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Enquiries:

***Director of SEEC and Editor of SEEDS*:**
Lester C Hunt
SEEC,
Department of Economics,
University of Surrey,
Guildford GU2 7XH,
UK.

Tel: +44 (0)1483 686956
Fax: +44 (0)1483 689548
Email: L.Hunt@surrey.ac.uk

www.seec.surrey.ac.uk

Surrey Energy Economics Centre (SEEC)
Department of Economics
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ENERGY DEMAND AND ENERGY EFFICIENCY IN THE OECD COUNTRIES: A STOCHASTIC DEMAND FRONTIER APPROACH *

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ABSTRACT

This paper attempts to estimate a panel 'frontier' whole economy aggregate energy demand function for 29 countries over the period 1978 to 2006 using parametric stochastic frontier analysis (SFA). Consequently, unlike standard energy demand econometric estimation, the energy efficiency of each country is also modelled and it is argued that this represents a measure of the underlying efficiency for each country over time, as well as the relative efficiency across the 29 OECD countries. This shows that energy intensity is not necessarily a good indicator of energy efficiency, whereas by controlling for a range of economic and other factors, the measure of energy efficiency obtained via this approach is. This is, as far as is known, the first attempt to econometrically model OECD energy demand and efficiency in this way and it is arguably particularly relevant in a world dominated by environmental concerns with the subsequent need to conserve energy and/or use it as efficiently as possible. Moreover, the results show that although for a number of countries the change in energy intensity over time might give a reasonable indication of efficiency improvements; this is not always the case. Therefore, unless this analysis is undertaken, it is not possible to know whether the energy intensity of a country is a good proxy for energy efficiency or not. Hence, it is argued that this analysis should be undertaken to avoid potentially misleading advice to policy makers.

JEL Classification: D, D2, Q, Q4, Q5.

Keywords: Energy demand; OECD; efficiency and frontier analysis; energy efficiency

Energy demand and energy efficiency in the OECD countries: a stochastic demand frontier approach[$]

Massimo **Filippini**[#] and Lester C **Hunt**

Centre for Energy Policy and Economics (cepe), ETH Zurich and Department of Economics, University of Lugano, Switzerland

Surrey Energy Economics Centre (SEEC) and Research Group on Lifestyles Values and Environment (RESOLVE), Department of Economics, University of Surrey, UK

Massimo.Filippini@usi.ch

L.Hunt@surrey.ac.uk

 # Corresponding Author

1 Introduction

During the last 20 years, there has been considerable debate within energy policy about the possible contribution from an improvement in energy efficiency and on the effectiveness of ecological tax reforms in the alleviation of the greenhouse effect and in the decrease of the dependency on fossil fuels. In order to design and implement effective energy policy instruments to promote an efficient and parsimonious utilization of energy, it is necessary to have information on energy demand price and income elasticities in addition to sound indicators of energy efficiency.[1]

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[1] An energy efficiency indicator reflects the relationship between energy use and some relevant monetary or physical indicators measuring an economic activity. This type of indicator can defined at different levels of

In practical energy policy analysis, the typical indicator used is energy intensity, defined as the ratio of energy consumption to GDP. This is highlighted by a report from the International Energy Agency (IEA, 2009) on the Energy Efficiency Policies in the G8, which states that since the 1970s many countries have promoted energy efficiency improvements, which is illustrated by the decline in energy intensity. The report goes on to say that **"**Energy intensity is the amount of energy used per unit of activity. It is commonly calculated as the ratio of energy use to GDP. *Energy intensity is often taken as a proxy for energy efficiency, although this is not entirely accurate* since changes in energy intensity are a function of changes in several factors including the structure of the economy and energy efficiency" (our emphasis, p. 15). This highlights the weakness of this simple aggregate energy consumption to GDP ratio in that it does not measure the level of 'underlying energy efficiency' that characterizes an economy; hence, it is difficult to make conclusions for energy policy based upon this simple measure.

In the energy economics literature some approaches have been proposed in order to overcome the problems related to the use of simple monetary based energy efficiency indicators such as the energy-GDP ratio; such as Index Decomposition Analysis (IDA) and frontier analysis. IDA is basically a bottom-up framework that can be used to create economy-wide energy efficiency indicators.[2] Whereas frontier analysis is based on the estimation of a parametric, as well as a non-parametric, best practice production frontier for the use of energy

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economic activity aggregation, e.g. economy-wide, sector, sub-sector, firm etc. See Patterson (1996) for further discussion.

[2] See Ang (2006) for a general discussion and application of this method.

where the level of energy efficiency is computed as the difference between the actual energy use and the predicted energy use.[3]

An example of the use of parametric frontier analysis at the sectoral level is Buck and Young (2007) who used a parametric approach to estimate a stochastic energy use frontier function for a sample of Canadian commercial buildings, with energy use per square foot as a function of several variables pertaining to the activities and physical characteristics of the building. Another example, Boyd (2008), estimated an energy use frontier function for a sample of wet corn milling plants, where energy use is a function of four output variables and the capacity utilization. Both of these studies utilize the stochastic frontier function approach introduced by Aigner et al. (1977). An example of a non-parametric approach is Zoe and Ang (2008) who measured the energy efficiency performance of 21 OECD countries over 5 years (1997-2001) using a DEA model that consisted of four energy inputs, two non-energy inputs, a desirable output, GDP, and an undesirable output, CO2 emissions.[4]

In this paper, following the parametric frontier approach, an energy demand frontier function is estimated in order to attempt to isolate 'underlying energy efficiency', by explicitly controlling for income and price effects, country specific effects, climate effects and a common Underling Energy Demand Trend (the UEDT, capturing 'exogenous' technical progress and other exogenous factors). Hence, it allows for the impact of 'endogenous' technical progress' through the price effect and 'exogenous' technical progress through the UEDT.

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[3] See Huntington (1994) for a discussion on the relation between energy efficiency and productive efficiency using the production theory framework. One of the first studies that made use of the frontier approach was Ferrier and Hirschberg (1992).

[4] During the last few years several studies have also been published on the measurement of environmental performance of OECD countries using an environmental DEA approach that also considers energy as an input in to the production process. See for instance, Zofio and Prieto (2001) Zhou, et al. (2008).

The aim is to analyse economy wide energy efficiency; hence, the estimated model introduced below is for aggregate energy consumption for the whole economy. Economy wide aggregate energy demand is derived from the demand for energy services such as heat, illumination, cooked food, hot water, transport services, manufacturing processes, etc. To produce the desired services it is generally necessary to use a combination of energy fuels and capital equipment such as household appliances, cars, insulated walls, machinery, etc. This implies that the demand for energy is influenced by the level of energy efficiency of the equipment and, generally, of the production process. For instance, some relatively new equipment and production processes are able to provide the same level of services and products using less energy than old equipment. This comes from research and development that improves the thermodynamic efficiency of appliances and the capital stock, as well as production processes – there is a technical improvement. Of course, in reality, apart from the technological and economic factors, there are a range of exogenous institutional and regulatory factors that are important in explaining the level of energy consumption, furthermore, these exogenous changes are unlikely to impact in a consistent rate over time. Hence, it is important that the UEDT is specified in such a way that it is 'non-linear' and could increase and/or decrease over the estimation period as advocated by Hunt et al. (2003a,b). Therefore, given a panel data set is used this is achieved by time dummies as proposed by Griffin and Schulman (2005) and Adeyemi and Hunt (2007). Nevertheless, as discussed by Kumbhakar and Lowell (2000), the use of a large number of time dummies in a parametric frontier framework can create estimation problems; consequently an alternative approach is also considered with a time trend for the specification of the UEDT.

