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ENERGY EFFICIENCY RESEARCH AND DEVELOPMENT: CONSUMPTION- AND ENVIRONMENT-CENTRIC PERSPECTIVES

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Abstract

The quest to develop technologies with minimal adverse environment impact has led to investments in research and development (R&D) targeted at developing energy-efficient technologies or improving the energy efficiency of existing technologies. Despite the increased focus on energy efficiency R&D, studies that examine their impact on environmental performance over time are lacking. Invoking the rebound effect and the ecological modernization theory, we hypothesize relationships between energy efficiency R&D with energy consumption, and emissions, and test them using panel data for OECD countries from 1987 to 2009. Econometric analysis suggests that energy efficiency R&D is negatively associated with per capita emission only. This suggests that any investment in energy efficiency achieves the objective of reducing the adverse environmental impact, thus positively contributing to the environment. The results further suggest that concerns about energy efficiency R&D may be misplaced as it is reducing adverse environmental impact without any significant association with energy consumption. Thus, the rebound effect, which postulates that increased energy efficiency results in more energy consumption, is not valid in the present context. We further examine the growth of improvement in environmental performance over time and show that the effectiveness of energy efficiency R&D remains consistent over time. This suggests that carbon neutral policies are plausible. Implications for research and practice are discussed.

Keywords: *Energy efficiency, Rebound effect, Ecological modernization theory*

1 INTRODUCTION

Recent years have witnessed growing concerns about the harmful ramifications of industrial development and urbanization in the form of climate change and global warming. Findings from the International Panel on Climate Change (IPCC), a body formed by the United Nations (UN), suggest that greenhouse gas (GHG) emissions are responsible for global warming (National Geographic 2011). The growing realization that GHGs are the key reason behind global warming has resulted in two key international legislations, namely, the Kyoto Protocol and the Montreal Protocol aimed at controlling GHG emissions. However, GHG emissions are the outcome of energy consumption (World Resources Institute 1998). Energy-related emissions account for a significant proportion of CO_2 emissions (Baumert et al. 2005). Past estimates suggest that energy-related emissions account for over 80% of the total CO_2 emissions (World Resources Institute & United Nations Environment Program 1996). Hence, energy consumption is a major culprit of global warming.

The identification of energy consumption as a major contributor towards GHG emissions has led to an increased focus on initiatives targeted at curbing the adverse environmental impact of energy consumption. However, such initiatives require heavy capital investment. A yearly investment of $ 170 billion until 2020, will curtail GHG in the atmosphere at 450 ppm, which in turn will prevent the global air temperature from rising beyond $2^{\circ}C$ (Farrell & Remes 2008). Thus, any investment in energy can minimize the damage from global warming. However, the initiatives aimed at reducing the adverse impact of energy face another challenge: energy consumption has a direct impact on a nation’s economic progress (Bozon et al. 2007). With growing industrialization globally, energy consumption is expected to follow suit. Nations concerned about their economic development cannot afford to curtail their energy consumption.

Hence, the challenge in the energy area is two-fold: nations need to reduce the adverse environmental impact of energy consumption, without compromising on energy consumption. This two-fold challenge can be achieved if the ratio of usable energy output to input termed as “energy efficiency” can be improved (Hoffert et al. 2002). Put simply, if the amount of energy required to provide product and services can be reduced, then less energy will be required to support the current level of products and services. This will also result in a decline in energy lost during the conversion of inputs to outputs. This energy is also lost in the form of emissions. Consider the example of automotives, where conversion of fuel (petrol and diesel) into kinetic energy (movement of vehicles) is accompanied by the emission of harmful GHG such as CO_2, and sulphur dioxide. Hence, improving energy efficiency can lead to emissions reduction. The development of new technologies can help reduce the adverse environmental impact of energy consumption by reducing the GHG emissions associated with energy consumption, thus improving energy efficiency as well as achieving decarbonization (Hoffert et al. 2002). Thus, technology is at the heart of the success of energy-related initiatives in improving environmental performance.

This realization has led to an investment in research and development (R&D) targeted at developing energy efficient technologies. Despite the critical role played by energy efficiency R&D investments in reducing the adverse environmental impact of energy consumption, prior research (Geller 2005; Bosetti et al. 2007; Gillingham et al. 2009) have either focused on the evaluation of policies on energy efficiency technologies, or examined the best R&D strategy to achieve emissions reduction. There are micro-level studies such as Haas and Schipper (1998), which examined the impact of efficiency on household energy demand, or industry level studies such as Rohdin and Thollander (2006), which examined the adoption of energy efficiency in Sweden’s manufacturing sector.

