except the country group with low fossil resource use. This exception is very plausible since low fossil resource use indicates diversity in energy composition. Dependency is by-passed by national alternative resources and has no significant pressure on energy R&D.

The environmental dimension is represented by two different indicators. The share of renewable energy represents environmental improvement, and CO_2 intensity, represents environmental degradation. Our findings put forward that the countries with nuclear technology, low fossil resource use or high fossil resource use do not have a significant environmental improvement motivation in R&D expenditures. Non-nuclear countries and medium fossil resource using countries have a positive incentive of environmental improvement. Environmental degradation, on the other hand, does not have a significant effect on energy R&D expenditures in any groups.

Table 6: Summary of Regression Models

Dimension	Indicator	Nuclear	Non-Nuclear	Low Fossil	Medium Fossil	High Fossil	All Sample
Efficiency[2]	*energy intensity*	(-)*	(-)*	(-)*	(-)*	(-)*	(-)*
Dependency	*import dependency*	(+)*	(+)*	(-)	(+)*	(+)*	(+)*
Environmental Improvement	*renewable share*	(+)	(+)*	(+)	(+)*	(+)	(+)*
Environmental Degradation	*CO_2 intensity*	(-)	(+)	(+)	(+)	(+)	(+)

Note: * indicates statistical significance with prob. value of 0.10 at least. (+) and (-) show direction of relationship with energy R&D expenditure.

In low and high fossil resource using countries, renewable energy and environmental degradation do not have a significant effect on R&D expenditures. In other words, countries using high fossil resources care more about energy efficiency and external dependency, and countries using low fossil resources care more about efficiency. Therefore, while countries with a high fossil resource use focus on economic factors in their energy R&D strategies, countries using moderate fossil fuels give prominence to environmental improvement in addition to economic factors. As the dependency on fossil fuels decreases, environmental recovery becomes more important.

[2]Since high energy intensity means low energy efficiency, the negative relationship between energy intensity and R&D expenditures has been interpreted in the opposite direction, i.e. as positively.

Conclusion And Policy Implications

Notably after the oil crises in the 1970s, energy supply security and sustainability have been endangered in addition to the increase in the concentration of CO_2 in the atmosphere. These challenges have led to the dissemination of cleaner and sustainable technologies and thus a transformation motive in the energy sector. The main driving force behind this transformation has been R&D activities in various fields of energy.

In our current global economic system, R&D expenditures in the energy sector are directly triggered by a synthesis of market dynamics and country-level regulations. Some developed countries, especially in countries that have signed the Kyoto Protocol, have national emission reduction commitments. Based on this situation, this study aims to analyze the main factors that shape R&D tendencies in the energy sector in 29 IEA countries. While determining energy R&D trends, we considered three conditions: (i) explanatory factors related with R&D expenditure, i.e., energy intensity, import dependency, share of renewable energy and emission intensity; (ii) whether the impact of the factors in (i) differ in countries with dependence degree on fossil resources; (iii) use of nuclear energy technology in energy supply.

In overall evaluation, economic dimensions, namely efficiency and dependency, seem to be more decisive in R&D tendencies of IEA countries compared to environmental concerns. Energy resource structures play a critical role on the formation of pressure towards environmental dimension. Only non-nuclear and medium fossil resource using countries are found to be taking account of environmental improvement concerns. Low fossil resource using countries are found to build R&D strategies mainly on energy efficiency.

