Environmental Science and Pollution Research (2022) 29:60012–60023
https://doi.org/10.1007/s11356-022-19950-0

RESEARCH ARTICLE

Energy R&D trends and sustainable energy strategies in IEA countries: efficiency, dependency, and environmental dynamics

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Received: 13 January 2022 / Accepted: 24 March 2022 / Published online: 12 April 2022

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.

Keywords Energy · Energy intensity · Environment · Import dependency · Panel data · R&D expenditure

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 an economy, 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 et al. 2011). Objectives of environmental concerns can be defined in two cohorts. The 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).

Investments in energy technology are fundamental to countries' ability to respond to changing economic and environmental needs (Margolis and Kammen 1999). Especially advancements in energy technology have been conceived as a key driver to reducing greenhouse gas emissions globally

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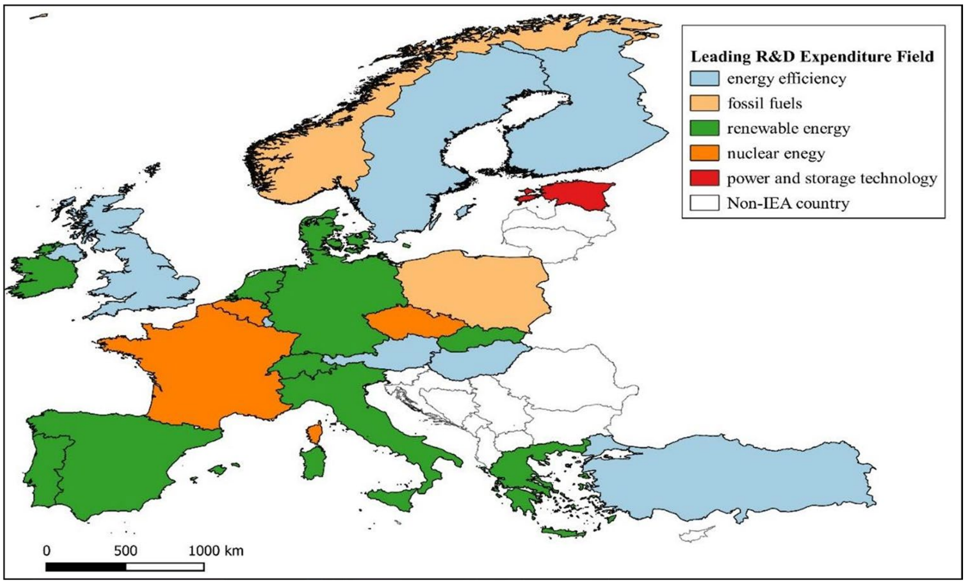

Fig. 1 IEA countries leading R&D expenditure field in IEA countries (2010–2019 average) (Other IEA countries are as the following: Australia and Canada in fossil fuels; South Korea and New Zealand in renewable energy; Japan in nuclear energy; and the USA in other cross-cutting technologies in energy.). *Source:* Authors' computation based on IEA (2021b)

(Jordaan et al. 2017). According to IEA (2021a), average energy efficiency technology R&D budgets of IEA countries expanded from 7% in 1990s to 23% in 2000s. The success and sustainability of investments in energy R&D are linked to persistent implementation of energy strategy necessities (Blanford 2009; Sterlacchini 2020). Economic and environmental returns of developing new energy technologies are the key factors 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 (Popp and Newell 2012; Bergquist and Söderholm 2014). R&D expenditures, which enable 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 emerges in the energy sector coinciding with the structural priorities of the countries.

In the literature, studies generally aim to examine the effect of energy R&D expenditures on different variables such as energy intensity/efficiency (Huang et al. 2020; Zhu et al. 2021), energy consumption (Churchill et al. 2021; Huang et al. 2021), carbon emissions (Garrone and Grilli 2010; Lee and Min 2015; Álvarez-Herránz et al. 2017; Shahbaz et al. 2018; Koçak and Ulucak 2019; Altıntaş and Kassouri 2020; Bilgili et al. 2021), and economic growth (Kocsis and Kiss 2014; Haseeb et al. 2019). Also, some studies use R&D performance to analyze aggregate level innovativeness by using indicators such as R&D intensity (R&D expenditure/GDP), patent applications, and patent citations (Lee and Lee 2013; Noailly and Shestalova 2017). However, there has been limited focus on explaining the factors that determine country-level R&D expenditures. This basic point distinguishes our study from other studies in the literature. Therefore, the main purpose of this study is to clarify the factors that push countries to invest in R&D activities in the energy sector in relation to their energy strategies.

