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Nuclear energy consumption and economic growth in nine developed countries

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ABSTRACT

This article attempts to test the causal relationship between nuclear energy consumption and real GDP for nine developed countries for the period 1971-2005 by including capital and labour as additional variables. Using a modified version of the Granger causality test developed by Toda and Yamamoto (1995), we found a unidirectional causality running from nuclear energy consumption to economic growth in Japan, Netherlands and Switzerland; the opposite uni-directional causality running from economic growth to nuclear energy consumption in Canada and Sweden; and a bi-directional causality running between economic growth and nuclear energy consumption in France, Spain, the United Kingdom and the United States. In Spain, the United Kingdom and the USA, increases in nuclear energy consumption caused increases in economic growth implying that conservation measures taken that reduce nuclear energy consumption may negatively affect economic growth. In France, Japan, Netherlands and Switzerland increases in nuclear energy consumption caused decreases in economic growth, suggesting that energy conservation measure taken that reduce nuclear energy consumption may help to mitigate the adverse effects of nuclear energy consumption on economic growth. In Canada and Sweden energy conservation measures affecting nuclear energy consumption may not harm economic growth.

1. Introduction

The high degree of concentration of energy supply sources where over 68% of oil is concentrated in the volatile region of the Middle East, and where 67% of gas reserves are concentrated in Russia, clearly involves risks in terms of the reliability of the supply of energy needs for many energy-importing countries (World Coal Institute, 2006; Fiore, 2006; Toth and Rogner, 2006; Elliot, 2007; Ferguson, 2007; World Energy Council, 2007; Gnansounou, 2008; Squassoni, 2009; Tol et al., 2009). Since the 1973 oil crisis, supply security has become a primary concern for many oil-importing countries and this insecurity has made the search for alternative sources of cheap domestic energy supply one of the main deriving forces behind the energy policy of many energy importing countries (Toth and Rogner, 2006). Diversifying the sources of energy and finding a stable, safe and clean energy supply have become one of the main priorities of energy policy for many countries (see, Fiore, 2006; Toth and Rogner, 2006; Elliot, 2007; Ferguson, 2007). As part of their strategy of increasing energy security, many countries have built nuclear power plants not only to reduce dependence on imported oil but also to increase the supply of secured energy and also to minimize the price volatility associated with oil imports (Toth and Rogner, 2006; Vaillancourt et al., 2008). The advantage of nuclear energy has also become even more pressing as a result of the Kyoto Agreement that requires signatories to cut back substantially on their emissions of CO_2 in order to reduce global warming (Becker and Posner, 2005). Many believe that nuclear energy, as a virtually carbon free source of energy, is one of the solutions to global warming and energy security (Elliot, 2007; Ferguson, 2007). Hence, serious concerns over rising fossil fuel prices, energy security, and greenhouse gas emissions have brought the importance of nuclear energy to the forefront of the wider issue of the energy debate. As the IEA notes, nuclear energy is attracting new interest for increasing the diversity of energy supplies, for improving energy security, and for providing a low-carbon alternative to fossil fuels (International Energy Agency, IEA, 2008). Thus, the importance of nuclear energy as a potential source of energy security and as a virtually carbon free source of energy necessitates not only further research but also the use of alternative testing methodologies to examine the causal relationship between nuclear energy consumption and economic growth.

In a recent bivariate study on the causal relationship between nuclear energy consumption and economic growth, Yoo and Ku (2009) suggest that future research should investigate causal relationships using a more generalized multivariate system. In this paper, we do exactly that. Specifically, we examine the casual relationship between nuclear energy consumption and real GDP in nine developed countries for the period 1971-2005 which also includes capital and labor as additional variables. We include capital and labor as additional variables because nuclear energy alone might not be strong enough to spur economic growth. Further, exclusion of a

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relevant variable(s) makes the estimates not only biased as well as inconsistent but also no-causality in a bivariate system can result from neglected variables (Lütkepohl, 1982). It is possible that the introduction of a third or a fourth variable in the causality framework may not only alter the direction of causality but also the magnitude of the estimates (Loizides and Vamvoukas, 2005). In addition, since a four-variable case incorporates more information than a bivariate case, the causal inference drawn may be more reliable (Loizides and Vamvoukas, 2005). Thus, the previous bivariate causality tests between energy consumption and economic growth may be invalid due to the omission of important variables affecting both energy consumption and economic growth.

