Renewable Energy RD&D Expenditure and CO_2 Emissions in 15 European countries

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Abstract

Purpose:

Renewable energy is an important component to the complex portfolio of technologies that have the potential to reduce CO_2 emissions and to enhance the security of energy supplies. Despite RE's potential to reduce CO_2 emissions, the expenditure on renewable energy research, development & demonstration (RERD&D) as a percentage of total government energy research, development & demonstration (ERD&D) investment remains low in developed countries. The declining ERD&D expenditure prompted this research to explore the relationship between CO_2 emissions per capita and RERD&D as opposed to ERD&D.

Methodology:

An econometric analysis of annual CO_2 emissions per capita during the period 1990 – 2004 for the 15 pre-2004 European Union (EU15) countries was carried out. It was hypothesized that the impact of RERD&D expenditure on the reduction of CO_2 emissions would be higher than that of ERD&D expenditure, primarily due to several RE technologies being close to carbon neutral. Country-level GDP per capita and an index of the ratio between industry consumption and industrial production (IICIP) were introduced in the analysis as proxies to control for activities that generate CO_2 emissions. A number of panel data econometric models that are able to take into account both country- and time-specific unobserved effects were explored.

Findings:

It was found that random effect models were more appropriate to examine the study hypothesis. The results suggest that expenditure on RERD&D is statistically significant and negatively associated with CO_2 emissions per capita in all models, whereas expenditure on ERD&D is statistically insignificant (*ceteris paribus*).

Originality:

The findings of this paper provided useful insight into the effectiveness of renewable energy RD&D investment in reducing CO2 emissions and are of value in the development of policies for targeted RD&D investment to mitigate the impacts of climate change.

Keywords: Energy, Renewable Energy, RD&D, CO_2 emissions, Econometric models, European Union

1. Introduction

There is growing interest in energy research, development & demonstration (ERD&D), in particular in renewable energy RD&D (RERD&D) and its impact on future energy supply (Davis and Owens, 2003) and environment (McGowan, 1991; Sims, 2004). The developments in Renewable Energy (RE) technologies over the past decades have demonstrated a clear potential in reaching CO_2 emissions reduction target, set out in the international agreements such as Kyoto Protocol (UNFCCC, 1997). Substantial literature exists on climate change and the need to reduce CO_2 emissions to tackle global warming and other anthropogenic greenhouse gas emissions for environmental sustainability (Hulme *et al.*, 2002; IPCC 2007a; UKCCP, 2006; US-EPA, 2007; USGCRP, 2000).

Around 13.4% of the world's total primary energy comes from renewable energy sources (IEA, 2005), which includes hydro-power and the often inefficient use of traditional biomass for cooking and heating in developing countries. Several RE technologies have matured to a level for broad market deployment, as well as for cost effective applications in niche markets (IEA, 2005). Despite competition from cheap conventional energy sources, the RE industry has been '*most successful with factors within its control*' (McVeigh *et al.*, 1999). Usually considered a high-tech sector with emerging technologies, the RE industry requires continued investment in RD&D (Ragwitz and Miola, 2005) and in associated human and institutional capacity to realize its full potential. This has been echoed by Sims (2004) who made a detailed argument on the potential of various energy technologies in slowing down the impacts of climate change by reducing CO_2 emissions. It was concluded that renewable energy had substantial potential in the long term if there was continued worldwide support from governments.

Public expenditure on energy RD&D has decreased in recent decades in real terms. In the case of EU15 countries (i.e., member of the European Union before 2004 expansion), the total annual government ERD&D budget decreased by 74% (based on 2005 price and exchange rates) and RERD&D by 34% since they peaked in 1985 and 1984 respectively (Figure 1). The decades of declining real public RD&D investments in renewable energy in the US (Margolis and Kammen, 1999; McVeigh *et al.*, 1999) and other International Energy Agency (IEA) member countries (IEA, 2005) has been highlighted previously. According to Dooley (1998), the reduction in national investment in ERD&D is driven in part by the deregulation of energy sectors in the industrialized nations. In a deregulated energy sector, government RD&D funding is increasingly being allocated for public-private partnerships. For example, In a study of public-private partnerships for RD&D in new generation low-energy vehicle development, Sperling (2001) has questioned the efficacy of the instruments and scope in the policy to accelerate the commercialization of socially beneficial technologies. Discussions on the impact of under-investment can be found in Dooley (1998), Elliott (1994) and Kobos *et al.* (2006).