Declarations

Author contribution Dr. Bicil: supervision, data collection and preparation, writing of introduction and empirical findings sections

Dr. Erkul: study design, data analysis, visualization of tables and figures, writing of data and methodology section

Dr. Türköz: evaluation of findings, writing of literature review and conclusion sections

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Figures

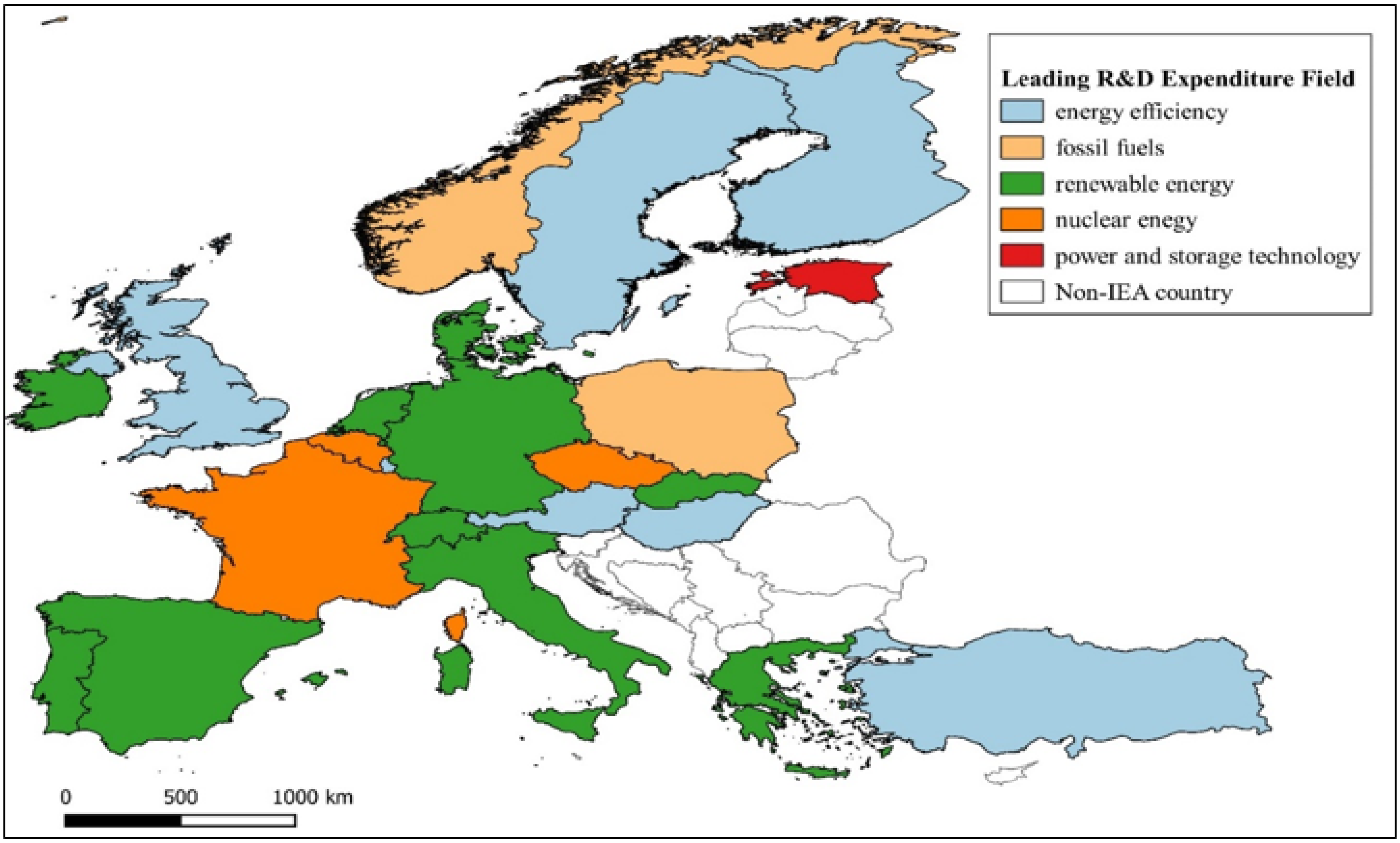

Figure 1

Leading R&D Expenditure Field in IEA Countries (2010-2019 Average)[1]

Source: Authors' computation based on IEA (2021)

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