In this paper the empirical evidence is carried out using the procedure developed by Toda and Yamamoto (1995, hereafter TY) which is valid regardless of whether a series is I(0), I(1) or I(2), non-cointegrated or cointegrated of any arbitrary order. Secondly, unlike previous studies, this paper attempts to quantify how much feedback exists from one series to the other using the recently developed generalized forecast error variance decomposition technique proposed by Pesaran and Shin (1998) which is invariant to the ordering of the variables (see Payne, 2002).

The rest of the paper is structured as follows. In Section 2 we give a brief account of the role of nuclear energy followed in Section 3 by a short summary of the empirical literature. In Section 4 we present a short description of the methodology used, while the empirical evidence is discussed in Section 5. The summary and the concluding remarks are presented in Section 6.

2. The role of nuclear energy

Nuclear energy is one of the major sources of energy for many countries (see Fiore, 2006; Toth and Rogner, 2006). In the 1970s almost 25% of global electricity was generated from oil with nuclear energy accounting for only 3%. By 2002 while the global electricity supply from oil declined to 7.2%, nuclear energy expanded to 16.6% where it absorbed 75% of the decline in oil's share (see Toth and Rogner, 2006). As Fig. 1 shows, electricity production from nuclear sources as a share of total electricity production has significantly increased over the last three decades. In 2005 electricity production from nuclear sources as a share of total electricity production was

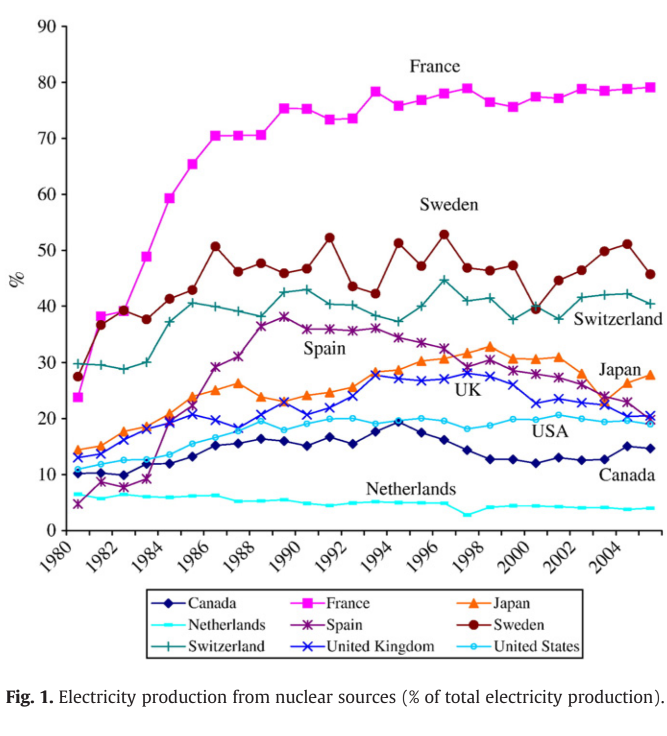

Fig. 1. Electricity production from nuclear sources (% of total electricity production).

14.6% in Canada, 79.1% in France, 27.9% in Japan, 19.8% in Spain, 45.7% in Sweden, 40.4% in Switzerland, 20.9% in the UK, and 19.0% in the USA (World Bank, 2008). Only in the Netherlands did the share of electricity production from nuclear sources as share of total electricity production declined from 6.2% in 1975 to 4.0% in 2005.

