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n. 407 March 2011

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The impact of renewable energy sources on economic growth and CO_2 emissions - a SVAR approach

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Abstract

Over the last years renewable energy sources (RES) have increased their share on electricity generation of most developed economies due to environmental and security of supply concerns. The aim of this paper was to analyze how an increasing share of RES on electricity generation (RES-E) affects Gross Domestic Product (GDP) and carbon dioxide (CO_2) emissions. Several methodologies could be used for this purpose. The Structural Vector Autoregressive (SVAR) methodology considers the interactions among all variables in the model and is well suited to predict the effects of specific policy actions or important changes in the economy. Therefore, we chose to implement this methodology. We used a 3 variable SVAR model for a sample of four countries along the period 1960-2004. The existence of unit roots was tested to infer the stationarity of the variables. The countries chosen have rather different levels of economic development and social and economic structures but a common effort of investment in RES in the last decades. Through the impulse response functions (IRF), the SVAR estimation showed that, for all countries in the sample, except for the USA, the increasing RES-E share had economic costs in terms of GDP per capita. As expected, there was also an evident decrease of CO_2 emissions per capita. The variance decomposition showed that a significant part of the forecast error variance of GDP per capita and a relatively smaller part of the forecast error variance of CO_2 per capita were explained by the share of RES-E.

Keywords: Renewables, economic growth, CO_2 emissions, SVAR

JEL classification: O13, Q42, Q43, Q56

1 Introduction

Since the negotiation of the Kyoto Protocol, in 1997, there has been a strong emphasis on the need to replace fossil fuels for renewable energy sources (RES). This Protocol obliged industrialized countries to limit their Greenhouse Gas (GHG) emissions, namely carbon dioxide (CO_2). Indeed, a sharp increase of CO_2 concentration cannot be ignored, mostly due to the combustion of fossil fuels (coal, oil and natural gas) [(Halicioglu, 2009), (Soytas and Sari, 2009)] arising from the energy sector [(Jaccard et al., 2003), (Köhler et al., 2006)][1]. This is responsible, to a large extent, for climate change (Sadorsky, 2009a). Simultaneously, most energy balances of developed and developing countries reveal increasing shares of electricity on total energy production largely contributing to CO_2 emissions. Therefore, the negative environmental impact of the energy sector may be remarkably reduced by a larger share of RES on total electricity generation (RES-E). These sources are crucial to achieve sustainability by reducing the GHG emissions and to improve the security of energy supply for countries dependent on fossil fuels imports[2].

To evaluate the existence and the extent of economic and environmental effects of a growing RES-E share, we take a sample of four countries with distinct economic and social structures as well as different levels of economic development. The single country analysis allows assessing a central question: do countries with diverse geographic, economic and social conditions react differently to an increase in the RES-E share?

The relationship between RES, economic growth and carbon emissions has been treated in the literature using different methodological approaches such as Granger causality tests, the Structural Equation modeling approach, the data envelopment analyses method, the autoregressive distributed lag approach, the panel threshold regression model, panel empirical models, among others. Although some alternative methodologies could be used for this purpose, the Structural Vector Autoregressive (SVAR) methodology considers the interactions among all variables in the model and is well suited to predict the effects of specific policy actions or important changes in the economy. Therefore, we chose to implement this methodology. In spite of the constraint placed by the unavailability of reliable, comparable data, we have simulated the Structural Vector Autoregressive (SVAR) model for 44 years (44 observations) for each country. We are aware that the reduced number of observations limits the significance of our results, but have decided to implement the model in the same line of other contributions [(Narayan et al., 2008), (Soytas and Sari, 2009)].

The paper is organized as follows. Section 2 presents a literature survey; section 3 describes the model; section 4 depicts the sample and the data. The empirical results are presented in section 5. Conclusions and policy implications are presented in section 6.

[1] According to the European Environment Agency, the energy sector is responsible for about 80% of the Greenhouse Gas (GHG) emissions in Europe.
[2] See, for instance, (Böhringer and Löschel, 2006), (Neuhoff, 2005), (Stocker et al., 2008).

2 Literature survey

Various studies focused on the relationship between electricity consumption (or even more commonly, energy consumption) and economic growth measured by real Gross Domestic Product (GDP) using different econometric methodologies, countries and time periods [for example, (Aqeel and Butt, 2001), (Bowden and Payne, 2009), (Cheng and Andrews, 1998), (Erbaykal, 2008), (Narayan and Prasad, 2007), (Narayan et al., 2008), (Ortega-Cerdà and Ramos-Martín, 2003), (Soytas and Sari, 2003), (Stern, 1993), (Stern and Cleveland, 2004), for a complete review on this literature see (Payne, 2010) and (Ozturk, 2010)]. These studies typically concerned the effects of energy conservation policies on economic growth. Some of them found that energy (or electricity) consumption contributed to economic growth both directly and/or indirectly (growth hypothesis), others that economic growth determined energy consumption and not the inverse (conservation hypothesis), others that energy consumption and real GDP were interdependent and that there was bidirectional causality among them (feedback hypothesis) or even that there was no causality relationship among the variables (neutrality hypothesis) (Payne, 2009, 2010).

