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## 1 **1. Introduction**

2 As a result of recent concerns relating to the harmful effects of climate change, policy makers  
3 have become increasingly interested in reducing greenhouse gas emissions using a variety of  
4 policy tools such as environmental taxation and the increased use of renewable energy. In  
5 addition, countries have been set targets for greenhouse gas emissions, such as through the  
6 Kyoto Protocol, whilst EU members, including the UK, have been set voluntary targets for  
7 the reduction in these emissions. Even before greenhouse gas emissions became an important  
8 issue, the UK was seeking to pass legislation in order to reduce the production of key  
9 pollutants such as sulphur dioxide (SO<sub>2</sub>), which started with the Alkali Act of 1874. Evidence  
10 of the harmful effects of pollutants to the environment has led to increasing political efforts to  
11 reduce them and academic efforts to model how the pollutants relate to the economy. In the  
12 1990s one of the main developments in understanding the link between the environment and  
13 economy was the Environmental Kuznets Curve (EKC), which suggested a non-linear  
14 relationship between income and pollutants.

15 Stern (2004, p.1420) asserts that “The EKC is an essentially empirical phenomenon, but most  
16 of the EKC literature is econometrically weak.” Researchers are increasingly employing more  
17 advanced econometric techniques to try and uncover any statistical shortcomings of the EKC.  
18 Single country studies have used time series econometrics, with various methodological  
19 developments taking the form of unit root testing and cointegration analysis. These  
20 developments have been necessary as in the absence of these tests there is the possibility of  
21 the ‘spurious’ regression problem arising from looking at variables with common trends.  
22 Recent studies generally look at the EKC over very short time spans; something which could  
23 be potentially problematic when using time-series models, such as cointegration, which

24 perform better in large samples. Secondly, papers to date have only looked at symmetric  
25 cointegration.

26 This paper aims to look at re-specifying the EKC in an asymmetric framework to allow for a  
27 different speed of adjustment to the long-run relationship depending on whether emissions  
28 are above or below the EKC in the short-run. In addition further explanatory variables are  
29 added into this model, such as energy prices, to test the robustness of the results. Regulation  
30 on air pollution has become increasingly stringent, including international protocols such as  
31 the Oslo Protocol and the Kyoto Protocol. Such regulations may explain why actions are  
32 more likely if emissions are too high – as there may be penalties for industry and the threat of  
33 increased legislative action. Thus, in the presence of environmental regulation we may expect  
34 any short-run deviations in emissions to be corrected more quickly if they are too high,  
35 whereas if emissions are too low, there is no immediate pressure for them to rise back to their  
36 long-run levels.

37 This could essentially imply that emissions are ‘sticky upwards’ with respect to the long-run  
38 EKC. Two different environmental hypotheses are constructed and tested using the threshold  
39 autoregressive (TAR) and momentum threshold autoregressive (M-TAR) cointegration  
40 method of Enders and Siklos (2001), which as far as we know has not been used to analyse  
41 emissions in the current EKC literature.

42 Following the introduction, we discuss the related literature on the EKC, then the data and  
43 non-linear cointegration techniques are examined. We then discuss the results and finally  
44 offer some conclusions.

## 45 **2. Literature Review**

46 Empirical work into the Environmental Kuznets Curve (EKC) to date has produced mixed  
47 findings. Studies use a very wide variety of countries, pollutants, data sources and  
48 econometric techniques<sup>1</sup>, each one coming up with a slightly different perspective on the  
49 acceptance or rejection of the EKC hypothesis, and what it means for the theory<sup>2</sup>. Perhaps the  
50 most important distinction between studies is the approach they use with regards to multiple-  
51 or single-country analysis and therefore the use of panel data or time series techniques. One  
52 of the reasons why time series aspects are appearing is that over the last few years there has  
53 been an increasing acceptance of the fact that not only with time series studies, but now with  
54 panel data there is the need for checking the order of integration and the cointegration of  
55 variables used in the models. This is due to the fact that ‘large N, large T’ datasets are  
56 becoming feasible and available.

### 57 **2.1. Panel data Estimation**

58 The original work in the area of the EKC came from Grossman and Krueger (1995) who  
59 employed a database for a range of cities from the Global Environmental Monitoring Systems  
60 (GEMS). They used panel data techniques, confirming the existence of the inverse-U  
61 relationship between air and water basin pollution and income per capita. As such, after this  
62 paper, the majority of work was to perform analysis in a panel data framework. For instance,  
63 Managi and Jena (2008) create an environmental productivity index to be used as a dependent  
64 variable, and use additional explanatory variables such as urbanisation and population density.

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<sup>1</sup> These include cross-section, time series and panel methods. Here we focus on studies with a time dimension.

<sup>2</sup> The literature on the EKC is dominated by empirical studies, Harbaugh *et al.* (2002) point out there is little theoretical literature to guide the correct specification, so most studies follow the approach used by Grossman and Krueger (1995).

65 However, there have been several criticisms of panel data techniques in the context of the  
66 EKC mentioned in the literature, all of which would seem to be in favour of focussing on  
67 individual country analysis in a time series framework. In his survey Dinda (2004, p.449)  
68 points to the critical flaw in the panel approach, noting that “the basic assumption behind  
69 pooling the data of different countries in one panel is that economic development trajectory  
70 would be the same for all.”

71 Another point about the use of panels is that, due to data limitations, researchers are generally  
72 restricted to a small time period over many countries. Since this period is generally from the  
73 early 1980s until the current day, Vincent (1997) notes that panel studies of the EKC may be  
74 little more than a statistical artefact. This is because over this data range, developing  
75 countries can generally be seen to have a positive relation between emissions and output and  
76 many developed countries may exhibit a negative relation, thus leading to an overall  
77 conclusion that the EKC holds over all countries.

## 78 **2.2 Time Series Estimation**

79 Some studies, noting the above criticisms of cross-country panels, go on to estimate a single-  
80 country panel regression by pooling data for regions within the country. While this  
81 circumvents some of the problems discussed, de Bruyn et al. (1998, p.173) argue that “the  
82 EKC, as estimated from panel data does not capture dynamic processes well enough to justify  
83 the claim that economic growth is de-linked from environmental pressure in individual  
84 countries”. This argument suggests that using panel data even within countries may not be  
85 capable of measuring the EKC relation.

86 With this in mind, several studies have employed time series analysis of emissions in  
87 individual countries, deploying a range of unit root and cointegration techniques to examine a  
88 non-spurious long-run EKC relationship. Perman and Stern (2003) look at sulphur emissions

89 for a large number of countries both at an individual level, and then at a panel level. Using  
90 the Engle-Granger (1987) method they find that a long-run cointegrating relationship only  
91 exists in 35 out of 74 countries. They also found that in more than one third of cases, the  
92 EKC hypothesis was rejected. However, their analysis was only performed on a relatively  
93 small dataset from 1960-1990. Other studies such as Markandya *et al.* (2006) and Lindmark  
94 (2002) also use long datasets stretching back to the nineteenth century, with the former using  
95 a similar dataset to the one used in this paper and the latter a Swedish dataset starting in 1870.

96 Other time series studies use the more recently developed Pesaran *et al.* (2001)  
97 Autoregressive Distributed Lag (ARDL) bounds testing approach to cointegration. This has  
98 benefits over other cointegration methods as it allows for a mixture of I(1) and I(0) variables  
99 to be included in the long-run cointegrating relation, as is often the case with CO<sub>2</sub> emissions.

100 Ang (2007) looks for a quadratic EKC relationship in French CO<sub>2</sub> emissions over the period  
101 1960-2000. The results give the correct signs, lending evidence towards the EKC hypothesis.

102 With the above mentioned advantages of single-country studies in mind, this paper aims to  
103 look at how the EKC is dynamically misspecified. The specification of the empirical model is  
104 subject to some discussion, and this can be seen to change dramatically across studies. Carson  
105 (2010) provides a survey of the EKC literature and suggests several possible sources of  
106 misspecification. Amongst other, he mentions omitted variables and the functional form as  
107 key factors which could lead to misspecification. Studies that have examined omitted  
108 variables include Soytaş *et al* (2007), who added total labour force and energy use as  
109 additional explanatory variables.

110 Very few studies have looked to move away from the classic quadratic or cubic specification  
111 of the EKC. Galeotti *et al.* (2006) moves away from this specification of per capita income by  
112 imposing the inverse-U shape into the relationship through other bell-shaped distributions.

113 They do this for CO<sub>2</sub> emissions in OECD and non-OECD countries, finding that the bell-  
114 shape fits the OECD countries but not the non-OECD countries, where they find an  
115 increasing, or “slowly concave” pattern.