<Figure 1 is about here>

A growing body of literature exists on the value and impact of energy RD&D. Using energy related patents as an indicator for innovation in the field, Margolis and Kammen (1999) found that energy RD&D investments and patents were highly correlated between 1976 and 1996. Davis and Owens (2003) used 'real option' pricing techniques to estimate the value of renewable electric technologies in the US in the face of uncertain fossil fuel prices. Their analysis suggests that the value of renewable electric technologies enhances with the increase in current and future research and development (R&D) funding levels. This indicates that current level of US renewable electric R&D funding is sub-optimal. Ragwitz and Miola (2005) analyzed the performance of RD&D expenditure in RE in EU15 countries.

In CO_2 emissions context, Bengochea-Morancho *et al.* (2001) examined the relationship between GDP growth and CO_2 emissions in 10 selected EU countries using a panel data analysis for the period 1981-1995. An econometric model was employed to evaluate GDP as an independent variable and CO_2 emissions as a dependent variable. The analysis indicated that the countries with a level of income above the EU average and those with a below average level of income had different patterns of CO_2 emissions. When sub-samples of countries based on their income level are applied, the behavior conformed to the equal slope hypothesis for the member of each group. Martinez-Zarzoso *et al.* (2006) analyzed the impact of population growth on CO_2 emissions in EU countries using data covering the period 1975-1999: "the impact of population growth on emissions is more than proportional for recent accession countries whereas for old EU members, the elasticity is lower than unity and non significant when the properties of the timeseries and dynamics are correctly specified". New accession countries in this study included the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia and Malta.

This current study examines whether the expenditure in RERD&D is more effective in reducing CO_2 emissions per capita than the expenditure in ERD&D, which includes a myriad of technologies. The fifteen pre-2004 EU countries are selected for analysis as they share a certain level of homogeneity in the economic and environmental policies and indicators and on the maturity achieved in renewable energy research, development, demonstration and deployment. An econometric analysis for the period 1990-2004 is applied using panel data on CO_2 emissions per capita, total ERD&D expenditure, RERD&D expenditure, country-level gross domestic product (GDP) per capita and index of ratio between industry consumption and industrial production (IICIP). ERD&D and RERD&D expenditures are used as the main variable of interest in two separate models to establish the individual effect on CO_2 emissions and also because of the high co-linearity between them. GDP per capita and IICIP were used as control variables in both models where they served as proxies for activities that generate CO_2 emissions. The result suggests that the RERD&D is negatively associated with CO_2 emissions per capita and the relationship is statistically significant, where as ERD&D is found to be statistically insignificant.

The underlying theoretical framework of the relationship between CO_2 emissions and economic variables (including control variables) is presented below, followed by a brief description of the data used in the analysis. The econometric models used to formulate the relationship are discussed; followed by the presentation of the results, a summary of the findings and some thoughts for future research directions.

2. Theoretical framework

Economic instruments are often implemented along with other environmental policy measures that aim to reduce CO_2 emissions (Maréchal, 2007). Therefore, it can at times be difficult to separate the effect from such economic instruments (e.g., the expenditure on RERD&D and ERD&D) from other policy measures (e.g., subsidy on energy efficiency measures). In order to obtain a reliable result, an economic model was used to explain CO_2 emissions using expenditure on ERD&D and RERD&D, other economic (such as GDP per capita) and policy variables. However, policy variables normally differ among developed countries so it is not straightforward to include them in a model. One approach is to choose an econometric model that can handle all unobserved heterogeneity within the sample. The model should also include some other variables that control all activities responsible for CO_2 emissions. The IICIP is such a control variable as it measures output in the manufacturing, mining (including oil extraction), electric and gas utility industries. This index is usually used as the reference series for aggregate economic activity because it constitutes the most cyclical subset of the aggregate economy and the availability of the data for most countries (OECD, 2007). Therefore, the following econometric model can be used to formulate a relationship between CO_2 emissions and other factors:

$$Y_i = X_i^{\beta} \eta_i e^{-\delta_t} \quad (1)$$

where Y_i is the CO_2 emissions per capita for entity i, X_i is the vector of economic and control variables, η_i is the entity-specific unobserved effect (random or fixed across entities), δ_t is the time specific unobserved effect and β is the vector of parameters to be estimated.

The logarithm of this function was used to obtain the following equation:

$$\ln Y_i = \beta \ln X_i + \ln \eta_i - \delta_t + \varepsilon_i \quad (2)$$

where ε_i is the error term.

Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden and United Kingdom, the EU 15 were selected for this analysis (Figure 2).

<Figure 2 is about here>

Nuclear energy RD&D enjoyed modest investments during the study period. Its share in the total ERD&D investment in EU15 was at least 50% in the period 1974-2000; the effect of which on CO2 emissions will be represented by the variable ERD&D.

