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On the structure and form of the GDP-nuclear nexus: new perspectives and new findings

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Abstract

Much of the existing literature on the relationship between nuclear energy consumption and gross domestic product (GDP) deals only with the causal links between these two variables. However, very little attention has been paid to the structure and form of this relationship. This paper first uses panel cointegration techniques to illustrate the form of an inverted U-shaped curve that arise from pooled data, then, applies the iterative empirical Bayesian procedure to in order to account for the heterogeneity in the coefficients of the long-term relationship. The empirical results from a multivariate framework involving carbon dioxide (CO₂) emissions reveal that for only 3 of the 21 nuclear countries studied a linear form of the relationship can be justified and that nuclear energy goes from being a normal good to being an inferior good for the majority of the sample countries.

Keywords: Nuclear energy; Panel cointegration; Shrinkage estimators

JEL Codes: C11; C23; Q43;

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1 Introduction and brief literature review

Uranium was discovered by a German chemist, Martin Klaproth, in 1789. It took more than one century and a half before this chemical element could be used as a fuel in the nuclear power industry for the generation of electricity and in the war industry for the construction of nuclear weapons. In the decades after the Second World War, commercial use of nuclear power has gained impetus in order to meet the growing demand for electricity. Despite two major accidents (the first one was in 1979 in Three Mile Island in Pennsylvania and the second one was seven years later at Chernobyl in Ukraine), nuclear power plants have been continuously built and operated throughout the world. As of December 2010, 441 nuclear power plants are in operation worldwide with a global nuclear generating capacity of 375 gigawatts of electric power (GW(e)) (IAEA, 2011) and the share of nuclear electricity in world electricity generation is 13.4% (OECD, 2011). Recently, the Fukushima nuclear accident (following the earthquake and tsunami on the East coast of Japan on March 11, 2011) raised once again public concerns about nuclear energy safety. In fact, the risks and benefits of nuclear power have been up for debate for a long time within scientific, political and environmental groups.

Croper (1980) lists some of the ways in which nuclear energy production can affect the environment. According to her, the least serious problem is the routine emission of gaseous fission products such as tritium and krypton from the power plant. However the more serious problem is the environmental release of very long-lived radioactive elements such as plutonium and iodine. What we mean by "very long-lived" can be perceived from the fact that the U.S. Environmental Protection Agency requires that high-level radioactive wastes should be isolated from the human environment for one million years (Solomon, 2009). Furthermore, Croper (1980) indicates decommissioning

of nuclear facilities and nuclear accident risks (such as sabotage or loss of control of a power plant) as the other ecological and environmental problems related to nuclear power. We may add to this list at least two further problems. First, although the nuclear power is seen as the major source of “carbon-free” energy, construction of nuclear energy plants and uranium mining operations release some amounts of carbon dioxide into the atmosphere. Second, since nuclear reactors need to be cooled, the water pulled from either a sea, a lake or a river is used for this purpose and then the heated water is discharged back into the original source. This cooling process generates, *in fine*, a detrimental thermal impact on some species of fish.

Returning back to the radioactive isotopes, it should be indicated that they may remain in the atmosphere or enter the soil or water and "this feature, combined with the slow decay rate of plutonium, implies that nuclear pollution must be viewed as a stock which, at least in historical time, is nondecreasing" (Croper, 1980, p. 335). This viewpoint suggests that nuclear energy production and the ecological and environmental degradation resulting from it can be regarded, to some extent, as other pollution sources such as combustion of fossil fuels and resulting CO₂ emissions. Consistent with this argument, our research builds on two lines of literature: the literature on the environmental Kuznets curve (EKC) and the literature on the nuclear energy-income nexus. Let us now briefly review recent developments in these two research fields.

The EKC hypothesis suggests that environmental degradation (typically measured as per capita carbon dioxide (CO₂) emissions) follows an inverted U-shaped curve relative to economic development (typically measured as per capita GDP). This hypothesis was first introduced by Grossman and Krueger (1992, 1995) and Shafik and Bandyopadhyay (1992). Subsequently, many researchers have contributed towards this and have used a

number of proxies for the level of environmental degradation, such as CO₂ emissions (Richmond and Kaufmann, 2006), sulphur dioxide (SO₂) or nitrous oxides (NO_x) (Panayotou, 1993), energy consumption (Luzzati and Orsini, 2009), biological oxygen demand emissions (Lee et al., 2010) or ecological footprint (Caviglia-Harris et al., 2009). To our knowledge, nuclear data have not been used before to study the EKC relationship. However, the data on nuclear energy have been employed in the relatively recent empirical research on the causal relationship between nuclear energy consumption and economic growth. In two separate papers, Lee and Chiu (2011a, b) introduced, as additional variables, oil prices and oil consumption into the nuclear energy-income nexus and using panel cointegration techniques, found the existence of a long-run equilibrium relationship among these variables. Furthermore they reported that unidirectional causality runs from oil prices and economic growth to nuclear energy consumption in the long run (Lee and Chiu, 2011a). Their results also indicate a unidirectional causality running from real income to nuclear energy consumption in Japan, a bidirectional relationship in Canada, Germany and the U.K., and no causality in France and the U.S (Lee and Chiu, 2011b). On the other hand, Apergis et al. (2010) used instead CO₂ emissions and renewable energy consumption as additional variables in a panel error correction model. Their results show that there is a bidirectional causality between nuclear energy consumption and economic growth and that the use of nuclear energy can reduce CO₂ emissions. From another point of view, using capital and labor inputs as additional variables, Wolde-Rufael and Menyah (2010) found that there is a unidirectional causality running from nuclear energy consumption to economic growth for the case of Japan, the Netherlands, and Switzerland, whereas the causality is in the opposite direction for Canada and Sweden. Their results point also a bidirectional causality in France, Spain, the U.K. and the U.S.