116 However, to the best of the authors’ knowledge, no studies to date have looked for  
117 asymmetric behaviour in emissions with regards to disequilibrium from the long-run EKC.  
118 Time series studies, such as those mentioned above, all favour symmetric (linear)  
119 cointegration techniques. However, as mentioned in Section 1, there is substantial reason to  
120 believe that we may expect pressure from environmental agreements to cause a quicker  
121 adjustment back to the EKC when emissions are temporarily too high compared to when they  
122 are too low.

### 123 **3. Materials and Methods**

#### 124 **3.1 Data**

125 This paper uses a long historical dataset, which yields benefits in terms of sample size. The  
126 vast majority of time series studies use less than 50 observations. We use historical CO<sub>2</sub> data  
127 from the Carbon Dioxide Information Analysis Centre (CDIAC) based in the Oak Ridge  
128 National Laboratory (ORNL). This is fossil-fuel CO<sub>2</sub> emissions measured in metric tonnes  
129 estimated from historical energy statistics and spans the period 1751-2007 for the United  
130 Kingdom. Holtz-Eakin and Selden’s (1995) important work also used this dataset though it  
131 was truncated to a shorter dataset due to the data availability of the countries selected to form  
132 a panel. The SO<sub>2</sub> data is that of David Stern and is available over the period 1850-2002 for  
133 the UK. The data for real GDP is taken from Maddison and measured in 1990 international  
134 Geary-Khamis dollars (GK\$). Population data is taken from the same source and is used to  
135 transform the variables into per capita terms. The real GDP and population variables run from  
136 1830-2003 and 1820-2008 respectively. This data is also used by papers such as Markandya

137 et al. (2006) to analyse European countries in a panel data context. The data for energy  
138 prices<sup>3</sup> comes from a series generated by Fouquet (2011), where this series is expressed in a  
139 form equivalent to their energy service, which requires that they are combined with the  
140 energy efficiency of the equipment used, the adjustment required to produce energy prices in  
141 this form is explained in Fouquet (2011).

142 In order to maximise the number of useable observations the largest common sample for the  
143 per capita CO<sub>2</sub> and SO<sub>2</sub> emissions with real GDP per capita are used. This means a sample  
144 from 1830 to 2003 for the CO<sub>2</sub> model and from 1850 to 2002 for the SO<sub>2</sub> model. Charts of the  
145 data and the common sample descriptive statistics are shown in Figures 1 and 2. The clearest  
146 falls in both series occur in 1921, 1926 and from 1956 onwards. Markandya et al (2006)  
147 largely attribute these to regulation – 1926 being the year of the Smoke Abatement Act and  
148 1956 onwards being the epoch of the Clean Air Acts. However, 1926 also saw the General  
149 Strike in the UK and the National Coal Strike took place in 1921. These broader economic  
150 events may have had a more significant impact than regulation in those particular years. This  
151 also explains the lack of a continuing downward trend after these years. The steeper fall in  
152 SO<sub>2</sub> emissions shows that these have been easier to reduce using new technologies applied to  
153 power stations, such as the use of ‘Flue Gas desulphurisation’ techniques, whereas with CO<sub>2</sub>  
154 the technology has been less effective.. In addition there has over recent years been a move  
155 away from the use of coal which emits large quantities of SO<sub>2</sub> to other fuels such as gas  
156 which emit far lower levels.

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<sup>3</sup> We would like to thank Roger Fouquet for allowing us access to this dataset. Other energy prices in addition to gas prices could have been included but gave similar results to gas prices. Although Lindmark (2002) uses a price index which includes non CO<sub>2</sub> emitting energy carriers, as he adds it could also be concluded that the relative price for them could be insignificant. In addition to the results included here, other tests were conducted on energy prices without the trend, but the results are similar to the standard model.



157 Clearly the range of real GDP per capita is smaller for the common sample with SO<sub>2</sub> per  
 158 capita emissions due to the removal of observations from the beginning and end of the dataset  
 159 as compared with the CO<sub>2</sub> dataset. This range of values will be relevant when looking at the  
 160 turning points of the EKC relation to see whether they lay within the observed dataset. The  
 161 data will be transformed into natural logarithms for the econometric analysis; this is  
 162 important as the real GDP variable in particular exhibits an exponential trend in levels.

### 163 **3.2. Methodology**

164 Enders and Siklos (2001) propose two methods to test for asymmetric cointegration which  
 165 are based on the two-step cointegration procedure of Engle and Granger (1987). In this way  
 166 the first stage is to estimate the long-run regression using ordinary least squares (OLS). To  
 167 allow for the most flexible shape for the EKC, we will follow much of the literature by  
 168 allowing polynomial terms for real GDP per capita up to and including the third order  
 169 (cubic). This produces a relatively parsimonious model, which is of importance as the  
 170 addition of variables to the cointegrating relation not only uses up degrees of freedom but  
 171 also changes the appropriate response surface for the cointegration test statistic, making it  
 172 harder to find significant cointegrating relationships. The basic model is written as follows:

$$173 \quad e_t = \beta_0 + \beta_1 y_t + \beta_2 y_t^2 + \beta_3 y_t^3 + \mu_t \quad (1)$$

174 where  $e_t$  denotes emissions of CO<sub>2</sub> or SO<sub>2</sub> in metric tonnes (MT) per capita and  $y_t$  denotes  
 175 real GDP per capita and both series are in natural logarithms.  $\mu_t$  is the residual. We also  
 176 consider energy prices as an explanatory variable which is discussed later in this section.

177 Having run the long-run regression, the second stage is to perform a unit root test on the  
 178 residual series  $\mu_t$ , with the null hypothesis of a unit root being equivalent to no cointegration.

179 The original test of Engle and Granger (1987) tests for symmetric cointegration by running  
 180 the standard Dickey-Fuller (1979) test on the residuals of the regression as follows:

$$181 \quad \Delta\mu_t = \rho\mu_{t-1} + \varepsilon_t \quad (2)$$

182 The residual term of this regression  $\varepsilon_t$ , is assumed to be pure white noise with a zero mean  
 183 and a constant variance. Enders and Siklos (2001) present two modifications to this simple  
 184 model in order to test for asymmetries: a threshold autoregressive (TAR) model, and a  
 185 momentum-threshold autoregressive (M-TAR) model. We can use these two models to test  
 186 for two different hypotheses.

187 The first hypothesis is that the pressure of environmental agreements causes more attention  
 188 to be given to emissions when they are temporarily above the EKC;  $\mu_t \geq 0$ , than when they  
 189 are below the EKC;  $\mu_t < 0$ . In other words certain regulations or the existence of emissions  
 190 penalties mean that there is more motivation to reduce emissions when they are too high in  
 191 levels, but there is less urgency to increase emissions when they are too low. This notion can  
 192 be tested with use of the TAR modification to the Engle-Granger (1987) test:

$$193 \quad \Delta\mu_t = I_t\rho_1\mu_{t-1} + (1-I_t)\rho_2\mu_{t-1} + \varepsilon_t \quad (3)$$

194 Where  $I_t$  is the Heaviside indicator function, described as follows<sup>4</sup>:

$$195 \quad I_t = \begin{cases} 1 & \text{if } \mu_t \geq 0 \\ 0 & \text{if } \mu_t < 0 \end{cases} \quad (4)$$

196 A second hypothesis asks whether the pressure of environmental agreements means that  
 197 deviations of emissions from the long-run EKC are corrected more quickly when emissions

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<sup>4</sup> In fact, they suggest a threshold for  $\mu_t$  of  $\tau$  rather than 0. However, in this case we are only interested in what happens when we are either above or below the EKC, so we set it equal to 0, as in Enders and Siklos (2001).

198 are tending to increase relative to the EKC;  $\Delta\mu_t \geq 0$ , than when they decrease relative to the  
 199 EKC;  $\Delta\mu_t < 0$ . Unlike the TAR framework it does not matter whether emissions are above or  
 200 below the EKC, only the direction in which emissions are moving, in other words their  
 201 momentum. This can be tested using the second modification of Enders and Siklos (2001):

$$202 \quad \Delta\mu_t = M_t \rho_1 \mu_{t-1} + (1 - M_t) \rho_2 \mu_{t-1} + \varepsilon_t \quad (5)$$

203 Where  $M_t$  is the Heaviside indicator function, described as follows:

$$204 \quad M_t = \begin{cases} 1 & \text{if } \Delta\mu_t \geq 0 \\ 0 & \text{if } \Delta\mu_t < 0 \end{cases} \quad (6)$$

205 So both of these specifications can test for the different ways in which we may expect  
 206 emissions to be more ‘sticky upwards’, so as to meet environmental regulation.