3. Data

Cross-sectional time-series data for the EU15 countries from 1990 to 2004 were used in the analysis. To eliminate missing data points as far as possible and some inconsistencies (e.g., the differences in data collection and reporting methods in Germany prior to unification) pre-1990 data was not used. Data were primarily collected from the International Energy Association (IEA) energy-economy datasets available via the Economic and Social Data Services (ESDS) portal (ESDS, 2007). Annual country-level RD&D data for EU15 countries over the 15 years were given in US dollar at 2005 prices and exchange rates. The RD&D data include public expenditures and covers a broad range of technologies. Both supply and demand side technologies are covered in the ERD&D dataset. Details of the coverage are given in Table 1. Data on IICIP were derived from the index of industrial production and industrial consumption, where the year 2000=100. The dataset is obtained from the Organization for Economic Co-operation and Development data (OECD, 2007). GDP data were compiled for individual countries using market prices in local currency and annual rates and scaled to the price levels of 2000 then converted to US dollars using the yearly average 2000 exchange rates (IEA, 2006a).

<Table 1 is about here>

Data on annual country-level CO_2 emissions were obtained from the IEA's Energy Balance data that used the '*Sectoral Approach*' methods and emissions factors from the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2007b). IPCC allows countries to use either the reference approach or the sectoral approach to estimate CO_2 inventories. The latter only incorporates end-use fossil fuel combustion within various sectors and excludes emissions from refining, flaring and other fugitive emissions that do not result directly from end-use fuel combustion. Reference approach estimates are based on the supply rather than the combustion of fuels. There are slight variations in estimates using both approaches. However, the reference approach can lead to slight overestimates of emissions. Comparing CO_2 emissions per capita among EU15 countries for 2004 (Figure 2), it can be seen that Luxemburg, Ireland and Netherland have relatively high CO_2 emissions per capita compared with other EU15 countries. From 15 datasets from 15 EU countries over 15 years, the total number of observations was 225. However, missing values in the sample resulted in a total of 192 valid observations. Given the number of explanatory variables to be included in the model, these observations should provide a reliable estimate of model parameters. Summary statistics of the variables to be included in the models are shown in Table 2.

<Table 2 is about here>

4. Methodology

As discussed in the previous section, the dataset to be used in this study is a panel consisting of 15 cross-sectional units (i.e., 15 EU countries) and 15 time-series units (from 1990 to 2004). Since the number of time-series observations differed among cross-section units, the dataset is an *unbalanced* panel. Although a panel dataset potentially provide a larger number of data points, additional sample variability, less co-linearity among variables, more degrees of freedom and improve the efficiency of econometric estimates, the ordinary least-squared (OLS) estimation method cannot be applied as such a method ignores both individual- and time-specific effects and therefore results in biased estimates of the model coefficients (Baltagi, 2003). Therefore, a panel data econometric model which can take into account unobserved effects (such as country-specific policies to reduce CO_2 emissions, political culture and factors, etc.) was used. Equation (2) can be rewritten for panel data as:

$$Y_{it} = \alpha + \boldsymbol{\beta X}_{it} + \mu_i + \phi_t + u_{it} \qquad (3)$$

where Y_{it} is the CO_2 emissions per capita for country i and year t, $\boldsymbol{X}$ is the vector of country-level factors affecting the amount of CO_2 emissions, μ_i is the country-specific unobserved effects, ϕ_t is the time-specific unobserved effects, u_{it} is the identically and independently distributed error term with 0 mean and constant variance, α is the common intercept and $\boldsymbol{\beta}$ is the vector of parameters to be estimated.

The unobserved effects (μ_i or ϕ_t) of equation (1) can be modeled as a random variable (leading to a random effects model) or a fixed variable (leading to a fixed effects model). The standard assumption for a random effects model is that the unobserved effect (μ_i or ϕ_t) is randomly distributed with a common mean and not correlated with the observed, $\boldsymbol{X}$ (Woolbridge, 2002; Baltagi, 2002). On the other hand, a fixed effects model does not have such an assumption but the unobserved effect μ_i is fixed (i.e., does not vary over time) for a particular cross-section and is allowed to be correlated with explanatory variables.