There is a lack of studies, which examine the impact of national energy efficiency R&D investments on the national environmental performance measured in terms of emissions. There is also a need to examine the impact of national energy efficiency R&D investment on energy consumption. The examination of these two relationships will demonstrate the role of energy efficiency R&D in curbing global warming as well as its contribution to energy consumption in a country. It is also pertinent to examine if the impact of energy efficiency R&D on national environmental performance remains consistent over time. This will demonstrate whether the effectiveness of such investment improves or declines over time. We therefore address three research questions:

RQ1*: Does energy efficiency R&D increase or decrease energy consumption?*

RQ2*: Does energy efficiency R&D investment curb emissions?*

RQ3*: Does energy efficiency R&D investment influence emissions in a similar fashion over time?*

This study makes the following contributions. First, we empirically examine the relationship between energy efficiency R&D investments and energy consumption, and between energy efficiency R&D and emissions. In so doing, we provide empirical evidence of the performance impact of energy efficiency R&D investment on a country's environmental performance and demonstrate the effect of energy efficiency R&D investment on a country's environmental performance over time.

Second, we draw upon theories from energy economics and industrial ecology to examine the various relationships. Thus, we contribute to the IS literature by bringing theoretical lenses unexplored in the IS domain to examine emerging issues associated with IS, such as the role of technology in combating climate change and global warming.

Third, we integrate two distinct streams of theories, one primarily related to the microeconomic domain, and the other related to the macroeconomic domain to examine the relationship between two distinct but intertwined outcome variables. In doing so, we illustrate that technology can achieve two conflicting objectives, one driven by microeconomic behavior, and the other driven by macroeconomic concerns.

Fourth, our analysis is based on the objective measures of environmental performance and energy efficiency R&D investments reported by countries. In addition, our analysis spans a 21-year time period rather than a single point of time and thus our results indicate the impact of energy efficiency R&D investment on energy consumption, and a country's environmental performance over a long time period. The analysis of objective data over two decades allows us to control for various causes of endogeneity and provides robust estimates for the various relationships.

The rest of the paper is structured as follows. We review the relevant literature. We then propose our framework and hypotheses. Next, we describe our dataset and analysis procedure. This is followed by the results, discussion, implications for research and practice, and concluding remarks.

2 THEORETICAL ORIENTATION AND HYPOTHESES

Any investment in energy efficiency R&D has to meet two conflicting objectives. First, it has to improve environmental performance. Second, it has to achieve this without compromising on energy consumption, as energy consumption is strongly related to economic development (UNEP 2005). Energy consumption at the national level is the sum total of energy consumed by various units (individuals and firms) in a country. The energy consumption by different units has microeconomic roots as individual consumption depends on demand, supply, and price (Haas & Schipper 1998).

Thus, there is a need to examine the possible ramifications of energy efficiency R&D investment on factors such as energy prices, supply, and demand to understand the relationship between energy efficiency R&D investment and energy consumption. We therefore draw upon microeconomic theory in energy economics to hypothesize the relationship between energy efficiency R&D investment and energy consumption.

2.1 Prior Research on Energy Efficiency

There is a long tradition of research on energy efficiency. Energy efficiency has been a subject of continuous investigation in domains such as energy policy, and engineering. Prior research on energy efficiency has focused on policy-related issues such as barriers to investment in energy efficiency (Sutherland 1991), implications of energy efficiency gap (Jaffe and Stavins 1994), salience of organizational characteristics in investment in energy efficiency (DeCanio and Watkins 1998), impact of energy efficiency on energy savings (Herring 1999), implications of energy efficiency for environment (Herring 2000), impact of energy efficiency on consumption (Greening et al. 2000), and contribution of industrial energy efficiency technologies and policies to reduce GHG emissions

(Worrell et al. 2009). Research in the domain of engineering has focused on technological solutions that are targeted at improving energy efficiency such as wireless sensor networks (Sankarasubramaniam et al. 2003)

More recently, the idea of energy efficiency has also been examined in the IS domain. Laitner (2003) discussed the potential impact of IT on energy consumption in the US. Collard et al. (2005) examined the impact of diffusion of information and communication technologies (ICT) on electricity consumption in the French service sector. Watson et al. (2010) discussed the potential of IS to increase energy efficiency. Hilty (2008) focused on the potential of IT to improve eco-efficiency. IS research on energy consumption has focused on smart grids which include smart meters, and self-monitoring infrastructure (Corbett 2011). IT is now a major component of initiatives aimed at improving energy efficiency. IT artifacts focused on energy efficiency include applications such as "Visual" and IT assets such as "wireless controls" (EERE 2012). The applications can perform various functions such as whole building analysis (energy simulation, load analysis), and standard compliance. IT assets include wireless sensors and wireless control technology for advanced sensing, and power metering. We now incorporate theoretical lens dominant in the streams of energy economics and industrial ecology to understand the potential impact of energy efficiency R&D.