207 If the residual series  $\varepsilon_t$  is not deemed to be white noise, then lags of the dependent variable  
 208 may be added to Equations 3 and 5, according to an information criterion. The necessary and  
 209 sufficient conditions for stationarity of  $\mu_t$  are that  $\rho_1 < 0, \rho_2 < 0$  and  $(1 + \rho_1)(1 + \rho_2) < 1$ , as  
 210 stated by Petrucelli and Woolford (1984). Enders and Siklos (2001) propose to test the first  
 211 two conditions jointly using the null hypothesis  $H_0 : \rho_1 = \rho_2 = 0$ . Since this F-statistic does  
 212 not follow a standard distribution, it must be compared with the  $\phi_\mu$  tables for the TAR  
 213 model and the  $\phi_\mu^*$  tables for the M-TAR model, which Enders and Siklos (2001) compute  
 214 through Monte Carlo simulation. However, since this response surface changes with the  
 215 number of observations, the number of variables in the long-run regression and the number of  
 216 lagged dependent variables, the more complete tables of Wane, Gilbert and Dibooglu (2004)  
 217 as cited in Wang and Thi (2010) have been used. Having established cointegration, to test for  
 218 asymmetric cointegration, the F-statistic for the null hypothesis  $H_0 : \rho_1 = \rho_2$  is calculated,

219 which Enders and Siklos (2001) note can be compared to the standard F-distribution. We  
 220 would have a priori expectations that  $|\rho_1| > |\rho_2|$  for both the TAR and M-TAR frameworks.

221 If there is evidence to support the existence of a single cointegrating vector, then Engle and  
 222 Granger (1987) show that there exists an error-correction model (ECM) representation. For  
 223 the Enders and Siklos (2001) TAR model these can be written for  $e_t$  and  $y_t$  as follows:

$$224 \quad \Delta e_t = \rho_{11}I_t\mu_{t-1} + \rho_{12}(1-I_t)\mu_{t-1} + \sum_{i=1}^3 \alpha_{1i}\Delta y_{t-1}^i + \alpha_{14}\Delta e_{t-1} + v_{1t} \quad (7)$$

$$225 \quad \Delta y_t = \rho_{21}I_t\mu_{t-1} + \rho_{22}(1-I_t)\mu_{t-1} + \sum_{i=1}^3 \alpha_{2i}\Delta y_{t-1}^i + \alpha_{24}\Delta e_{t-1} + v_{2t} \quad (8)$$

226 where  $i$  denotes the power operator on emissions. Similarly for the M-TAR model the  
 227 indicator function  $I_t$  can be replaced with  $M_t$ . The two further ECMs exist for the variables  $y_t^2$   
 228 and  $y_t^3$  though these have little useful economic interpretation, so the regressions are run but  
 229 not reported (Results available from authors on request). Clearly for cointegration between  
 230 these variables to be meaningful, some of the  $\rho$  terms should be statistically significant for a  
 231 given pollutant. If none of the  $\rho$  terms were significant it would mean that no variables adjust  
 232 in the short-run to correct for any disequilibrium from the long-run EKC. Furthermore some  
 233 of the  $\rho$  terms should be negative so that if the error term is positive, one of the variables  
 234 decreases rather than increases, thus ensuring that the system is dynamically stable.

235 In addition to the above approach, we have incorporated two further factors into the basic  
 236 EKC model in Equation 1 to control for the effects of technological change on emissions and  
 237 changes in energy prices. This also enables us to determine whether the asymmetric  
 238 adjustment is due to technological changes, for instance there may only be government  
 239 backed incentives for firms to invest in technologically advanced processes for reducing

240 pollutants, when the authorities are trying to ensure targets for pollution emissions are met,  
 241 that is when they are above the EKC. When below the EKC, there is little need to invest in  
 242 the more technologically advanced products, so any asymmetry can be accounted for by  
 243 technological progress<sup>5</sup>. We have also included energy prices as a further factor in the model,  
 244 as other studies such as Lindmark (2002) suggest these may have a significant effect on  
 245 emissions. This produces the following augmented model:

$$246 \quad e_t = \gamma_0 + \gamma_1 y_t + \gamma_2 y_t^2 + \gamma_3 y_t^3 + \gamma_4 ep_t + \gamma_5 Trend + v_t \quad (9)$$

247 Where  $ep_t$  is the log of energy prices and  $Trend$  is a linear trend, which proxies technological  
 248 change. In the models estimated here, we have used gas prices to represent energy prices, as  
 249 this has been a popular source of energy throughout the data span used here, in contrast to  
 250 coal, oil or wood, which have varied in popularity. However although over the entire data  
 251 span gas has been a major source of energy, during some time periods, such as the 1990s, oil  
 252 was the most popular source of energy. This fact may also suggest the potential for structural  
 253 breaks as different sources of energy have varied in popularity over the data range. If this  
 254 were the case then we need to account for this when performing unit root tests, which we  
 255 discuss in the next section with reference to the structural break unit root test of Zivot and  
 256 Andrews (1992).

## 257 **4. Results and Discussion**

### 258 **4.1 Long-run EKC and cointegration results**

259 Table 1 contains the summary statistics for all the variables, showing that CO<sub>2</sub> emissions are  
 260 considerably higher on average than SO<sub>2</sub> emissions. Before performing any cointegration

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<sup>5</sup> See Jaffe *et al.* (2002) for a review of some of the theoretical implications of technological change to environmental policy.

261 analysis, unit root tests were run to check the order of integration of the variables. First of all  
 262 we run three basic tests with no structural breaks, namely the augmented Dickey-Fuller test,  
 263 the GLS-detrended ADF test of Elliot, Rothenberg, and Stock (1996) – ERS and the  
 264 Phillips-Perron (1988) test - PP. However given the above point that there could be reason to  
 265 believe that there is a structural break in the time series we also run the structural break unit  
 266 root test of Zivot and Andrews (1992) - ZA.

267 This is a test of the null hypotheses of a unit root process without a structural break (equation  
 268 6 in ZA) against the alternative of trend-stationarity with a structural break in the intercept  
 269 and trend. We have chosen this test as it determines the breakpoint  $\lambda$  endogenously, unlike its  
 270 predecessor Perron (1989) where the researcher must specify the break date. For maximal  
 271 generality we allow for breaks in both the constant and trend, and therefore only consider the  
 272 third model of ZA, and hence run the regression:

$$273 \quad \Delta y_t = \mu + \theta DU_t(\lambda) + \beta t + \gamma DT_t^*(\lambda) + \alpha y_{t-1} + \sum_{j=1}^k \varphi_j \Delta y_{t-j} + v_t \quad (10)$$

274 Here  $DU_t(\lambda)$  denotes the dummy variable for the break in the constant term from the  
 275 estimated breakpoint  $\lambda$  so  $DU_t(\lambda) = 1$  if  $t > T(\lambda)$  0 otherwise.  $DT_t^*$  is the variable for the  
 276 break in the trend, namely  $DT_t^* = t - T(\lambda)$  if  $t > T\lambda$ , 0 otherwise, As usual, the estimate of  
 277 interest is  $\alpha$  though we are also interested in the breakpoint if we can reject the null  
 278 hypothesis and conclude trend stationarity with a structural break.

279 The results of these tests are reported in Tables 2a and 2b. Table 2a confirms that the  
 280 variables are all I(1), meaning we can look for a long-run cointegrating vector amongst the  
 281 variables. More notably perhaps, the evidence in Table 2b shows that we cannot reject the  
 282 null hypothesis of a unit root without structural breaks, so there is not an issue of controlling

283 for structural breaks in the following analysis.<sup>6</sup> The estimated break dates are reported in  
 284 parentheses though they are not relevant following the non-rejection of the null hypothesis.

285 Table 3 presents the results of running the OLS regressions of Equation 1 for both CO<sub>2</sub> and  
 286 SO<sub>2</sub> emissions and therefore shows the long-run EKC relations. Before analysing the results  
 287 in terms of the acceptance or rejection of the EKC hypothesis, it is necessary first to look at  
 288 the cointegrating behaviour of these variables, otherwise the above regressions can be  
 289 deemed spurious. In tables 4 and 5 for the TAR and M-TAR tests, the  $\rho$  estimates are  
 290 presented, along with the  $\phi_\mu$  or  $\phi_\mu^*$  statistics for cointegration, the standard F test for the null  
 291 hypothesis  $H_0 : \rho_1 = \rho_2$  to detect asymmetry and the Schwarz-Bayesian information  
 292 criterion (SBC) of the regression..

