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Energy R&D towards Sustainability: A Panel Analysis of Government Budget for Energy R&D in OECD Countries (1974–2012)

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Abstract: Energy transition is one of the greatest challenges for sustainability. However, the overall composition of the world energy supply has not changed much since the late 1970s, with fossil fuels providing 81% of the world's total primary energy supply. While political leaders increasingly call for proactive policies to innovate the energy sector in the face of climate change, governments around the world commit vastly different levels of budgets to energy R&D. This research examines the potential determinants of cross-national variations in government budget allocations for energy R&D with three perspectives. With the panel data analysis of OECD countries (1974–2012), we check the supply-side, demand-side, and institutional factors inducing government investment in R&D for energy in general as well as for renewable energy. Among the multitude of factors tested in our analysis, gross domestic R&D expenditure, refinery output, and the rightist orientation of the governing party show significantly positive influences on government R&D budgets for energy in general. However, refinery output shows the negative effect on government R&D budget for renewables. This contrasting finding about the impact of refinery output on government investment in energy R&D in general vs. renewable energy R&D suggests that policymakers and scholars need to better appreciate the complex roles of the oil sector in driving public R&D investment in energy. It also calls for more proactive renewable energy policy to make progress towards sustainable energy transition.

Keywords: energy; renewable energy; R&D; innovation; climate change; sustainability; energy security

1. Introduction

Since *The Limits to Growth* (1972) opening the floodgates to numerous publications on sustainability [1], energy issues have been a central part of the sustainability discourse. The famed definition of sustainability from the Brundtland Report (1987), "meeting the needs of the present without compromising the ability of future generations to meet their needs" is quite pertinent to the discussion of energy issues these days, for keen interest in renewable energy and concern with fossil fuels are all rooted in the need to ensure the provision of energy not just for the present but for the future of humanity [2]. More recently, climate change has intensified public concerns with the sustainable energy transition, which have been met by aggressive calls for investment in energy technologies by high-ranking government officials and energy policy scholars around the world [3–5].

However, the overall composition of world energy supply has not changed much. In addition, 81% of the world's total primary energy supply (TPES) still comes from fossil fuels, which is not much different from the TPES level (87%) in 1973 [6]. Furthermore, fossil fuels expectedly continue to a major source of global energy consumption, projected to account for 78% of global energy use in 2040 [7].

It is then somewhat puzzling why progress towards the sustainable energy transition has been too slow to make a real impact in world energy supply and demand despite the decades-long concerns with energy security and climate change.

Motivated by the apparent gap between the persistent calls for sustainable energy and the reality reflected in the energy statistics, this study examines public investment in energy technologies as manifested in the government budget appropriations for energy research and development (R&D) on energy. Since much of the development for sustainable energy depends on technological innovations enabling the cost-effective extraction and reliable storage of sustainable energy, R&D investment for energy technologies is the crucial link in the sustainable energy transition. In this regard, it is quite notable that governments around the world spend astonishingly different amounts on energy R&D. Why is this so? What can explain the level of government investment in energy R&D across countries?

This study assesses various factors explaining cross-national variations in public R&D on energy including R&D on renewable energy in order to uncover the major determinants of public commitment to R&D on energy technologies in advanced countries as manifested in government budget appropriations for energy R&D. In what follows, we first introduce three theoretical perspectives on public expenditure in R&D for energy technologies, reviewing the existing accounts of different factors underlying government investment levels on energy R&D. We then present an empirical analysis of the governmental expenditure on energy R&D based on the panel data from 34 OECD countries (1974–2012). One of the key empirical findings from the study concerns the significant impact of the petroleum refining sector on energy R&D investment. The size of refinery output turns out to be positively linked to government budgets for energy R&D but negatively linked to government budgets for renewable energy R&D. We discuss the implications of our findings and conclude the study with the suggestions for further research.

2. Existing Explanations

Existing research on investment on energy technologies takes three perspectives in identifying and understanding the determinants of governmental investment in R&D for energy technologies, which can be named as the supply-side, demand-side, and institutional perspectives [8]. Before turning to each perspective, it should be noted that the research on public R&D for energy are relatively little compared to the firm or industry level research on energy R&D, as pointed out in a recent overview of public expenditures on energy R&D [9]. As for the latter, there exist a couple of stylized findings. One of them relates to the effect of firm size, as large fixed costs acts as a barrier for firms' investment in energy R&D [10–12]. Another finding is that it is the access to knowledge and the market structure (such as the degree of existing monopoly), rather than the cost and financing of R&D, that explain firms' energy R&D choices better [13–17]. This finding resonates with one of the discussions of the national innovative capacity explained below.

When it comes to public R&D on energy technologies, one may consider three general perspectives that are complementary to one another. The first perspective focuses on the supply side viewing R&D investment to be driven largely by resources and capabilities to initiate and implement technological innovation for sustainable energy, which largely corresponds to the technology-push model of innovation [18].

In the context of generic R&D investment, scholars have identified several factors related to resources and capabilities such as scientific talent pool, knowledge stock, or research infrastructure [19–22]. As R&D is a capital-intensive and knowledge-intensive process, R&D investment hinges critically on material and non-material input whether in the form of research funding, personnel, or experimental equipment. Like any other kind of R&D, energy R&D also requires extensive investment in various forms of input. In particular, technological innovation for alternative forms of energy tends to be more of a more radical nature, which often is made available by a large-scale outlay of capital, labor, and knowledge.