2.2 Rebound Effect

The rebound effect evolved as a theoretical lens for empirical examination in the form of the "Khazzoom – Brookes postulate" (Saunders 1992). This postulate states that energy efficiency gains results in an increase in energy use. The rebound effect has been at the center of debate and discussion in the field of energy economics (Sorrell & Dimitropoulos 2007), and was first described in the context of improving the efficiency of steam engines (Jevons 1865), where improving the efficiency of steam engine leads to increased coal demands. The rebound effect emerged in modern research literature, when Khazzoom (1980) proposed that an improvement in energy efficiency would not achieve a reduction in energy use, as energy becomes cheaper and thus more accessible. This idea has been debated in prior research, as researchers such as Grubb (1990) and Amory et al. (1988) countered that microeconomic household consumption cannot be linked to macroeconomic consumption level. Brookes (1990) argued that energy efficiency would not limit GHG emissions due to the growth in energy consumption. The rebound effect can be classified into three types, namely, direct rebound effects (decrease in price of energy due to improved energy efficiency), indirect rebound effects (increase in demand of products that consumes energy due to improved energy efficiency), and economy-wide effects (reduction in price of energy intensive goods and services due to improved energy efficiency) (Sorrell & Dimitropoulos 2007). The different types of rebound effect thus incorporate both microeconomic and macroeconomic effects (Saunders 1992). Hence, the rebound effect, which initially was focused on the microeconomic context, has been extended to the macroeconomic context. Hilty (2008) raised the potential problem of rebound effect in context of IT. He argued that growth of IT is a striking example of the rebound effect. His primary argument was that despite the fact that Moore's law has consistently been valid and computing power has drastically grown, energy consumption has continued to increase. Williams (2011) proposed the rebound effect as a serious challenge that can act as an impediment to the contribution of IT in improving the environment. However, the rebound effect has not been empirically investigated in IS domain, but continues to be examined in the energy literature. Drawing on the rebound effect, we argue that an investment in energy efficiency R&D will result in increased per capita consumption.

Energy efficiency R&D investments are targeted at improving the energy efficiency of industrial processes, equipment and systems, facility design, appliances, transportation, and agriculture (IEA 2011). Technologies play an important role in improving energy efficiency, and thus are at the center of such investments. The focus of such investments is on the technologies used in different processes and encompasses technological artifacts such as smart meters, energy management systems, efficient communication technologies, control systems, smart chargers, metering devices, grid architecture, sensors, and IT systems (IEA 2011). Thus, IT artifacts are salient in R&D investments targeted at improving energy efficiency.

Energy generation requires a combination of inputs such as technology, labor and material. When nations invest in energy efficiency R&D, the cost of energy generation may come down due to decrease in technology cost, substitution of labor by technology through automation, and substitution of costlier materials by cheaper materials (Birol & Keppler 2000; Greening et al. 2000). This makes it affordable for a larger proportion of the population and thus may increase energy consumption.

With the decrease in energy prices, products and services that consume energy may become more affordable, as their cost of ownership may reduce. In addition, households may direct their savings from the direct rebound effect to the consumption of products and services that consume energy (Murray 2011). Hence, an investment in energy efficiency R&D may result in indirect rebound effects.

The reduction in energy prices due to technological improvement may result in an increased consumption of energy by different sectors of an economy, and hence an increased energy consumption at the national level (Sorrell 2007). This may result in an economy-wide rebound effect.

The investment in R&D targeted at energy efficiency may reduce the cost of energy consumption (through developing technologies that substitute costly inputs with relatively cheaper inputs), and make the energy generation process more efficient (through the use of new monitoring and sensor technologies, and energy management systems). Therefore, an investment in energy efficiency R&D may yield an increase in energy consumption at the individual as well as the national level, which implies that per capita consumption of energy may increase. We therefore hypothesize:

H1: Per capita energy efficiency R&D investment is positively associated with per capita energy consumption.

The key underlying argument behind hypothesis H1 is that technology development triggered by investment in R&D may make the energy more affordable, and hence promote its increased use.

2.3 Ecological Modernization Theory

As discussed, investing in technology can reduce the cost of services such as energy, and increase their consumption. This view is consumption-centric as technology plays a role in increasing the consumption of a service. The key issue is the role of technology in preventing environmental degradation, and hence, we focus on an environment-centric perspective.

One theory that has emerged in the stream of environmental sociology is the ecological modernization theory (EMT) whose key premise is that technological development can facilitate ecological sustainability (York & Rosa 2003). EMT emphasizes on the role of technological development to reduce the adverse environmental impact of industrial production (Huber 1982, 1985). Science and technology are valued for their role in addressing environmental problems (Mol & Sonnenfeld 2000). While EMT has evolved over time, and now encompasses social practices, institutional designs, and policies, the salience of technology in improving the ecological compatibility of industrial processes remains a core EMT hypothesis (Mol & Sonnenfeld 2000; Buttel 2000). EMT assumes that society can tackle environmental problem by developing technology through the process of modernization (York et al. 2010). Technology is considered as the cornerstone of the EMT argument. Economics and technology can positively influence environmental quality, and economic growth simultaneously (York et al. 2010). There is even empirical support for the view that the use of technologies can improve environmental performance (Sarkis & Cordeiro 2012). EMT also emphasizes on government policies as a promoter of technological development to achieve superior environmental performance (Mol 2010). We draw on EMT to hypothesize the relationship between energy efficiency R&D investments and environmental performance, measured by per capita emissions.