293 The results for the asymmetric cointegration tests yield some interesting findings about  
 294 dynamic misspecification in the EKC<sup>7</sup>. In all cases no lags are included in any of the tests as  
 295 unit root tests on the  $\varepsilon_t$  residual series reveal that they are sufficiently white noise for all  
 296 regressions. Firstly, it can be seen that the necessary and sufficient conditions for  
 297 cointegration hold in all cases. The  $\rho$  terms have negative signs, which are significant due to  
 298 the rejection of the null hypothesis  $H_0 : \rho_1 = \rho_2 = 0$  in all cases and at every conventional  
 299 significance level. In the basic model, equation 1, using the standard F-statistic for the  
 300 restriction;  $H_0 : \rho_1 = \rho_2$  shows that asymmetric cointegration is strongly significant in the  
 301 TAR framework for both the CO<sub>2</sub> and SO<sub>2</sub> EKC relations. In the more powerful M-TAR

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<sup>6</sup> We did not present the results of the Zivot Andrews (1992) test on the differences of the variables as there is no reason why the alternative hypothesis of trend-stationarity with a structural break is appropriate for the differences of these variables.

<sup>7</sup> The cointegration tests did not include a trend, as it was insignificant in all of them. It is only included in the long-run EKC model when testing the augmented model in equation (9).

302 framework, asymmetric cointegration is only detected in the case of per capita CO<sub>2</sub>  
303 emissions, but not for SO<sub>2</sub>. Therefore the results show that the TAR adjustment process is  
304 more appropriate for SO<sub>2</sub>. As for the CO<sub>2</sub> model we will follow Enders and  
305 Chumrusphonlert's (2004) advice in using the AIC or SBC to select the best adjustment  
306 mechanism. Looking at the reported SBC for each regression shows that indeed for the SO<sub>2</sub>  
307 model, the TAR model is more appropriate, and the M-TAR model is the most appropriate  
308 adjustment mechanism for the case of CO<sub>2</sub> (the appropriate minimum SBC is in bold.)

309 With respect to the  $\rho$  coefficients of the estimated models, we can see in both cases  
310  $|\rho_1| > |\rho_2|$ . Therefore we can say that, in the basic specification, the hypothesis of stickiness  
311 of emissions holds for both CO<sub>2</sub> and SO<sub>2</sub> emissions, though they both follow slightly  
312 different adjustment processes, namely M-TAR and TAR respectively. These results point to  
313 a significant effect of environmental pressure when emissions are either rising, or above  
314 equilibrium. This may in part reflect the role of environmental regulation, with penalties from  
315 existing regulation. For the CO<sub>2</sub> result, the finding of an M-TAR model could be due to the  
316 emphasis placed on it in terms of reducing greenhouse gas emissions. As the political  
317 momentum has swung towards reducing CO<sub>2</sub> emissions, the emphasis has been on *increases*  
318 in CO<sub>2</sub>, rather than its actual level, which drives the return to equilibrium.

319 Furthermore, we can see that the correction back to equilibrium is faster for CO<sub>2</sub> than SO<sub>2</sub>.  
320 Comparing the TAR models of both CO<sub>2</sub> and SO<sub>2</sub>, and the M-TAR models reveals this to be  
321 the case. For the selected M-TAR model for CO<sub>2</sub>, we see that 62.11% of the deviation from  
322 equilibrium is corrected when emissions are rising, compared to only 21.57% when they are  
323 falling. Using the selected TAR model for SO<sub>2</sub>, we can see that when emissions are  
324 temporarily above the long-run EKC, only 38.91% of the deviation is corrected in the next  
325 period, and only 15.34% is corrected when SO<sub>2</sub> emissions are below the EKC. This may also



326 reflect the relative marginal abatement costs of SO<sub>2</sub> and CO<sub>2</sub>, with CO<sub>2</sub> being relatively  
327 easier to abate. The marginal abatement cost curves of each show that currently for the UK  
328 SO<sub>2</sub> is significantly more expensive to abate (Rabl et al, 2005).

329 Having established M-TAR cointegration in the long-run relation for CO<sub>2</sub>, and TAR  
330 cointegration in that of SO<sub>2</sub>, it is now possible to analyse the estimation results and what they  
331 imply for the EKC hypothesis. For CO<sub>2</sub>, one can see that in terms of the  $\beta$  coefficients  
332 described in the EKC relation in Equation 1, we have  $\beta_0 < 0, \beta_1 > 0, \beta_2 < 0$  and  $\beta_3 > 0$ ,  
333 which implies an N-shaped function. This pattern is the same as found for Turkish CO<sub>2</sub>  
334 emissions in the time series study by Akbostanci et al. (2009). The fitted values of CO<sub>2</sub>  
335 emissions for the observed values of real GDP are displayed in Figure 3. These results show  
336 that there is strong evidence in favour of the EKC hypothesis. The only turning point in the  
337 observed range of real GDP for CO<sub>2</sub> occurs at GK\$7691 in 1990 international Geary-Khamis  
338 dollars. This shows that the inverted-U shape holds and, due to the cubic term, the curve  
339 seems to flatten-out towards the upper-end of the real GDP range.

340 For SO<sub>2</sub> emissions, the regression results are quite different, as shown in Figure 4. In this  
341 case we see the opposite signs to the CO<sub>2</sub> case, namely  $\beta_0 > 0, \beta_1 < 0, \beta_2 > 0$  and  $\beta_3 < 0$ .  
342 This finding is similar to the result that Fodha and Zaghoud (2010) find in Tunisian SO<sub>2</sub>  
343 data. These estimates indicate an inverse-N shape, so it is necessary to check the location of  
344 the turning points in order to see whether the EKC hypothesis is rejected or not. Once again,  
345 ignoring infeasible turning points shows that the EKC is again seen to be an inverse-U shape  
346 when looking at the estimated EKC at the observed levels of real GDP per capita. The main  
347 turning point here is located at GK\$8167, whereas using the same datasets for both real GDP  
348 per capita and SO<sub>2</sub> emissions, Markandya et al. (2006) find the turning point in the UK to be  
349 GK\$10,700. The graphs seem to indicate that a steeper inverted U shape for the EKC of SO<sub>2</sub>

350 compared to CO<sub>2</sub>. This is resulting from the observed sharp drop in SO<sub>2</sub> emissions explained  
351 in section 3.1, and this attribute of the data is translated directly into the fitted EKC for  
352 SO<sub>2</sub>. These results are therefore strongly in favour of the EKC hypothesis in the UK for both  
353 CO<sub>2</sub> and SO<sub>2</sub> emissions with turning points of GK\$7691 and GK\$8167 respectively. Looking  
354 at the Maddison dataset we see that the turning point for CO<sub>2</sub> occurred in 1954, whereas for  
355 SO<sub>2</sub> this would have been 1958 or 1959.

356 The addition of energy prices and a time trend to the model has not affected the results in  
357 terms of the presence of cointegration and in the long-run equations the non-linear  
358 relationship remains significant and correctly signed, suggesting the relationship is  
359 reasonably robust. However the trend is significant indicating that technological change has  
360 contributed to the emissions of pollutants, in addition to the change in income, although the  
361 energy prices tend to be insignificant when the trend is included in the model. However the  
362 results differ for the tests on whether  $\rho_1 = \rho_2$ , as for the TAR model, the hypothesis is only  
363 rejected at the 10% level of significance for both carbon dioxide and sulphur dioxide.  
364 However we fail to reject the null of symmetry for the M-TAR models for both pollutants.  
365 The addition of the trend and energy prices appears to have explained part of the asymmetry  
366 in adjustment. These findings could seem to suggest that the mis-specification of the EKC  
367 model could be partially through the econometric technique used, but also through the  
368 omission of factors such as technological change.

#### 369 **4.2 Short-Run Error Correction Model Results**

370 Having established asymmetric cointegrating relationships of different kinds of CO<sub>2</sub> and SO<sub>2</sub>  
371 emissions, we can now estimate the ECMs as described in Equations 7 and 8, using the  
372 appropriate TAR or M-TAR indicator functions. These results are reported in Tables 5 and 6  
373 for CO<sub>2</sub> and SO<sub>2</sub> emissions respectively.