Equation (3) is a two-way unobserved effects model. If ϕ_t is assumed as zero, then equation (3) becomes a one-way individual-effect (either random or fixed) model and if μ_i is assumed as zero, then equation (1) is known as a one-way time-effect (either random or fixed) model. Statistically, fixed effects models always give consistent results, but they may not be the most efficient model to estimate. Random effects models provide more accurate *t*-statistics as they are a more efficient estimator (see Baltagi, 2002 for details). The statistical Hausman test (Hausman, 1978), can be used to identify a suitable model (either a random effects or a fixed effects model) for a given dataset. This tests the null hypothesis that the coefficients estimated by the efficient random effects estimator are the same as those estimated by the consistent fixed effects estimator. If the null hypothesis cannot be rejected then the random effect estimates should be employed.

A fixed effects model is normally estimated using the within-effects estimation technique and a random effects model is estimated using the Feasible Generalized Least-Squared (FGLS) or a

Maximum Likelihood (ML) estimation method (Baltagi, 2002). All possible specifications of equation (1) were explored in this study to effectively test the study hypothesis.

The analysis strategy was to evaluate two models: a per-capita CO_2 emissions model with RERD&D expenditure as the main variable of interest (Model A), and a per-capita CO_2 emissions model with ERD&D expenditure as the main variable of interest (Model B). Due to high co-linearity between these two variables, it was not possible to include both in the same model. In the models, the control variables were country-level GDP per capita and index of ratio between industry consumption and industrial production (IICIP). This leads to a reliable testing of the study hypothesis by identifying the actual impact of the main variable of interest.

Since all variables (both response and explanatory) were observed over a period of 15 years per country, it is essential to test whether there is a problem of *unit root*. An econometric model in the presence of unit root may result a spurious regression that produces a meaningless relationship between variables (Gujrati, 2003). A statistical test suggested by Levin *et al.* (2002) was used to detect the presence of unit root in the panel dataset. The results suggested that the null hypothesis of non-stationarity can be rejected at the 95% confidence level for both response and explanatory variables[*] implying there was no problem of spurious regression. To reduce the effect of heteroscedasticity among observations and to interpret the model parameters $\boldsymbol{\beta}$ easily, all variables were transformed into a logarithmic scale in which $\boldsymbol{\beta}$ became elasticities rather than slope coefficients. Models A and B were estimated for three different specifications of equation (3): (a) only country-specific unobserved effects, (b) only time-specific unobserved effects, and (c) both country- and time-specific unobserved effects. Each of the models are discussed in the results section.

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[*] Due to missing values, this unit root test could not conducted for variables – RD&D expenditures on renewable energy and RD&D expenditure on total energy

5. Estimation results

5.1. Country-specific unobserved effects

Equation (3) was employed to develop both models (A and B). The unobserved time-specific effect was assumed to be zero in equation (3) and hence this equation became a country-specific unobserved effect (either fixed or random effects) model. Both random and fixed effects specifications were considered while estimating model parameters for each model. The log-transformation of the variables was used in all models (Table 3). In both models, the F-test statistic for the fixed effects specification and the Wald statistic for the random effects specification indicate that both models were statistically significant. Both F-test (fixed effects vs. pooled OLS) and the Lagrange Multiplier (LM) test (Breusch and Pagan, 1979) (random effects vs. pooled OLS) suggested that there were significant unobserved country-specific effects in the data and therefore, a pooled OLS could not be used to estimate the model parameters. The random effects estimates were similar to the fixed effects estimates for both models A and B suggesting that the country-specific unobserved effect is large and important. The Hausman test statistics were 1.2 (with a *p*-value of 0.75) and 1.79 (with a *p*-value of 0.62) for models A and B respectively. This implies that the coefficients estimated by the random effects estimator were the same as those estimated by the fixed effects estimator. Therefore, the null hypothesis of random effects specification for both models cannot be rejected at the 95% confidence level. The rest of the interpretation was based on the log-linear random effects specification.

The results of the random effects specification of model A suggested that the variable - RERD&D - is not statistically significant at the 95% confidence level but significant at the 90% confidence level (*p*-value=0.10 for a two-tailed test) and negatively associated with CO_2 emissions per capita for EU15 countries. This means that an increase in RERD&D expenditure would decrease CO_2 emissions per capita. However, the relatively coefficient of -0.017 suggested that a 10% increase in RERD&D expenditure would decrease CO_2 emissions per capita by only about 0.2% (*ceteris peribus*). Both control variables were highly significant at the 100% confidence level and are positively associated with CO_2 emissions per capita. This was expected as economic growth is usually accompanied with more energy use and hence more emissions. These findings are consistent with the findings of other existing studies (Bengochea-Morancho *et al.*, 2001), in particular for the countries with higher than average level of GDP within the EU. The elasticity of CO_2 emissions per capita with respect to GDP per capita for EU15 countries was 0.65 implying that if GDP per capita of a country is increased by 10% then CO_2 emissions per capita of that country would increase by 6.5% (*ceteris paribus*). The other control variable IICIP (the value for year 2000 taken as 100) - was also found to be positively related with CO_2 emissions per capita and again highly statistically significant at the 99.9% confidence level. Given that this variable is served as a proxy for total industrial activities that produce CO_2 emissions, this was also an expected result.