Investment in energy efficiency R&D is targeted at reducing the energy lost during the energy generation process. A significant portion of energy is lost as CO_2 emissions (Hoffert et al. 2002). A reduction in energy loss during the energy generation process will thus result in a reduction in emissions. The development and utilization of technologies such as smart grids can facilitate energy conservation by increasing the awareness about energy usage and wastage. Smart grids also facilitate the adoption of renewables (Haas 2010). Thus, smart grids can facilitate emissions reduction by promoting an efficient use of energy and reducing its waste during processes such as transmission and distribution (Pratt et al. 2010).

Likewise, technologies such as smart sensors, smart metering, and communication technologies can reduce emissions by facilitating a reduction in transmission and distribution losses, integration of renewable energy resources, demand side management, and providing usage information to users (OECD 2009). In addition, investment in energy efficiency R&D also promotes the use of renewable energy such as solar, wind, and tidal energy that have lower carbon footprints as compared to conventional sources of energy such as fossil fuels, thus facilitating emissions reduction. Investments in energy efficiency R&D also foster an improvement in energy efficiency of existing technologies, and in turn reduce energy loss and emissions from existing technologies (EPA 2009)

We therefore argue that investments in energy efficiency R&D promote technologies that have the potential to reduce emissions, and will therefore reduce per capita emissions. We summarize the above arguments in the following hypothesis:

H2: Per capita energy efficiency R&D investment is negatively associated with per capita emissions.

2.4 Time Dimension of Energy Efficiency R&D Investment

We have hypothesized a positive relationship between energy efficiency R&D investments and per capita energy consumption, and a negative relationship between energy efficiency R&D investments and per capita emissions. However, research on R&D investments suggests that R&D investment is associated with diminishing marginal returns (Faff et al. 2013). We have hypothesized returns (in the form of negative relationships between energy efficiency R&D investments and per capita emissions) from R&D investments in the context of per capita emission, whereas the hypothesized relationship between energy efficiency R&D investments and per capita energy consumption indicates risks associated with energy efficiency R&D investments. Prior research on R&D investment have focused on returns rather than risks; following them we focus on returns from energy efficiency R&D investment.

This raises an interesting question: will investing in energy efficiency R&D consistently influence per capita emissions. The support for diminishing returns in the context of R&D investments has been observed (Everson 1993; Kortrum 1993; Griliches 1994). The underlying argument is that R&D investments are targeted at a wide array of innovations, and due to its spread, there is a tendency for diminishing returns (Ha & Howitt 2005).

However, in the context of OECD countries, Madsen (2007) did not find any support for diminishing returns to R&D. The rationale for this finding was that R&D was not diluted as the economy was also growing, which contributed to innovation. Drawing on this rationale, we argue that there will no diminishing returns to energy efficiency R&D as it may promote the growth of the energy efficient sectors, and consequently economic growth. The growth of economies and the subsequent changes it will bring in production processes and domestic consumption further promote energy efficient and environment friendly practices. Thus, per capita energy efficiency R&D investments will negatively influence per capita emissions consistently. We therefore hypothesize:

H3: There are no diminishing returns to per capita energy efficiency R&D investments.

3 METHOD

3.1 Operationalization of Constructs

We compiled data on annual energy efficiency R&D investments from the OECD iLibrary (IEA Energy technology R&D Statistics), which houses the annual energy efficiency R&D investment data for OECD countries from 1987 to 2009. The 25 OECD countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the U.K., and the U.S. The annual energy efficiency R&D investment is in million USD at 2010 prices. Hence, our data control for inflationary pressures and exchange rates. We compute per capita energy efficiency R&D investment using the annual population data drawn from the World Bank portal. We lag the independent variables by two years, as research suggests that there is a time lag between R&D investment and the realization of benefits (Seldon 1987). Thus, we include per capita energy efficiency R&D investment from 1987 to 2007 as our predictor variable in the analysis. We have 404 observations for 25 countries (16 observations per country).

We have emissions for the corresponding countries from 1989 to 2009 from the OECD statistics portal. The emissions include total emissions of CO_2 (emissions from energy use and industrial processes), methane emissions, nitrous oxide, hydro fluorocarbons, perfluorocarbons, and sulphur hexafluoride in terms of thousand tonnes CO_2 equivalent. We compute the per capita emissions by dividing the annual emissions by population.

We have energy consumption in KT oil equivalent for the corresponding countries from 1989 to 2009 from the World Bank data portal. The energy used here includes indigenous production, imports and stock changes. This reflects the total primary energy used (energy used before conversion) in an economy. As discussed, energy efficiency will lower the cost of energy generation, and hence more energy may be consumed by users, which may manifest as an increase in primary energy usage. Thus, this measure is appropriate for examining the rebound effect.