The above-mentioned literature on the nuclear energy-economic growth nexus specifies nuclear energy consumption in either a linear or a log-linear form. However, such a specification does not allow for a non-monotonic relationship between these variables, thus imposing an important restriction. In consequence, these studies have fallen short of capturing a possible increasing and then decreasing trend in nuclear energy production. The existence of this trend implies that there is a turning point income level at which nuclear energy consumption starts decreasing. Indeed, it seems reasonable to anticipate such a pattern from Fig. 1.

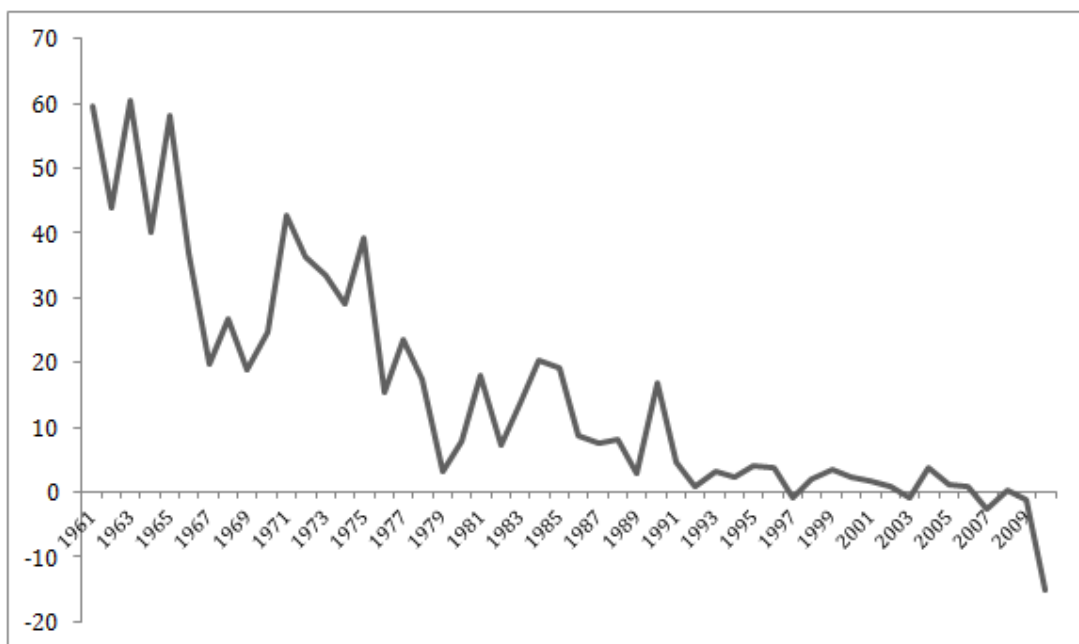


Fig. 1. Growth rate (in percentage points) of world electricity production from nuclear sources (authors calculation based on WB (2012)).

On the other hand, unlike the panel cointegration tests which assume common coefficients for all countries, some of the aforementioned studies (or others) used time-series techniques with individual country data to estimate different coefficients for each country and to provide country-specific analyses. However, no study so far has examined the nuclear energy-income relationship using the iterative empirical Bayesian

procedure that allows for taking into account heterogeneity of the parameters across countries in a panel.

In light of these critiques, the present study attempts to contribute to the literature in two ways. First, it tests for a quadratic relationship between nuclear energy consumption and GDP to investigate whether a non-linear functional relationship exists between them. The estimated models include also CO₂ emissions or petroleum consumption as additional variables not only to follow the common practice in the literature but also to study the robustness of the results and the possible interactions between nuclear energy consumption and the additional regressors. Second, it uses Bayesian iterative shrinkage estimators that shrink the individual heterogeneous coefficient estimates towards the estimated pooled homogeneous coefficients of an equation giving the nuclear energy-GDP relationship. By doing so, it considers at the same time both group behavior and country-specific behavior for the relationship in question.

An outline of the remainder of the paper follows. The next section describes the data used in the study, presents panel cointegration and dynamic ordinary least square (DOLS) analysis, then gives some preliminary results regarding the nuclear energy-GDP nexus. In Section 3, the iterative empirical Bayesian method is outlined, applied to the same panel data, and then the results produced by this method are presented. A discussion of the results and conclusions are drawn in Section 4.

2 Data and preliminary results

2.1 Data

Before we present our empirical framework, we first describe our sample in this section. According to the World Bank, there have been 31 countries that produced nuclear energy in the period 1965-2011. However we had to exclude from our analysis: (1) countries having irregular nuclear production (Italy produced nuclear energy during the period 1965-1988); (2) states emerged after the collapse of the Soviet Union for which data are available after 1992 (Lithuania, Russia, Slovakia, Ukraine, Armenia, Slovenia); (3) countries that have lately started nuclear production (China in 1993, Romania in 1996, Mexico in 1989). The resulting sample includes the following 21 countries (with abbreviations in parentheses): Argentina (ARG), Belgium & Luxembourg (BEL), Brazil (BRZ), Bulgaria (BLG), Canada (CND), Czech Republic (CZE), Finland (FIN), France (FRA), Germany (DEU), Hungary (HUN), India (IND), Japan (JPN), the Netherlands (NLD), Pakistan (PKS), South Africa (AFR), South Korea (KOR), Spain (ESP), Sweden (SWE), Switzerland (SWZ), the United Kingdom (GBR) and the United States of America (USA).