In one of the most comprehensive studies of the so-called "national innovative capacity", Furman et al. outlined the analytical framework accounting for a number of factors underlying national innovation competitiveness based on three theories—endogenous growth theory, national industrial competitive advantage, and national innovation systems [23]. Furman et al.'s framework has been widely applied in cross-country innovation studies including technology spillovers in the Chinese high-tech industries, studies of firms' location strategies and knowledge spillover patterns in the United States, the factors of radical innovation across nations, and the national innovative capacity of latecomer countries in East Asia [24–27]. Many of the variables included in Furman et al.'s analysis such as R&D personnel, gross domestic expenditure on R&D (GERD) and international patent stocks would probably matter as well for innovations in energy technologies as well as government investment in them.

The second perspective for understanding the drivers of government investment in R&D for energy technologies is the demand-side explanation, which hinges on the role of the needs or challenges facing sustainable energy transitions. Two such factors stand out in the discourse on sustainable energy transitions—energy security and climate change [28,29].

Defined simply as "the uninterrupted availability of energy sources at an affordable price" [30], energy security has long been a critical issue for national security. Especially in the aftermath of the oil shocks, many industrialized countries came to view dependence on imported oil as a serious threat to national security, out of concern for vulnerability to supply disruption of oil exporting countries located in one of the most volatile regions in the world. Dependence on imported oil is often equated to energy security, yet the same rate of imported oil dependence can mean different levels of energy security depending on the political, economic, and social context of each country [31,32]. In many countries of widely different political and economic circumstances, however, the insecurity of energy supply has been a common rationale for proactive government roles in technological innovations for sustainable energy.

In addition to the need to reduce imported oil dependence, the need to reduce greenhouse gas emissions for climate change mitigation has emerged as a key driver of governmental investment in energy technologies. Governments around the world undergoing a series of international climate negotiations in the last decade have become keen on technological solutions to reduce reliance on fossil fuels. Climate change mitigation and adaptation are now the cornerstones of energy policy in many countries including the European Union [9,28].

The third perspective is an institutional explanation focusing on the politics and policies underpinning government R&D decisions on energy innovation. The well-known Porter hypothesis, for example, states that government regulatory policies imposing strict environmental standards can trigger technological innovations, thereby raising competitiveness [33]. While the Porter hypothesis being relevant to the firm level has been tested extensively with industry or sectoral data on environmental innovation [34], there are relatively fewer studies that delve into the effect of political and institutional factors on energy innovation at the country level.

Some such studies include those examining the effect of legislative fractionalization and government partisanship on cross-national differences in public R&D expenditure on energy technologies [35–37]. In a more general context of policy initiation and change, veto player theory [38] is often utilized to model the constraints of existing power constellations in the government on proactive policy change such as increased expenditure on particular purposes like welfare reforms, environmental protection, or energy security [39].

In the following empirical analysis, we present a comprehensive test of the potential determinants of energy R&D investment including government R&D on renewables by deriving the explanatory variables from those three perspectives.

3. Empirical Tests

This study intends to explore the determinants of energy R&D investment at the country rather than the firm level. The empirical tests of this study are mainly designed to check the potential determinants of governmental R&D investment in energy technologies across countries over a certain period time, thus necessitating the use of panel regressions.

More specifically the data for the current empirical tests come from 34 OECD countries observed between 1974 and 2012. While the choice of OECD countries is largely due to the data availability, it is also justifiable given that these countries have taken more than a half of the world's primary energy supply over the last four decades [40].

We use three indicators for government R&D investment on energy technologies in general and two indicators for energy R&D on renewables as dependent variables. One of the government R&D investments on energy technologies is the government budget appropriation or outlays for R&D (GBAORD) for energy expressed in million dollars (2005 constant prices and PPP). GBAORD for energy is a better measure for fiscal commitment of the government for energy R&D than government-financed gross domestic expenditure on R&D. This is because GBAORD is based on reports by R&D funders unlike the government-financed expenditure on R&D that draws on reports by R&D performers that could over- or under-estimate the level of funding. It is also more comprehensive as it covers payments to foreign R&D performers including international organizations, unlike government-financed gross domestic expenditure on R&D (GERD) that is limited to R&D performed within the national territory. The second indicator for government R&D investment on energy technologies is the energy share of GBAORD expressed as % of total GBAORD. As such, it just represents GBAORD on energy R&D in relative terms.

The third indicator for government investment in general energy R&D is the total government budget of energy research, development, and demonstration (RDD) expressed in millions of dollars (2012 prices and exchange rates). While GBAORD for energy covers only basic and applied research and experimental development (i.e., R&D), total energy RDD includes "demonstration" (often in the forms of prototyping, field tests, or lab trials). The data for energy RDD are compiled by the International Energy Agency (IEA), while the GBAORD data are collected by the OECD Directorate for Science, Technology, and Industry following the well-known Frascati Manual [41].

Two indicators for energy R&D on renewables are energy RDD for renewables in absolute and relative terms. The absolute measure is the amount of energy RDD for solar energy, wind energy, ocean energy, biofuels, geothermal energy, hydroelectricity, other renewable energy sources, and unallocated renewable energy sources denominated in million dollars (2012 prices and exchange rates). The relative measure is the share (%) that renewable energy sources take in the whole energy RDD.

As for the explanatory variables, we use three groups of variables drawing on the theoretical perspectives for the drivers of government R&D on energy innovations as reviewed in the previous section. The first group of the explanatory variables derived from the supply-side perspective include the variables capturing resources and capabilities for energy innovation such as international patent stocks, total R&D personnel, gross domestic expenditure on R&D (GERD), public spending on education, GERD financed by industry, and GERD performed by higher education institutes. These are the very variables identified in Furman et al.'s study to be part of the national innovative capacity.

The second group of the independent variables is based on the demand-side explanations. Touching upon two challenges boosting energy policy demands—energy security and climate change—these variables are the share of energy import in total energy use, refinery gross output, CO_2 emissions, and total electricity consumption.