3.2 Control Variables

We control for various confounding variables to investigate the relationship between predictor and criterion variables. We control for a country's size as size has been found to influence emissions and consumption (UNEP 2004). We operationalize size using the logarithm of the total area in km^2. The population of a country may be associated with the characteristics of the economy such as labour or capital intensity. It may also influence the various programs aimed at the distribution of wealth and hence, the income level. We therefore control for population using the logarithm of population. The GDP of a country may indicate the level of development and hence, the income effect. Citizens of more developed countries have higher incomes and thus higher energy consumption and emissions. Thus, we control for GDP using the logarithm of GDP. These sampled OECD countries are developed countries and the services sector account for a major proportion of their economies. As the size of the services sector varies across countries, we control for the effect of size of this sector, operationalizing it using the GDP generated by the services sector. Despite various controls, there may be many variables at the country level, which may influence a country's consumption and emissions. We therefore control for country specific effects by using country dummies as controls in our study.

3.3 Econometric Specifications

We use two models to investigate our research questions. Model 1 examines if energy efficiency R&D investment is associated with per capita energy consumption. Model 2 examines the relationship between energy efficiency R&D investments and per capita emissions. Hence, the econometric specification for our models is as follows:

Model I

$(\text{Per capita energy consumption})_{i,\,t+2} = \alpha + \beta_1 (\text{per capita energy efficiency R\&D investment})_{i,\,t} + \beta_2 (\log(\text{GDP})) + \beta_3 (\text{services sector size}) + \beta_4 (\log(\text{size})) + \beta_5 (\log(\text{population})) + \beta_6 ((\text{country specific effects})) + \varepsilon$

Model II

$(\text{Per capita emissions})_{i,\,t+2} = \alpha + \beta_1 (\text{per capita energy efficiency R\&D investment})_{i,\,t} + \beta_2 (\log(\text{GDP})) + \beta_3 (\text{services sector size}) + \beta_4 (\log(\text{size})) + \beta_5 (\log(\text{population})) + \beta_6 ((\text{country specific effects})) + \varepsilon$

Analyses

We have an unbalanced panel data linear model, as there are different numbers of observations for different countries. There is also the possibility of serial correlation within a panel as the values of consumption, and emissions may be linked to prior values. We address these issues through OLS regression with clustered robust standard errors. By using robust standard errors, we ensure that our estimates are robust against any heteroskedasticity in the sample, and our estimates are unbiased. We check the robustness of our results using the random and fixed effects models. We also check the robustness of our estimates using the Hausman Taylor regression. The rationale is that increased energy consumption may result in a higher income effect by influencing the growth of a country, thus making energy consumption, and GDP endogenous.

4 RESULTS

We used STATA 11 for our analysis. Table 1 contains the descriptive statistics for the variables and their intercorrelations. Table 2 shows the OLS regression results with clustered robust standard errors for the two models. Starting with the estimates for Model 1, we note that the coefficient for per capita energy efficiency R&D investment (β= -.003, $p>.05$) is insignificant. Hence, H1 is not supported. Among the control variables, population, and GDP (β= 1.271, $p<.05$; β= 0.174, $p<.05$) are positively associated with per capita energy consumption, whereas the services sector (β = -.115, $p<.05$) is negatively associated with per capita energy consumption. Most of the country specific effects are significant. For Model II, the coefficient for per capita energy efficiency R&D investments (β = -.026, $p<.01$) is negative and significant. Therefore, H2 is supported. Among the control variables, population (β= 1.638, $p<.05$) is positively associated with per capita emissions, while GDP (β = -.181, $p<.05$) is negatively associated with per capita emissions. Like Model I, the services sector (β = -.125, $p<.05$) is negatively associated with per capita emissions. Most of the country specific effects are significant.

4.1 Robustness Checks

We conducted various tests to ensure the robustness of our results. Since Table 2 showed relatively high correlations between the different control variables, we conducted an OLS clustered robust regression after dropping log (population), and the services sector size due to their high correlations with log (GDP). The estimates are similar to previous results.

The results of the panel data analysis such as the random effects model and fixed effects model also provide credence to our results (Tables 3 and 4). We further test the robustness of our results using the Hausman Taylor regression to check for reverse causality (Table 5). The underlying argument is that a reduction in per capita emissions may lead to a decrease in energy efficiency R&D investment, or per capita energy consumption might influence economy size manifest in the form of GDP. The estimates are similar, lending support for the robustness of our results.

The dependent variables in our study are per capita energy consumption, and per capita emissions. The minimum possible values for both the dependent variables are zero. This implies that our outcome variable is left-censored; hence, we check the robustness of our estimates using Tobit regression. The estimates are similar, thus providing support for the robustness of our results.

There is a wide variation in the scales of our variables; hence, we do a log- log transformation to further check the robustness of our findings. All variables without any scaling were log transformed and estimates were computed using clustered robust regression. The results were similar to our prior analysis, suggesting adequate robustness of our estimates.