Data for real GDP (GDP) in US Dollars at constant 2005 prices and constant exchange rates and data for population are from Conference on Trade and Development (UNCTAD, 2012). Electricity production from nuclear sources (NE) in kWh has been taken from World Development Indicators and Global Development Finance (WB, 2012) and data for CO₂ emissions (CO₂) in million metric tons and for total petroleum consumption (PC) in thousand barrels per day have been taken from the US Energy Information Administration (EIA, 2012). All data used in this study are annual and cover the period from 1980 to 2009. The length of the sample period as well as the above-indicated

selection of countries are dictated by the availability of the data for electricity production from nuclear sources.

The 21 countries involved in the analysis produce over 85% of nuclear electricity worldwide during the period considered. These countries can be classified into three groups: (1) small producers (less than 1% of global share); (2) average producers (between 1% and 5%); and (3) large producers (more than 5%). In 1980, the largest producers account for two thirds of the global nuclear electricity production: the United States of America (37%), Japan (11.6%), France (8.6%) and Germany (7.8%). In 2009, their share still represent over 61%: the United States of America (30.7%), France (15.4), Japan (10.5) and Germany (5%).

We can also make another classification according to the share of nuclear energy in total electricity production in each country. From this perspective, we group the 21 countries into three classes: (1) those with a nuclear share below the average of all countries; (2) those in the middle; and (3) countries whose share of nuclear power is relatively high. The results of these classifications are presented in Table 1.

Table 1. Classification of countries with respect to their nuclear power.

	Small share	Average share	Large share
Large producers		USA	FRA, DEU, JPN
Average producers		GBR, CND	BEL, KOR, ESP, SWE, SWZ
Small producers	ARG, BRZ, IND, NLD, PKS, AFR		BLG, CZE, FIN, HUN

Before we proceed to a detailed examination of the relationship between nuclear electricity generation and economic growth, a useful preliminary is to draw a scatter plot of these variables. Fig. 2 provides thus a first look at the nuclear energy-GDP nexus for a 21-country sample over the period 1980-2009.

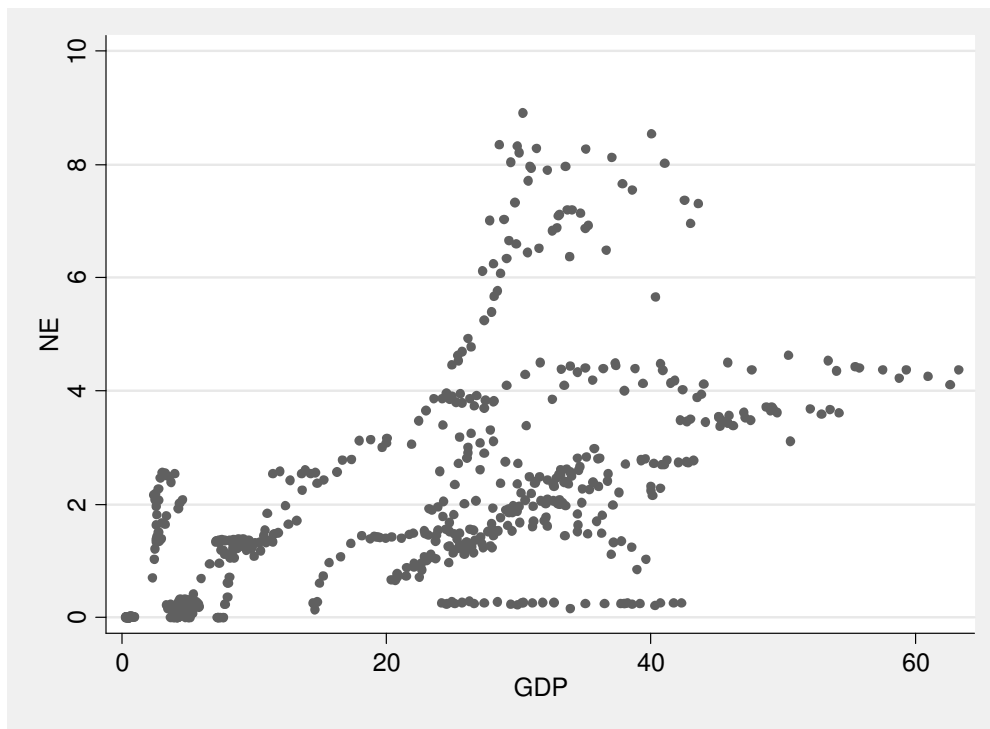


Fig. 2. Relationship between per capita nuclear energy production and per capita GDP.

From Fig. 2, one can expect that per capita nuclear energy production exhibits an inverted U-shaped pattern when plotted against per capita GDP. In what follows, we study this pattern on the basis of panel cointegration and iterative Bayesian procedures.

2.2 Panel cointegration framework

The empirical work conducted in this section consists of three stages: (1) panel unit root tests to determine order of integration of the variables; (2) testing for cointegration

between them; and (3) estimating the parameters of the equation giving the long-term relationship. We do not discuss the methodology in detail since all techniques used here in the panel cointegration framework are standard (see Stock and Watson (1993) and Baltagi and Kao (2000) for an overview).

First of all, the stationarity of the variables (including a quadratic term for per capita GDP (GDP2)) is checked by employing the most widely used panel unit root tests (namely, the Fisher-type Augmented Dickey Fuller (ADF) and Phillips Peron (PP) tests (Maddala and Wu, 1999; Choi, 2001;), the LLC test (Levin et al., 2002) and the IPS test (Im et al., 1997). The results indicate that each of the variables has a unit root in level, but stationary in the first difference.¹ This means that the variables are integrated of order one, that is I(1).