Our framework 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, the "Literature review" section gives literature review on the dynamics of energy R&D activities. The "Data and econometric model" section presents dataset, econometric modeling, and estimation method. Findings of the econometric analysis are discussed in the “Empirical findings” section. Conclusion summarizes the findings of the study.

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 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 this context, we categorize related literature in three groups. In the first group of energy R&D literature, energy R&D activities are considered as a fact to be explained alone and an indicator for innovation effort. 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 macro indicators, third group is more specific, namely on environmental improvement.

Energy R&D and innovation

Constructing an innovation indicator for the technological development in energy sector is not a straightforward issue (Lee and Lee 2013). One of the main reasons behind this is the nature of energy sector with complex links to sub-sectors of manufacturing and services. Although patent classifications for energy related technologies are available (See León et al. 2018), there is not a distinct classification as energy sector in patent classification methods of WIPO, EPO, USPTO, and other patenting authorities. So that, studies using knowledge production function modeling specifies technology classification such as renewables, fossil fuel, and storage technology, etc. (Wangler 2013; Conti et al. 2018; Plank and Doblinger 2018). Only a small number of studies use aggregate R&D expenditure/investment as dependent variable to analyze total energy sector R&D activities.

Inglesi-Lotz (2019), for instance, examine energy R&D trends of Australia, Canada, Germany, the UK, and the USA 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 analyzes 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 knowledge. 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.

Kim (2014) shows the negative impact of oil resources endowment on energy-related alternative transportation technology development. The study also points to positive impact of rising energy prices on alternative energy technologies. For a similar research agenda, Brutschin and Fleig (2016) use a wide panel of 116 countries to investigate the impact of fossil fuel rents on energy R&D expenditures. The study shows negative effect of resource abundance on R&D activity. Comparing different energy technology R&D investments, Popp et al. (2011) illustrates crowding-out effect of hydroelectric and nuclear technology investments on renewable technology investments. For two different cases, Yu et al. (2016) and Wang et al. (2020) investigates the impact of governmental policies on energy R&D investments. Yu et al. (2016) illustrates crowding-out impact of subsidies in renewable energy technologies on firm-level R&D expenditures in China. Wang et al. (2020), on the other hand, gives evidence for the stimulating effect of policy generation on R&D activities in high-income G20 countries.

Energy R&D and macro indicators

A substantial amount of study in the literature consider energy sector R&D activities as a means of increasing energy efficiency in production. Huang et al. (2017), Saudi et al. (2019), and Huang et al. (2020) present evidence for the relation between R&D investments and lower energy intensity in production for different country cases. Koçak et al. (2021) investigate 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 shows significant increase in total factor productivity because of energy R&D investments.

The impact on energy consumption and economic growth is also a widely studied theme in the second group. Zhu et al. (2021), for instance, 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. 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 expenditures and economic growth is relatively weak in the short-term, the long-run estimations reveal a bilateral correlation between energy consumption and energy R&D. Churchill et al. (2021) also present evidence for energy consumption impact of energy technology R&D expenditures for a panel of 10 OECD countries. Lastly, Huang et al. (2021) provides counter example for the effect on energy demand in China. Using a relatively shorter time span and provincial data, the study shows temporal and spatial deviation of the impact of R&D activities on energy consumption.

Energy R&D and environment

Studies in this group consider innovative activities in energy sector as a causal factor 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 Inglesi-Lotz (2020), Wang et al. (2020), and Kılınç and Kılınç (2021) are studies that propose alternative models for the relation between renewable energy and R&D activities. 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 the expansion of renewable resource use in energy generation 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 et al. (2018), and Kılınç (2021) are the examples of studies that conceive of total energy R&D investments as facilitator of CO_2 or ecological footprint reduction. Apergis et al. (2013) and Lee and Min (2015) provide firm-level evidence for R&D expenditure and reduction in carbon emissions.

Some studies differentiate energy sector R&D activities according to the type of technology. 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 analyze 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 diminish carbon emission, while efficiency and fossil fuel R&D are found to be positively related to carbon emission.