<Table 3 is about here>

Interestingly, the random effects specification of model B indicated that the variable - ERD&D expenditure - had significant effect on CO_2 emissions per capita for EU15 countries. However, both control variables were found to be statistically significant and the values of the coefficients for these two variables were close to those of model A.

Therefore, the study hypothesis cannot be rejected[†]. This implies that a country should focus on increasing the RERD&D expenditure compared to the increase in ERD&D expenditure if the aim is to reduce CO_2 emissions per capita.

5.2. Time-specific Unobserved Effect

If the unobserved country-specific effects were assumed to be zero, then the equation (3) became a time-specific unobserved effect (either fixed or random) model. The log-transformation of the variables led to a log-linear time-specific panel data model (Table 4). Both fixed and random effect specifications of models A and B were statistically significant at the 100% confidence level. However, the F-test suggested there was no time-specific unobserved fixed effect in the data for both models (*p*-values 0.98 and 0.99 respectively). On the other hand, the results of the Lagrange Multiplier (LM) test indicated that there were time-specific

[†] Only at the 90% confidence level

unobserved random effects in the data for both models (*p*-values are 0.05 and 0.02 respectively). This was confirmed by the Hausman test suggesting that the random effects specification is the correct specification to use. Therefore, the rest of the interpretation was based on the random effects specifications of models A and B.

The results for the control variables of the time-specific random unobserved effect specification of models A and B (Table 4) are similar to those of the country-specific random unobserved effect specification of models A and B (Table 3). The variable - RERD&D expenditure - is now highly statistically significant[‡] at the 99.9% confidence level (with the absolute value of t-statistic more than 4.5) in model A and again negatively associated with CO_2 emissions per capita. The elasticity of CO_2 emissions per capita with respect to RERD&D expenditure is now 0.05 suggesting that if all else are equal then 10% increase in RERD&D expenditure would decrease CO_2 emissions per capita by 0.52%. It is worthwhile to mention that there are limited control variables in the model and therefore, one should be cautious in interpreting the impact of RERD&D on CO_2 emissions. The variable – ERD&D expenditure- was again statistically insignificant in model B. The effects of the other variables in the time-specific version of model B were the same as the effects found in the country-specific version of model B.

<Table 4 is about here>

RERD&D expenditure had a significant impact on the reduction of CO_2 emissions per capita in both country-specific and time-specific unobserved random effects specification of the model shown in equation (3). Whether such an impact remains while both country-specific and time-specific unobserved effects are included in the same model is discussed below.

5.3. Country-and Time-specific Unobserved Effects

Models A and B were estimated for equation (3) when both country-specific and time-specific random unobserved effects were included in the same specification (Table 5).

[‡] This variable was statistically significant only at the 90% confidence level in the random effect model with the country-specific unobserved effect (see Table 3). .

<Table 5 is about here>

The likelihood ratio (LR) test suggested that there were both country- and time-specific unobserved random effects in the data for both models (A and B). The variable - RERD&D expenditure - was now marginally significant at about 90% confidence level (p-value=0.11 for a two-tailed test) and the variable - ERD&D expenditure - again found to be statistically insignificant. The results for all other variables remain the same as Table 3 for country-specific random effect specification and Table 4 for time-specific random effect specification.

In summary, it can be stated that different specifications of equation (3) produced similar results. The variable - RERD&D expenditure– is consistently found to be statistically significant in all three different specifications and the variable – ERD&D - was statistically insignificant, confirming the hypothesis that RERD&D had a significant impact on the reduction of CO_2 emissions per capita among EU15 countries.

6. Conclusions

The impact of energy RD&D expenditure on reducing annual CO_2 emissions per capita during the period 1990 – 2004 for the EU15 countries was assessed using a panel data econometric model. Total governmental energy RD&D and renewable energy RD&D expenditure were introduced in the models separately while controlling for some other factors such as country-level GDP per capita and index of ratio between industry consumption and industrial production (IICIP). Both random effect and fixed effect models were considered. The Hausman test confirmed that a random effect model was more suitable than a fixed effect model for the data. In addition, different specifications of the random effect model (including country-specific, time-specific and both) were examined and a consistent result obtained. The government RERD&D expenditure has consistently been found to be statistically significant in all specifications suggesting that increased RERD&D expenditure would reduce CO_2 emissions. Whereas, the ERD&D expenditure was found to have no impact on reducing CO_2 emissions for the data analyzed. The results are consistent with conventional wisdom in the area.