Variables	Mean	S.D.	1	2	3	4	5	6
1.Per capita emissions (in 1000 tonnes CO_2 equivalent)	0.012	0.005	1.00					
2. Per capita energy consumption (in KT oil equivalent)	0.004	0.002	0.76*	1.00				
3. Per capita energy efficiency R&D investment (in million USD at 2010 prices and exchange rates scaled by 10^{-6})	1.96	2.26	0.04	0.36*	1.00			
4. Log(size)	5.57	0.70	0.61*	0.52*	-0.10	1.00		
5. Log(population)	7.30	0.53	0.15*	0.08	-0.27*	0.43*	1.00	
6. Log (GDP)	11.69	0.56	0.27*	0.31*	-0.10	0.43*	0.89*	1.00
7. Services sector size (in trillions USD)	0.9	1.7	0.41*	0.39*	-0.04	0.45*	0.72*	0.78*

*Note: ** denotes significance at 5%*

Table 1. Descriptive Statistics and Correlation

Variables	Estimates	Standard Errors	Beta Estimates	Estimates	Standard Errors	Beta Estimates
	Model I per capita energy consumption (in KT oil equivalent)			Model II per capita emissions (in KT CO_2 equivalent)		
Per capita energy efficiency R&D investment (in million USD at 2010 prices and exchange rates)	-2.522	16.425	-0.003	-61.433*	29.900	-0.026*
Log(size)	-0.001	0.001	-0.537	-0.003	0.004	-0.365
Log(population)	0.004*	0.002	1.271*	0.016**	0.006	1.638**
Log (GDP)	0.001*	0.000	0.174*	-0.002*	0.001	-0.181*
Services sector size	0.000**	0.000	-0.115**	0.000**	0.000	-0.125**

*Note: **,* denote significance at 1%, and 5%, respectively (one-tailed). Country dummies were included in the regressions, but their estimates are not shown for the sake of brevity. They are discussed in the Results section.*

Table 2. Model I and II Estimates

Variables	Estimates	Standard Errors	Estimates	Standard Errors
	Model I Per capita energy consumption (in KT oil equivalent)		Model II Per capita emissions (in 1000 tonnes CO_2 equivalent)	
Per capita energy efficiency R&D investment (in million USD at 2010 prices and exchange rates)	0.024	16.248	-56.766*	28.064
Log(size)	0.001	0.000	0.004**	0.001
Log(population)	0.000	0.001	0.002	0.002
Log (GDP)	0.001**	0.000	0.000	0.001
Services sector size	0.000**	0.000	0.000**	0.000

*Notes: **,* denote significance at 1%, and 5%, respectively (one-tailed).*

Table 3. Random effect Estimates

Variables	Estimates	Standard Errors	Estimates	Standard Errors
	Model I Per capita energy consumption (in KT oil equivalent)		Model II Per capita emissions (in 1000 tonnes CO_2 equivalent)	
Per capita energy efficiency R&D investment (in million USD at 2010 prices and exchange rates)	-2.522	15.923	-61.433*	28.986
Log(population)	0.004**	0.002	0.016**	0.006
Log (GDP)	0.001**	0.000	-0.002*	0.001
Services sector size	0.000**	0.000	0.000**	0.000

*Notes: **,* denote significance at 1%, and 5%, respectively (one-tailed).*

Table 4. Fixed effect Estimates

Variables	Estimates	Standard Errors	Estimates	Standard Errors
	Model I Per capita energy consumption (in KT oil equivalent)		Model II Per capita emissions (in 1000 tonnes CO_2 equivalent)	
Per capita energy efficiency R&D investment (in million USD at 2010 prices and exchange rates)	-2.522	8.490	-61.432*	29.069
Log(size)	-0.001	0.001	-0.003	0.002
Log(population)	0.004**	0.000	0.016**	0.004
Log (GDP)	0.001**	0.000	-0.002**	0.000
Services sector size	0.000**	0.000	0.000**	0.000

*Notes: **,*, denote significance at 1%, and 5%, respectively (one-tailed).*

Table 5. Hausman Taylor Regression Estimates

4.2 Alternative Measure

One goal achieved through energy efficiency is the reduction in energy required to attain the current level of products and services (Hoffert et al. 2002), and consequently a reduction in the adverse environmental impact associated with economic activities. We therefore examine if energy efficiency R&D is negatively associated with the energy required to produce an output. The energy required to produce an output is measured by energy intensity, which is defined as the energy consumption per dollar of GDP. A low energy intensity indicates that a country is able to produce a unit of output using less energy (Tay 2009). We conduct clustered robust regression to examine the relationship between the energy efficiency R&D, and energy intensity. The results provide support for the negative relationship between the energy efficiency R&D, and energy intensity ($\beta = -.083$, $p<.05$). This suggests that energy efficiency R&D helps nations to reduce the energy required to produce a unit of output. The energy used during the transformation of inputs into outputs is associated with emissions, thus the negative relationship between energy efficiency R&D and energy intensity provides further credence to our finding that energy efficiency R&D is negatively associated with per capita emissions.

4.3 Testing the Time Dimension

We attempt to answer our question on the diminishing returns associated with energy efficiency R&D investments using latent growth curve modeling, which is a statistical technique to examine the growth trajectory of variables (Acock 2008). The mean values show that there is an overall trajectory, with decline in per capita emissions over time. However, the slope does not have significant covariance implying the absence of a time dimension. The latent graph (Figure 1) shows that there is no support for diminishing returns with energy efficiency R&D investments.