Since all variables are found to be I(1), the second stage consists of testing for the existence of a cointegration relationship between them. To do this, we consider the panel cointegration technique proposed by Pedroni (2004) which extends the two-step procedure by Engle and Granger (1987) to panel data. Furthermore, we employ also the Johansen-Fisher panel cointegration test proposed by Maddala and Wu (1999) which is a panel version of the individual Johansen (1988) cointegration test. The results suggest that there is a cointegrating relationship between the variables involved in the analysis. The results obtained so far are in line with those of previous related studies (e.g. Apergis et al., 2010; Lee and Chiu, 2011a).

These findings bring us to the third and last stage of our panel cointegration analysis. We now proceed by estimating the long-run parameters of the nuclear energy-GDP

¹ Full results are not reported in order to conserve space. All statistical results are available from the authors upon request.

relationship by means of the DOLS procedure, which will give us the first insight into the functional form of this relationship.

The panel DOLS estimator proposed by Kao and Chiang (2000) consists of including leads and lags of the dependent variable as regressors in order to correct for endogeneity and serial correlation. In the literature, this approach has been reported to be superior to other conventional methods (i.e. OLS or fully modified OLS) when both cross section and time dimensions are small. In the case of three cointegrated variables the panel DOLS regression to be estimated takes the following form:

$$NE_{it} = \delta_i + \alpha GDP_{it} + \beta GDP2_{it} + \sum_{j=-p}^q \gamma_j \Delta GDP_{it+j} + \sum_{j=-p}^q \phi_j \Delta GDP2_{it+j} + \varepsilon_{it} \quad (1)$$

where Δ is the first-difference operator, δ_i is constant, ε_{it} is the error term having the usual i.i.d. properties, q and p represent the number of leads and lags, respectively. The significance and the sign of the parameters α and β indicate the form of the relationship between NE and GDP. As in most of the related literature, we include two additional regressors to control for both environmental degradation and substitution effect. For this purpose, per capita CO₂ emissions (CO2) and per capita petroleum consumption (PC) are considered.² The estimation results are summarized in Table 2. In all models, the coefficients of the linear and quadratic term for per capita GDP are significant. Furthermore, the parameters' signs (linear term positive and quadratic term negative) suggest that there is an inverse U-shaped relationship between these two variables.³ Thus we can reasonably conclude

² We also tested the cubic form of each model. However, the cubic term for per capita GDP in all of these models was found to be statistically insignificant. In consequence, final models were estimated only with the quadratic form.

³ The tabulated values of the DOLS estimator are obtained for one lead and one lag (i.e. in Eq(1), p=1 and q=1) of the first-differenced variables. In order to check the robustness of the results to the choice of

that there is an EKC-type relationship for nuclear energy generation. As a result, in contrast to the commonly used linear specification, it would be more adequate to consider a curvilinear relationship.

Table 2. DOLS long-run estimates.

	Variable	Coef.	Std. Err.	t-stat.	P value
Base Model	GDP	0.1335	0.0180	7.40	0.000
	GDP2	-0.0012	0.0004	-2.81	0.005
Model with CO2	GDP	0.1971	0.0199	9.90	0.000
	GDP2	-0.0022	0.0004	-4.91	0.000
	CO2	-127.22	16.832	-7.56	0.000
Model with PC	GDP	0.1516	0.0227	6.67	0.000
	GDP2	-0.0013	0.0004	-2.80	0.005
	PC	-14.441	6.6316	-2.18	0.030

The estimation results for the model including per capita petroleum consumption as an additional regressor show that a reduction in petroleum consumption leads to an increase in nuclear energy consumption, which indicate thus a substitute relationship between petroleum consumption and nuclear energy consumption. This is in line with the finding of Lee and Chiu (2011a). On the other hand, in the model that involves the variable for CO₂ emissions, the sign of the coefficient associated with CO₂ emissions is found to be negative. This result is in contrast with those reported by Apergis et al. (2010). Their results from a panel causality framework indicate that in the short run, nuclear energy consumption has a negative impact on CO₂ emissions whereas the latter has a significant positive impact on the former. They conclude that nuclear energy can

number of lags and leads, we replicated our analysis with different numbers. The results show that most parameter estimates are very similar having always the same signs (i.e. $\beta < 0 < \alpha$).

thus play a role in reducing emissions, but they do not explain why emissions positively affect nuclear energy consumption. However, our explanation for the negative sign of the CO₂ coefficient will be based on the assumption that the dependent variable in our model can be viewed as a "potential" pollution associated with nuclear energy consumption. We leave this interpretation to the last section.

Although our results provide a strong evidence for an EKC-type trend for nuclear energy consumption, there is one further point that should be considered here. Both the panel cointegration analysis and the DOLS estimations assume that the parameters α and β are identical for all countries. Hence, as it is suggested that the long-run relationship is the same for all of the countries, so is the shape of the functional form. This implies that we have a complete homogeneity. However, on the other hand, in order to investigate, in a rigorous way, the same relationship at the country level, one should conduct time-series analyses separately for each of the countries in the panel. Country-specific parameters can then be obtained and the differences in terms of the GDP-nuclear energy consumption nexus can be properly assessed. In consequence, in opposition to the panel cointegration analysis that we presented in this section, such a time-series approach allows all parameters to vary across countries, suggesting thus a complete heterogeneity at this time.