Since carbon emission targets or ecological concerns are generally policy-oriented, some studies aim to assess sustainability of environmental policies in countries with various levels of economic development. Balsalobre-Lorente et al. (2019) finds a conditional impact of energy R&D on carbon emissions for OECD countries. According to the study, the degree of corruption diminishes positive impact of energy innovations on environmental quality. Altıntaş and Kassouri (2020) investigate the impact of energy technology R&D activities on environmental improvement in 12 developed European countries for 1985–2016 period. The findings show the substantial role of public support for energy R&D on the reduction of carbon footprints. Lastly, Álvarez-Herránz et al. (2017), in their analysis of 28 OECD countries, points to time requirements of public R&D supports to exert their full impact.

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 Table 7 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 and 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.

Energy sector R&D expenditures and energy imports data are compiled by the IEA (IEA 2021b). The data for other variables were taken from the World Bank's *World Development Indicators* (World Bank 2021). Selected variables represent 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 in the second column is considered, it is seen that our panel data set is unbalanced due to the missing values for *rd_total* variable for some countries between 1990 and 1995. There are no missing values for other series. In addition, there is no high correlation between the variables that can

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

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	11,593.84
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

cause multicollinearity (See Appendix Table 8 for cross correlations).

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 methodology

Different from Griliches (1979) and successor studies' theoretical modelling of R&D expenditure as input variable in knowledge production function, we consider R&D expenditures as the target variable to be explained in our modelling. Studies that aim to explain determinant factors of R&D expenditure can be divided into two groups as firm-level and macro-level studies. While the first group associate R&D expenditure with firm characteristics, related industry dynamics, and public policies (Becker and Pain 2008; Coad and Rao 2010), macro-level studies focus on national policy indicators, institutional environment, and structural factors (Guellec and Van Pottelsberghe De La Potterie 2003; Alam et al. 2019; Haseeb et al. 2019). We follow second group of econometric modeling and consider R&D expenditure as the dependent variable.

Accordingly, the main model used in econometric analysis is in a linear panel form and given by Eq. (1).

$$\ln\ rd\_total_{it} = \beta_0 + \beta_1 e\_\text{int}_{it} + \beta_2 imp\_dep_{it} + \beta_3 renew\_share_{it} + \beta_4 \ln co2_{it} + \varepsilon_{it} \quad (1)$$

Subscripts i and t represent cross-section units (countries) and time (year) respectively. In the model, logarithm of 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 logarithm of CO_2 emissions (*lnco2*).

Estimation methodology of Eq. (1) relies on the nature of our sample. Since our dataset consists of a sample of heterogeneous cross-sectional units, country-specific unobservable factors or omitted variables that are not included in the model must be taken into consideration. A common way of estimating this type of panel data models is the fixed effects estimator (Bramati and Croux 2007; Bliese et al. 2020). Consider general representation of a linear panel data model given by Eq. (2).

$$y_{it} = \alpha + \beta x_{it} + \varepsilon_{it} \quad (2)$$

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}. The FIrst part of the disturbance u_i represents time-invariant country-specific factors. The presence of this term leads biased and inconsistent coefficient estimates by pooled ordinary least squares (OLS) and other generalized or weighted least squares (LS) estimators (Hausman and Taylor 1981). The second part v_{it} is the remainder disturbance. We assume v_{it} to be uncorrelated with x_{it} and identically distributed with $(0, \sigma_v{}^2)$. By subtracting individual means, country-specific parts of the equation are eliminated (Baltagi 2005). Eq. (3) shows general form of fixed effects (classical within-groups) estimator.

$$\widetilde{y}_{it} = \beta \widetilde{x}_{it} + \widetilde{\varepsilon}_{it} \quad (3)$$

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

The fixed effects estimator will yield standard errors that are consistent based on assumptions of 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 and 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 use robust standard errors by Arellano (1987)'s clustering method. Yet, fixed effects estimation with robust standard errors must also be tested for CD. So, we check spatial and temporal dependence of countries with Pesaran (2015) CD test (See Appendix Table 9). The test is implemented to residuals of fixed effects estimation and the dependent variable (*lnrd_total*). The test results reject null hypothesis of cross-section independence and confirms correlation between the panel groups.

Under serial correlation, heteroscedasticity, and CD, fixed effects estimate of coefficients are consistent, but clustered covariance matrix estimation is still 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).