In order to try to tease out these different influences, a general energy demand relationship found in the standard energy demand modelling literature, relating energy consumption to economic activity and the real energy price, is utilised for the estimation of an aggregate energy demand function for a panel of OECD countries. Moreover, in order to control for other important factors that vary across countries and hence can affect a country's energy demand, some variables related to climate, size, and structure of the economy are introduced in to the model. Thus the framework adopted here attempts to isolate the 'underlying energy efficiency' for each country after controlling for income, price, climate effects, technical progress and other exogenous factors, as well effects due to difference in area size and in the structure of the economy.[5] The estimated model therefore isolates the level of underlying energy efficiency, defined with respect to a benchmark, e.g. a best practice economy in the use of energy by estimation a 'common energy demand' function across countries, with homogenous income and price elasticities, and responses to other factors, plus a homogenous UEDT. This is seen as important, given the need to isolate the different underlying energy efficiency across the countries.[6] Consequently, once these effects are adequately controlled for, it allows for the estimation of the underlying energy efficiency for each country showing i) how efficiency has changed over the estimation period and ii) the differences in efficiency across the panel of countries.

The paper is organized as follows. The next section, discusses the rationale and specification of the energy demand frontier function, with the data and econometric

[5] Note, previous studies by Buck and Young (2007) and Boyd (2008) did not base their estimation on an energy demand function, in that they did not consider the energy price as an explanatory variable; hence omitting this important control variable.

[6] The UEDT includes exogenous technical progress and it could be argued that even though technologies are available to each country they are not necessarily installed at the same rate; however, it is assumed that this results from different behaviour across countries and reflects 'inefficiency' across countries; hence, it is captured by the different (in)efficiency terms for all countries.

specification introduced in Section 3. The results of the estimation are presented in Section 4, with a summary and conclusion in the final section.

2 An aggregate frontier energy demand model

Given the discussion above, it is assumed that there exists an aggregate energy demand relationship for a panel of OECD countries, as follows:

$$E_{it} = E(P_{it}, Y_{it}, POP_{it}\ C_i, A_i, ISH_{it}, SSH_{it}, D_t, EF_{it}) \quad (1)$$

where E_{it} is aggregate energy consumption, Y_{it} is GDP, P_{it} is the real price of energy,[7] C_i is climate, POP_{it} is population, A_i is the area size, ISH_{it} is the share of value added of the industrial sector and SSH_{it} is the share of value added for the service sector all for country i in year t.[8] D_t is a variable representing the UEDT that captures the common impact of important unmeasured exogenous factors that influence all countries simultaneously. Finally, EF_{it} is the unobserved level of 'underlying energy efficiency' of an economy. This could incorporate a number of factors that will differ across countries, including different government regulations as well as different social behaviours, norms, lifestyles and values. Hence, a low level of underlying energy efficiency implies an inefficient use of energy (i.e. 'waste energy'), so that in this situation, awareness for energy conservation could be increased in order to reach the 'optimal' energy demand function. Nevertheless, from an empirical perspective, when using OECD aggregate energy data, the aggregate level of energy efficiency of the capital equipment

[7] In this model specification, it is assumed that the price effect is symmetric. Gately and Huntington (2002), amongst others, discuss the possibility of specifying a demand model with asymmetric price effects and some experimentation with asymmetric prices was undertaken here, however, the model did not fit the data well. Future research will investigate this further.

[8] Unfortunately, it is not possible to get more sectoral disaggregated data (e.g. data on energy intensive sectors) on a consistent basis for all 29 countries for all the years.

and of the production processes is not observed directly. Therefore, this underlying energy efficiency indicator has to be estimated. Consequently, in order to estimate this economy-wide level of underlying energy efficiency (EF_{it}) and identify the best practice economy in term of energy utilization, the stochastic frontier function approach introduced by Aigner et al. (1977) is used.[9]

The stochastic frontier function has generally been used in production theory to measure, using an econometric approach, the economic performance of production processes. The central concept of the frontier approach is that in general the function gives the maximum or minimum level of an economic indicator attainable by an economic agent. For a cost function, the frontier gives the minimum level of cost attainable by a firm for any given level of output. For an input demand function (as utilised here) the frontier gives the minimum level of input used by a firm for any given level of output; hence, the difference between the observed input and the cost-minimizing input demand represents both technically as well allocative inefficiency.[10] In the case of an aggregate energy demand function, used here, the frontier gives the minimum level of energy necessary for an economy to produce any given level of energy services. In principle, the aim here is to apply the frontier function concept in order to estimate the baseline energy demand, which is the frontier that reflects the demand of the countries that use high efficient equipment and production process. This frontier approach allows the possibility to identify if a country is, or is not, on the frontier. Moreover, if a country

[9] The frontier function approach suggested by Aigner et al. (1977) was developed within the neoclassical production theory and the main goal of this literature has been to estimate production and cost frontier in order to identify the level of productive inefficiency (allocative and technical inefficiency). In this study, the neoclassical production theory is discarded and instead the concept of a stochastic frontier within the empirical approach traditionally used in the estimation of economy-wide energy demand function is employed. Of course, behind the concept of underlying energy inefficiency developed here, there is still a 'production process'.

[10] See Kumbhakar and Lowell (2000, p. 148) for a discussion on the interpretation of the efficiency in an input demand function.

is not on the frontier, the distance from the frontier measures the level of energy consumption above the baseline demand, e.g. the level of energy inefficiency.

The approach used in this study is therefore based on the assumption that the level of the economy-wide energy efficiency can be approximated by a one-sided non-negative term, so that a panel log-log functional form of Equation (1) adopting the stochastic frontier function approach proposed by Aigner et al. (1977) can be specified as follows:

$$e_{it} = \alpha + \alpha^{y} y_{it} + \alpha^{p} p_{it} + \alpha^{pop} pop_{it} + \delta_t D_t + \alpha^{C} DC_i + \alpha^{a} a_i + \alpha^{I} ISH_{it} \alpha^{S} SSH_{it} + v_{it} + u_{it} \tag{2}$$

where e_{it} is the natural logarithm of aggregate energy consumption (E_{it}), y_{it} is the natural logarithm of GDP (Y_{it}), p_{it} is the natural logarithm of the real price of energy (P_{it}), pop_{it} is the natural logarithm of population (POP_{it}), DC_i is a cold climate dummy variable, a_i is the natural logarithm of the area size of a country measured in squared km (A_i), ISH_{it} is the share of value added of the industrial sector, and SSH_{it} is the share of value added for the service sector. The time variable D_t has been specified in two ways, i.e. using a series of time dummy variables and using a time trend. [11] Furthermore, the error term in Equation (2) is composed of two independent parts. The first part, v_{it}, is a symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed. The second part, u_{it}, which represents the underlying energy level of efficiency EF_{it} in equation (1) is interpreted as an indicator of the inefficient use of energy, e.g. the 'waste energy'. [12] It is a one-sided non-

[11] As pointed out by Kumbhakar and Lowell (2000), the introduction in a frontier model of a time trend or a series of time dummies among the regressors as a proxy for technical progress can frequently cause problems in estimation. A possible reason for this problem is the difficulty to disentangle the separate effects of technical change and productive efficiency change when both vary over time. As will be seen later in the model, for this problem one model, the true random effects model could not be estimated with the time dummies.