Energy strategy and policy of the EU is strongly driven by the aspects of security of energy supply and sustainability (mostly economic and environmental) (EC, 2006; Beeck *et al.*, 2009). Findings from this study can be used as an evidence base for Europe wide policy making where more focused investments are made in renewable energy RD&D, which will contribute towards decarbonisation of the energy infrastructure and reduce Europe's dependence on imported fossil fuel.

It is difficult to separate directly the effect of RERD&D expenditure from the effect of other government policies (e.g., subsidies provided for micro-scale integration renewable energy in buildings); although the country specific unobserved effect specification of the model (equation 1) took this into account to some extent.

The use of aggregated data in this study enables an understanding of the interrelationships of various economic and environmental factors on a European scale. However, variability exists among EU member nations. Future studies can explore these aspects as well as the sectoral expenditures on RD&D. Expenditure in various groups of technologies having similar characteristics can be studied to see if the marketability and/or technological maturity levels of these technologies have any relationship with CO_2 emissions.

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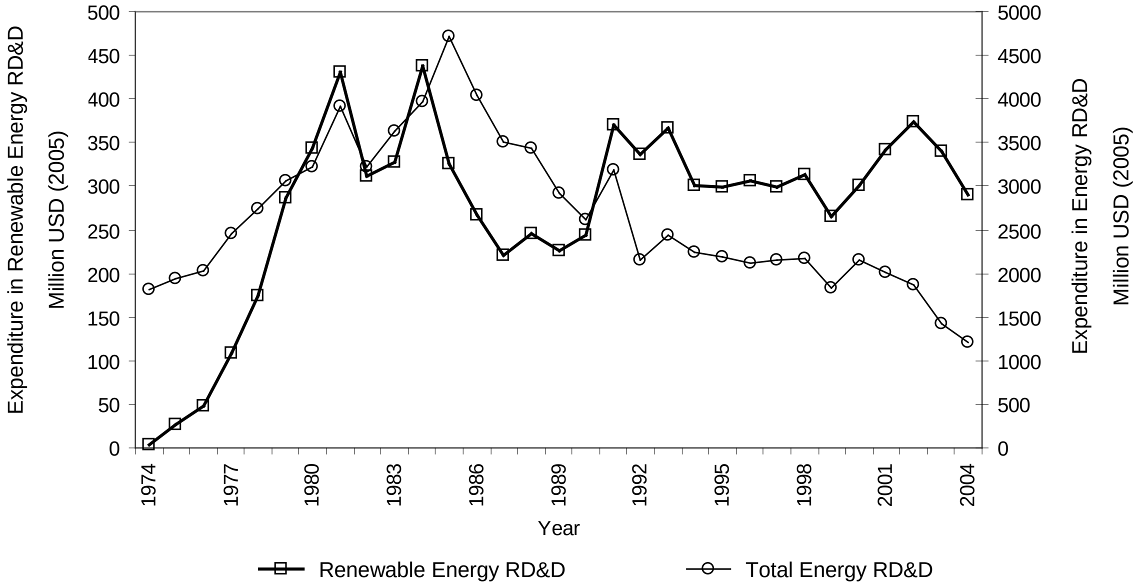

Figure 1: Governmental RD&D budget for energy and renewable energy in EU15 countries for 1974-2004, data source: IEA (2006b).

Figure 2: CO_2 emissions per capita among EU15 countries for 2004.

Table 1: Data coverage for the variables ERD&D and RERD&D

Variables	Coverage	
Energy RD&D	• *Energy Efficiency* Industry, residential, commercial, transportation and other conservation • *Fossil fuels* Enhanced oil and gas production, refining transportation and storage of oil and gas, non-conventional oil and gas production, oil and gas combustion, oil and gas conversion, coal production preparation and transportation,, coal combustion, coal conversion, CO_2 capture and storage, CO_2 capture/separation, CO_2 transport and CO_2 storage • Renewable energy Please see below	• *Nuclear fission and fusion* Light-water reactors, converter reactors, fuel cycle, nuclear supporting technology, nuclear breeder, other nuclear fission and nuclear fusion • Hydrogen and fuel cells Hydrogen production and storage, hydrogen transport and distribution, infrastructure and systems, hydrogen end uses including combustion, fuel cells and stationary and mobile applications • *Other power and storage technologies* Electric power conversion, electricity transmission and distribution and energy storage • *Other technologies or research* Energy system analysis
Renewable Energy RD&D	• *Renewable energy* Solar heating and cooling, photovoltaics, solar thermal power and high temperature applications, wind energy, ocean energy, transportation of bio-fuels, biomass derived fuels including wastes, applications of heat and electricity, geothermal energy, hydropower and other renewables	