Despite the controversies surrounding the nuclear energy sector, nuclear energy will remain a significant part of the energy needs of many countries and it is expected to be an important part of the strategy towards sustainable energy development (see Toth and Rogner, 2006; IEA, 2008). A scenario developed by the IEA (2003) projects very high annual growth rates for nuclear power, especially between 2020 and 2040, implying a 14-fold increase in global nuclear energy production between 2000 and 2050 (see Toth and Rogner, 2006). Yet this will only increase the global proportion of nuclear energy use from 16% to about 20%. However, according to Fiore (2006) the development of the nuclear project ITER (International Thermonuclear Experimental Reactor) will bring about a new era of nuclear fusion engineering. This technology, which is expected to be available in 2050, will have the potential of meeting the world energy needs for approximately a billion years (Fiore, 2006).

In addition to being an important source of energy, nuclear energy also has the potential for lowering greenhouse gas emissions produced by the electricity sector. According to the Nuclear Energy Agency (2002), over the past 40 years, nuclear power plants have already played a major role in lowering the amount of greenhouse gases produced by the electricity sector in OECD countries. Without nuclear power, OECD power plant emissions of carbon dioxide would have been about one-third higher than they are at present. This is an annual saving of some 1,200 million tonnes of carbon dioxide, or about 10% of total CO_2 emissions from energy use in the OECD (Nuclear Energy Agency, 2002). The European Union (2006) also believes that Europe would not have been able to make any significant impact on reducing CO_2 emissions without relying on nuclear energy.

While the combination of several factors mentioned above makes nuclear energy a creditable alternative source of energy and one of the potential panaceas for greenhouse gas reduction, its enormous risks are also equally substantial (see, Fiore, 2006; Toth and Rogner, 2006; Elliot, 2007; Ferguson, 2007; World Energy Council, 2007; Squassoni, 2009). These include high cost, proliferation of dangerous materials, nuclear terrorism, operation safety and radioactive waste disposal (see, Toth and Rogner, 2006; IEA, 2008). As a result of the fear of nuclear proliferation and health risks, some countries have indicated phasing out their nuclear power stations as a source of future energy. In the USA, ever since the meltdown at Three Mile Island in 1979, no new nuclear plant has been licensed. Italy and Spain remain opposed to new nuclear reactors (Fiore, 2006; Ferguson, 2007). However, of late, in view of the energy challenge facing these countries, they are now either reconsidering nuclear energy or they might delay or abandon phasing out nuclear power plants to meet the energy demand and climate changes challenges facing them (Squassoni, 2009). In contrast, Canada, the UK and the USA have plans to expand their nuclear energy programs (Squassoni, 2009).

3. Brief literature review

There is now a vast literature that deals with the relationship between energy consumption and economic growth (Chontanawat et al., 2008; Lee et al., 2008; Payne, 2009a, b, 2010; Ozturk, in press). Yet, there seems to be no consensus regarding the direction of causality between energy consumption and economic growth. There is ample evidence to support all the four competing hypotheses. For some countries there is a bi-directional causality while for others there is no causality at all. Still for some countries there is a unidirectional causality running from energy consumption to economic growth while for others there is the opposite causality running from economic growth to energy consumption.

Similar to the conflicting empirical evidence found regarding the causal relationship between aggregate energy consumption and economic growth, the empirical evidence between nuclear energy consumption and economic growth is also not conclusive. Yoo and Jung (2005), Yoo and Ku (2009) for Korea and Hoe et al. (in press) for India, and Wolde-Rufael (2010) also for India found a unidirectional causality running from nuclear energy consumption to GDP. In contrast, Payne and Taylor (in press) for the United States, Yoo and Ku (2009) for Argentina and Germany; and Wolde-Rufael (forthcoming) for Taiwan found no causality running in any direction. Yoo and Ku (2009) also found bi-directional causality in Switzerland, and unidirectional causality running from economic growth to nuclear energy consumption in France and Pakistan. However, for 14 out of the 20 countries Yoo and Ku (2009) investigated, they did not carry out causality tests, as they could not find their series integrated of the same order, i.e. I(1). In a panel cointegration and panel causality study, Apergis and Payne (2010) found bi-directional causality running between nuclear energy consumption and economic growth providing support for the feedback hypothesis associated with the relationship between nuclear energy consumption and economic growth.