[12] The energy demand function estimated in this paper can be considered an input demand function derived through a cost minimizing process from an aggregate production function. Of course, theoretically the demand for energy might also depend on the price of other inputs, but in line with previous energy demand studies, data limitations make it impossible to include these variables. For this reason this equation is specified, similar to the general energy demand literature, in a relatively *ad hoc* way with an indirect reference to production theory

negative random disturbance term that can vary over time, assumed to follow a half-normal distribution.[13] An improvement in the energy efficiency of the equipment or on the use of energy through a new production process will increase the level of energy efficiency of a country. The impact of technological, organisational, and social innovation in the production and consumption of energy services on the energy demand is therefore captured in several ways: the time dummy variables and the time trend respectively, the indicator of energy efficiency and through the price effect.

In summary, Equation (2) is estimated in order to estimate underlying energy efficiency for each country in the sample. The data and the econometric specification of the estimated equations are discussed in the next section.

3. Data and econometric specification

The study is based on an unbalanced panel data set for a sample of 29 OECD countries (i = 1, …, 29)[14] over the period 1978 to 2006 (t = 1978-2006). This data set is based on information taken from the International Energy Agency (IEA) database "World Energy Statistics and Balances of OECD Countries" available at www.iea.org and from the general OECD database "Country Profile Statistics" available at www.oecd.org.

[13] It could be argued that this is a strong assumption for *EF*, but it does allow the 'identification' of the efficiency for each country separately.

[14] Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the UK, and the US. For some countries, information on the share of the industrial and service sector in the economy are only available for the years after 1990. For this reason the data set is unbalanced.

E is each country's per capita aggregate energy consumption in tonnes of oil equivalent (toe), *Y* is each country's per capita GDP in thousand US2000$PPP, *P* is each country's index of real energy prices (2000=100), and *POP* is population in millions. The climate dummy variable, *DC*, indicates whether a country belongs to those characterized by a cold climate (according to the Köppen-Geiger climate classification[15]) and *A* is the area size of a country is measured in squared kilometres. Finally, the value added of the industrial and service sectors is measured as percentage of GDP (*ISH* and *SSH*). Descriptive statistics of the key variables are presented in Table 1.

Table 1: Descriptive statistics

Variable		Mean	Std. Dev.	Minimum	Maximum
Description	Name				
Energy consumption (toe)	**E**	120194	264883	2266.06	1597580
GDP (1000 US2000$PPP)	**Y**	813.42	1546.19	8.55	112654.2
Population in Millions.	**POP**	38.70	53.75	0.36	299.63
Real Price of energy (2000=100)	**P**	99.65	16.42	53.56	170.30
Area size in km^2	**A**	1269850	2786260	2590	9984670
Share of industrial sector in % of GDP	**ISH**	31.37	5.22	15.80	44.80
Share of service sector in % of GDP	**SSH**	63.89	6.76	44.10	83.90
Climate Dummy	**DC**	0.45	0.50	0	1

From the econometric specification perspective, the literature on the estimation of stochastic frontier models using panel data needs to be considered.[16] A first approach that can be used for the estimation of model (2) is the panel data version of the Aigner et al. (1977) half-normal model proposed by Pitt and Lee (1981). In this "pooled" model specification the error term is composed of two uncorrelated parts: the first part u_{it}, is a one-sided non negative disturbance reflecting the effect of inefficiency (including both allocative and technical

[15] See for a discussion of this classification Peel et al. (2007).

[16] For a presentation of several approaches for the estimation of frontier models in the energy sector see Farsi and Filippini (2009).

inefficiencies), and the second component v_{it} , is a symmetric disturbance capturing the effect of noise. Usually the statistical noise is assumed to be normally distributed, while the inefficiency term u_{it} is assumed to follow a half-normal distribution.[17] A shortcoming of this model is that the unobserved, time-invariant, country-specific heterogeneity is not considered in the estimation. A second approach, also proposed by Pitt and Lee (1981), assumes the inefficiency effects, u_i, to be constant over time.[18] A major shortcoming of these models is that any unobserved, time-invariant, country-specific heterogeneity is considered as inefficiency. In order to solve this problem using panel data, Greene (2005a and 2005b) proposed to extend the SFA model in its original form (Aigner, et al., 1977) by adding a fixed or random individual effect in the model.[19] It should be noted that these models produce efficiency estimates that do not include the persistent inefficiencies that might remain more or less constant over time. In fact, the time-invariant, country-specific energy inefficiency is captured by the individual random or fixed effects. Therefore, to the extent that there are certain sources of energy inefficiency that result in time-invariant excess energy consumption, the estimates of these models could provide relatively high and imprecise levels of energy efficiency. Of course, one advantage of the approaches proposed by Greene (2005a and 2005b) with respect to the original approach proposed by Aigner et al. (1977) is the reduction of the potential so-called 'unobserved variables bias'; e.g. a situation where correlation between observables and unobservables could bias some coefficients of the explanatory variables. However, by

[17] Other extensions of this model have also considered exponential and truncated normal distributions for the inefficiency term.

[18] Battese and Coelli (1992) propose a model where the variation of efficiency with time is considered as a deterministic function that is commonly defined for all firms.

[19] For a successful application of these models in network industries, see Farsi, et al. (2006) and Farsi, et al. (2005).

introducing several explanatory variables such as the climate, the area size, population and some variables on the structure of the economy it is possible to reduce this problem.

Given this discussion, the 'pooled' model based on Aigner et al. (1977) and the True Random Effects (TRE) model proposed by Greene (2005) are used for the estimation of equation (2).[20] Furthermore, the TRE model was estimated using only the time trend specification, because the simulated maximum likelihood estimation method did not converge using the specification with time dummies. A possible explanation why this estimator did not perform well in her is that the model specification is too rich the data used and, as a result, some of the error terms degenerate to zero. Table 2 summarizes the econometric specification of the frontier models used in this study.