The findings differed from country to country and were often contradictory as a result of diverse energy consumption and output measures, econometric methods used, the presence of omitted variable bias, model specification and the time horizons considered [(Bowden and Payne, 2009), (Chontanawat et al., 2008), (Ozturk, 2010)].

Nevertheless, as referred by Yang (2000), the use of aggregate energy data does not capture the extent to which countries depend on different energy resources. Therefore, another branch of the literature started analyzing the relationship between disaggregated energy sources and GDP as an indicator of economic growth. Nonetheless, this branch is not as developed as the previous one and the number of published researches is rather small (Sadorsky, 2009b). We present a survey of some of the most important studies in this area.

In his study, Yang (2000) found bidirectional causality between aggregate energy consumption and GDP in Taiwan. However, the direction of the causality varied when he considered the disaggregation of energy sources (coal, oil, natural gas and electricity). He found bidirectional causality between GDP and coal, GDP and electricity consumption and GDP and total energy consumption, but unidirectional causality running from GDP to oil consumption and from natural gas to GDP. Sari and Soytas (2004) used a generalized forecast error variance decomposition analysis to examine how much of the variance in national income growth could be explained by the growth of different sources of energy consumption (coal, oil, hydro power, asphaltite, lignite, waste and wood) and of employment in Turkey. They found that waste had the largest initial impact, followed by oil. Yet, within the 3-year horizon, lignite, waste, oil and hydro power explained, respectively, the larger amount of GDP variation among energy sources. In general, total energy consumption was almost as important as employment in explaining GDP forecast error variance. Wolde-Rufael (2004) used the Toda-Yamamoto causality test to investigate the causal relationship between various kinds of industrial energy consumption and GDP in Shangai for the period 1952-1999. The study found unidirectional Granger causality from coal, coke, electricity and total energy consumption to real GDP, but no causality in any direction, between oil and real GDP. In their 2005 study, Domac *et al* (2005) claimed that bio-energy should help increase the economies macroeconomic efficiency through the creation of employment and other economic gains. Later, Awerbuch and Sauter (2006) defended that RES had a positive effect on economic growth by reducing the negative effects of oil prices volatility[3]. Furthermore, they contributed to energy supply security. These effects have to be considered when fully assessing the comparative costs of RES and fossil fuels. Ewing *et al* (2007) used the generalized forecast error variance decomposition analysis to investigate the effect of disaggregated energy consumption (coal, oil, natural gas, hydro power, wind power, solar power, wood and waste) on industrial output in the USA. The authors found that non-renewable energy shocks (coal, gas and oil) had more impact on output variation than other energy sources. Even so, several renewable sources also exhibited considerable explanatory power. Regardless of the sources, energy had always less impact on output variations than employment. In 2008, Chien and Hu (2008) studied the effects of renewable energy on GDP for 116 economies in 2003 through the Structural Equation Modeling (SEM) approach. They decomposed GDP by the "expenditure approach" and concluded that RES had a positive indirect effect on GDP through the increasing in capital formation. However, the authors found that RES did not improve the trade balance having no import substitution effect. In a 2007 paper (Chien and Hu, 2007), these authors claimed that RES significantly increased the technical efficiency (TE) of the economies studies. They used the data envelopment analyzes (DEA) method to estimate the TE for 45 OECD and non-OECD economies for 2001-2002. Sari *et al* (2008) used the autoregressive distributed lag (ARDL) approach to examine the relationship between disaggregated energy consumption (coal, fossil fuels, natural gas, hydro, solar and wind power, wood and waste), industrial output and employment for the USA. They found that, in the long-run, industrial production and employment were the key determinants of fossil fuel, hydro, solar, waste and wind energy consumption, but did not have a significant impact on natural gas and wood energy consumption. Chang *et al* (2009) used a panel threshold regression (PTR) model to investigate the influence of energy prices on RES development under different economic growth rates for the OECD countries over the period 1997-2006. They claimed there was no direct and simple relationship between GDP and the contribution of RES to energy supply. Changes in economic growth were related with past levels of renewable energy use and not with present ones. These authors concluded that the level of economic growth of a country

[3] These authors present the GDP avoided costs for a 10% increase in RES

influenced the use of RES as a way to respond to oil price shocks. High-economic growth countries used RES to minimize the effects of adverse price shock, but low-economic growth countries were unable to do so. Therefore, the first countries exhibited a substitution effect towards RES to avoid the negative relationship between oil prices and GDP. Sadorsky (2009a) used a panel empirical model to estimate renewable energy consumption for the G7 countries. The multivariate model included renewable energy consumption *per capita* (geothermal, wind and solar power, waste and wood), real GDP *per capita*, CO_2 emissions *per capita* and oil prices. The author found that, in the long-run, real GDP *per capita* and CO_2 *per capita* were the main drivers of renewable energy consumption *per capita*. In fact, a 1 percent increase in GDP lead to 8,44 percent increase in renewable energy consumption while a 1 percent increase in CO_2 emissions lead to an 5,23 percent increase. Oil prices had a smaller and negative effect on renewable energy consumption. In the short term, variations in renewable energy consumption were driven by movements back to the long term equilibrium rather than short term shocks. In the same year, the author (Sadorsky, 2009b) studied the relationship between renewable energy consumption (wind, solar and geothermal power, wood and wastes) and income estimating two empirical models for a panel of 18 emerging economies for the period 1994-2003. The study used panel cointegration techniques and a vector error correction model. Sadorsky found that increases in real GDP had a positive and statistically significant effect on renewable energy consumption *per capita*. However, there was not a bidirectional feedback between the two variables. Payne (2009) compared the causal relationship between renewable and non-renewable energy consumption and real GDP for the USA using annual data from 1949 to 2006. The author used Toda-Yamamoto causality tests in a multivariate framework (including employment and capital formation) and found no Granger causality between renewable and non-renewable energy consumption and real GDP. Finally, Apergis and Payne (2010) studied the relationship between renewable energy consumption and economic growth for 20 OECD countries over the period 1985-2005 within a multivariate framework. They included capital formation and labor in their analysis. The authors found a long-run equilibrium relationship between real GDP and renewable energy. In concrete, a 1 percent increase in renewable energy consumption increased real GDP by 0.76 percent. RES also indirectly affected GDP through capital formation. Furthermore, the Granger causality test indicated bidirectional causality between the two variables both in the short and long-run.