To check for robustness, after the estimation of Eq. (1) for a sample of 29 IEA member countries, Driscoll-Kraay fixed effects estimations are computed 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 (2021b) data. This process divided the dataset 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 sample 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 first-order autocorrelation. Therefore, coefficient estimates of the Driscoll Kraay estimator are the ones that we interpret in Tables 3, 4, and 5.

Table 3 Estimation 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

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

Table 4 Driscoll-Kraay estimation 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

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

Comparing three estimation results in the table, both coefficients and standard errors in pooled OLS are found

Table 5 Driscoll-Kraay estimation results — fossil resource use sub-groups

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

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

to be different from the other two methods. However, these estimations are biased and do not comprise country fixed effects. For instance, OLS estimations of the coefficients of *renew share* and *imp_dep* have negative signs contrary to fixed effects estimations. When we do not take into account time-invariant characteristics of the countries in the sample, the direction of the relationship between explanatory variables and the dependent variable change from positive to negative.

The last two columns show fixed effects estimations of the coefficients. The difference between the two is the robustness of standard errors to cross-sectional dependency. 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. This variable is significant in robust fixed effects estimation when we do not consider cross-sectional dependency. All other estimations are in the same direction and have highly close statistical significance levels in robust fixed effects and Driscoll and Kraay fixed effects.

Import dependency and the share of renewable energy in IEA member countries are found to be positively associated with energy R&D expenditures. The coefficient of *imp_dep* is 0.005 and relatively very small. This finding indicates long-term stability of energy composition and related difficulty to change it. Energy intensity in production is found to be negatively related with energy R&D expenditure with a coefficient value of −0.39. Considering diverse energy intensities of IEA countries, these findings associate lower levels of energy intensity (higher energy efficiency) with high R&D expenditures in energy sector. The share of renewable energy is found to have positive association with a coefficient value of 0.039. Except CO_2 intensity, these results are in line with theoretical expectations and empirical findings of previous studies for different samples (Kocsis and Kiss 2014; Ndlovu and Inglesi-Lotz 2020; Shen and Lin 2020; Zhu et al. 2021).

Comparing our finding on the relationship between CO_2 intensity and R&D expenditures, the results of previous studies are dependent on sample selection and time-perspective. For instance, Alam et al. (2021) illustrates a clear negative long-run relationship for 30 OECD countries. Contrarily, Koçak and Ulucak (2019), finds a positive impact of various energy sub-sector R&D expenditures on CO_2 emission for 19 high-income OECD countries. Petrović and Lobanov (2020), in accordance with our finding, shows that R&D expenditures are not always associated with reduction in CO_2 emissions in advance. As Garrone and Grilli (2010) points out, empirical studies have not given a clear answer to the relationship between CO_2 emissions and R&D expenditures. The design of public incentives on decarbonization practices can be missing the target that private sector can more properly price.

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 or not and their fossil energy use levels. The results in Table 4 show Driscoll and Kraay fixed effects estimation results for nuclear energy sub-groups. The second column in the table gives coefficients for the group of countries that have nuclear energy use, third column for the group that have not nuclear energy and the last column for the overall IEA countries.

According to the results in Table 4, import dependency has a statistically significant and positive effect on energy R&D expenditures in both groups. Energy intensity also has a statistically significant but negative effect and CO_2 intensity do not have a statistically significant effect on energy R&D expenditures in nuclear and non-nuclear country groups. Estimation results for these three variables are robust and in line with the overall sample estimation. The coefficient and probability value of renewable energy share differ between nuclear and non-nuclear countries. In non-nuclear countries, renewable energy share has a positive and statistically significant effect on energy R&D expenditures. In the 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

Table 6 Summary of regression models

Dimension	Indicator	Nuclear	Non-nuclear	Low fossil	Medium fossil	High fossil	All sample
Efficiency[a]	*energy intensity*	(−)*	(−)*	(−)*	(−)*	(−)*	(−)*
Dependency	*import dependency*	(+)*	(+)*	(−)	(+)*	(+)*	(+)*
Environmental Improvement	*renewable share*	(+)	(+)*	(+)	(+)*	(+)	(+)*
Environmental Degradation	CO_2 *intensity*	(−)	(+)	(+)	(+)	(+)	(+)