Table 2: Econometric specifications of the stochastic cost frontier

	Pooled model ***Half-Normal***	**TRE model** ***Half-Normal***
Country-specific component α_i	None	N $(0, \sigma_\alpha^2)$
Random error ε_{it}	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+ (0, \sigma_u^2)$ $v_{it} \sim N (0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+ (0, \sigma_u^2)$ $v_{it} \sim N (0, \sigma_v^2)$
Level of efficiency	$E(u_{it} \mid u_{it} + v_{it})$	$E(u_{it} \mid \alpha_{it} + \varepsilon_{it})$

[20] In order to verify the robustness of the results the "pooled" model is estimated using two assumptions for the distribution of the efficiency, i.e. the half-normal and the exponential distribution. The results are very similar in term of coefficients and in term of correlation between the efficiency indicators (correlation of 0.98)

The country's efficiency is estimated using the conditional mean of the efficiency term $E[u_{it}|u_{it}+v_{it}]$, proposed by Jondrow et al. (1982).[21] The level of energy efficiency can be expressed in the following way:

$$EF_{it} = \frac{E_{it}^F}{E_{it}} = \exp(-\hat{u}_{it}) \qquad (3)$$

where E_{it} is the observed energy consumption per capita and E_{it}^F is the frontier or minimum demand of the i^{th} country in time t. An energy efficiency score of one indicates a country on the frontier (100% efficient), while non-frontier countries, e.g. countries characterized by a level of energy efficiency lower than 100%, receive scores below one. This therefore gives the measure of underlying energy efficiency estimated below.[22]

In summary, Equation (2) is estimated and Equation (3) used to estimate the efficiency scores for each country for each year. Given the econometric specifications presented in Table 2 and given the two approaches chosen to take into account the effect of the impact of exogenous technical change and other exogenous factors, three models can be estimated. The results from the estimation are given in the next section.

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[21] See also Greene (2002b) and Battese and Coelli (1992).

[22] This is in contrast to the alternative indicator of energy inefficiency given by the exponential of u_{it}. In this case, a value of 0.2 indicates a level of energy inefficiency of 20%.

4. Estimation results

The estimation results for frontier energy demand model, Equation (2), are given in Table 3. This shows that the estimated coefficients and *lambda* have the expected signs and are statistically significant.[23]

Table 3: Estimated coefficients (*t*-values in parentheses)

Model / Coefficient	**Pooled Model** with time dummies	**Pooled Model** with a time trend)	**TRE Model** with a time trend
Constant (α)	4.241 (9.54)	3.769 (9.33)	3.940 (48.34)
α^y	0.819 (24.51)	0.805 (24.78)	0.402 (49.24)
α^p	-0.452 (-7.26)	-0.363 (-7.30)	-0.200 (-27.06)
α^{pop}	0.080 (2.59)	0.090 (3.02)	0.453 (61.40)
α^a	0.054 (8.87)	0.056 (9.06)	0.066 (28.31)
α^C	0.193 (10.83)	0.186 (10.50)	0.248 (45.38)
α^I	0.031 (8.39)	0.031 (8.66)	0.032 (46.54)
α^s	0.030 (7.52)	0.030 (7.82)	0.030 (36.76)
α^t		-0.010 (-8.62)	-0.001 (-2.46)
Time dummies	Yes	No	No
Lamda (λ)	0.712 (7.26)	1.113 (10.10)	6.706 (7.76)

Note: All models assume half normal efficiency distribution

For the variables in logarithmic form, the estimated coefficients are can be directly interpreted as elasticities. The estimated income elasticity and the estimated own price elasticity are about 0.8 and -0.4 respectively for the pooled models, but somewhat lower (in

[23] Lambda (λ) gives information on the relative contribution of u_{it} and v_{it} on the decomposed error term ε_{it} and shows that in this case, the one-sided error component is relatively large.

absolute terms) for the TRE model at about 0.4 and -0.2 respectively. Although none of these are too out of line with previous estimates, the estimated income elasticity for the TRE model is a little on the low side. The estimated population elasticity is about 0.08 to 0.09 for the pooled models but somewhat larger for the TRE model at about 0.5. The estimated area elasticity is about 0.05 to 0.06 across all specifications, indicating that a 10% larger country will demand between 0.5% and 0.6% more energy. The estimated coefficient for the climate variable, DC is about 0.2 across all specifications indicating that it has an important influence on a country's energy demand; with countries characterized by a cold climate experiencing a higher consumption of energy. Similarly, larger shares of a country's industrial and service sectors will also increase energy consumption.

The time dummies, as a group, are significant and, as expected, the overall trend in their coefficients is negative as shown in Figure 1; however, they do not fall continually over the estimation period, reflecting the 'non-linear' impact of technical progress and other exogenous variables. Furthermore, the downward trend in the time dummy coefficients of -0.011 is similar to the estimated coefficient for the time trend of -0.010 in the other pooled specification, but different to the estimate of -0.001 for the TRE specification. This illustrates that the coefficients from the TRE model are somewhat different from those obtained from the pooled models, probably because the TRE model considers the unobserved heterogeneity across countries.

Figure 1: Estimated Time Dummy Coefficients (relative to 1978)

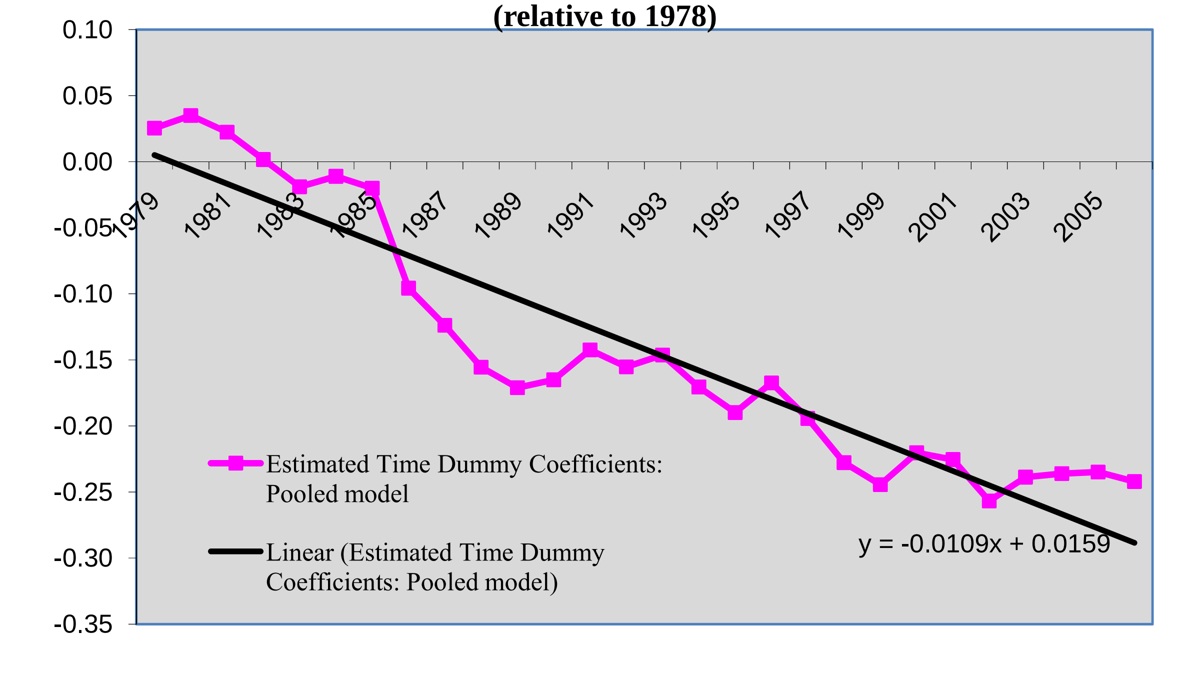


Table 4 provides descriptive statistics for the overall underlying energy efficiency estimates of the countries obtained from the econometric estimation, showing that the estimated mean average efficiency is about 85% to 89% (median 86% to 92%); nonetheless, there is a fair degree of variation around the average.