374 The ECM results for CO<sub>2</sub> and SO<sub>2</sub> emissions show some very similar findings. Firstly, any  
375 deviation away from the long-run EKC is corrected solely by movements in emissions, not by  
376 movements in real GDP per capita. This can be seen by the insignificance of the error  
377 correction parameter  $\rho_{21}$  in the ECM for  $y_t$  for both CO<sub>2</sub> and SO<sub>2</sub> emissions, though it is  
378 significant for CO<sub>2</sub> at the 10% level. This means that if emissions were above what is  
379 expected in long-run equilibrium, this error is corrected in the next period by a fall in  
380 emissions rather than a change in real GDP per capita. This is as expected because over the  
381 last two centuries there has been a policy of maximising economic growth regardless of  
382 effects on the environment, emissions have been reduced through legislation on the polluter.

383 Secondly, the results indicate that deviations from the long-run EKC for both CO<sub>2</sub> and SO<sub>2</sub>  
384 are corrected in the short-run by changes in emissions according to the hypotheses made in  
385 Section 4. In other words, since  $|\rho_{11}| > |\rho_{12}|$  in both cases, for CO<sub>2</sub> emissions adjust more  
386 quickly to correct disequilibrium when they are rising, and for SO<sub>2</sub> emissions change to  
387 correct disequilibrium when they are above the EKC. This is consistent with the results in  
388 Table 4 for the long-run relation. It also must be noted that the estimates of  $\rho_{12}$  and  $\rho_{21}$  are  
389 insignificant in both cases which reiterates the point that there is very little tendency for  
390 emissions to change in order to restore equilibrium when emissions are below the EKC as  
391 there is no pressure from the environmental movement for politicians to intervene if  
392 emissions are too low. Adding the gas price and trend to the error correction models makes  
393 little difference overall to the results although gas prices have a positive effect on SO<sub>2</sub>  
394 emissions. However this measure of gas prices also takes into account the efficiency of the  
395 machinery which uses the gas, so this probably reflects the increased efficiency of the  
396 machinery rather than increases in gas prices affecting emissions positively. In the income  
397 equation, both the technological change and gas prices have a significantly positive effect.

## 398 5. Conclusion

399 This study uses threshold cointegration methods to study the EKC and the results shed some  
400 interesting light on how emissions behave when they are above equilibrium and showing  
401 signs of potentially violating environmental regulation. In the case of CO<sub>2</sub>, we find that any  
402 temporary disequilibrium from the EKC relation is corrected quicker when per capita CO<sub>2</sub>  
403 emissions show momentum in an upwards direction than when they show momentum in a  
404 downwards direction (M-TAR adjustment.) For SO<sub>2</sub>, a similar result is found in that any  
405 disequilibrium from the EKC relation is corrected quicker when per capita SO<sub>2</sub> emissions are  
406 above the EKC than when they are below the EKC (TAR adjustment.) Furthermore, the  
407 short-run error correction models reveal that disequilibrium is corrected solely by changes in  
408 per capita emissions, and not by movements in real GDP per capita, as expected since  
409 emissions have been reduced by legislation rather than a policy of reducing economic growth.  
410 This suggests mitigating CO<sub>2</sub> or greenhouse gas emissions and SO<sub>2</sub> emissions will rely more  
411 on legislation than reductions in economic growth.

412 With this in mind, the long-run results find strong evidence in favour of the EKC hypothesis  
413 with per capita CO<sub>2</sub> and SO<sub>2</sub> emissions having an inverse-U relation with real GDP per  
414 capita. The evidence suggests that the turning point for SO<sub>2</sub> occurred at a higher level of  
415 income than CO<sub>2</sub>, at GK\$8167 and GK\$7691 respectively. The results also suggest that the  
416 asymmetry of the adjustment can be partially explained by technological change and energy  
417 prices. This suggests the EKC model needs to be estimated using an approach which accounts  
418 for asymmetric adjustment and also specified to incorporate technological change. Future  
419 studies need to concentrate on alternative measures of technological change, as the data  
420 becomes available.

421

## References

- 422  
423 Akbostanci, E., Türüt-Asic, S., Tunç, I., 2009. The relationship between income and  
424 environment in Turkey: Is there an environmental Kuznets curve? *Energy Policy* 37 (3),  
425 861-867.
- 426 Ang, J.B., 2007. CO<sub>2</sub> emissions, energy consumption, and output in France. *Energy Policy*  
427 35 (10), 4772-4778.
- 428 de Bruyn, S.M., van den Bergh, J.C.J.M., Opschoor, J.B., 1998. Economic growth and  
429 emissions: reconsidering the empirical basis of Environmental Kuznets Curves. *Ecological*  
430 *Economics* 25 (2), 161–175.
- 431 Carson, R.T., Jeon, Y., McCubbin, D.R., 1997. The relationship between air pollution  
432 emissions and income: US data. *Environment and Development Economics* 2 (4), 433–  
433 450.
- 434 Carson, R.T., 2010. The Environmental Kuznets Curve: Seeking empirical regularity and  
435 theoretical structure. *Review of Environmental Economics and Policy* 4 (1), 3–23.
- 436 Dickey, D.A. and Fuller, W.A. (1979), Distributions of the estimators for autoregressive time  
437 series with a unit root. *Journal of the American Statistical Association*, 74, 427-431.
- 438 Dinda, S., 2004. Environmental Kuznets curve hypothesis: A survey. *Ecological Economics*  
439 49 (4), 431–55.
- 440 Elliott, G., Rothenberg, T. J., Stock, J.H., 1996. Efficient Tests for an Autoregressive Unit  
441 Root. *Econometrica* 64 (4), 813-837.
- 442 Enders, W., Chumrusphonlert, K., 2004. Threshold cointegration and purchasing power  
443 parity in the pacific nations. *Applied Economics* 36 (9), 889–896.
- 444 Enders, W. Siklos, P., 2001. Cointegration and threshold adjustment. *Journal of Business and*  
445 *Economic Statistics* 19 (2), 166–76.

- 446 Engle, R.F., Granger, C. W. J., 1987. Co-Integration and error correction: representation,  
447 estimation, and testing. *Econometrica* 55 (2), 251-276.
- 448 Fodha, M., Zaghoud, O., 2010. Economic growth and pollutant emissions in Tunisia: An  
449 empirical analysis of the environmental Kuznets curve. *Energy Policy* 38 (2), 1150-1156.
- 450 Fouquet, R. 2011. Divergences in long-run trends in the prices of energy and energy services.  
451 *Review of Environmental Economics and Policies*. (2) 196-218
- 452 Galeotti, M., Lanza, A., Pauli, F., 2006. Reassessing the environmental Kuznets curve for  
453 CO<sub>2</sub> emissions: A robustness exercise. *Ecological Economics* 57 (1), 152-163.
- 454 Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. *Quarterly*  
455 *Journal of Economics* 110 (2), 353– 377.
- 456 Harbaugh, W., Levinson, A. and Wilson, D., 2002. Reexamining the empirical evidence for  
457 an environmental Kuznets curve, *Review of Economics and Statistics*, 84, 541-551.
- 458 Holtz-Eakin, D., Selden, T.M., 1995. Stoking the fires?: CO<sub>2</sub> emissions and economic  
459 growth. *Journal of Public Economics* 57 (1), 85–101.
- 460 Jaffe, A., Newell, R. and Stavins, R. 2002. Environmental policy and technological change,  
461 *Environmental and Resource Economics*, 22, 41-69.
- 462 Johansen, S., 1988. Statistical analysis of cointegration vectors. *Journal of Economic*  
463 *Dynamics and Control* 12 (2-3), 231-254.
- 464 Lindmark, M. 2002. An EKC-pattern in historical perspective: Carbon dioxide emissions,  
465 technology, fuel prices and growth in Sweden 1870-1997. *Ecological Economics*, 42, 333-  
466 347.
- 467 Managi, S., Jena, P.R., 2008. Environmental productivity and Kuznets curve in India.  
468 *Ecological Economics* 65 (2), 432-440.