As for climate change risks, greenhouse gas emissions such as CO_2 emissions are generally considered as a reliable proxy for them. In contrast, there is no common indicator for energy security challenges agreed upon among policy makers and scholars, for each country faces different kinds and levels of energy security challenges as pointed out previously [31,32]. However, for most energy importing countries, the level of their dependence on imported energy sources is considered as a critical indicator of energy security [42]. In addition, the size of the oil sector as captured by refinery gross output can be taken as another demand-side indicator, for the larger the oil sector, the more challenging the shift towards sustainable energy [43]. Total electricity consumption generally captures the market demand for energy investment [44].

The last group of the independent variables captures political and institutional aspects that might as well relate to governmental decisions to make proactive policy changes such as the promotion of energy R&D. One of these variables is the partisanship of the governing party, for partisan orientations of top political leadership have general influence on the directions of many governmental policies [45]. Two other variables of this category, the degree of control of parliamentary houses and the vote share of opposition parties, are used to check the veto player theory in relation to energy transition. Figure 1 outlines the variables categorized into each group with detailed data descriptions for each variable available in Table 1.

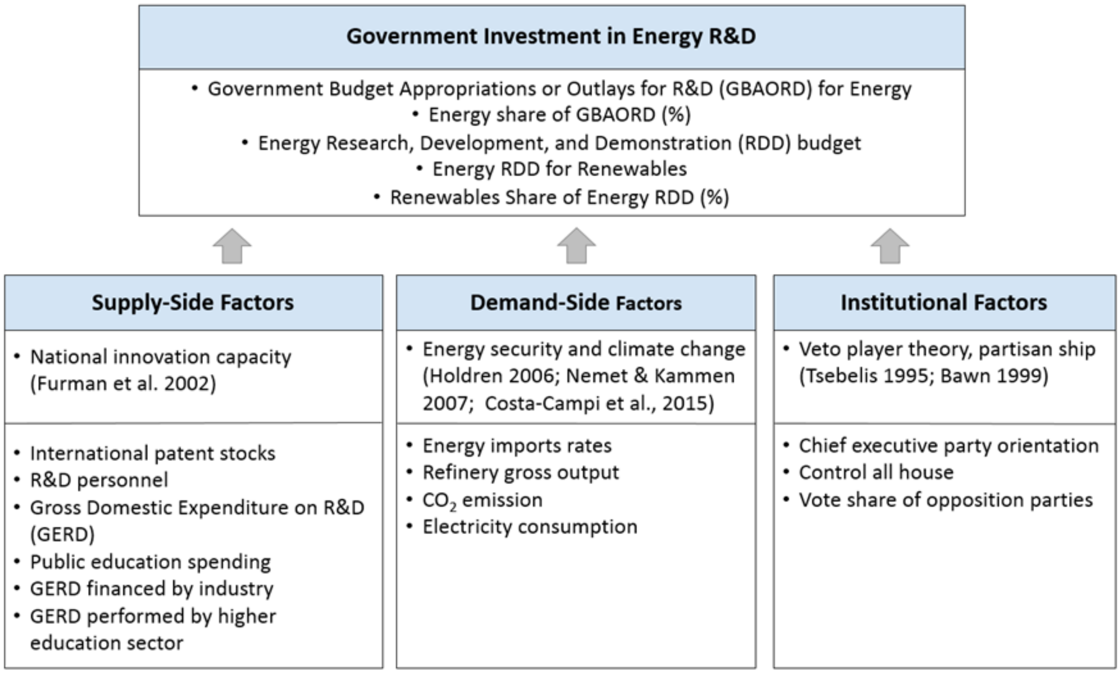

Figure 1. Analytical framework for government investment in energy R&D.

Table 1. Variables and Definitions.

Full Variable Name	Definition	Source
	Government Energy R&D	
GBAORD for energy	Government budget appropriations or outlays for R&D (GBAORD) for energy in millions of 2005 dollars, constant prices and PPP	MSTI
Energy share of GBAORD	Energy share of GBAORD as % of GBAORD	MSTI
Energy RDD budget	Total budget of energy research, development and demonstration (RDD) in millions of dollars, 2012 prices and exchanges rates	ERDD
Energy RDD for renewables	Energy RDD for renewable energy sources (incl. solar energy, wind energy, ocean energy, biofuels, geothermal energy, hydroelectricity, other renewable energy sources, and unallocated renewable energy sources) in millions of dollars, 2012 prices and exchange rates	ERDD
Renewables share of Energy RDD	Renewable energy sources share of total Energy RDD as % of Energy RDD	ERDD

Table 1. *Cont.*

Full Variable Name	Definition	Source
Supply-Side Factors		
Log of international patent stocks	Log of cumulative triadic patent families	MSTI
Log of total R&D personnel	Log of total R&D personnel (FTE)	MSTI
Gross domestic expenditure on R&D (GERD)	Gross domestic expenditure on RD (GERD) in million 2005 dollars, constant prices and PPP	MSTI
Public spending on education	Public spending on education as % of GDP	WDI
GERD financed by industry	GERD financed by industry as % of GERD	MSTI
GERD performed by higher education	GERD performed by the higher education sector as % of GERD	MSTI
Demand-Side Factors		
Energy imports rate	Energy imports rate as % of total energy use	WDI
Refinery gross output	Refinery gross output in megatonne (Mt)	IEA Oil
Log of CO_2 emissions	Log of carbon dioxide emissions excluding land-use, land-use change, and forestry (total emissions) in thousand tonnes of CO_2 equivalent	OECD Env.
Log of total electricity consumption	Log of total electricity consumption in terawatt hour (TWh)	IEA WESB
Institutional Factors		
Chief executive party orientation	Chief executive party orientation with respect to economic policy. Right (1); Left (3); Center (2); No information (0); No executive (NA)	DPI
Control all house	Does party of executive control all relevant houses? Yes (1); No (0)	DPI
Vote share of opposition parties	Vote share of opposition parties in the legislature as % of total vote	DPI

MSTI (OECD Main Science and Technology Indicators); ERDD (OECD IEA Energy Technology RD&D Statistics); WDI (World Bank, World Development Indicators); IEA Oil (IEA Oil Information Statistics); OECD Env (OECD Environment Statistics); IEA WESB (IEA World Energy Statistics and Balances); DPI (World Bank, Database of Political Institutions).