Table 4: Energy efficiency scores

Model / **Summary measure**	**Pooled Model** with time dummies	**Pooled Model** with a time trend	**TRE Model** with a time trend
Min	0.758	0.599	0.647
Max	0.950	0.945	0.992
Mean	0.894	0.854	0.897
median	0.901	0.868	0.919
st.dev.	0.030	0.057	0.075

Table 5 presents the average energy efficiency score for each specification for every country over the whole sample, with their ranking. Comparing the two models that incorporate a time trend it can be seen that the TRE model generally produces a higher level of efficiency than that from the pooled model; probably due to the time-invariant country-specific energy inefficiency being captured by the individual random effects. Therefore, to the extent that there are certain sources of energy inefficiency that result in time-invariant excess energy consumption, the estimates from the TRE model arguably provide imprecise estimates resulting in overestimated levels of energy efficiency. For example, the estimates of energy efficiency for Australia and Canada from the TRE model suggest that these two countries are both very efficient, whereas this is probably just because the individual effects in the TRE model capture the inefficiency. In fact, the value of the individual effects of these two countries is among the highest of the countries considered in the analysis. There is, therefore, a trade-off in the choice of the most appropriate estimator: the estimated coefficients of the pooled models could be affected by the so-called unobserved heterogeneity bias, whereas the estimated levels of efficiency obtained using the TRE could be imprecise, because they do not include the persistent inefficiencies that might remain constant over time. Furthermore, it was not possible to specify the UEDT in a "non-linear" way using time dummies with the TRE model.[24]

[24] The results reported in Figure 1 confirm that the non-linear approach is more appropriate that just the linear time trend approach.

Table 5: Average energy efficiency scores and rankings

Country \ Model	**Pooled Model** with time dummies		**Pooled Model** with a time trend		**TRE Model** with a time trend	
	Score	Rank	Score	Rank	Score	Rank
Australia	0.904	13	0.874	13	0.940	2
Austria	0.930	2	0.919	2	0.918	9
Belgium	0.864	26	0.795	25	0.890	16
Canada	0.852	27	0.773	27	0.929	3
Czech Rep	0.878	19	0.824	20	0.889	18
Denmark	0.916	8	0.892	9	0.896	15
Finland	0.872	24	0.808	24	0.921	8
France	0.896	15	0.858	15	0.929	3
Germany	0.873	23	0.814	23	0.886	20
Greece	0.923	3	0.908	3	0.883	22
Hungary	0.875	22	0.820	21	0.911	12
Ireland	0.888	16	0.847	16	0.871	24
Italy	0.923	3	0.906	5	0.918	9
Japan	0.916	8	0.897	8	0.915	11
Korea	0.878	19	0.819	22	0.805	29
Luxembourg	0.845	29	0.759	29	0.888	19
Mexico	0.922	5	0.907	4	0.884	21
Netherlands	0.865	25	0.795	25	0.927	5
New Zealand	0.910	11	0.886	11	0.869	25
Norway	0.922	5	0.905	6	0.926	6
Poland	0.880	18	0.827	18	0.868	26
Portugal	0.912	10	0.892	9	0.849	28
Slovak Rep.	0.878	19	0.825	19	0.911	12
Spain	0.922	5	0.905	6	0.860	27
Sweden	0.909	12	0.879	12	0.903	14
Switzerland	0.941	1	0.936	1	0.941	1
Turkey	0.887	17	0.841	17	0.883	22
UK	0.900	14	0.865	14	0.922	7
USA	0.846	28	0.763	28	0.890	16

Consequently, given the focus of this paper is to attempt to 'discover' the different levels of underlying energy efficiency both across countries and over time by considering in a non-linear way a common UEDT capturing 'exogenous' technical progress and other exogenous factors, all further analysis focuses on the results obtained using the pooled model with time dummies.[25]

Table 6 presents the average energy efficiency score for every country for three sub periods of the estimation period considered in the analysis and over the whole period and Figure 2 shows that the estimated underlying energy efficiency scores for each country over the estimation period (relative to energy intensity). It should be noted that, although presented individually for each country, the estimated efficiencies of each country should not be taken as the precise position of each country given the stochastic technique used in estimation. However, they do give a good relative indication of a country's change in efficiency over time and a country's relative position vis-à-vis other countries.

Bearing this in mind, Table 6 and Figure 2 show that the estimated underlying energy efficiency generally increased over the estimation period for some countries, such as Denmark, Finland, Germany, Ireland, Luxembourg, the UK, and the USA. Whereas for some countries the opposite is the case, with the estimated underlying energy efficiency generally decreasing, such as Italy, Mexico, New Zealand, Portugal, and Spain. Figure 2 also illustrates that the estimated underlying energy efficiency would appear to be negatively correlated with energy intensity for most countries (i.e. the level of energy intensity decreases with an increase of the level of energy efficiency), but with some exceptions (discussed further below). This is to be expected in one sense. However, if this technique were to be a useful tool for teasing out underlying energy efficiency then a perfect, or even near perfect, negative correlation would not be expected since all the useful information would be contained in the standard energy to GDP ratio.

[25] It is worth noting , that the correlation coefficient between the level of efficiency obtained using both pooled models (time dummies and time trend) is relatively high (0.98).

Table 6: Average energy efficiency scores over time for the Pooled model with Time Dummies

	1978 – 1987	1988 – 1997	1998 – 2006
Australia	0.908	0.902	0.902
Austria	0.928	0.933	0.928
Belgium	0.874	0.869	0.847
Canada	0.854	0.850	0.852
Czech Rep	n/a	0.860	0.893
Denmark	0.907	0.919	0.922
Finland	0.867	0.873	0.874
France	0.891	0.901	0.897
Germany	0.852	0.882	0.886
Greece	0.929	0.917	0.922
Hungary	n/a	0.861	0.886
Ireland	0.860	0.886	0.923
Italy	0.930	0.925	0.913
Japan	0.916	0.919	0.914
Korea	0.883	0.892	0.857
Luxembourg	0.810	0.867	0.862
Mexico	0.932	0.919	0.915
Netherlands	0.860	0.868	0.867
New Zealand	0.925	0.906	0.894
Norway	0.922	0.920	0.924
Poland	n/a	0.851	0.898
Portugal	0.920	0.909	0.905
Slovak Rep.	n/a	0.870	0.883
Spain	0.933	0.923	0.909
Sweden	0.911	0.906	0.910
Switzerland	n/a	0.943	0.940
Turkey	0.894	0.895	0.870
UK	0.894	0.900	0.906
USA	0.814	0.858	0.868

Note: n/a represents the situation where the average is not available over the sub-period.

Due to the unbalanced panel, some averages are calculated over a slightly shorter period than indicated.