The relationship between economic growth and CO_2 emissions has also been largely studied using different methodologies [for references on this theme see (Halicioglu, 2009) and (Jalil and Mahmud, 2009)]. Others have studied this relationship including energy consumption (Soytas and Sari, 2009). The studies on this area aimed to analyze whether an Environmental Kuznets Curve (EKC) (that is, an inverted U-shaped relationship) exists between economic growth and CO_2 emissions (Halicioglu, 2009). If it exists, economic growth would become a solution for the environmental problems by itself (Soytas and Sari, 2009). Other authors have studied the relationship between RES and emissions. For instance, Green *et al* (2007) emphasize the role of these energy sources to stabilize atmospheric GHG concentration. The economic growth-CO_2 emissions relationship is more consensual than the economic growth-energy one and is often assumed in the literature [(Sims et al., 2003), (Wisniewski et al., 1995)].

Our study departs from previous studies in several aspects. First, we use electricity generation instead of consumption. This distinction is relevant if the amount of energy consumed is not generated domestically due to imports/exports. The relationship between electricity generation and economic growth has not yet been extensively studied [(Aqeel and Butt, 2001), (Yoo and Kim, 2006)]. Furthermore, using the share instead of its absolute value may prevent some bias that could occur. In fact, if there is a positive causality relationship from energy generation to GDP, an increase in energy generation may increase GDP whatever the energy source used.

To our knowledge, the use of the SVAR methodology with disaggregated electricity sources is also new. Some authors have studied the relationship between total energy (electricity) consumption and economic growth using the VAR methodology. For instance, Lee and Chang (2007) used a panel bi-variated VAR of 22 developed and 18 developing countries to study that relationship taking into account structural breaks in the time series. They found bidirectional causality between energy consumption and real GDP in developed countries but unidirectional causality, running from GDP to energy consumption in developing countries. Soytas and Sari (2009) studied the relationship between income, energy consumption and carbon emissions controlling for gross fixed capital formation and labor for Turkey using a VAR model. They found Granger causality running from carbon emissions to energy consumption and not the reverse. Furthermore, their study showed a lack of long run causality between income and emissions.

Narayan *et al.* (2008) used a bi-variated SVAR to study the impact of electricity consumption on real GDP for the G7 countries. The authors found a statistically significant positive relationship for every country except the USA, the only country common to our analysis.

In spite of the contradictory results reported in the literature, it is commonly proclaimed that energy-conservation policies aimed at reducing polluting emissions harm economic growth (Soytas and Sari, 2003, 2006). In that case, it is important to find alternative energy sources and invest in technological progress to make them economically feasible (Soytas and Sari, 2006). Furthermore, even if an EKC exists for all countries, it is possible that, when it reaches the inversion point, environmental degradation is no longer reversible. There is a need to find alternative and additional means to reduce CO_2 emissions. But what are the consequences of achieving those goals by changing the mix of sources for electricity generation? The aim of our study is to answer this question.

If an increasing RES share enhances economic growth and at the same time reduces CO_2 emissions, this will be the best policy choice. On the other hand, if promoting RES negatively impacts economic growth, at least initially, governments will need to use complementary policies, such as energy-conservation ones, to achieve environmental goals at the least cost.

3 The model

In this paper we analyze the relationship between the fuel mix for electricity generation, economic growth and CO_2 emissions using a SVAR methodology.

Usually macroeconomic variables are mutually affected. The VAR approach takes into consideration those interactions and all variables are treated as endogenous as a function of all variables in lags. It is a methodology frequently used to analyze the dynamic impacts of different types of random disturbances on the variables in the model (Ferreira *et al*., 2005). However, the reduced form VAR does not consider the structural relationships among the variables unless some identification restrictions are assumed. In this sense, SVAR analysis is an attempt to solve the traditional identification problem. The restrictions are based on economic theory or reveal information about the dynamic properties of the economy investigated. Therefore, the SVAR can be used to predict the effects of specific policy actions or of important changes in the economy (Narayan *et al.*, 2008). That is the case of a change in the energy supply mix. Consequently, the results obtained from the model can be used by policy makers and economic forecasters to predict how some variables, for example, GDP and CO_2 emissions respond over time to changes in policies (Buckle *et al.*, 2002).