For Maddala and al. (1997), the reality is situated between complete homogeneity and complete heterogeneity: "The truth probably lies somewhere in between. The parameters are not exactly the same, but there is some similarity between them. One way of allowing for the similarity is to assume that the parameters all come from a joint distribution with a common mean and a nonzero covariance matrix" (Maddala and al., 1997, p. 91). What they mean by this is explained in more detail in the next section.

3 Bayesian shrinkage estimator

Maddala et al. (1997) estimated short- and long-run elasticities of energy demand for each of 49 US states over 21 years (1970-1990). They found that, while estimation using pooled data was not valid, estimation using time-series data by each state gave several wrong signs for the coefficients. Shrinkage estimators gave more reasonable results for panel data, since the two other estimation methods, of either pooling the data or obtaining separate estimates for each cross-section, are based on extreme assumptions (namely, cross-sectional homogeneity and heterogeneity of slope coefficients). The solution relies on the use of a random-coefficient model in which the parameters are assumed to come from a joint distribution with a common mean and a non-zero covariance matrix. Each individual estimate is thus “shrunk” towards the pooled estimates, from this comes the term “shrinkage estimator”.

Maddala and Hu (1996) presented some Monte Carlo evidence to suggest that the iterative procedure gave better estimates (in the mean squared sense) for panel data models. Hsiao et al. (1999) have also confirmed that in the case of panel data model with coefficient heterogeneity, the Bayesian approach performs fairly well, even when the time dimension is small. To conclude, these are the reasons why the Bayesian shrinkage estimator can be considered as an alternative estimation method, capturing cross-sectional heterogeneity in the nuclear energy-GDP relationship.

3.1 Iterative Empirical Bayesian Procedure

Let us consider the simplified form of the relationship between nuclear energy consumption and GDP including also CO₂ emissions as an additional regressor:

$$NE_{it} = \delta_i + \alpha_i GDP_{it} + \beta_i GDP2_{it} + \lambda_i CO2_{it} + \varepsilon_{it} \quad (2)$$

In the framework of the random-coefficients model, the Bayesian approach for Eq. (2) can be rewritten with the following specification:

$$y_i = X_i \gamma_i + u_i \quad (3)$$

where y_i contains NE_i time series, X_i is the matrix with explanatory variables (GDP_{it} , $GDP2_{it}$ and $CO2_{it}$) and γ_i slope coefficients. In the Bayesian framework, the *prior* distribution of γ_i is given by: $\gamma_i \sim N(\mu, \Sigma)$ where the parameters μ (mean of γ_i), Σ (variance of γ_i) and σ_i^2 (residual variance) are unknown. That is why some assumptions have to be made on *prior* specification of these parameters. Then we can derive the *posterior* distribution for the parameters γ_i . On the other hand, if μ , Σ and σ_i^2 are all known, the *posterior* distribution of γ_i is normal and calculated by:

$$\gamma_i^* = \left[\frac{1}{\sigma_i^{*2}} X_i' X_i + \Sigma^{*-1} \right]^{-1} \left[\frac{1}{\sigma_i^{*2}} X_i' X_i \hat{\gamma}_i + \Sigma^{*-1} \mu^* \right] \quad (4)$$

where $\hat{\gamma}_i$ is the OLS estimator of γ_i . The *posterior* distribution mean of γ_i and its variance are shown in Eqs. (5) and (6) respectively.

$$\mu^* = \frac{1}{N} \sum_{i=1}^N \gamma_i^* \quad (5)$$

$$V[\gamma_i^*] = \left[\frac{1}{\sigma_i^{*2}} X_i' X_i + \Sigma^{*-1} \right]^{-1} \quad (6)$$

Since in general, Σ and σ_i^2 are unknown parameters, one needs to specify priors for them. For this purpose, Smith (1973) suggested using the mode of the joint posterior distribution given by the following equations:

$$\sigma_i^{*2} = \frac{1}{T + \zeta_i + 2} \left[\zeta_i \lambda_i + (y_i - X_i \gamma_i^*)' (y_i - X_i \gamma_i^*) \right] \quad (7)$$

and

$$\Sigma^* = \frac{1}{T-k-2+\delta} \left[R + \sum_{i=1}^N (\gamma_i^* - \mu^*)(\gamma_i^* - \mu^*)' \right] \quad (8)$$

where the parameters ζ_i , λ_i , δ and R arise from the specification of the prior distributions. Moreover, Smith (1973) proposed the approximation of these parameters by setting $\zeta_i = 0$, $\delta = 1$ and R as a diagonal matrix with small positive entries (e.g., 0.001). By doing so, the estimators take the following forms:

$$\sigma_i^{*2} = \frac{1}{T+2} \left[(y_i - X_i \gamma_i^*)' (y_i - X_i \gamma_i^*) \right] \quad (9)$$

$$\Sigma^* = \frac{1}{T-k-1} \left[R + \sum_{i=1}^N (\gamma_i^* - \mu^*)(\gamma_i^* - \mu^*)' \right] \quad (10)$$

$$\gamma_i^* = \left[\frac{1}{\sigma_i^{*2}} X_i' X_i + \Sigma^{*-1} \right]^{-1} \left[\frac{1}{\sigma_i^{*2}} X_i' X_i \hat{\gamma}_i + \Sigma^{*-1} \mu^* \right] \quad (11)$$

and

$$\mu^* = \frac{1}{N} \sum_{i=1}^N \gamma_i^* \quad (12)$$

$$V[\gamma_i^*] = \left[\frac{1}{\sigma_i^{*2}} X_i' X_i + \Sigma^{*-1} \right]^{-1} \quad (13)$$