4. Findings

This section presents our empirical findings in two sub-sections—one from descriptive analyses and the other from panel regression analyses.

As shown in Table 2, countries in the sample of the current analysis show substantially large variation in both absolute and relative amounts of R&D budget for energy in general as well as of R&D for renewable energy in particular. For instance, the government budget appropriation for energy averaged for the period of study ranges from 1.7 million (Iceland) to 3.9 billion dollars (Japan). If grouped into quartiles, it still ranges from 4.9 million to 1.3 billion dollars.

Table 2. Cross-national variation in government budget for energy.

Dependent Variable	Mean	Range	Countries
GBAORD for Energy (in million $)			
1st Quartile	1327.46	307.81~3902.58	Japan, UK, Germany, France, Italy, Korea, Mexico, Canada
2nd Quartile	114.50	37.78~265.12	Turkey, Spain, Netherlands, Sweden, Australia, Finland, Belgium, Norway
3rd Quartile	25.49	15.08~37.61	Denmark, Czech Republic, Hungary, Switzerland, Poland, Portugal, Greece, Austria
4th Quartile	4.87	1.70~8.43	Israel, New Zealand, Slovak Republic, Ireland, Estonia, Luxembourg, Slovenia, Iceland

Table 2. *Cont.*

Dependent Variable	Mean	Range	Countries
Energy Share of GBAORD (as % of GBAORD)			
1st Quartile	8.82	4.99~18.12	Japan, Mexico, Italy, Germany, Canada, Finland, Korea, France
2nd Quartile	4.06	3.28~4.71	Belgium, Sweden, Hungary, Spain, Iceland, Denmark, Greece, Netherlands
3rd Quartile	2.6	2.00~3.28	UK, Norway, Luxembourg, Australia, Estonia, Slovak Republic, Turkey, Portugal
4th Quartile	1.18	0.34~1.92	Switzerland, Czech Republic, New Zealand, Ireland, Slovenia, Austria, Israel, Poland
Energy RDD (in million $)			
1st Quartile	1826.13	573.14~4669.17	US, Japan, France, Germany, Italy, Canada, UK
2nd Quartile	245.64	151.56~443.44	Korea, Australia, Netherlands, Switzerland, Belgium, Sweden, Spain
3rd Quartile	73.58	21.78~147.31	Finland, Norway, Denmark, Hungary, Austria, Slovak Republic, Czech Republic
4th Quartile	10.91	4.67~17.81	New Zealand, Ireland, Portugal, Greece, Turkey, Poland
Energy RDD for Renewables (in million $)			
1st Quartile	161	53.26~542.53	US, Japan, Germany, Korea, Italy, Canada, Australia
2nd Quartile	43.74	29.54~52.24	Netherlands, UK, France, Sweden, Switzerland, Spain, Denmark
3rd Quartile	12.88	6.38~25.29	Finland, Norway, Austria, Ireland, Belgium, Slovak Republic, New Zealand
4th Quartile	2.57	0.31~4.67	Greece, Portugal, Czech Republic, Hungary, Turkey, Poland, Luxembourg
Renewables Share of Energy RDD (as % of Energy RDD)			
1st Quartile	32.75	28.47~37.39	Slovak Republic, New Zealand, Denmark, Portugal, Ireland, Greece, Spain
2nd Quartile	21.49	18.41~25.44	Sweden, Austria, Hungary, Switzerland, Netherlands, Czech Republic, Germany
3rd Quartile	15.47	10.78~18.38	Turkey, Korea, Australia, UK, Finland, Poland, Norway
4th Quartile	7.36	4.07~10.45	Italy, US, Canada, Belgium, Japan, France

Reported means and ranges are obtained from national averages for the period of study (1974~2012).

The relative amount of the R&D budget for energy also shows a large variation across countries, ranging from 0.34% (Poland) to 18.12% (Japan) of the government R&D budget allocation. In terms of quartiles, the first-quartile countries turn out to allocate about 8.8% of the government R&D budget to energy, which is more than eight times that of the fourth-quartile countries. The total government budget for energy research, development and demonstration ranges from 4.7 million (Poland) to 4.7 billion (US) dollars. Finally, energy R&D for renewables also reveals substantial variation across countries. Most notably, the US, which spends the largest amount in absolute terms, turns out to be one of the countries devoting the least share of its energy RDD expenditures to renewable energy sources.

What can then explain such large cross-national variations in government investment in energy R&D as well as on R&D for renewables? Following the framework introduced in the previous section, we run the panel regressions with three groups of explanatory variables capturing supply-side, demand-side, and institutional factors.

Before we proceed to the regression analysis of the potential determinants of government budget allocations for energy R&D, we present the descriptive statistics including those for the dependent variables in Table 3. The ratio of the standard deviation (SD) to mean shown in the last column of this table allows us to compare the degree of variations in each variable as it adjusts the SD to the scale of the variable. It turns out that the three dependent variables have generally larger variation compared to the independent variables except a few ones such as R&D expenditure (GERD), energy imports rate, and refinery gross output.

Table 3. Descriptive statistics.