- 469 Markandya, A., Golub, A., Pedroso-Galinato, S., 2006. Empirical analysis of national income  
470 and SO<sub>2</sub> emissions in selected European countries. *Environmental and Resource*  
471 *Economics* 35 (3), 221-257.
- 472 Perman, R., Stern, D.I., 2003. Evidence from panel unit root and cointegration tests that the  
473 Environmental Kuznets Curve does not exist. *The Australian Journal of Agricultural and*  
474 *Resource Economics* 47 (3), 325-347.
- 475 Perron, P., 1989. The great crash, the oil price shock and the unit root hypothesis.  
476 *Econometrica* 57, 1361-1401.
- 477 Petrucci, J., Woolford, S.W., 1984. A Threshold AR(1) Model. *Journal of Applied*  
478 *Probability* 21 (2), 270–286.
- 479 Pesaran, M.H., Shin, Y., Smith, R.J., 2001. Bounds testing approaches to the level analysis of  
480 level relationships. *Journal of Applied Econometrics* 16 (3), 289-327.
- 481 Phillips, P.C.B., Perron, P., 1988. Testing for a unit root in a time series regression.  
482 *Biometrika* 75 (2), 335-346.
- 483 Rabl, A., Spadaro, J., van der Zwaan, B., 2005. Uncertainty of air pollution cost estimates: To  
484 what extent does it matter? *Environmental Science and Technology* 39(2), 399-408.
- 485 Stern, D., 2004. The rise and fall of the environmental Kuznets curve. *World Development*,  
486 32:1419-1439.
- 487 Soytaş, U., Sari, R., Ewing, B.T., 2007. Energy consumption, income, and carbon emissions  
488 in the United States. *Ecological Economics* 62 (3-4), 482-490.
- 489 Vincent, J.R., 1997. Testing for environmental Kuznets curves within a developing country.  
490 *Environment and Development Economics* 2 (4), 417-431.
- 491 Wane, A., Gilbert, S., Dibooglu, S., 2004. Critical values of the empirical F-distribution for  
492 threshold autoregressive and momentum threshold autoregressive models, 2004

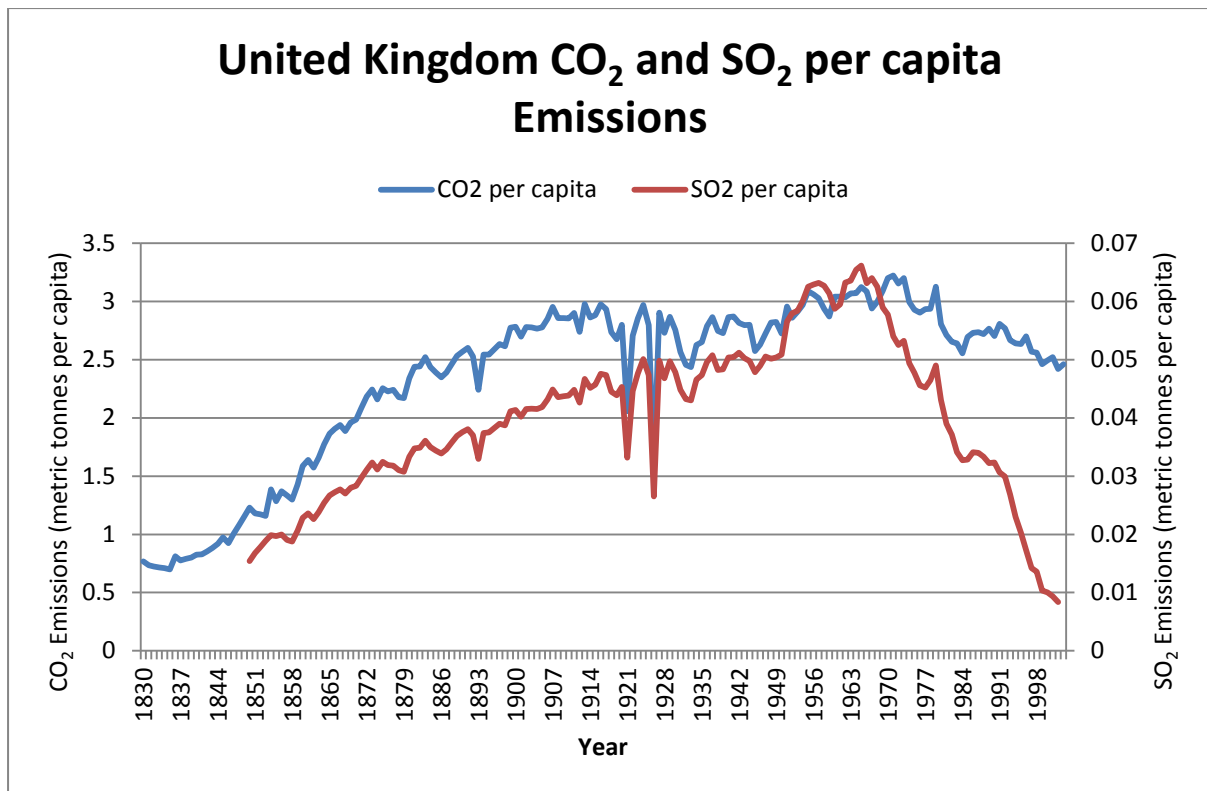
493 Discussion Papers for the Department of Economics, Southern Illinois University at  
494 Carbondale.

495 Wang, K.M., Thi, T.B.N., 2010. Asymmetric pass-through and risk of interest rate: an  
496 empirical exploration of Taiwan and Hong Kong. *Applied Economics* 42 (5), 659-670.

497 Zivot, E., Andrews, D.W.K., 1992. Further evidence on the great crash, the oil-price shock  
498 and the unit-root hypothesis. *Journal of Business & Economic Statistics* 10 (3), 251-270.



**Figure 1: Graph of per capita CO<sub>2</sub> and SO<sub>2</sub> emissions for the UK from 1830.**



**Figure 2: Graph of UK real GDP per capita in 1990 international Geary-Khamis dollars from 1830**

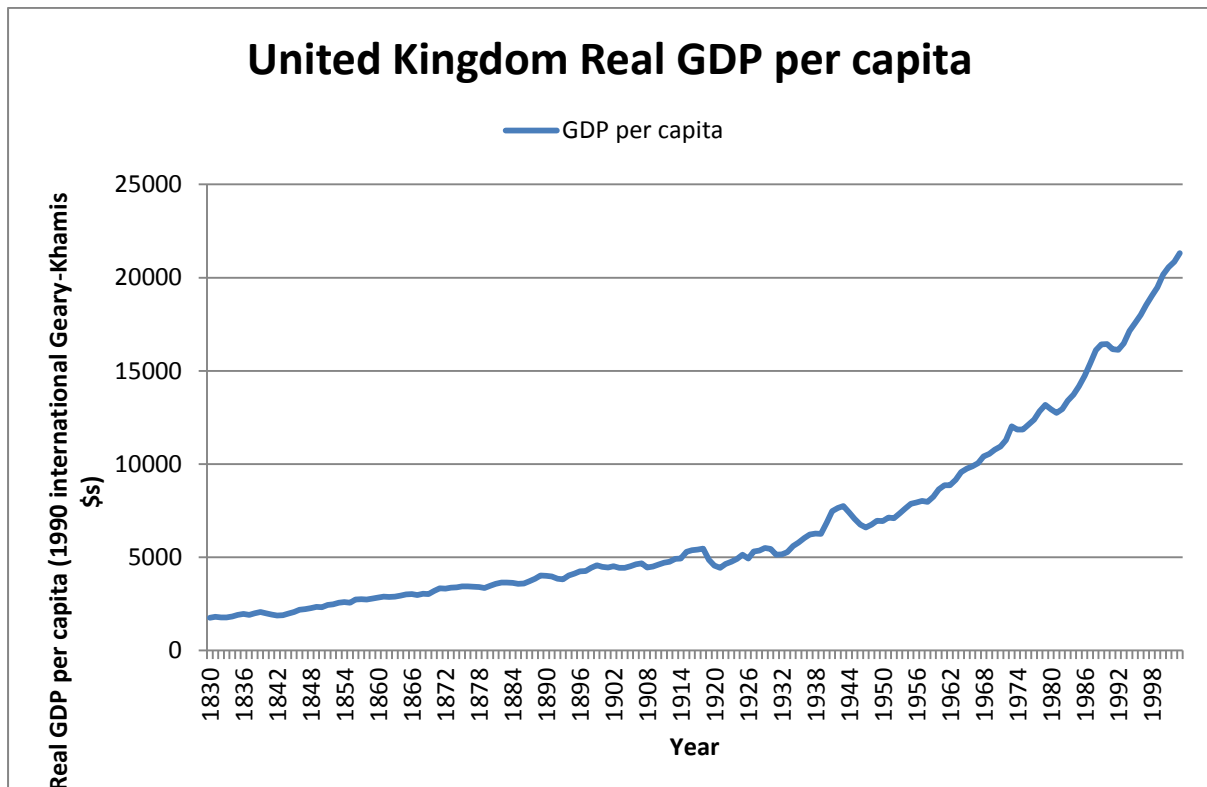


Figure 3: Graph of the fitted values of the estimated EKC results for CO<sub>2</sub>