Our model used Gross Domestic Product (*gdp*), CO_2 emissions (*co2*) and the weight of renewable sources on total electricity generation (*rentotal*). This last variable is defined as:

$$rentotal = \frac{ren}{ren + ther}$$

Where *ren* is the electricity generated from RES (hydro power, wind power, geothermal power, photovoltaic, biomass, tidal and wave power) and *ther* is the electricity generation from non-renewable sources[4]. In spite of the increasing share of electricity on the energy balances of most countries, this secondary energy source is the most expensive one, with the

[4] All variables come from the World Bank database. Variables specification: GDP per capita (constant prices 2000, USD); CO_2 emissions (t per capita). Since we do not have the CO_2 emissions value for 2004, we use the same value of 2003; Electricity generation from non-renewable sources per capita (coal, oil, natural gas and nuclear) (kWh per capita); Electricity generation from renewable sources per capita (hydro, wind, solar, geothermic, biomass and waste). Per capita variables permit a better and least biased comparison among countries with different population dimensions (Aqeel and Butt, 2001).

largest effects on CO_2 and the strongest efficiency problems, because of the losses in the generation, transmission and distribution process.

GDP is the main economic growth indicator and is used in most of the studies referred in the literature review as a proxy of income (Sadorsky, 2009a). Furthermore, the use of GDP instead of GNP seems appropriated in our model since we refer to electricity generation within the country (Yoo and Kim, 2006).

CO_2 is the most important polluting gas, being responsible for 58,8% of the GHG emissions worldwide (Halicioglu, 2009).

All variables are logarithm transformed [(Aqeel and Butt, 2001), (Apergis and Payne, 2010), (Brischetto and Voss, 1999), (Ewing et al., 2007), (Lee, 2006), (Narayan et al., 2008), (Sadorsky, 2009b), (Soytas and Sari, 2003)] and we use the logarithmical differences as a proxy of the growing rates [(Robalo and Salvado, 2008), (Soytas and Sari, 2006)]. This procedure guarantees that all variables are stationary.

First, we identify the order of the integration of the series using unit root tests. Then, we construct a SVAR and plot the impulse response function (IRF) of *gdp* and *co2* when a positive shock to *rentotal* occurs. Finally, we study the forecast error variance decomposition.

For the SVAR, 5 lags were used according to the Akaike Information Criterion (AIC). Our constraints are based on technical and empirical evidence. We assume that *gdp* does not affect *rentotal* in the short-run, meaning that *gdp* increases do not alter the energy supply mix structure. Therefore, the ratio *rentotal* does not change even if energy supply from each source increases. In fact, when *gdp* increases requiring additional energy generation hydro power and *ther*[5] respond to that necessity. In general, other RES except hydro enter the grid before the other sources supported by feed-in tariffs. Their electricity generation depends on the installed capacity which is fixed in the short-run and prevents them from immediately responding to *gdp* increases. Hydro power and *ther* also have fixed installed capacity in the short-run but allow for different degrees of capacity utilization. Although electricity is non-storable, hydro systems allow some storage levels (Amundsen and Bergman, 2002) and *ther* installed capacity is often under-used in the generation process. To maintain the electricity supply-mix we assume that *ren* (through hydro power) and *ther* increase in the same proportion. Our other restrictions are based on the assumption that *co2* has no short-term effect on *gdp* and *rentotal* since there is no direct causality relation[6].

[5] Hydro power is a peak load technology. Peaking power plants are electricity plants that generally run only when there is a high demand, known as peak demand.

[6] We are able to assume this because our period does not include the emission trade system.

Coincidently, this SVAR identification corresponds to Cholesky decomposition imposing the order *rentotal*, *gdp*, *co2* (from the most to the less exogenous). This order means *rentotal* affects *gdp* and *co2*, *gdp* affects *co2* and *co2* does not affect directly any of the other variables.

In summary, we use a SVAR whose variables capture the three elements under analysis: RES, economic growth and the environment.

4 The sample and the data

4.1 The sample

We have chosen countries with rather different levels of economic development, social and economic structures but with a common effort of investment in RES in the last decades.

The USA (USA) is the largest world economy for the whole period and provides excellent, detailed, reliable data. Being the world's biggest energy producer, consumer and net importer, it ranks 11th worldwide in reserves of oil, 6th in natural gas and first in coal. Furthermore, it was the first country to liberalize its electricity market, in 1978. The PURPA (Public Utilities Regulatory Act) Law determined the end of the territorial monopoly of electricity companies, opening the market to independent producers and forcing the electricity companies to buy the energy generated by those small producers. In 1992, the US National Policy Act definitely ended the market entry barriers through the creation of a new entity: the Electric Wholesale Generator (EWG). Besides, for the whole period, the USA exhibited a diversified electricity generation-mix, with a significant RES share.

Denmark (DK), in spite of its small dimension and scarce natural resources, had a remarkable economic performance through the period. It is a particular case of sustainable economic growth with a strong share of (non-hydro) RES-E over the last 20 years. Furthermore, it is one of the world's most significant cases of wind power development (Lund, 2009). Our data covers the period before and after Denmark entrance in the integrated marker pool (Nord Pool) in 2000 (Amundsen & Bergman, 2002)[7].