Then Eqs. (9-13) should be solved iteratively, with the initial iteration using the OLS estimator $\hat{\gamma}_i$ to compute μ^* , Σ^* and σ_i^{*2} . The second iteration is based on the empirical iterative Bayes' estimator γ_i^* . The third and the following iterations are identical to the second one. The empirical Bayes' estimator was proposed by Maddala et al. (1997). The only difference with the Smith's estimator lies in the computation of the parameters σ_i^{*2} and Σ^* , that is, we have:

$$\sigma_i^{*2} = \frac{1}{T-k} (y_i - X_i \gamma_i^*)' (y_i - X_i \gamma_i^*) \quad (14)$$

$$\Sigma^* = \frac{1}{N-1} \left[R + \sum_{i=1}^N (\gamma_i^* - \mu^*)(\gamma_i^* - \mu^*)' \right] \quad (15)$$

In what follows, we present our results from applying this procedure to our reference model given in Eq. (2).

3.2 Empirical results

As in the DOLS framework, we estimated three separate models, of which the first is the base model, the second includes per capita CO₂ emissions as an additional regressor, and the third includes per capita petroleum consumption. The iterative Bayesian estimation results for the base model are presented in Appendix A (Table A.1). These results would allow us to conclude whether nuclear energy consumption has an inverted U-type relationship with respect to economic growth, and this without the presence of any additional variable. Based on both the estimated coefficients and their t-statistics reported in Table A.1 and the classification of countries given in Table 1, three groups of countries can be distinguished. One group contains countries where there is no relationship between nuclear energy consumption and economic growth (ARG, BRZ, BLG, HUN, NLD, AFR). These countries are all small producers of nuclear energy. In the largest group containing 12 countries, an inverted U-shaped relationship is present (BEL, CND, FIN, FRA, DEU, IND, JPN, ESP, SWE, SWZ, GBR, USA). With the only exception of South Korea, all average or high producers of nuclear energy fall into this group. Finally, the last group contains three countries for which nuclear energy is an increasing linear function of GDP (CZE, PKS, KOR). This result indicates that the choice of a linear functional form estimated in previous studies can be justified for only these three countries.

Let us now consider the model including an additional variable: per capita CO₂ emissions.⁴ The estimation results are given in Table 3 and based on the estimated coefficients, countries are grouped in Table 4 according to their functional form of the nuclear energy-GDP nexus.

Table 3. Parameter estimates from the empirical iterative Bayes' estimator.

Variables	Country	Parameters	T-Stat	Country	Parameters	T-Stat	Country	Parameters	T-Stat
Const		-0,0301	-0,20		-33,5832	-10,23		-0,0987	-0,30
GDP	ARG	0,0107	0,15	FRA	2,5764	11,27	AFR	-0,0332	-0,38
GDP2		-0,0037	-0,54		-0,0379	-9,70		-0,0073	-1,02
CO2		65,9672	1,28		-491,8960	-7,18		74,7359	1,47
Const		-4,8452	-3,36		-14,5097	-8,35		-0,8392	-6,97
GDP	BEL	0,4695	8,51	DEU	0,9187	9,75	KOR	0,4614	7,76
GDP2		-0,0045	-7,32		-0,0141	-8,86		-0,0062	-4,28
CO2		-200,5245	-2,90		-150,0785	-2,73		-245,0099	-4,23
Const		-0,2023	-1,32		1,3469	2,69		-6,6196	-9,63
GDP	BRZ	0,0406	0,57	HUN	0,4957	4,78	ESP	0,7736	11,51
GDP2		-0,0017	-0,24		-0,0251	-4,21		-0,0160	-9,84
CO2		49,7656	1,79		-413,9142	-7,83		-158,6562	-3,39
Const		2,6176	8,30		-0,0087	-3,45		-20,5875	-3,79
GDP	BLG	0,2050	2,75	IND	0,0452	2,73	SWE	1,7843	5,37
GDP2		-0,0059	-0,66		-0,0237	-2,90		-0,0253	-5,17
CO2		-174,7255	-5,40		2,8704	0,36		-381,3168	-4,23
Const		-8,6293	-2,58		-5,3083	-2,97		-13,4942	-3,27
GDP	CND	1,0238	4,26	JPN	0,3703	3,00	SWZ	0,6080	3,61
GDP2		-0,0160	-4,02		-0,0046	-2,18		-0,0056	-3,12
CO2		-268,3311	-3,20		29,7398	0,45		137,0582	1,71
Const		-0,1780	-0,22		0,4208	2,43		-5,1505	-5,59
GDP	CZE	0,2678	2,79	NLD	-0,0068	-0,54	GBR	0,4806	10,57
GDP2		-0,0004	-0,09		0,0001	0,56		-0,0078	-10,23
CO2		-94,5343	-2,59		-4,4018	-0,48		-75,6788	-2,32
Const		-3,3012	-1,79		-0,0220	-5,09		-8,8586	-9,47
GDP	FIN	0,5465	4,56	PKS	0,1148	5,27	USA	0,6041	11,12
GDP2		-0,0075	-3,93		-0,0063	-0,67		-0,0076	-9,67
CO2		-198,4047	-3,45		-52,6108	-3,79		-15,0434	-0,44

We first remark that introducing CO₂ emissions strengthens the link between nuclear energy and GDP, since this makes some previously insignificant GDP coefficients become statistically significant: two countries (BLG and HUN) are now found to have a

⁴ When petroleum consumption was used instead of CO₂ emissions, we found similar results to those reported herein.

relationship between nuclear energy and GDP (inverted U-shaped and linear relationship, respectively). South Korea, which was the only exception of the largest producers of nuclear energy that does not belong to the group of countries having an inverted U-shaped relationship, joined now to this group. These results reinforce our findings from the base model indicating the existence of an EKC-type relationship for nuclear energy consumption. Because not only for the 12 countries, that are found to have this relationship, the EKC hypothesis holds true, but also we have two other countries (HUN and KOR) supporting the evidence of an inverse U-shaped relationship between these two variables.