Variable	Obs	Mean	SD	Min	Max	SD/Mean
Government Energy R&D						
GBAORD for energy (in million $)	775	424.39	942.83	0.00	6704	2.22
Energy share of GBAORD (as % of GBAORD)	801	4.29	4.67	0.00	34.46	1.09
Energy RDD (in million $)	776	687.55	1365	0.00	10,329	1.99
Energy RDD for renewables (in million $)	796	67.12	165.15	0.00	2322.63	2.46
Renewables share of Energy RDD (as % of Energy RDD)	743	18.98	14.09	0.00	81.65	0.74
Supply-Side Factors						
Log of international patents stocks	870	7.03	2.93	−0.69	13.83	0.42
Log of total R&D personnel	724	10.86	1.43	6.61	13.76	0.13
Gross domestic expenditure on R&D (GERD) (in million $)	791	23,054	54,234	33.49	37,419	2.35
Public spending on education (% of GDP)	915	5.09	1.32	0.00	8.98	0.26
GERD financed by industry (% of GERD)	730	49.55	13.76	5.74	90.68	0.28
GERD performed by higher education (% of GERD)	772	24.30	10.64	0.25	71.05	0.44
Demand-Side Factors						
Energy imports rate (% of total energy use)	1294	26.95	108.49	−842.43	99.90	4.03
Refinery gross output (megaton)	680	60.51	137.60	0.00	840.6	2.27
Log of CO_2 emissions	726	11.66	1.53	7.64	15.63	0.13
Log of total electricity consumption	1294	4.27	1.45	0.74	8.33	0.34
Institutional Factors						
Chief executive party orientation (1 = right, 2 = center, 3 = left)	1193	1.87	1.01	0.00	3.00	0.54
Control all house (1 = yes, 0 = no)	1214	0.27	0.44	0.00	1.00	1.65
Vote share of opposition parties (% of legislature vote)	1227	24.46	12.91	0.00	57.10	0.53

Our main regression findings are reported in two sets of tables. Tables 4 and 5 shows the regression results for government energy R&D expenditures, while Tables 6 and 7 show those for government R&D expenditures on renewable energy. All regressions contain the absolute and relative measures of government energy R&D expenditures. Furthermore, in all tables, we report the results of the fixed-effects and random-effects panel regressions. While the Hausman specification test is available for the choice over fixed-effects vs. the random-effects model, it does not provide a definite result for the current data due to the finite sample problem. We thus report the results from both models.

As for the regressions of government energy R&D expenditures reported in Tables 4 and 5, three variables in our explanatory framework of government investment turn out to have relatively consistent effects, each of which happens to correspond to each of three dimensions.

One of them is the size of overall investment in R&D (GERD) among the supply-side factors. Other than in the random-effects regression of energy share of GBAORD, GERD shows a statistically significant coefficient in all regressions. In particular, according to the random-effects estimation, an increase in GERD by a million dollars turns out to boost government budget allocation for energy by as much as $18,000. The same increase also leads to $17,000 more in the total budget for energy RDD. This finding may be quite a straightforward result of GERD encompassing R&D on energy, but given that much of the existing literature focuses on R&D at the industry level as well as looks into the effect of GERD on energy innovation output (such as patents), this finding is worth contemplating, as it is perhaps one of the first pieces of evidence on the direct effect of GERD on public R&D expenditure on energy technologies.

The second variable that shows a consistently significant effect is the refinery gross output measured in megaton among the demand-side factors. While this variable is insignificant in the fixed-effects estimation, it is strongly significant in all random-effects regressions. An additional megaton of refinery gross output is associated with a $8.8 million increase in the government R&D budget for energy, which suggests that countries with greater output in refinery products allocate more, not less, R&D for energy. In addition, in terms of relative investment in energy, refinery gross output has a positive effect on the share of energy in the government R&D budget.

Table 4. Panel regressions of public energy R&D investment of OECD countries (1974–2012).

	Dependent Variables	**GBAORD for Energy**		**Energy Share of GBAORD**		**Energy RDD**	
	Independent Variables	**I**	**II**	**III**	**IV**	**V**	**VI**
Supply-Side Factors	Log of international patents stocks	65.102	10.444	0.241	−0.078	76.857 **	4.177
	Log of total R&D personnel	−30.113	−14.944	0.712	0.518	2.013	−5.585
	Gross domestic expenditure on R&D (GERD)	0.009 *	0.018 ***	−0.000 **	−0.000	0.010 ***	0.017 ***
	Public spending on education (% of GDP)	41.891	42.229	−0.633 ***	−0.469 **	3.844	20.175
	GERD financed by industry (% of GERD)	1.137	−0.938	−0.138 ***	−0.117 ***	3.294	4.166
	GERD performed by higher education (% of GERD)	−3.930	−2.657	−0.110 **	−0.086 **	9.801 ***	11.337 ***
Demand-Side Factors	Energy imports rate (% of total energy use)	1.067	−0.048	−0.002	−0.001	0.884	0.537
	Refinery gross output (megaton)	5.545	8.817 ***	0.012	0.063 ***	−0.259	4.631 **
	Log of CO_2 emissions	55.998	59.833	−2.796	−1.711 *	−121.991	−136.077
	Log of total electricity consumption	−259.438	−187.723	1.691	1.148	−74.115	72.862
Institutional Factors	Chief executive party orientation (right 1; center 2; left 3)	−44.536 **	−38.300 **	−0.096	−0.101	−33.211 ***	−35.091 ***
	Control all house (yes 1; no 0)	−14.378	−0.967	0.236	0.102	−72.689 **	−81.926 ***
	Vote share of opposition parties (% of legislature vote)	−0.641	0.216	−0.041 **	−0.039 **	−2.284	−2.285
Constant		277.367	−78.189	33.979	22.710 **	1161.48	718.354
R^2	within	0.0743	0.0619	0.1127	0.0953	0.3370	0.3023
	between	0.4861	0.8018	0.2183	0.3870	0.1853	0.7821
	overall	0.5116	0.7838	0.1940	0.3401	0.2264	0.8268
	corr(u_i, Xb)	0.3627		−0.7871		0.2111	
	N	310	310	327	327	240	240

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Regressions I/III/V draw on the fixed-effects model, and regressions II/IV/VI on the random-effects model.