The Iberian Peninsula – Portugal (PT) and Spain (SP) – stands as an example of late energy market liberalization, as well as an (almost) isolated regional market due to the weak interconnections with the rest of Europe. For these countries, market structure remains critical – almost a monopoly in Portugal and a strong duopoly in Spain. Notwithstanding, the Iberian Electricity Market (MIBEL) was created and has been active since 2007. Both countries, unlike Denmark, suffered severe economic growth problems and strong political and structural changes over the last decades. They are also highly dependent on fossil fuels

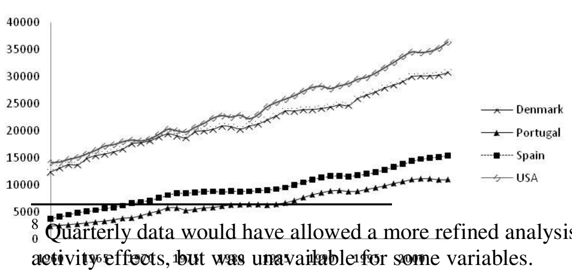
[7] The Nord Pool started in 1996, with the integration of the Norwegian and Swedish power markets. In 1998 it included Finland, and in 2000, Denmark power market was integrated as well.

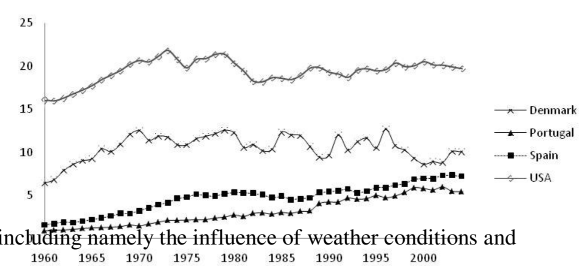
imports. For instance, Spain is one of Europe's largest LNG (Liquefied Natural Gas) importers.

From the countries in our sample, the USA has the largest number of studies and Denmark, Portugal and Spain have rarely been considered. Nevertheless, Narayan and Prasad (2007) found a causality relationship from electricity consumption to GDP for Portugal. In that case, energy-conservation policies would harm economic growth. Stern (2000) found that relationship for the USA whereas Lee (2006) claimed the existence of bi-directional causality between energy consumption and income for that country. Ciarreta and Alonso (2007) established a unidirectional causality running from real GDP to electricity consumption for Spain. Finally, Ciarreta and Zarraga (2008) found no short-run causality relation between electricity consumption and economic growth for Denmark, but a long-run co-integration between the two variables.

Our annual data covered the period 1960 - 2004[8]. The implementation of the model with a reduced number of observations was in line with other contributions [(Narayan et al., 2008), (Soytas and Sari, 2009)]. This time span covered the most relevant events in the energy sector, from the creation of OPEC (Organization of the Petroleum Exporting Countries) in 1960, to the oils shocks in 1973 and 1979 and the counter-shock in 1986, as well as the energy market liberalization for all countries and the emergence of environmental concerns. It was a period characterized by high oil prices volatility leading to different fuel choice dynamics. The lack of reliable, comparable data beyond 2004 impeded us to extend the analysis, which we intend to do in our future research since these last years involve important environment mechanisms and constraints, as well as a high volatility of fuels prices, including coal.

4.2 Data analysis





8 Quarterly data would have allowed a more refined analysis including namely the influence of weather conditions and activity effects, but was unavailable for some variables.

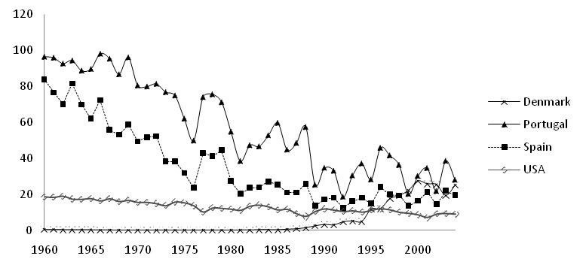
Source: World Bank

Source: World Bank

Figure 1 – GDP *per capita*

Figure 2 – CO_2 emissions *per capita*

As can be seen in Figures 1 and 2, the Iberian countries had the lowest GDP and CO_2 emissions *per capita* levels. Nevertheless, those levels continuously increased in the period under analysis. The USA showed the highest GDP and CO_2 emissions *per capita* levels. However, similarly to Denmark, while GDP *per capita* increased steadily in the period, CO_2 emissions oscillated around the same levels. In spite of the close GDP *per capita*, Denmark had considerably lower CO_2 emissions *per capita* than the USA.



Source: World Bank

Figure 3 – Weight of renewable sources on total electricity generation (*rentotal*)

The RES-E weight analysis provides interesting insights. Portugal started the period with nearly 100 per cent of electricity generated from RES, mainly hydro power. However, that weight decreased drastically over the period considered. A similar situation was observed in Spain. It is interesting to refer that Portuguese and Spanish Governments are currently trying to reverse the situation and rely more heavily on RES. At present the emphasis is being given to wind and solar power. On the contrary, Denmark had no RES-E for a long period. After the mid eighties, these sources, mainly wind power, have steadily increased in this country. Finally, the weight of RES-E in the USA has remained relatively steady.