The above conflicting evidence has major implications for nuclear energy policy. If there is a unidirectional causality running from nuclear energy consumption to economic growth, reducing nuclear energy consumption could lead to a fall in economic growth. In contrast, if there is a unidirectional causality running from economic growth to nuclear energy consumption, it could imply that policies aimed at reducing nuclear energy consumption may be implemented with little or no adverse effect on economic growth. On the other hand, if there is no causality running in any direction, the neutrality hypothesis is accepted, and reducing nuclear energy consumption may not affect income and nuclear energy conservation policies may not affect economic growth. In contrast, if there is a bi-directional causality running between the two, nuclear energy consumption can stimulate economic growth and in turn economic growth may induce more demand for nuclear energy. In this case, nuclear energy consumption and economic growth complement each other and nuclear energy conservation measures may negatively affect economic growth.

4. Methodology

Despite the fact that nuclear energy is considered to be an important source of energy for many countries, there are only few studies that have employed modern advances in times series econometrics of cointegration and causality to test the causal relationship between nuclear energy consumption and economic growth (see, Apergis and Payne, 2010; Heo et al., in press; Payne and Taylor, 2010; Yoo and Jung, 2005; Yoo and Ku, 2009; Wolde-Rufael, 2010, forthcoming). Yoo and Ku (2009) did not find their two series integrated of the same order for 14 out of the 20 countries they studied; consequently they excluded 14 countries or 70% of their sample from testing for non-causality. The validity of their causality test was conditional upon testing for unit root and cointegration among the variables. However, it is well known that pre-tests for unit root and cointegration might suffer from size distortions, which often imply the use of an inaccurate model for the non-causality test (Clarke and Mirza, 2006). Moreover, the need for pre-testing for unit roots and cointegration and the inapplicability when the variables have different orders of integration further adds to the distortions associated with Granger causality from within VAR or vector error correction (VEC) settings. To obviate some of these problems, TY based on augmented VAR modelling, introduced a Wald test statistic that asymptotically has a chi square (χ^2) distribution irrespective of the order of integration or cointegration properties of the variables. This approach fits a standard vector auto-regression model on levels of the variables (not on their first differences) that give allowances for the long-run information often ignored in systems that require first differencing and pre-whitening (Clarke and Mirza, 2006). The approach developed by TY employs a modified Wald test (MWALD) for restriction on the parameters of the VAR (k) where k is the lag length of the system. The basic idea of the TY approach is to artificially augment the correct order, k, by the maximal order of integration, say d_{max}. Once this is done, a $(k+d_{max})^{th}$ order of VAR is estimated and the coefficients of the last lagged d_{max} vectors are ignored (see Caporale and Pittis, 1999).

Unlike Yoo and Ku (2009) where they have used the traditional Granger causality test or causality from within a VEC, we utilize a causality procedure suggested by TY. The TY procedure requires the estimation of an augmented VAR that guarantees the asymptotic distribution of the Wald statistic. Moreover the procedure does not require pre-testing for the cointegration properties of the VAR system, and thus avoids the potential biases of pre-testing that undermine the traditional causality tests. The test is valid regardless of whether a series is I(0), I(1) or I(2), non-cointegrated or cointegrated of any arbitrary order.[1]