Figure 2: Comparison of Estimated Underlying Energy Efficiency with Energy Intensity

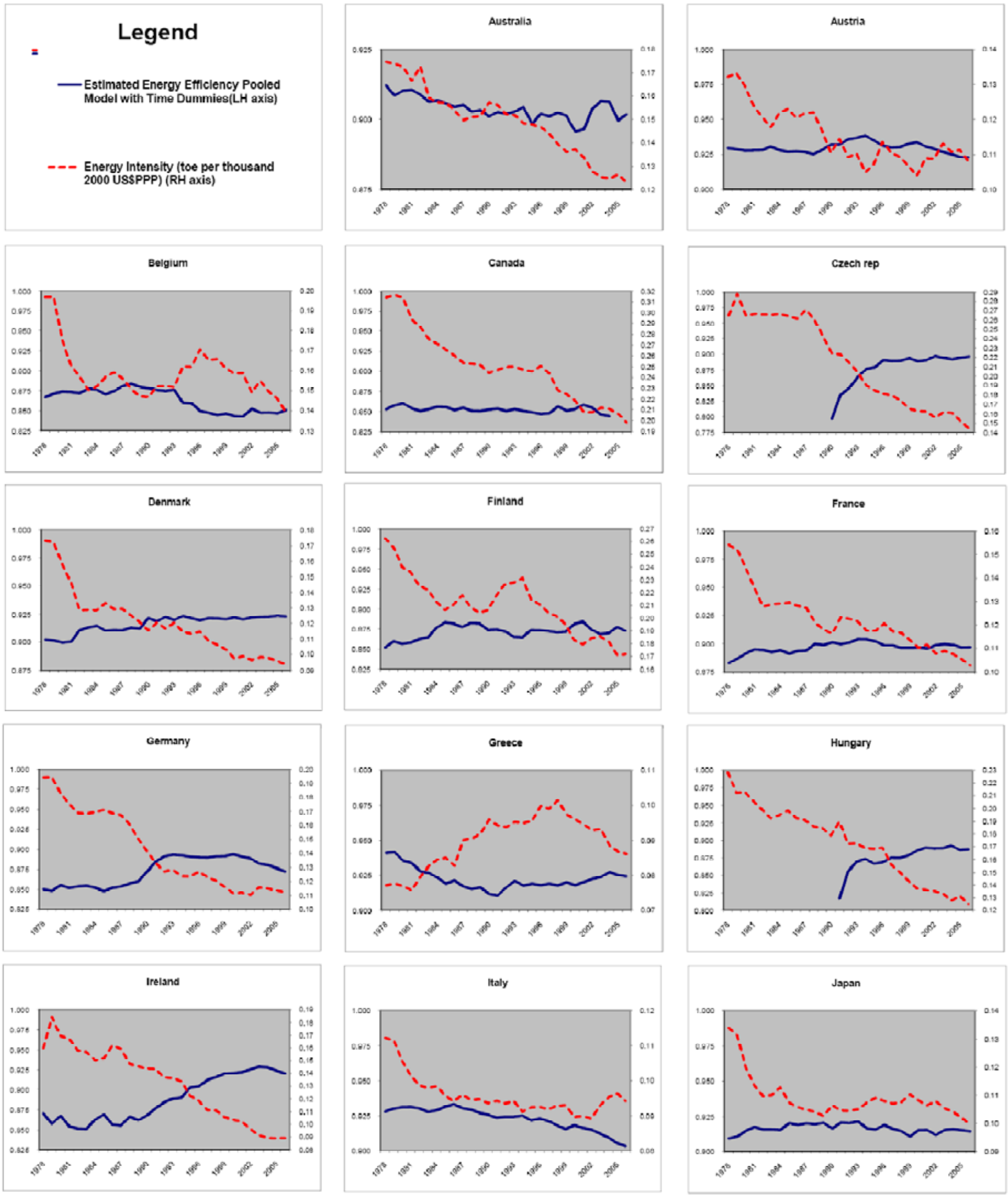
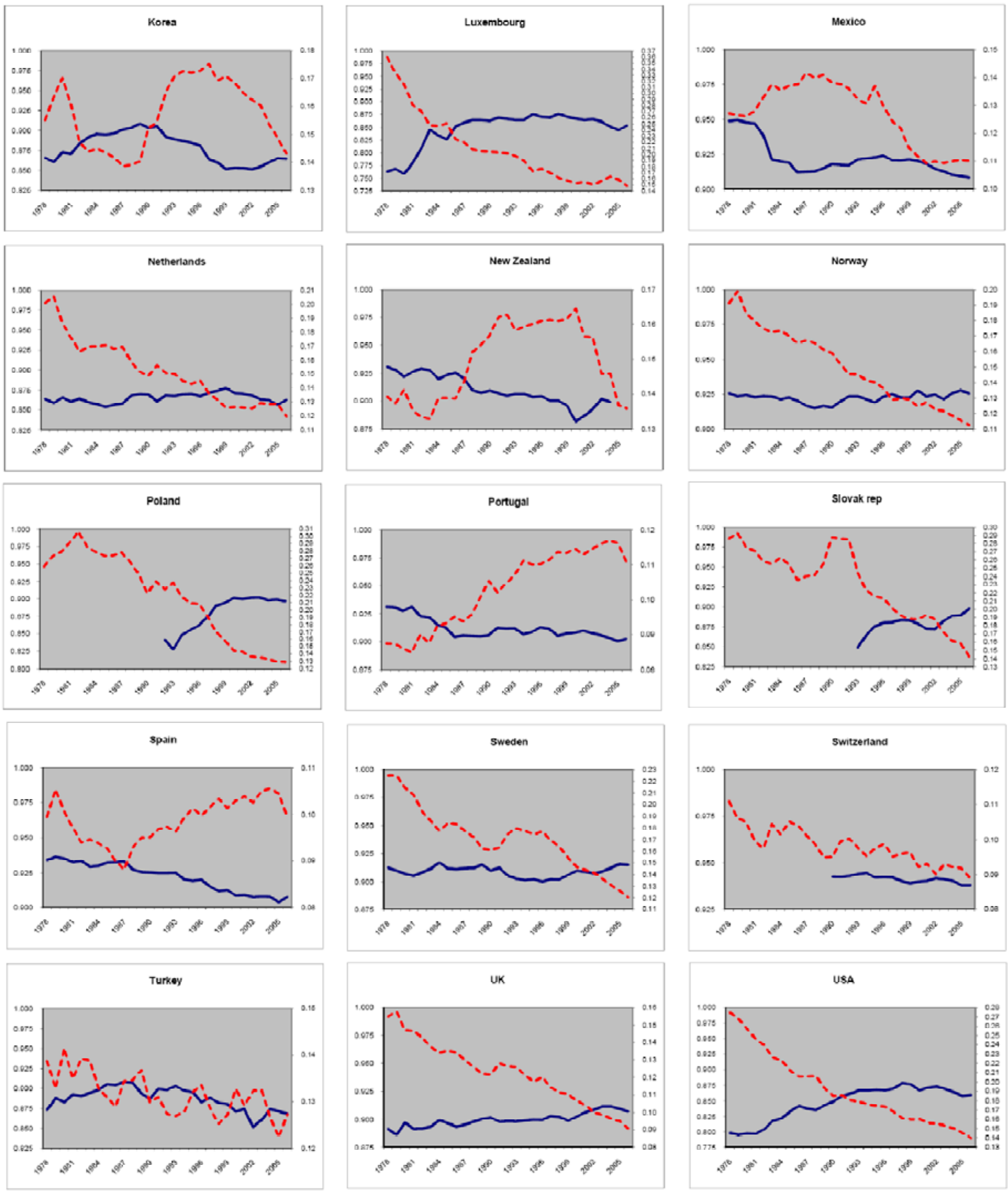