Table 5. First-order autoregressive panel regressions of public energy R&D investment of OECD countries (1974–2012).

	Dependent Variables	GBAORD for Energy		Energy Share of GBAORD		Energy RDD	
	Independent Variables	**I**	**II**	**III**	**IV**	**V**	**VI**
Supply-Side Factors	Log of international patents stocks	−197.956 *	20.089	−0.463	−0.122	−115.322 ***	−33.823
	Log of total R&D personnel	179.040	48.617	−0.144	−1.246	155.312	−3.555
	Gross domestic expenditure on R&D	0.015 *	0.023 ***	−0.000	0.000	0.014 ***	0.025 ***
	Public spending on education (% of GDP)	−8.494	−0.799	0.038	0.021	17.589	20.866
	GERD financed by industry (% of GERD)	−0.256	−1.617	−0.021	−0.020	1.812	1.835
	GERD performed by higher education (% of GERD)	3.878	−0.250	−0.048	−0.036	9.136	7.201 *
Demand-Side Factors	Energy imports rate (% of total energy use)	0.253	−0.334	−0.004	−0.000	1.066	0.240
	Refinery gross output (megatonne)	1.152	4.712 *	0.007	0.049 ***	3.758	4.690 **
	Log of CO_2 emissions	−26.759	7.111	0.523	−0.181	−159.959 *	−128.704
	Log of total electricity consumption	13.847	−155.178	1.861	1.153	141.826	49.656
Institutional Factors	Chief executive party orientation (1 = right; 2 = center; 3 = left)	−22.128	−21.307	−0.077	−0.104	−28.269 *	−18.679
	Control all house (1 = yes; 0 = no)	−19.703	25.601	−0.148	−0.226	−100.695 **	−67.379 *
	Vote share of opposition parties (% of legislature vote)	−1.645	−0.077	−0.026	−0.028	−2.837	−1.133
Constant		97.098 **	−86.729	−2.788 ***	15.332 *	186.210 ***	1047.549
R^2	within	0.0554	0.0405	0.0428	0.0077	0.3031	0.2476
	between	0.3714	0.8387	0.1208	0.5111	0.7863	0.8328
	overall	0.3519	0.8112	0.0989	0.4672	0.7753	0.8709
	corr(u_i, Xb)	−0.0832		−0.2855		0.5264	
	N	281	310	298	327	215	240

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; These are the panel regressions with first-order autoregressive terms. Regressions I/III/V draw on the fixed-effects model, and regressions II/IV/VI on the random-effects model.

Table 6. Panel regressions of renewable energy research, development & deployment (RDD) investment of OECD countries (1974–2012).

	Dependent Variables	**Energy RDD for Renewables**				**Renewables Share of Energy RDD**			
	Independent Variables	**I**		**II**		**III**		**IV**	
Supply-Side Factors	Log of international patents stocks	13.239	*	1.516		1.781		0.524	
	Log of total R&D personnel	28.676	*	27.907	**	9.926	*	16.033	***
	Gross domestic expenditure on R&D (GERD)	0.004	***	0.003	***	0.000		0.000	*
	Public spending on education (% of GDP)	1.587		6.097	*	1.137		1.124	
	GERD financed by industry (% of GERD)	0.327		0.312		−1.041	***	−0.569	***
	GERD performed by higher education (% of GERD)	3.233	***	1.819	***	0.450		0.347	*
Demand-Side Factors	Energy imports rate (% of total energy use)	0.279	**	0.008		0.021		0.025	
	Refinery gross output (megatonne)	−1.455	***	−0.473	**	−0.157		−0.234	***
	Log of CO_2 emissions	−13.536		−11.675		17.531		−7.028	
	Log of total electricity consumption	−52.846		−9.109		16.367		−4.655	
Institutional Factors	Chief executive party orientation (right 1; center 2; left 3)	−4.037	*	−2.920		0.924		0.874	
	Control all house (yes 1; no 0)	2.723		2.082		0.118		0.174	
	Vote share of opposition parties (% of legislature vote)	−0.005		0.051		−0.068		0.029	
Constant		−67.418		−214.737	*	−356.062	***	−36.180	
R^2	within	0.5247		0.4724		0.3150		0.2157	
	between	0.0018		0.8508		0.1505		0.4321	
	overall	0.0227		0.7158		0.0627		0.3029	
	corr(u_i, Xb)	−0.7840				−0.9667			
	N	248		248		240		240	

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Regressions I/III draw on the fixed-effects model, and regressions II/IV on the random-effects model.

Table 7. First-order autoregressive panel regressions of renewable energy RDD investment of OECD countries (1974–2012).