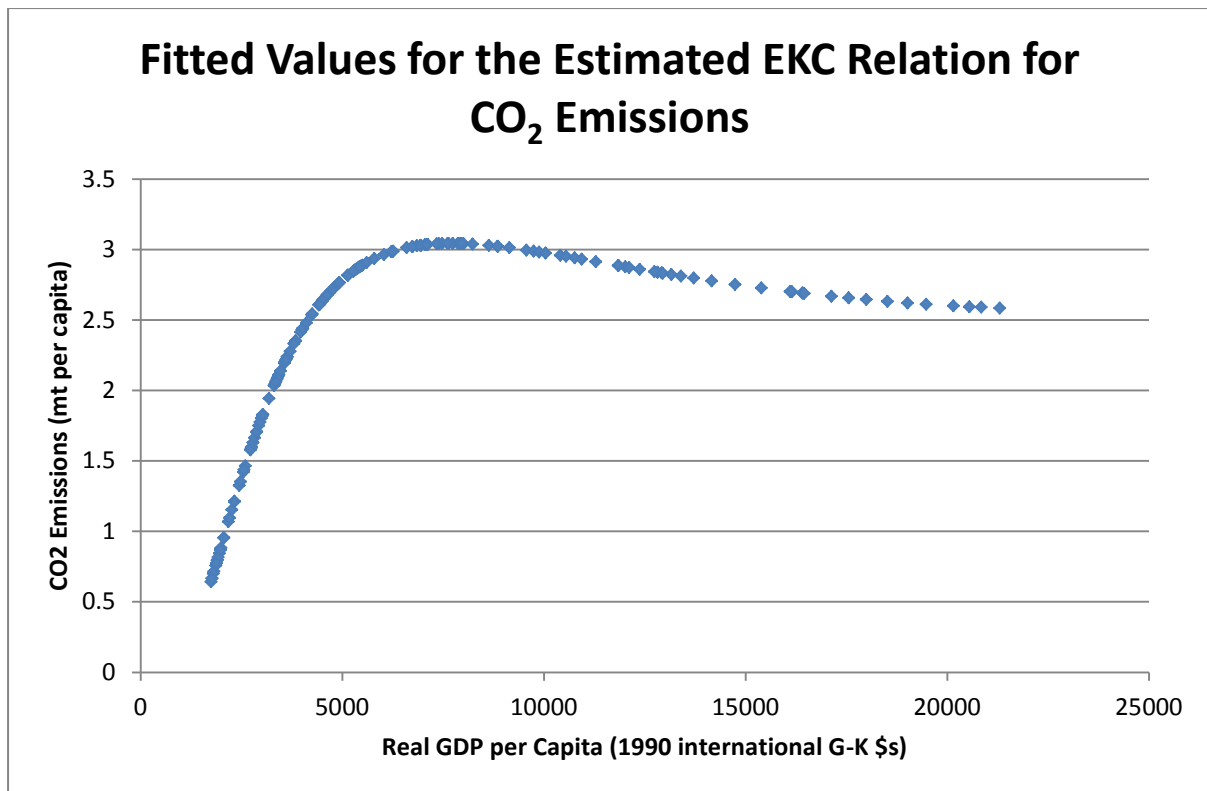
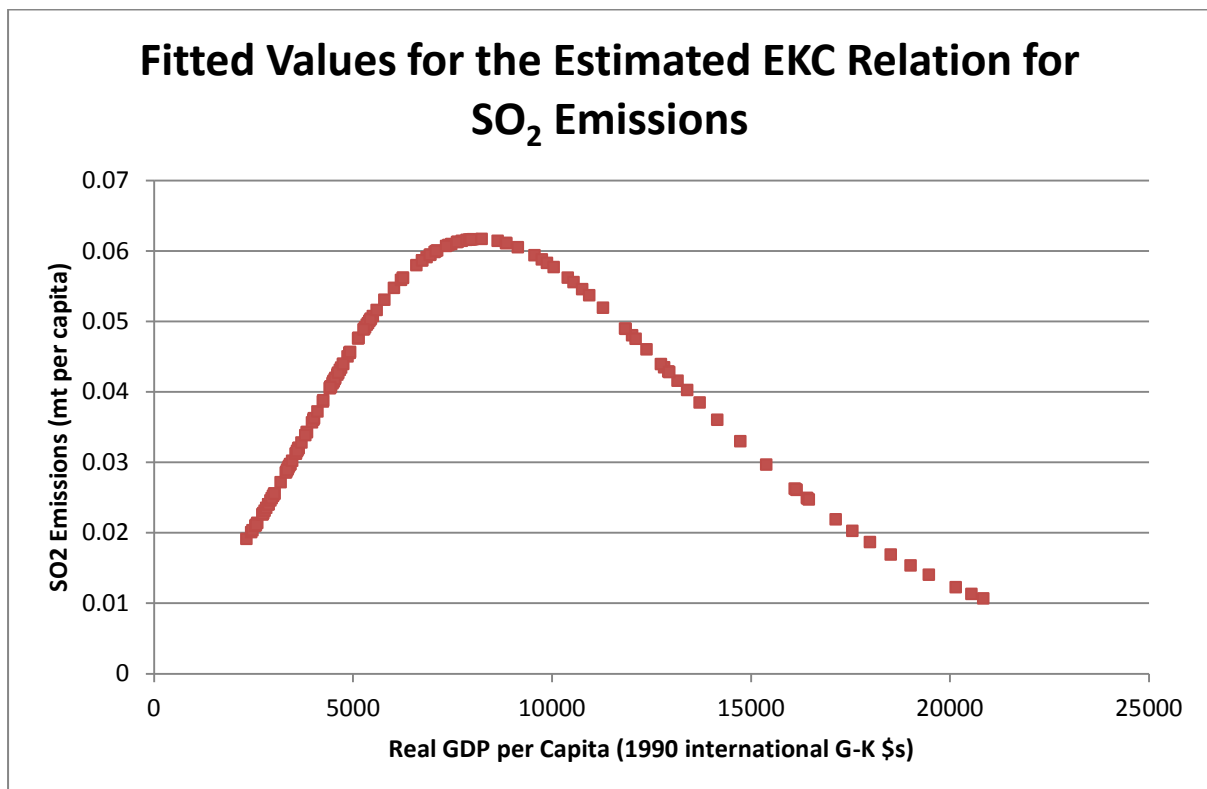


Figure 4: Graph of the fitted values of the estimated EKC results for SO<sub>2</sub>



**Table 1: Descriptive statistics for the common samples of per capita CO<sub>2</sub> and SO<sub>2</sub> emissions with real GDP per capita.**

	CO <sub>2</sub> per capita	Real GDP per capita	Gas prices	SO <sub>2</sub> per capita	Real GDP per capita	Gas prices
Sample	[1830-2003 – 174 obs.]			[1850-2002 - 153 obs.]		
Mean	2.360	6733.099	909.723	0.0400	7259.7798	668.962
Median	2.640	4816.078	676.403	0.0415	5288.2658	594.225
Minimum	0.700	1749.368	4181.461	0.0084	2330.3778	1435.890
Maximum	3.224	21310.137	130.477	0.0662	20851.0396	132.630

**Notes:** All data is in levels

**Table 2a Unit Root Tests**

CO <sub>2</sub> – Data Range: 1830-2003 (174 observations)															
	ADF					ERS					PP				
	C and t		C only			C and t		C only			C and t		C only		
$e_t$	-1.9561	(4)	-5.2326	***	(4)	0.1634	(4)	0.6440		(4)	-1.6406	-	-3.0377	**	-
$y_t$	-1.7524	(1)	0.7162		(1)	-1.9331	(1)	3.5538		(1)	-0.7214	-	1.3564		-
$y_t^2$	-1.1899	(1)	1.1866		(1)	-1.3541	(1)	3.7783		(1)	-0.0136	-	2.1984		-
$y_t^3$	-0.7006	(1)	1.6509		(1)	-0.8592	(1)	4.0009		(1)	0.6190	-	3.0764		-
$ep_t$	-3.209	(0)	-1.061		(0)	-1.507	(0)	2.580		(0)	-2.883	-	-1.097		-
$\Delta e_t$			-10.6139	***	(3)			-2.8269	***	(4)			-18.6032	***	-
$\Delta y_t$			-9.5558	***	(0)			-7.9071	***	(0)			-9.1186	***	-
$\Delta y_t^2$			-9.3367	***	(0)			-8.2786	***	(0)			-8.8349	***	-
$\Delta y_t^3$			-9.0852	***	(0)			-8.4999	***	(0)			-8.7043	***	-
$\Delta ep_t$			-11.937	***	(0)			-3.722	***	(1)			-11.933	***	-
SO <sub>2</sub> – Data Range: 1850-2002 (154 observations)															
	ADF					ERS					PP				
	C and t		C only			C and t		C only			C and t		C only		
$e_t$	2.5209	(1)	0.8104		(1)	1.4276	(1)	-0.2121		(1)	2.4682	-	0.3577		-
$y_t$	-1.5739	(1)	0.9094		(1)	-1.7175	(1)	3.3469		(1)	-0.4571	-	1.6767		-
$y_t^2$	-1.1782	(1)	1.2666		(1)	-1.2892	(1)	3.5136		(1)	0.0580	-	2.4035		-
$y_t^3$	-0.8264	(1)	1.6214		(1)	-0.9265	(1)	3.6817		(1)	0.5338	-	3.1654		-
$ep_t$	-2.515	(1)	-0.007		(1)	-2.518	(1)	1.353		(1)	-2.058	-	0.406		-
$\Delta e_t$			-3.1446	**	(4)			-1.1880		(4)			-14.6694	***	-
$\Delta y_t$			-8.9150	***	(0)			-5.7949	***	(0)			-8.5164	***	-
$\Delta y_t^2$			-8.7024	***	(0)			-6.2227	***	(0)			-8.2599	***	-
$\Delta y_t^3$			-8.4737	***	(0)			-6.6150	***	(0)			-8.1181	***	-
$\Delta ep_t$			-8.247	***	(0)			-6.181	***	(0)			-8.256	***	-