We check the robustness of our finding by computing estimate for time variable in a multilevel model with per capita emissions as the dependent variable. The rationale behind using the multilevel model is that it is similar to latent growth curve model (UCLA Academic Technology Services 2012). The estimate for time is insignificant ($b = -0.000$, $p = 0.179$), thus providing support for the absence of time dimension. Thus, this result provides support for robustness of our finding. We summarize our results in Table 6.

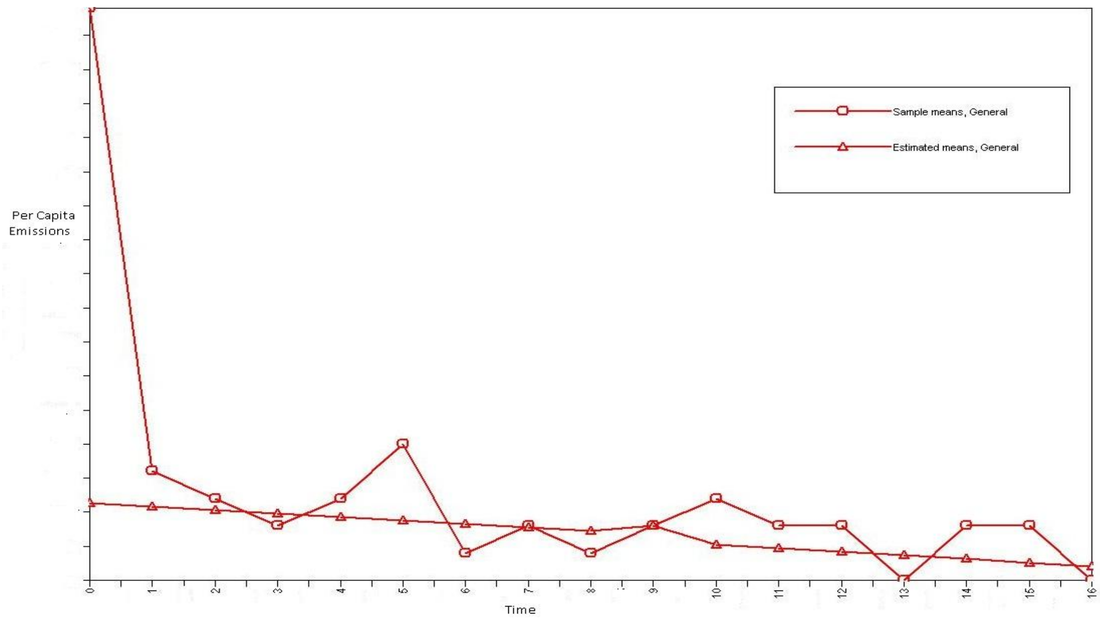

Figure 1. *Latent Growth Model*

Hypotheses	Effects	Supported
Per capita energy efficiency R&D investment → Per capita energy consumption	-	**No**
Per capita energy efficiency R&D investment → Per capita emissions	+	**Yes**
Per capita energy efficiency R&D investment → Per capita emissions	No time dimension	**Yes**

Table 6. *Summary of Results*

5 DISCUSSION

In Model 1, the results show that there is no significant relationship between per capita energy efficiency R&D investment and per capita energy consumption. One plausible explanation is that energy efficiency R&D investment may not result in a substantial decrease in energy service prices, thus restricting their use. Another explanation is that due to the improvement in energy efficiency, the amount of primary energy required to generate a prior level of usable energy may reduce, thus compensating for any increase in energy consumption due to a reduction in the energy services price. The non-significant results can also be attributed to the inelasticity of energy demand in OECD countries (Sorrell 2007). Our results are consistent with prior policy studies such as Afsah et al. (2012), which did not find any support for the rebound effect in domestic energy consumption as well as few sectors' energy consumption in the US and Canada.

Our results show that the per capita energy efficiency R&D investment is negatively associated with per capita emissions, and thus has a positive influence on national environmental performance. This suggests that per capita energy efficiency R&D investment facilitates the development of technologies with lower carbon footprint, thereby supporting the policy stance of agencies such as the IEA, and EPA, which promote energy efficiency as a key tool to combat GHG emissions and global warming.

The results suggest that there are no diminishing returns to energy efficiency R&D investment. This finding is consistent with the findings on R&D investment in OECD countries such as Madsen (2007). One explanation is that energy efficiency R&D investment leads to the growth of sectors that are less energy intensive, which adds to the positive influence of energy efficiency R&D investment. Another explanation is that we have not yet reached the phase where such investments will start yielding diminishing returns. The space for energy efficient products and services are still evolving, it has not saturated yet, and thus there are no diminishing returns.

The results also show that GDP and the services sector are negatively associated with per capita emissions, suggesting that economic growth is good for the environment, thus providing support for the other tenets of EMT. As our sample comprises only developed countries, our interpretation must incorporate this context. Hence, a higher GDP means more money for such R&D investments, compared to developing economies who tend to commit more of their GDP to poverty alleviation programs. The higher allocation for energy efficiency R&D investment will positively influence environmental performance. The rationale for a negative relationship between services sector size and per capita emissions is that the services sector is characterized by less polluting inputs.