5 Empirical results

In general, our empirical findings show that all series have at least one unit root, being non stationary. An increasing share of RES negatively affects economic growth but decreases CO_2 emissions. Finally, the variance decomposition showed that a significant part of the forecast error variance of GDP *per capita* and a relatively smaller part of the forecast error variance of CO_2 *per capita* were explained by the share of RES-E.

5.1 Unit root tests

We use the ADF and the PP tests to analyze the existence of unit roots in the variables in levels and in first difference.

Although the results depend on the test used (ADF or PP) and on the trend specification we provide some generic conclusions.

Table 1 - Unit root tests for the series in levels

	ADF test							
	Ct and No Trend				Ct and Trend			
Variable	lags	t-stat	Prob		lags	t-stat	Prob	
gdp_dk	0	-2,59	0,102	**	1	-3,06	0,128	**
gdp_pt	6	-2,50	0,123	**	5	-2,39	0,377	**
gdp_usa	2	-1,09	0,711	**	1	-4,39	0,006	-
gdp_es	1	-1,60	0,476	**	1	-2,59	0,289	**
co2_dk	0	-3,61	0,009	-	0	-3,35	0,072	**
co2_pt	1	-1,92	0,319	**	0	-2,11	0,527	**
co2_usa	1	-3,24	0,024	-	1	-2,89	0,177	**
co2_es	0	-3,26	0,023	-	0	-1,98	0,594	**
rentotal_dk	3	-0,96	0,76	**	3	-2,46	0,34	**
rentotal_pt	5	-1,60	0,47	**	5	-1,06	0,92	**
rentotal_USA	2	-2,10	0,25	**	0	-1,59	0,78	**
rentotal_es	6	-0,53	0,87	**	6	-2,46	0,35	**

	PP test							
	Ct and No Trend				Ct and Trend			
Variable	lags	t-stat	Prob		lags	t-stat	Prob	
gdp_dk	1	-2,64	0,093	**	2	-3,44	0,059	**
gdp_pt	2	-2,70	0,082	**	2	-1,72	0,723	**
gdp_usa	17	-1,80	0,375	**	11	-2,37	0,389	**
gdp_es	4	-3,24	0,024	-	4	-3,61	0,041	-
co2_dk	2	-3,63	0,009	-	1	-3,35	0,071	**
co2_pt	2	-2,14	0,231	**	2	-1,94	0,618	**
co2_usa	1	-2,52	0,117	**	0	-2,07	0,547	**
co2_es	3	-3,02	0,041	-	3	-1,98	0,597	**
rentotal_dk	5	-0,03	0,951	**	4	-2,02	0,577	**
rentotal_pt	3	-2,72	0,078	**	4	-3,84	0,024	-
rentotal_USA	9	-2,15	0,228	**	4	-1,42	0,841	**
rentotal_es	4	-1,44	0,555	**	3	-3,25	0,088	**

** indicates the level of significance at 5%.

Both the ADF and the PP tests examine the null hypothesis of a unit root against the alternative hypothesis stationarity.

Optimal lag length selected using Akaike's information criterion (AIC) is given in the first column.

Table 2 - Unit root tests for the series in first differences

	ADF test							
	Ct and No Trend				Ct and Trend			
Variable	lags	t-stat	Prob		lags	t-stat	Prob	
Δgdp_dk	0	-6,30	0,000	-	0	-6,62	0,000	-
Δgdp_pt	4	-2,10	0,248	**	5	-2,88	0,180	**
Δgdp_usa	1	-5,18	0,000	-	1	-5,22	0,001	-
Δgdp_es	0	-	0,014	-	0	-	0,049	-

	PP test							
	Ct and No Trend				Ct and Trend			
Variable	lags	t-stat	Prob		lags	t-stat	Prob	
Δgdp_dk	1	-6,30	0,000	-	0	-6,62	0,000	-
Δgdp_pt	3	-3,69	0,008	-	2	-4,07	0,013	-
Δgdp_usa	15	-5,24	0,000	-	20	-6,25	0,000	-
Δgdp_es	1	-	0,014	-	2	-	0,058	**

		3,48				3,53					3,46				3,45		
Δco2_dk	3	-4,14	0,002	-	3	-4,55	0,004	-	Δco2_dk	2	-7,24	0,000	-	1	-7,57	0,000	-
Δco2_pt	0	-8,14	0,000	-	0	-8,53	0,000	-	Δco2_pt	1	-8,14	0,000	-	2	-8,61	0,000	-
Δco2_usa	0	-4,76	0,000	-	0	-4,97	0,001	-	Δco2_usa	0	-4,76	0,000	-	1	-5,01	0,001	-
Δco2_es	1	-3,34	0,019	-	0	-6,03	0,000	-	Δco2_es	4	-5,65	0,000	-	3	-6,11	0,000	-
Δrentotal_dk	2	-1,90	0,330	**	2	-1,72	0,722	**	Δrentotal_dk	4	-5,36	0,000	-	4	-5,45	0,000	-
Δrentotal_pt	1	-7,94	0,000	-	6	-6,25	0,000	-	Δrentotal_pt	3	-9,81	0,000	-	3	-9,98	0,000	-
Δrentotal_USA	1	-5,70	0,000	-	1	-6,14	0,000	-	Δrentotal_USA	6	-5,99	0,000	-	14	-8,38	0,000	-
Δrentotal_es	0	-8,03	0,000	-	3	-4,53	0,004	-	Δrentotal_es	3	-8,11	0,000	-	0	-8,36	0,000	-

** indicates the level of significance at 5%.

Both the ADF and the PP tests examine the null hypothesis of a unit root against the alternative hypothesis stationarity.