Notes: Unit root test results for  $y_t$ ,  $y_t^2$  and  $y_t^3$  are reported for both sample sizes as the test statistics are different.

Lag length displayed in parentheses and is selected by the Schwarz-Bayesian information criterion, subject to a maximum lag length of 4 for annual data. As usual \*\*\* (\*\*) denotes rejection of the null hypothesis at the 1% (5%) level .

**Table 2b. Zivot-Andrews (1992) Unit Root Tests**

CO <sub>2</sub>	Level	
Variable	Break date	Statistic
$e_t$	(1859)	-3.024
$y_t$	(1919)	-4.782
$y_t^2$	(1919)	-4.599
$y_t^3$	(1919)	-4.157
$ep_t$	(1970)	-4.416
SO <sub>2</sub>	Level	
$e_t$	(1972)	-1.041
$y_t$	(1919)	-5.322
$y_t^2$	(1919)	-4.742
$y_t^3$	(1919)	-4.157
$ep_t$	(1970)	-4.416

Notes: Critical values -5.57 (-5.08 ) at the 1% (5% ) level of significance. Lag length determined using the Akaike Information criterion. Test includes intercept and trend.

**Table 3: Estimated parameters of long-run EKC equation for both CO<sub>2</sub> and SO<sub>2</sub> emissions.**

Parameter	CO <sub>2</sub> Emissions		SO <sub>2</sub> Emissions	
<i>constant</i>	-186.841*** (12.969)	-173.596*** (8.828)	300.288*** (8.752)	291.930*** (8.827)
$y_t$	59.583*** (11.870)	53.687*** (7.816)	-114.156*** (9.752)	-113.605*** (10.065)
$y_t^2$	-6.275*** (10.802)	-5.490*** (6.835)	14.140*** (10.646)	14.289*** (11.106)
$y_t^3$	0.220*** (9.828)	0.187*** (6.022)	-0.578*** (11.526)	-0.589*** (12.061)
<i>ep</i>		0.059 (1.489)		0.035 (0.568)
<i>trend</i>		-0.004*** (3.487)		-0.007*** (3.486)

Notes: t-statistics are in parentheses, see Table 2. Estimated parameters for equations (1) and (9).

**Table 4. Results of TAR and M-TAR Enders-Siklos (E-S) test for cointegration on the standard EKC model**

TAR	$\rho_1$	$\rho_2$	$\phi_\mu$	$F(\rho_1 = \rho_2)$	Lag	SBC
CO <sub>2</sub>	-0.592*** (7.307)	-0.286*** (2.896)	30.893***	5.743***	0	-2.419
SO <sub>2</sub>	-0.3891*** (-5.1960)	-0.1534* (-1.7649)	15.0567***	4.2193**	0	<b>-2.1944</b>
M-TAR						
CO <sub>2</sub>	-0.621*** (-7.933)	-0.216** (-2.142)	33.763***	10.102***	0	<b>-2.443</b>
SO <sub>2</sub>	-0.354*** (-4.856)	-0.189** (-2.076)	13.750**	1.982	0	-2.180

Notes: Results from the estimation of Equations 3 and 5 for CO<sub>2</sub> and SO<sub>2</sub> emissions\*\*\* (\*\*)

(\*) Indicates significance at the 1% (5%) (10%) level. T-statistics for  $\rho$  in parentheses

Critical values from Wane *et al.* (2004).

**Table 5. Results of TAR and M-TAR Enders-Siklos (E-S) test for cointegration including gas prices and Trend.**

TAR	$\rho_1$	$\rho_2$	$\phi_\mu$	$F(\rho_1 = \rho_2)$	Lag	SBC
CO <sub>2</sub>	-0.598*** (6.798)	-0.3926*** (4.125)	31.614***	3.472*	0	<b>-2.449</b>
SO <sub>2</sub>	-0.382*** (4.903)	-0.191** (2.240)	14.528***	2.885*	0	-2.197
M-TAR						
CO <sub>2</sub>	-0.605*** (7.224)	-0.359*** (3.532)	32.334***	2.406	0	-2.279
SO <sub>2</sub>	-0.340*** (-4.350)	-0.258*** (-2.837)	13.487**	0.465	0	<b>-2.218</b>

Notes: See Table 4, model includes *ep* and a trend.

**Table 6. Results for the M-TAR error correction models for CO<sub>2</sub>.**

Parameter	Dependent Variable $\Delta e_t$			Dependent Variable $\Delta y_t$	
$\rho_{11}$	-0.557*** (6.254)	-0.554*** (5.638)	$\rho_{21}$	-0.066* (1.876)	-0.027 (0.737)
$\rho_{12}$	-0.081 (0.773)	-0.169 (1.499)	$\rho_{22}$	0.038 (0.896)	0.069 (1.635)
$\alpha_{11}$	-24.073 (0.838)	-16.559 (0.543)	$\alpha_{21}$	0.501 (0.044)	-0.322 (0.028)
$\alpha_{12}$	2.942 (0.880)	2.014 (0.567)	$\alpha_{22}$	-0.105 (0.080)	0.076 (0.056)
$\alpha_{13}$	-0.118 (0.912)	-0.080 (0.581)	$\alpha_{23}$	0.008 (0.162)	-0.002 (0.046)
$\alpha_{14}$	-0.238*** (3.057)	-0.242*** (3.020)	$\alpha_{24}$	-0.066** (2.154)	-0.074** (2.463)
$\alpha_{15}(ep)$		0.048 (0.077)	$\alpha_{15}(ep)$		0.056* (1.918)
$\alpha_{16}(trend)$		-0.00002 (0.290)	$\alpha_{16}(trend)$		0.00001*** (3.045)

Notes: See Table 2. The first column includes the parameters contained in equations 7, the fourth column the parameters from equation 8. *ep* are energy prices.



**Table 7. Results for the TAR error correction models for SO<sub>2</sub>**

Parameter	Dependent Variable $\Delta e_t$			Dependent Variable $\Delta y_t$	
$\rho_{11}$	-0.342*** (3.589)	-0.285*** (2.758)	$\rho_{21}$	-0.009* (1.876)	0.001 (0.028)
$\rho_{12}$	-0.053 (0.480)	-0.134 (1.243)	$\rho_{22}$	-0.016 (0.459)	0.026 (0.747)
$\alpha_{11}$	-62.519 (1.013)	-67.328 (1.110)	$\alpha_{21}$	-10.648 (0.554)	-11.848 (0.650)
$\alpha_{12}$	7.809 (1.113)	8.297 (1.203)	$\alpha_{22}$	1.179 (0.540)	1.398 (0.674)
$\alpha_{13}$	-0.322 (1.211)	-0.338 (1.294)	$\alpha_{23}$	-0.041 (0.497)	-0.053 (0.673)
$\alpha_{14}$	-0.199** (2.173)	-0.215** (2.325)	$\alpha_{24}$	-0.074** (2.610)	-0.071** (2.446)
$\alpha_{15}(ep)$		0.258* (2.216)	$\alpha_{15}(ep)$		0.072** (2.044)
$\alpha_{16}(trend)$		-0.00001 (0025)	$\alpha_{16}(trend)$		0.0001** (2.857)

Notes: See Table 5.