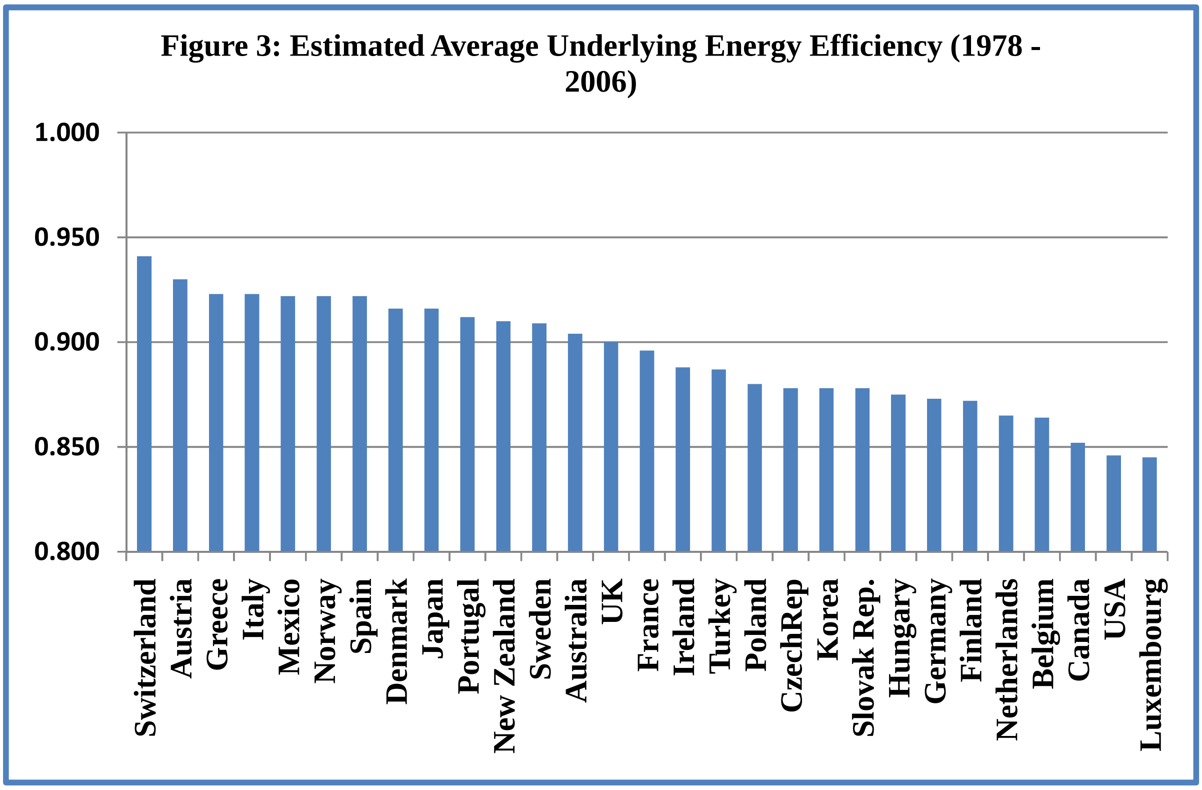
Figure 2: Continued



This is confirmed, given the average correlation coefficient between the estimated underlying energy efficiency and energy intensity across all countries is -0.48. Within this, there is a relatively high negative correlation for some countries, such as the Czech Republic, Denmark, Germany, Hungary, Ireland, Luxembourg, New Zealand, Poland, the Slovak Republic, the UK and the USA; whereas for some countries the (negative) correlation is somewhat less, such as Austria, Belgium, Norway and Sweden. Furthermore, for Australia, Canada, Italy, Mexico, Switzerland and Turkey, there appears to be a positive relationship between the energy to GDP ratio and estimated energy efficiency. This suggests that for some countries energy intensity is a reasonable proxy for energy efficiency, whereas for others it is a very poor proxy. Hence, unless the analysis undertaken here is conducted it is arguably not possible to identify for which countries energy intensity is a good proxy and for which it is a poor proxy.

Turning to the differences in estimated energy efficiency scores across the panel of countries in the sample it can be seen from the first column of results in Table 5 that there is some difference over the whole sample period. Luxembourg the USA, Canada, and Belgium are the estimated four least efficient countries, with Switzerland, Austria, Greece, and Italy the estimated five most efficient countries.[26] This is further shown in Figure 3, with the countries re-ordered from the most efficient to the least efficient. However, although Italy is estimated to be one of the most energy efficient countries over time its level of efficiency has been generally declining, despite a general fall in energy intensity. This highlights that energy intensity in this case gives a poor indication of Italy's change in energy efficiency over time.

[26] However, it should be noted that, given the unbalanced panel used in estimation, the figures for the Switzerland are over a much shorter period.



Countries will, however, have improved (or deteriorated) at different rates; hence, Figure 4 gives the ordered data for the latter period only, 1998-2006 and compares it with Energy Intensity over the same period. Part a) of Figure 4 shows that the ordering does d, with the four least efficient countries being Belgium, Canada Korea, and Luxembourg and the four most efficient countries being Switzerland, Austria, Norway, and Ireland.[27] Furthermore, as shown in Table 7, and illustrated when comparing part a) of Figure 4 with part b), it can be seen that although there is generally a negative relationship between the rankings of the estimated underlying energy efficiency and energy intensity there is not a one to one correspondence. For example, according to the measure of energy intensity over the period 1998 - 2006, Norway is ranked 14th, whereas it is estimated to be the third most efficient over

[27] Of course, the aggregate approach used in this paper does not directly identify the causes of the level of efficiency. For instance, one possible cause for the poor performance of Luxembourg could be the presence of 'tank tourism'..

Figure 4a: Estimated Average Underlying Energy Efficiency (1998 - 2006)