Optimal lag length selected using Akaike's information criterion (AIC) is given in the first column.

Generally, the tests indicate that GDP *per capita* has unit roots, i.e., is non-stationary in levels for all countries. Since it becomes stationary after one difference, GDP *per capita* has only one unit root. This is consistent with other studies, for instance, Lee and Chang (2007). The same pattern is observed for *co2* and *rentotal*.

5.2 Impulse Response Function analysis

The IRF shows how a residual shock to one of the innovations in the model affects the contemporaneous and future values of all endogenous variables (Robalo and Salvado, 2008). Therefore, it plots the responses of *gdp* and *co2* to a shock in *rentotal* for all countries.[9]

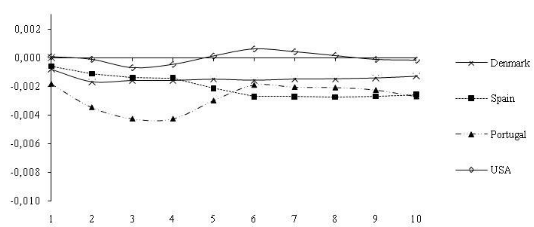


Figure 4 – Accumulated response of *gdp* to *rentotal*

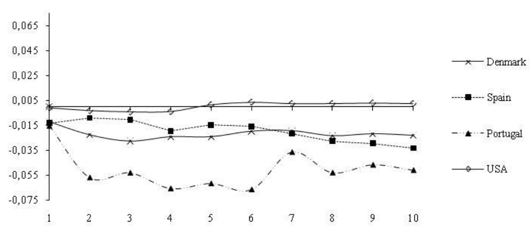


Figure 5 – Accumulated response of *co2* to *rentotal*

An increase in *rentotal* generally decreases *gdp* and *co2*. Notice that the *co2* effects (in percent points) are more significant than the *gdp* effects. In the USA, a positive shock in *rentotal* negatively affects *gdp* and *co2*, but after 5 periods the effect becomes positive. Nonetheless, it is important to notice that the effect is always close to zero. Portugal has the strongest *gdp* and *co2* decrease until the 5th period. After the 6th period Spain has the

[9] We have also performed the test for the USA using the installed capacity instead of electricity generation and obtained similar results.

strongest *gdp* negative effects. Spain and Denmark show close and negative responses to the positive shock on *rentotal*. The negative *gdp* impact for Denmark seems to stabilize at -0.002 pp after the second period. It is interesting to notice the joint behavior of *gdp* and *co2*.

The *gdp* decrease may be explained by additional generation costs imposed by RES-E (except large hydro). These costs may be imputed in several ways. In a liberalized power market they will be passed to final consumers. If there is political intervention, final consumers may not fully bear the additional costs. However, in that case a tariff deficit will occur causing a negative financial impact on the economy. Another possible explanation is highlighted by Robalo and Salvado (2008). They show that, for Portugal, a positive oil price shock negatively impacts *gdp*. That shock may be associated with an increase in the weight of RES-E, especially hydro, since it is a peak load technology. Therefore, a negative relation between oil prices and *gdp* may be associated with a negative relation between *rentotal* and *gdp*.

This analysis also shows that rather different countries have similar responses to increases in the RES-E share.

5.3 Variance Decomposition

The variance decomposition indicates how much of the forecast error variance of each variable can be explained by exogenous shocks (changes) to the variables in the same VAR model. Innovations to an individual variable can affect both own changes and changes in the other variables (Ewing et al., 2007). In concrete, we analyze how much of the forecast error variance of *gdp* and *co2* is explained by each variable in the model.

Table 3 - Generalized forecast error variance decomposition results

		Denmark			Potugal		
		DLRENTOT	DLGDP	DLCO2	DLRENTOT	DLGDP	DLCO2
DLGDP	1	16,985	83,015	0,000	34,737	65,263	0,000
	2	32,153	67,615	0,232	36,979	62,996	0,025
	3	30,986	66,735	2,278	39,114	60,226	0,660
	4	26,806	58,263	14,931	39,018	60,226	0,755
	5	25,838	56,644	17,518	43,388	54,186	2,425
	6	24,636	55,164	20,200	45,818	51,928	2,254
	7	24,611	55,011	20,378	45,805	51,942	2,253
	8	24,613	55,013	20,375	45,537	51,643	2,820
	9	24,543	54,821	20,636	44,917	52,085	2,998
	10	24,656	54,564	20,780	45,348	51,662	2,989
DLCO2	1	7,955	6,621	85,425	5,893	8,660	85,446
	2	12,151	5,832	82,017	25,845	10,318	63,837
	3	13,125	6,048	80,828	25,150	11,526	63,325
	4	13,411	6,461	80,128	26,328	12,050	61,622
	5	12,474	6,169	81,356	26,090	12,004	61,907