Table 4. Summary table for the estimated functional forms.

		Nuclear energy-CO₂ emissions nexus	
		No relationship	Negative
Nuclear energy-GDP nexus	No relationship (4 countries)	ARG, BRZ, NLD, AFR	
	Linear (3 countries)		BLG, CZE, PKS
	Inverted-U shaped (14 countries)	IND, JPN, SWZ, USA	BEL, CND, FIN, FRA, DEU, HUN, KOR, ESP, SWE, GBR

To conclude this section, from Tables 1 and 4, the following results can be drawn. We find that coefficient values vary widely which allows us to identify four groups of countries: (1) The first group of countries consists of those for which there is no relationship either between nuclear energy consumption and GDP or between CO₂ emissions and nuclear energy consumption. The distinguishing characteristic of the four countries in this first group is that they are small producers of nuclear energy and that the share of nuclear power in total energy consumption is also small (see Table 1). (2) Bulgaria, Czech Republic and Pakistan constitute another group of countries having a

linear nuclear-GDP nexus and a negative CO₂ parameter. (3) For another group of countries (IND, JPN, SWZ and USA) the parameter estimates indicate a significant inverted U-shaped relationship between nuclear energy consumption and GDP, while CO₂ emissions have no significant effect on nuclear energy consumption. (4) Finally, for the largest group (10 countries), the results suggest the existence of an inverted U curve for nuclear energy consumption and a negative impact of CO₂ emissions on nuclear power.

In the final section, more detailed interpretation of these findings are discussed.

4 Discussion of the findings and concluding remarks

In contrast to the previous literature, this paper investigated the nuclear energy - economic growth nexus by considering different model specifications that allow for a curvilinear relationship among these two variables. More specifically, the EKC hypothesis was examined for nuclear energy consumption. While doing so, cross-sectional heterogeneity was also accounted for in the analysis, which constitutes another important part of the contribution of this study. The existence of an inverted U-shaped relationship between nuclear energy consumption and income suggests that nuclear energy goes from being a normal good (i.e. its consumption increases as income rises) to being an inferior good (i.e. its consumption decreases as income increases). As briefly discussed in the introductory section, according to the classical interpretation of the EKC hypothesis, consumer preferences include an environmental component and the increase of wealth can improve the education of individuals, which, in turn, increases environmental awareness and demand for cleaner goods (Ostman and Parker, 1987). Atmospheric pollution caused by fossil fuel combustion can be captured mostly by the CO₂ emissions data, nevertheless, there is no efficient measure that is capable of assessing total environmental pollution caused by nuclear energy production. It is

logical to assume that nuclear energy generation in a country depends on the ability of its people to accept the presence of nuclear power plants in their regions and pollution risks associated with them. In the same perspective, nuclear energy consumption can be viewed as a proxy for "potential" nuclear pollution, since as yet, no macro data have been published on the external effects of nuclear power. Thus, it seems reasonable to expect an inverted U-shaped relationship indicating that a higher level of wealth would lead to an increase of public concern about the security of nuclear facilities, management of nuclear power and waste disposal, and in consequence, lead to a decreasing demand for nuclear power.

On the other hand, in the existing literature (for example, Apergis et al. 2010), the estimated coefficients for CO₂ emissions are interpreted as the elasticity of CO₂ emissions on nuclear energy consumption. Nevertheless, in accordance with the "potential" pollution hypothesis, a negative sign for the coefficient associated with CO₂ emissions indicates, in the framework of our approach, that when CO₂ emissions increase, the "potential" pollution of nuclear energy decreases. This creates an effect that transforms nuclear energy, which is not a non-polluting source, to a cleaner energy. In the opposite direction, a decrease of CO₂ emissions increases the "potential" nuclear pollution. In other words, nuclear power is no longer considered as a clean energy when the level of CO₂ emissions are "tolerable". Studies using public opinion survey data provide support for this approach. For example, according to the OECD (OECD, 2010), when the role of nuclear energy in reducing CO₂ emissions is clearly explained, public support for nuclear energy increases significantly.

In light of these arguments, the empirical results obtained in this paper can be interpreted in the following manner. The 14 countries for which an inverted U-shaped

relationship is found produce more than 80% of nuclear energy worldwide. For these countries, using the estimated parameter values reported in Table 3, we can calculate the value of turning point income in order to determine which date corresponds to this turning point. The results show that: for GBR the turning point is reached in 1997-1998; for BEL, CAN, DEU and SWE in 1999-2000; for ESP in 2000-2001; for USA in 2001-2002; for HUN in 2002-2003; for FIN in 2003-2004; for FRA in 2004-2005; and for IND, JNP, KOR, SWZ the turning point has not been reached yet. Note that the values of turning point are robust to the removal of the CO₂ variable in the estimated equation. Taken together, the curve begins to fall in 1997 for the case of the United Kingdom, and between 1999 and 2004 for the other countries. These dates correspond with the observation we made above about the evolution of the world electricity production from nuclear sources depicted in Fig. 1: starting from 1997, the growth rate of nuclear energy production falls close to zero and even becomes negative. Our results are thus in accordance with this evolution.