Table 2: Summary statistics of the variables

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Luxemburg	Netherlands	Portugal	Spain	Sweden	UK	**Total**
CO_2 emissions per capita																
Min	7.23	10.85	9.39	10.60	5.87	10.06	6.76	8.60	6.79	16.93	10.57	3.96	5.32	5.62	8.80	3.96
Max	9.28	11.99	13.48	14.00	6.55	12.18	8.54	11.23	7.95	28.58	11.54	6.11	7.72	6.75	9.85	28.58
Mean	8.04	11.38	10.71	11.69	6.21	10.73	7.49	9.73	7.24	22.40	11.10	5.08	6.36	6.05	9.16	9.56
SD	0.64	0.34	1.13	0.97	0.18	0.62	0.68	0.92	0.32	4.17	0.25	0.73	0.81	0.26	0.33	4.22
Renewable energy RD&D expenditure																
Min	2.67	0.45	11.64	2.48	3.88	70.91	2.56	0.70	31.78	0.02	28.38	0.33	20.97	10.02	6.92	0.02
Max	13.59	5.15	29.27	21.84	30.74	159.19	8.96	3.63	70.02	0.72	61.64	3.32	32.91	42.67	44.24	159.19
Mean	9.58	2.87	21.60	9.62	12.03	105.95	5.01	1.77	53.10	0.23	45.81	1.55	24.88	22.75	22.96	24.72
SD	3.19	1.49	5.42	5.30	8.08	25.12	1.88	1.37	11.78	0.25	11.58	0.85	3.73	9.96	13.24	28.96
Energy RD&D expenditure																
Min	16.17	60.72	29.72	52.97	523.40	243.57	6.99	1.83	328.45	-	163.03	1.34	56.58	62.73	60.95	1.34
Max	42.60	98.45	65.22	111.70	845.20	661.28	23.71	12.67	857.99	-	267.03	17.72	165.53	125.25	459.25	857.99
Mean	32.87	75.12	52.49	80.09	683.20	411.35	12.14	7.19	445.53	-	214.51	5.03	93.28	95.35	159.86	177.39
SD	6.71	13.93	10.91	19.66	83.30	104.08	4.75	4.72	169.68	-	29.84	4.55	29.32	21.34	127.12	207.95
GDP per capita																
Min	19628	18850	24105	17627	18547	19447	8707	13776	16176	30105	19415	8104	11293	21929	19419	8104
Max	25076	23642	30798	25273	22754	23669	12209	29120	19167	48451	24488	10522	15357	29264	26591	48451
Mean	22314	21036	27615	21049	20397	21756	9847	20590	17612	38577	22102	9413	13109	25074	22558	20870
SD	1905	1697	2422	2588	1574	1374	1164	5736	1098	6223	2003	902	1505	2452	2494	7397
Ratio of IE consumption and production																
Min	68.2	79.6	75.4	55	82.5	84.4	79.2	30.9	82.7	75.7	83.9	80.9	74.3	67.5	85	30.9
Max	112.3	104.3	103.2	108.4	101.6	102.6	100.2	123.8	100	117.8	102.1	103.1	101.6	105.4	100	123.8
Mean	85.3	91.5	90.4	79.9	92.4	93.4	89.1	71.9	92.5	90.8	93.4	92.4	89.1	86.2	93.5	88.8
SD	15.9	8.1	10.7	19.3	6.7	5.8	8.4	35.5	5.7	13.5	6.7	8.0	9.5	13.7	4.9	14.5