	Dependent Variables	**Energy RDD for Renewables**				**Renewables Share of Energy RDD**			
	Independent Variables	**I**		**II**		**III**		**IV**	
Supply-Side Factors	Log of international patents stocks	12.960		1.267		−0.407		0.382	
	Log of total R&D personnel	11.518		25.310	**	10.424		16.547	***
	Gross domestic expenditure on R&D (GERD)	0.003	***	0.002	***	0.000		0	
	Public spending on education (% of GDP)	7.340		6.332	**	0.730		1.401	
	GERD financed by industry (% of GERD)	−0.352		0.408		−0.987	***	−0.319	**
	GERD performed by higher education (% of GERD)	2.176	**	1.200	***	0.450		0.486	***
Demand-Side Factors	Energy imports rate (% of total energy use)	0.189		−0.009		0.027		0.015	
	Refinery gross output (megatonne)	−1.194	**	−0.246		−0.357	*	−0.150	*
	Log of CO_2 emissions	−34.698	*	−2.583		−10.461	**	−5.267	
	Log of total electricity consumption	24.249		−12.708		17.569		−11.784	**
Institutional Factors	Chief executive party orientation (right 1; center 2; left 3)	1.124		0.080		1.400		1.340	
	Control all house (yes 1; no 0)	12.150		7.194		0.112		0.235	
	Vote share of opposition parties (% of legislature vote)	0.472		0.244		0.075		0.122	
Constant		23.532	**	−274.437	**	−9.355		−51.952	
R^2	within	0.1936		0.4171		0.1800		0.1647	
	between	0.0848		0.8987		0.0470		0.5964	
	overall	0.1385		0.7238		0.0734		0.3833	
	corr(u_i, Xb)	−0.5217				−0.6257			
	N	223		248		215		240	

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; These are the panel regressions with first-order autoregressive terms. Regressions I/III draw on the fixed-effects model, and regressions II/IV on the random-effects model.

Among the institutional factors, the political orientation of the governing party is significantly linked to the government R&D budget for energy as well as to the total budget for energy RDD. The negative coefficient on the chief executive party orientation indicates that rightist governments tend to devote more R&D budget to energy. More specifically, when the political orientation of the chief executive party changes from right to center or center to left, it is likely to reduce the energy R&D budget by 38 million dollars and to reduce the total energy RDD budget by 35 million dollars, according to the random-effects estimation. However, the governing party orientation has no significant effect on the relative share of energy in the government R&D budget.

Table 5 presents the first-order autoregressive panel regression results, as the budget data are typically time-series that often become stationary after first-differencing. Once first-order autoregression is accounted for, most variables lose statistical significance. However, the overall size of R&D investment (GERD) still shows a positive effect on the absolute amount of the energy R&D budget. Refinery gross output also shows a positive effect on both absolute and relative amounts of R&D budget in the random-effects regressions.

As for the regressions of government expenditure on energy RDD for renewables presented in Tables 6 and 7, we find three notable differences in the results from the previous ones. First, gross domestic R&D (GERD) performed by higher education shows much more significant effects on government expenditure on energy RDD for renewables than on government expenditure on energy R&D in general. For instance, as seen in Table 6, the coefficient on GERD performed by higher education ranges from 0.347 (for the renewable share of energy RDD in Regression IV) to 3.233 (for energy RDD for renewables in absolute amount in Regression I). The latter figure implies that one percentage point increase in gross domestic R&D performed by the higher education sector turns out to generate 3.2 million dollars more based on fixed-effect estimation (or 1.8 million dollars more based on random-effects estimation), if other conditions are held constant. Even the first-order autoregressive regressions turn out highly significant results for the effect of GERD performed by the higher education sector on the absolute size of energy RDD for renewables.

This result makes a great deal of sense. Renewable energy technologies tend to be of a more radical nature compared to other types of more traditional and more mature energy technologies that tend to develop in the incremental fashion. Compared to the industry sector, the higher education sector performs more basic research, which brings more opportunities for breakthrough inventions or innovations. Thus, renewable energy R&D would critically hinge on research capabilities of higher education institutions.

Second, contrary to the finding for government expenditure on energy R&D in general, refinery gross output has a negative effect on renewable energy R&D. As seen in the last two tables, in both regressions with and without the first-order autoregressive term, refinery gross output shows a consistently negative coefficient on energy RDD for renewables in both absolute and relative terms.

This result, together with the previous one, indicates that, while the governments of countries with a larger oil sector invest more on energy R&D in general, they spend less on R&D for renewable energy. This finding may be not surprising at all, yet it is still worth noting in two regards. First, our analysis is on government expenditure rather than total R&D expenditure on R&D. The contribution of the oil sector to energy R&D expenditure in general may be quite obvious, given that the oil industries (and other fossil fuel sectors such as natural gas or coal) have great incentives and need to pour money into energy R&D. However, it is not so straightforward that oil industries would also have similar effects on "government" expenditures on energy R&D. The effect of oil industries on government R&D spending on energy could be either positive or negative. The well-known crowding-out hypothesis in the public finance literature posits that public expenditure diminishes the incentives for private investment, thus reducing private spending rather than complementing it [46,47]. The current finding suggests a possibility of the oil sector wielding influence on governmental budget decisions for energy R&D, which may, in turn, crowd out the R&D investment by the oil sector.

Finally, we find virtually no institutional variables to have significant effects on government expenditure on energy RDD for renewables. This result is quite surprising, for the size of renewable R&D is very much likely to be tied to public commitment to sustainable energy transition, which, in turn, is reflected in various political and institutional features of the regime such as partisan orientation of the governing party.

When it comes to the overall explanatory power of the current models, the set of independent variables derived from our framework of government investment in energy R&D explain a fairly large portion of the variations in the absolute amount of energy R&D budget. The random-effects regression explains more than three fourths of cross-national variations in the absolute amount of government energy R&D budget—78% of government R&D budget allocation and 82% of total government budget for energy RDD (81% and 87%, respectively, in the first-order autoregressive regression). The current set of explanatory variables also explains about 34% of the relative size of government energy R&D budget with the random-effects estimation. Furthermore, for the renewable energy R&D expenditure, our explanatory framework explains about 72% of the cross-national variations in the absolute amount of government expenditure on energy RDD for renewables when estimated with the random-effects model. In contrast, our model explains 39% of the variation in the relative share of renewables in energy RDD when estimated by the random-effects model with the first-order autoregressive term.