	6	13,025	6,141	80,834	26,220	11,983	61,797
	7	12,857	6,373	80,770	33,446	10,845	55,709
	8	13,356	6,509	80,135	35,345	10,583	54,071
	9	13,273	6,417	80,310	35,181	10,820	53,999
	10	13,328	6,443	80,228	35,117	10,768	54,115

		Spain			USA		
		DLRENTOT	DLGDP	DLCO2	DLRENTOT	DLGDP	DLCO2
DLGDP	1	9,089	90,911	0,000	0,120	99,880	0,000
	2	10,650	88,672	0,678	0,905	98,679	0,417
	3	10,059	83,629	6,313	7,998	91,164	0,838
	4	9,209	84,417	6,374	8,666	90,051	1,282
	5	14,136	80,168	5,695	14,017	83,894	2,089
	6	17,324	77,042	5,633	17,522	79,922	2,556
	7	17,217	76,568	6,215	17,772	79,461	2,767
	8	17,164	76,634	6,203	18,739	78,365	2,896
	9	17,171	76,630	6,200	19,679	77,422	2,899
	10	17,295	76,463	6,242	19,693	77,363	2,945
DLCO2	1	16,177	21,514	62,309	0,836	52,388	46,776
	2	16,349	26,006	57,645	6,910	52,914	40,175
	3	13,168	39,750	47,082	7,943	52,363	39,694
	4	16,099	43,210	40,691	7,763	50,925	41,312
	5	16,583	40,962	42,455	30,533	38,627	30,841
	6	14,365	48,966	36,669	31,464	37,835	30,701
	7	15,498	48,870	35,633	31,774	37,285	30,942
	8	16,365	49,264	34,371	31,559	37,303	31,137
	9	16,472	49,169	34,358	31,415	37,074	31,511
	10	16,760	49,237	34,002	31,496	37,100	31,404

Table 3 reports the results of the forecast error variance decomposition for the four countries under analysis. We focus on GDP *per capita* and CO_2 emissions *per capita*. Portugal is the country where a largest part of *gdp* variation is explained by *rentotal*, reaching over 45 per cent after the 6^{th} period. Nevertheless, the other countries also reach considerable values, ranging from 32 per cent in Denmark for the second period, 17 per cent after the 6^{th} period in Spain and more than 19 per cent after the 9^{th} period in the USA. For this last country, the longer the horizon, the larger the impact of *rentotal* on *gdp* variations. The contribution of *co2* to the variation of *gdp* is relatively small for all countries except Denmark, where it reaches over 20 per cent after the 6^{th} period. In fact, for Denmark the impact of *rentotal* on *gdp* variations reaches the maximum in the second period and decreases after that as the weight of *co2* increases.

Variations in *co2* are more explained for variations in *rentotal* than from variations in *gdp* in Portugal (reaching 35 per cent) and Denmark (reaching 13 per cent). On the other hand, for Spain and the USA, variations in *gdp* are the main responsible for variations in *co2*. For the USA, in the first periods after the shock, *gdp* explains over 50 per cent of *co2* variation. Nevertheless, the longer the horizon, the larger the impact of *rentotal* on *co2* variations. The same happens for Portugal.

6 Concluding Remarks and policy implication

In the last decades RES gained an increasing share on the electricity mix of most developed economies.

The relationship between economic growth and energy consumption and between these variables and CO_2 emissions has been studied using different methodologies and for different countries. However, as far as we know, that has never been done taking into account the energy sources shares used for electricity generation and using the SVAR methodology. Therefore, our results are not directly comparable to any other study because of the methodology used, the variables included in the model and the aim of the analysis.

The country sample was selected according to criteria related to economic performance and RES share on the electricity generation-mix.

A SVAR model was used, and the IRF plotted, to estimate the impacts on real GDP *per capita* and CO_2 emissions *per capita* arising from a positive shock on the RES-E share. In general, a positive shock on the *rentotal* decreased *gdp* and *co2*. The variance decomposition showed that a significant part of the forecast error variance of GDP *per capita* and a relatively smaller part of the forecast error variance of CO_2 *per capita* were explained by the share of RES-E.

Our results indicate that an increase in the RES-E share may initially harm economic growth, except for the USA, but contribute to the CO_2 emissions reduction. Therefore, the Danish, Portuguese and Spanish Governments may need to complement RES support with other policies, such as demand-side management and energy conservation, in order to achieve environmental goals at the least cost. Evidence shows that for the USA, the RES support may be least costly. Furthermore, we have shown that rather different countries have similar responses to increases in the RES-E share.

Technical change is making RES cheaper and the economic cost may disappear as these sources become economically competitive. These sources are still being developed and until 2004, they were not as significant as the UE targets require. It would be interesting to include this idea in the analysis. Also, the number of observations (44 for each country) was relatively small. Future research will extend the period and the country sample.

Even though our results may seem controversial, we have shown in the literature survey that results concerning these issues depend widely on the countries studied, the period covered and especially on the methodology applied.

Nonetheless, this paper provides some useful insights on the relationship between RES, economic growth and the environment with a methodology which, to our knowledge, has never been used.

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