Table 3: Estimation results of country-specific panel data econometric models

Response variable - ln(CO2 per capita)	Model A				Model B			
	Fixed Effects		Random Effects		Fixed Effects		Random Effects	
	Coefficients	*t*-stat	Coefficients	*t*-stat	Coefficients	*t*-stat	Coefficients	*t*-stat
Explanatory Variables								
ln(R&D expenditure on renewable energy)	-0.0140	-1.26	-0.0173	-1.62	-		-	
ln(R&D expenditure on total energy)	-		-		0.0200	1.32	0.0122	0.88
ln(GDP per capita)	0.6457	8.65	0.6413	9.37	0.6599	8.89	0.6204	9.22
ln(Ratio of industrial energy cons and prod)	0.4803	7.66	0.4727	7.91	0.4012	6.33	0.3713	6.28
Constant	-6.4321	-6.71	-6.3254	-7.16	-6.3533	-6.33	-5.7665	-6.37
Descriptive statistics and Tests								
Tests for model significant								
F-statistic (Fixed effects)	29.28		-		29.23		-	
p-value > F-statistic	0.00		-		0.00		-	
Wald statistic (Random effects)	-		103.18		-		91.89	
p -value > Wald-statistic	-		0.00		-		0.00	
Observations								
Observations per group								
Minimum	4		4		4		4	
Maximum	12.8		12.8		12.8		12.8	
Average	15		15		15		15	
Fixed or Random effects vs. pooled OLS	Fixed effects vs. pooled OLS				Random effects vs. pooled OLS			
F-statistic (Fixed effects)	135.78		-		158.11		-	
p-value > F-statistic	0.00		-		0.00		-	
LM statistic (Random effects)	-		997.79		-		922.9	
p-value > LM-statistic	-		0.00		-		0.00	
Model goodness-of-fit								
Within	0.335		0.335		0.351		0.350	
Between	0.536		0.543		0.321		0.328	
Overall	0.498		0.503		0.349		0.352	
Hausman test	Fixed vs. random effects				Fixed vs. random effects			
Test statistic	1.2				1.79			
p-value > Test statistic	0.75				0.62			
Decision	Random effects				Random effects			

Table 4: Estimation results of time-specific panel data econometric models

Response variable = ln(CO2 per capita)	Model A				Model B			
	Fixed Effects		**Random Effects**		**Fixed Effects**		**Random Effects**	
	Coefficients	***t*-stat**	**Coefficients**	***t*-stat**	**Coefficients**	***t*-stat**	**Coefficients**	***t*-stat**
Explanatory Variables								
ln(R&D expenditure on renewable energy)	-0.0512	-4.48	-0.0523	-4.73	-		-	
ln(R&D expenditure on total energy)			-		-0.0094	-0.65	-0.0080	-0.6
ln(GDP per capita)	0.6309	11.37	0.6140	12.38	0.4910	7.33	0.4834	8.53
ln(Ratio of industrial energy cons and prod)	0.3362	2.25	0.3971	3.18	0.2353	1.51	0.2407	1.89
Constant	-5.5250	-7.78	-5.6398	-8.33	-3.7897	-4.77	-3.7469	-4.93
Descriptive statistics and Tests								
Tests for model significant								
F-statistic (Fixed effects)	66.34		-		29.34		-	
p-value > F-statistic	0.00		-		0.00		-	
Wald statistic (Random effects)			211.77				91.89	
p-value > Wald-statistic	-		0.00		-		0.00	
Obsetvations								
Observations per group								
Minimum	9		9		9		9	
Maximum	12.8		12.8		12.8		12.8	
Average	14		14		14		14	
Fixed or Random effects vs. pooled OLS	Fixed effects vs. Pooled OLS				Random effects vs. Pooled OLS			
F-statistic (Fixed effects)	0.33		-		0.19		-	
p-value > F-statistic	0.98		-		0.99		-	
LM statistic (Random effects)	-		3.89		-		5.25	
p -value > LM-statistic	-		0.08		-		0.02	
Model goodness-of-fit								
Within	0.533		0.533		0.354		0.353	
Between	0.386		0.368		0.577		0.578	
Overall	0.529		0.529		0.358		0.359	
Hausman test	Fixed vs. random effects				Fixed vs. random effects			
Test statistic	0.82				0.1			
p-value > Test statistic	0.85				0.99			
Decision	Random effects				Random effects			

Table 5: Estimation results of country- and time-specific random effects panel data econometric models

Response variable = ln(CO_2 emissions per capita)	Model A		Model B	
Explanatory variables	**Coefficients**	***t*-stat**	**Coefficients**	***t*-stat**
ln(RD&D expenditure on renewable energy)	-0.0168	-1.59	-	
ln(RD&D expenditure on energy)	-		0.0127	0.91
ln(GDP per capita)	0.6696	8.98	0.6364	8.97
ln(Ratio of industrial energy consumption and production)	0.4779	8.1	0.3777	6.43
Constant	-6.6314	-7.14	-5.9560	-6.4
Descriptive statistics and tests				
Observations	179			
Random effects vs. pooled OLS				
Likelihood ratio (LR) test				
Observed Chi-squared	389.36		383	
p-value > observed-statistic	0.00		0.00	