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

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

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, only "Medium fossil" group has statistical significance and coefficients estimates in line with the overall sample estimation. CO_2 intensity does not have a significant effect on energy R&D expenditures in three groups. 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, the share of renewable energy, and carbon intensity variables do not have a statistically significant effect on energy R&D expenditures for this group. For "Medium Fossil" countries where fossil fuel use is between 50% and 80%, the share of renewable energy and import dependency have a statistically significant and positive effect on energy R&D expenditures. Energy intensity, on the other hand, has a statistically significant but negative effect. In "High Fossil" IEA member countries with more than 80% fossil 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. Energy intensity 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 intensity 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 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. Yet, the coefficient of efficiency is higher in non-nuclear group compared to nuclear group and higher in "Medium fossil" group compared to "Low fossil" and "High fossil" groups.

Dependency has positive effect on energy R&D expenditures in all groups except "Low fossil". This exception is very plausible since low fossil resource use indicates diversity in energy composition. Dependency is by-passed by local alternative resources and has no significant pressure on energy R&D expenditure.

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" and "High fossil" countries do not have a significant environmental improvement motivation in R&D expenditures. Non-nuclear countries and “Medium fossil” 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.

In “Low fossil” and “High fossil” 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 improvement becomes more important.

In sum, energy efficiency, as an economic objective, steps forth among others. It is the most robust finding of this study that all sample and sub-sample estimations indicate. As an indicator of both economic and security objectives, import dependency is also robustly valid for all IEA countries, except “Low fossil”. Considering supply security objective (Costa-Campi et al. 2015), having nuclear energy technologies and low fossil use in energy production seem to bring trade-off and crowding out effects on energy R&D expenditures for IEA countries. The share of renewable sources in these two groups do not cause a significant effect on R&D expenditure. This finding coincides with crowding-out effect of nuclear technology on renewable technology R&D investment as emphasized by Popp et al. (2011).

Policy implementations have been a driver of public R&D investments especially in clean energy technologies for IEA countries (IEA 2021c). Decarbonization targets have been declared by most of the IEA countries in the last decade[1]. Yet, their impact on changing the main trend of energy R&D expenditure is limited. As Popp and Newell (2012) shows, firm-level R&D expenditure decision is motivated by market-based profit-maximizing behavior. So, in essence, country-level energy R&D strategies fail to capture this principle to produce outputs that contribute to decarbonization agenda. In other words, as implied by Yu et al. (2016), while governmental supports can create room for the expansion of new clean energy technologies, it may also lead to private sector to transfer investment funds to other fields. At the end, environmental objective falls behind economic objectives.

Conclusion

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 investments 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 context, 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.

Assessing the determinants of country-level R&D expenditure in energy sector with this study, we showed that efficiency, dependency and environmental improvement are found to be valid factors. When fossil resource use level and nuclear energy technology possession is considered, R&D expenditure priority of countries are shown to be changing. 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. 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. Energy resource compositions play a critical role on the formation of pressure towards environmental dimension.

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[1] See for instance European Commission (2019) and IEA (2022) for various policy documents.

Appendix

Table 7 IEA country List

1	Australia	11	Greece	21	Poland
2	Austria	12	Hungary	22	Portugal
3	Belgium	13	Ireland	23	Slovak Republic
4	Canada	14	Italy	24	Spain
5	Czech Republic	15	Japan	25	Sweden
6	Denmark	16	Korea, Rep.	26	Switzerland
7	Estonia	17	Luxembourg	27	Turkey
8	Finland	18	Netherlands	28	United Kingdom
9	France	19	New Zealand	29	United States
10	Germany	20	Norway		

Table 8 Cross correlations

	lnrd_total	*e_int*	*renew_share*	*imp_dep*	$lnco_2$
lnrd_total	1				
e_int	0.2	1			
renew_share	−0.2	0.0323	1		
imp_dep	−0	−0.0204	−0.6136	1	
$lnco_2$	0.5	0.5918	−0.2761	−0.1114	1

Table 9 Cross-sectional dependency – pesaran CD test

Variable	CD-test	p-value	average joint T	mean ρ	mean abs (ρ)
lnrd_total	28.163	0.00	17.15	0.31	0.46
residuals	7.468	0.00	17.15	0.08	0.37

p-values close to zero indicate data are correlated across panel groups

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

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability Not applicable.

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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