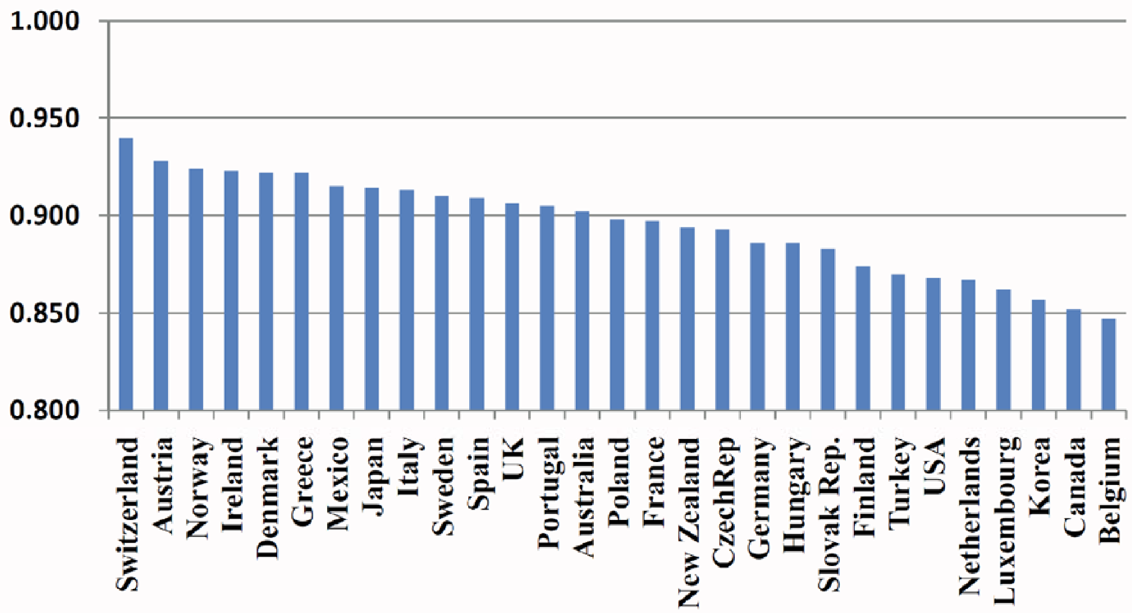
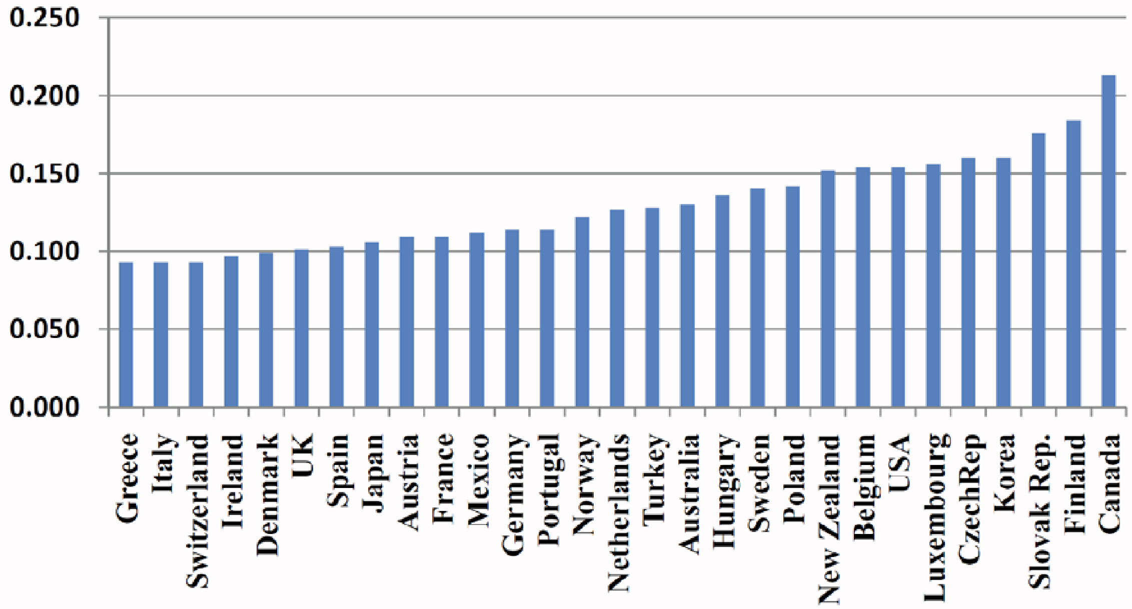


Figure 4b: Energy Intensity (toe per 1000US$PPP, 1998 - 2006)



the period, suggesting that Norway is relatively more energy efficient than the simple energy intensity measure would suggest. Conversely, the Netherlands is ranked seventh in terms of energy intensity but is only ranked 25th in terms of underlying energy efficiency; suggesting that the Netherlands is somewhat less energy efficient than the simple energy intensity measure suggests.

Table 7: Comparison of the Rankings for Estimated Underlying Energy Efficiency (from the pooled model with time dummies) and Energy Intensity (1998-2006)

	Estimated Underlying Energy Efficiency (symmetric model)		***Energy Intensity (Energy GDP ratio, toe per 1000 US2000$PPP)***	
	Level	*Rank*	*Level*	*Rank*
Australia	0.902	14	0.130	17
Austria	0.928	2	0.109	9
Belgium	0.847	29	0.154	22
Canada	0.852	28	0.213	29
Czech Rep	0.893	18	0.160	25
Denmark	0.922	5	0.099	5
Finland	0.874	22	0.184	28
France	0.897	16	0.109	9
Germany	0.886	19	0.114	12
Greece	0.922	5	0.093	1
Hungary	0.886	19	0.136	18
Ireland	0.923	4	0.097	4
Italy	0.913	9	0.093	1
Japan	0.914	8	0.106	8
Korea	0.857	27	0.160	25
Luxembourg	0.862	26	0.156	24
Mexico	0.915	7	0.112	11
Netherlands	0.867	25	0.127	15
New Zealand	0.894	17	0.152	21
Norway	0.924	3	0.122	14
Poland	0.898	15	0.142	20
Portugal	0.905	13	0.114	12
Slovak Rep.	0.883	21	0.176	27
Spain	0.909	11	0.103	7
Sweden	0.910	10	0.140	19
Switzerland	0.940	1	0.093	1
Turkey	0.870	23	0.128	16
UK	0.906	12	0.101	6
USA	0.868	24	0.154	22

Note: A rank of 29 for underlying energy efficiency represents the least efficient country by this measure, whereas a rank of 1 represents the most efficient country. A rank of 29 for energy intensity represents the most energy intensity country whereas a rank of 1 represents the least energy intensive country.

5. Summary and Conclusion

This research is a fresh attempt to isolate core energy efficiency for a panel of 29 OECD countries, opposed to relying on the simple energy to GDP ratio – or energy intensity. By combining the approaches taken in energy demand modelling and frontier analysis, a measure of the 'underlying energy efficiency' for each country is estimated. This is, as far as is known, the first attempt to econometrically model OECD energy demand and efficiency in this way. The energy demand specification controls for income, price, climate country specific effects, area, industrial structure, and a underlying energy demand trend in order to obtain a measure of 'efficiency' – in a similar way to previous work on cost and production estimation – thus giving a measure of underlying energy efficiency (reflecting the relative inefficient use of energy, i.e. 'waste energy').

The estimates for the core energy efficiency using a full frontier model show that although for a number of countries the change in energy intensity might give a reasonable indication of efficiency improvements; this is not always the case both over time and across countries - Italy being a prime example. For Italy, energy intensity declines over the estimation period suggesting an improvement in energy efficiency, whereas the estimated underlying energy efficiency falls over the period. Moreover, according to energy intensity Italy is the most efficient country over the latter period covered by the data,[28] whereas the estimated underlying energy efficiency suggests it is the 9th most efficient country. Therefore, unless the analysis advocated here is undertaken, it is not possible to know whether the energy intensity of a country is a good proxy for energy efficiency or not. Hence, it is argued that this analysis should be undertaken in order to give policy makers an additional indicator other than

[28] Jointly with Greece and Switzerland.

the rather naïve measure of energy intensity in order to try to avoid potentially misleading policy conclusions.

Finally, it should be noted that this study does not claim, at this stage, to provide a definitive answer on how to measure the level of energy efficiency using a stochastic frontier demand approach. It is hoped, however, that it will spark future research and generate interest for further actions that could improve the models used for analysing and measuring aggregate energy efficiency.

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Note:

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Surrey Energy Economics Centre (SEEC)

Department of Economics

University of Surrey

Guildford

Surrey GU2 7XH

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