The countries for which nuclear energy is an increasing function of GDP are either from the Communist Bloc (BLG and CZE) or Asian countries (PKS (linear increasing), IND, JAP and KOR (on the rising part of the curve)). In other words, for all nuclear countries of Asia, economic growth stimulates nuclear energy production.

The four countries for which there is no relationship (ARG, BRZ, NLD and AFR) are all small producers of nuclear energy with a limited share of nuclear power in total energy supply. This result implies that the level of nuclear share matters in the nuclear energy - GDP nexus: if nuclear power represents only a small fraction of total energy consumption, then the "potential" pollution is low and wealth increases would not sufficiently raise public awareness of nuclear issues.

We now turn our attention to the interpretation of the negative coefficient associated with CO₂ emissions. The first thing we can note is that the CO₂ variable is not significant if there is no relationship between nuclear energy and GDP. In other words, the existence of a link between these two variables is a necessary condition for the variable CO₂ to have a negative impact on nuclear energy. We have also four other countries (IND, JPN, SWZ and USA) for which the inverted U-shaped relationship confirmed without any effect of CO₂ emissions on nuclear energy. Some explanations can be put forward. In our sample, the United States and Japan have the largest geophysical risk (or earthquake hazard). That is why, public concerns about the nuclear pollution may be motivated by this fact rather than CO₂ emissions. In line with this, it was shown that "people in both countries have the highest level of dread toward nuclear waste disposal, nuclear accidents, and nuclear war, greater even than their dread of crime and AIDS" (Hinman et al., 1993, p. 449). It is therefore understandable that an increase in CO₂ does not necessarily make the risk of a nuclear accident related to an earthquake more acceptable (i.e. it does not decrease "potential" pollution). Again in the same group of countries, Switzerland was producing in the 1960s over 99% of its electricity from hydropower. In order to satisfy increasing energy demand, the country developed its nuclear program, and in consequence, the share of electricity generation from fossil fuels became marginal (less than 2% between 1980 and 2009). This may explain the lack of linkage between nuclear energy and CO₂ emissions in Switzerland. On the other hand, India is the only country that belongs to the group of countries with small share of nuclear energy activities, and at the same time, for which the results validates the existence of an inverted U-shaped relationship without a link between CO₂ emissions and nuclear energy. In fact, the "potential" pollution of nuclear energy is perceived to be a minor problem in the existence of more pressing issues such as socio-cultural barriers,

poverty, education and health care. Therefore civic activism in opposition to nuclear power has not grown in India (Sovacool and Valentine, 2010).

From their review of the literature on public risk perception of nuclear energy, Sjoberg and Drottz-Sjoberg (2009) concluded that "the perceived nuclear waste risk was closely related to the attitude to nuclear power" (Sjoberg and Drottz-Sjoberg, 2009, p.266). In fact, studies in this strand of research have used so far individual-level survey data (i.e. micro regressions) to examine this attitude and most of the results suggest that knowledge about nuclear issues may increase opposition to nuclear which makes nuclear power plants undesirable local facilities (i.e. "not in my backyard" standpoint). We showed in this paper that at the macro-level of countries, nuclear energy consumption exhibits an inverted U-shape pattern as a function of income. Although this form of relation holds for the majority of the countries under analysis, the results pointed also to some heterogeneity among them with respect to both the nuclear-CO₂ nexus and the location of the turning point income.

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Appendix A.

Table A.1

Variables	Country	Parameters	T-Stat	Country	Parameters	T-Stat	Country	Parameters	T-Stat
Const		0,0735	0,44		-43,4856	-8,77		0,3590	1,28
GDP	ARG	0,0407	0,58	FRA	3,0023	8,75	AFR	-0,0057	-0,06
GDP2		-0,0035	-0,47		-0,0446	-7,61		-0,0045	-0,54
Const		-7,1206	-5,15		-11,9786	-7,32		-0,7607	-5,03
GDP	BEL	0,4559	7,03	DEU	0,9070	7,90	KOR	0,2319	8,01
GDP2		-0,0044	-6,15		-0,0146	-7,39		-0,0017	-1,38
Const		-0,3114	-2,01		-0,1868	-0,25		-7,8472	-11,32
GDP	BRZ	0,1012	1,49	HUN	0,1558	1,11	ESP	0,8364	12,10
GDP2		-0,0052	-0,69		-0,0010	-0,14		-0,0185	-11,14
Const		1,3283	4,13		-0,0073	-2,99		-27,6374	-4,79
GDP	BLG	0,1652	1,50	IND	0,0450	5,28	SWE	2,0069	5,79
GDP2		0,0003	0,04		-0,0205	-2,91		-0,0280	-5,50
Const		-14,1985	-3,30		-5,1556	-2,81		-10,4876	-2,83
GDP	CND	1,1154	3,78	JPN	0,3733	2,89	SWZ	0,5215	3,24
GDP2		-0,0181	-3,65		-0,0046	-2,07		-0,0048	-2,74
Const		-2,4672	-3,37		0,4226	2,47		-6,0497	-9,08
GDP	CZE	0,4300	3,16	NLD	-0,0102	-0,95	GBR	0,4853	10,58
GDP2		-0,0043	-0,68		0,0001	0,87		-0,0077	-10,16
Const		-5,4669	-2,61		-0,0184	-4,00		-9,0219	-10,67
GDP	FIN	0,5610	4,03	PKS	0,0447	3,77	USA	0,5966	11,78
GDP2		-0,0079	-3,52		-0,0003	-0,04		-0,0075	-10,18