6 IMPLICATIONS

6.1 Implications for Research

There are several implications for research emerging from this study. First, this study builds on the rebound effect and EMT to examine the environmental value of energy efficiency R&D investment. The findings indicate that in terms of overall energy consumption, rebound effects are not applicable. Future research can examine in detail the reasons behind this finding. Specifically, researchers can examine if different types of rebound effects are individually insignificant or some rebound effects are individually significant but collectively otherwise. This will demonstrate empirically the presence or absence of any synergy between the different types of rebound effects.

Second, our findings lend support to EMT in the context of OECD countries. The results show a negative relationship between per capita energy efficiency R&D investment and per capita emissions. This result necessitates the need to examine the relationships in context of emerging and developing economies and investigate country specific characteristics that contribute to the positive influence of per capita energy efficiency R&D investments, and the generalizability of per capita energy efficiency R&D investment as an important component of global initiatives to combat global warming beyond national boundaries.

Third, there is a need to examine the returns to per capita energy efficiency R&D investments in the context of emerging economies to determine if the relationship is driven by the development of energy efficient industries or other factors. Future research can investigate if per capita energy efficiency R&D investment will continue to yield consistent effect or start exhibiting diminishing returns, once the energy efficiency of the overall economy reaches a certain threshold value.

Fourth, among the control variables, GDP and services sector size are negatively associated with per capita emissions. Future research can investigate if these findings are generalizable to developing economies. There is a need to examine the contribution of economic characteristics of a nation in terms of the distribution of GDP among the different sectors to ascertain, if the negative relationship between GDP and per capita emissions is valid in different economies in different stages of development. Future research can also examine if the expansion of the services sector will always contribute to better environmental performance, or beyond a certain threshold value, this relationship will reverse its direction.

Fifth, future research can examine the relationship between specific energy efficiency R&D investment such as investment on smart grids, sensor, or clean processes to ascertain the environmental value of specific energy efficiency technologies.

Sixth, future research can also examine the complex mediating relationships such as energy efficient technologies as mediators between per capita energy efficiency R&D investment, and per capita emissions or explore the causal linkages among per capita energy efficiency R&D investment, per capita energy consumption, and per capita emissions in a single model.

6.2 Implications for Practice

This study has several implications for practice. First, the results provide empirical evidence to policy makers that investing in energy efficiency R&D has environmental benefits. This study also demonstrates that there are no significant diminishing returns to energy efficiency R&D investments. Thus, nations can invest more in energy efficiency R&D and supplement it with policies and incentives to achieve further improvement in environmental performance and strive toward a carbon neutral economy.

Second, this study provides empirical evidence that investment in energy efficiency R&D need not have a rebound effect. An improvement in energy efficiency may only improve the energy conversion process, but the technologies involved may be expensive. This has two lessons for policy makers. First, they can control energy consumption by implementing pricing schemes and policies that do not reduce the cost of energy. However, this may be counterproductive as energy consumption is positively associated with economic growth. Policy makers can avoid this by discriminating policies for households and industry. Second, investment in energy efficiency R&D may be insufficient to make energy services affordable. This suggests a need for more initiatives apart from R&D investment to make technology affordable.

Third, our findings suggest that economic development (GDP growth) and the prominence of the services sector in an economy is positively associated with better environmental performance. Thus, countries need to work on increasing their GDP growth rate and move to a service-oriented economy.

7 LIMITATIONS

There are several limitations in this study. First, we have a limited set of countries. Future research can examine the various relationships discussed in this study using a larger sample. With an increasing interest in the human impact on the environment, and an increase in public availability of national data, future research can overcome the constraint related to information availability. Second, due to the paucity of data, we have treated major economic variables as control variables and tried to control for other omitted variables using country specific effects, rather than energy pricing and policy variables. This limitation will be reduced, as more granular sustainability data become available.

8 CONCLUSION

From a theoretical standpoint, this study contributes to the broader green IT and sustainability literature by empirically establishing the link between energy efficiency R&D investments and measures of environmental performance (per capita emissions). Energy efficiency R&D investments are targeted at development and deployment of energy efficient technologies and green IT artifacts such as smart grids, are a major component of such technologies. Thus by establishing the link between energy efficiency R&D investments and measures of environmental performance, we also provide a clue to the potential relationship of development and deployment of green IT technologies with measures of environmental performance. Our study also adds to the environmental economics literature by empirically demonstrating that the rebound effect may not be applicable in the context of macroeconomic indicators of energy consumption. Our work also suggests that the growth trajectory of per capita emission is independent of time. As such, there is no evidence for diminishing returns to energy efficiency R&D investments. Through this study, the notion of a rebound effect and EMT offers a rich theoretical framework with considerable potential for further enhancing our understanding of the impact of energy efficiency on a country's environmental performance. Future research can delve deeper into how nations can successfully adopt policies and mechanisms (market as well as regulatory) in their endeavour to improve environmental performance.

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