A high R^2 with relatively few significant individual coefficients is a symptom of the multicollinearity problem. According to the bivariate correlations among the variables, total R&D personnel shows very high correlations with three other variables—refinery output, CO_2 emissions, and total electricity consumption. The regressions excluding total R&D personnel—unreported here but available upon the request to the authors—show better results in terms of the significance of individual coefficients.

5. Discussion

Calls for energy transitions towards sustainability have been increasingly pervasive and intensive in energy policy discourses, echoed by various policies and programs to promote technological innovation for sustainable energy around the world [48]. When it comes to actual investment for energy R&D, however, governments have shown vastly different levels of commitment to energy transitions. Even if we take into account different rates of sustainable energy transitions across countries [49], government budget allocations for energy R&D in general as well as for R&D on renewable energy sources vary a great deal across countries in both absolute and relative terms.

In an effort to understand the sources of such variations in government investment in energy R&D, we have formulated an analytical framework to help sort out a multitude of factors directly or indirectly influencing public investment on energy R&D including governmental expenditures on renewable energy R&D. The framework consists of three—supply-side, demand-side, and institutional—dimensions, derived from the previous literature on the socioeconomic and infrastructural factors underpinning energy R&D. Based on this framework, our empirical analysis examines a score of potential determinants of cross-national variations in government investment in energy R&D in general as well as R&D on renewable energy using the panel data from 34 OECD countries for the period of 1974–2012.

One of the key empirical findings is the significant impact of the petroleum refining sector on energy R&D investment. The size of refinery output turns out to be positively linked to government budgets for energy R&D but negatively linked to government budgets for renewable energy R&D. This suggests that despite popular perceptions of the oil sector as an obstacle to energy innovations [50,51], countries with larger oil sectors invest more of their government budget on energy R&D. However, their governments spend less on research, development, and demonstrations for renewable energy, which largely conforms to the conventional wisdom of the reduction of dependence on fossil fuels for sustainable energy transition. However, the contrasting findings of the oil sector in government energy R&D in general vs. R&D for renewables call for a more in-depth analysis in the future of the roles of the oil sector in energy innovation towards sustainable energy transition.

In addition, the findings about the institutional factors—especially, the influence of governing party orientation—challenge the conventional wisdom, for leftist parties tend to be more critical of oligopolistic energy supply characteristic of the fossil-fuel driven energy sector and thus more supportive of sustainable energy R&D funded by governments.

One of the contributions of this study is that it provides a more comprehensive understanding of energy R&D and innovation activities by looking into cross-national differences in governmental budget for energy R&D, given that much of the existing literature on energy innovation has focused on the firm level [28]. In addition, our findings hold practical implications for making sustainable energy transitions.

The finding about the positive linkage of the oil sector and government budget for energy R&D suggests that energy policymakers need to recognize and analyze the role of the oil sector in driving government investment on energy R&D rather than simply scapegoating it as an obstacle to the transition to a sustainable economy. However, the negative effect of the oil sector on governmental investment in renewable energy implies that countries with large oil sectors need to come up with more proactive policies for public investment in renewable energy in order to compensate for such negative influence of oil industries on renewable R&D at least supported by the government budget.

6. Conclusions

Despite decades-long calls for sustainable energy transitions, the overall composition of the world energy supply has not changed much since the late 1970s, with fossil fuels comprising 81% of the world's total primary energy supply. In this study, we address this persistent gap between the call for sustainable energy transition and the reality of energy supply around the world with an empirical analysis of cross-national differences in government commitment to energy innovation as manifest in government budgets for energy R&D. Our panel regressions of cross-national data from 34 OECD countries (1974–2012) reveal a couple of variables to have significant influence on the size of government budget allocation for energy R&D in general as well as for R&D on renewables.

One is the gross domestic expenditure on R&D (GERD), which captures the level of overall R&D investment. As expected, this supply-side variable is positively linked to both government investment on energy R&D and R&D on renewables measured in absolute terms. However, the overall level of domestic R&D expenditure does not show significant effects on government R&D budget allocations for either energy R&D in general or renewable energy R&D measured in relative terms.

The second variable is refinery gross output, which reflects the demand side for energy R&D investment. Interestingly, refinery gross output measured in megatons show the opposite effects on government budget allocations for energy R&D in general and those for renewable R&D. It is positively linked to the former but negatively linked to the latter. That is, the governments of countries with a larger oil sector tend to devote more of their R&D expenditure to energy R&D but less to R&D for renewables.

The third variable of statistical significance is the political orientation of the governing party, with the rightist governments turning out to be more inclined to spend on energy R&D. However, none of the institutional variables have significant effects on government budget allocations for renewable R&D. Some of these findings seem to correspond to conventional wisdom, while others do not.

This study leaves some to be desired, which leads to the suggestions for further improvement in future research. One of the improvements that can be made relates to the sample of countries. The current empirical analysis is limited largely to affluent countries. While this is a result of data inaccessibility of developing countries, further research can modify the analytical framework to suit the data availability of developing nations even if that means the set of variables is relatively reduced compared to that of the current analysis.

Another improvement that can be made is to explore government R&D expenditures on different categories of renewables more in detail. It could be very likely that the aggregate effects we find in the current analysis may differ by the type of renewables. This would generate more specific policy implications for sustainable energy transitions. In particular, given the vastly different political economic regimes around the world, countries would have to develop more refined approaches to promoting sustainable energy supply and consumption rooted in their historical and political realities as documented well in the recent review of sustainable energy transitions [52].

Finally, if we are concerned with the overall impacts of the fossil fuel sector in energy innovation and sustainable energy transition, we should also consider the roles of other types of fossil fuel than oil, such as natural gas and coal. While the distribution of countries (and particularly the government budgets) is much wider in the data on petroleum, it is clearly worth investigating the effects of natural gas and coal sectors on governmental commitment to energy R&D.

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