To undertake the TY version of the Granger non-causality test, for VAR (4), ($k=3$ and $d_{max}=1$), we estimate the following system of equations:

$$\begin{bmatrix} \ln Y_t \\ \ln E_t \\ \ln K_t \\ \ln L_t \end{bmatrix} = \mathrm{A}_0 + \mathrm{A}_1 \begin{bmatrix} \ln Y_{t-1} \\ \ln E_{t-1} \\ \ln K_{t-1} \\ \ln L_{t-1} \end{bmatrix} + \mathrm{A}_2 \begin{bmatrix} \ln Y_{t-2} \\ \ln E_{t-2} \\ \ln K_{t-2} \\ \ln L_{t-2} \end{bmatrix} + \mathrm{A}_3 \begin{bmatrix} \ln Y_{t-3} \\ \ln E_{t-3} \\ \ln K_{t-3} \\ \ln L_{t-3} \end{bmatrix} + \mathrm{A}_4 \begin{bmatrix} \ln Y_{t-4} \\ \ln E_{t-4} \\ \ln K_{t-4} \\ \ln L_{t-4} \end{bmatrix} + \begin{bmatrix} \varepsilon \ln Y_t \\ \varepsilon \ln E_t \\ \varepsilon \ln K_t \\ \varepsilon \ln L_t \end{bmatrix} \tag{1}$$

Where $\ln Y_t$ is the log of real GDP (proxy for economic growth), $\ln E_t$ is the log of nuclear energy consumption (measured in million tons of oil equivalent), $\ln K_t$ is the log of real gross fixed capital formation and $\ln L_t$ is the log of the labour force. All data are annual for 1971-2005. Real GDP and real gross fixed capital formation are in US$ at 2000 constant prices and they were taken from the World Bank, 2008. Nuclear energy consumption is from British Petroleum, 2008. The employment variable is taken from the Conference Board and Groningen Growth and Development Centre, 2008. In line with many researchers, in the absence of capital stock, gross fixed capital formation has been used as proxy for the stock of physical capital (see, Sari and Soytas, 2007; Lee and Chang, 2008; Narayan and Smyth, 2008; Apergis and Payne, 2010; Payne and Taylor, in press; Wolde-Rufael, 2009). Sari and Soytas (2007) point out that since in the perpetual inventory method (PIM) of estimating the physical capital stock assumes a constant depreciation rate, any variance in capital is mostly related to a change in investment. Thus, it is possible to obtain a fairly reliable measure of the trend in physical capital stock from new fixed investment data (Sari and Soytas, 2007; Lee and Chang, 2008).

In Eq. (1), $\mathrm{A}_{1\ldots}\mathrm{A}_4$ are four 4×4 matrices of coefficients with A_0 being the 4 by 1 identity matrix and ε_s are the disturbance terms. From (1) we can test the hypothesis that nuclear energy consumption ($\ln E_t$) does not Granger cause economic growth ($\ln Y_t$), with the following hypothesis: $H_o = a^1{}_{12} = a^2{}_{12} = a^3{}_{12} = 0$, where $a^i{}_{12's}$ are the coefficients of the nuclear energy variable in the first equation of the system presented in Eq. (1). Similarly, we can test the opposite non-causality from economic growth ($\ln Y_t$) to energy consumption ($\ln E_t$) with the following hypothesis: $H_o = a^1{}_{21} = a^2{}_{21} = a^3{}_{21} = 0$, where $a^i{}_{21's}$ are the

[1] Despite the novelty of the TY approach, there are some major weaknesses associated with it. Even TY themselves warn that their approach is inefficient and it suffers some loss of power since their approach intentionally over-fits VAR.

coefficients of the economic growth variable in the second equation of the system presented in Eq. (1).

5. Empirical evidence

Before conducting any causality testing it is important to determine the order of integration of the series (d_{max}) and the optimal lag length k, in order to avoid spurious causality or spurious absence of causality (Clarke and Mirza, 2006). As there are many controversies surrounding the unit root testing (see Madalla and Kim, 1998), our strategy is to compare results obtained from several of these tests and examine whether the preponderance of the evidence makes a convincing case for stationarity or non-stationarity. Using several unit root tests, we found that all series were I(1).[2]

The second step in testing for causality is to determine the optimal lag, k. Granger causality test is very sensitive to the selection of the lag length. If the chosen lag length is less than the true lag length, the omission of relevant lags can cause bias. If the chosen lag length is high, the irrelevant lags in the equation cause the estimates to be inefficient (Clarke and Mirza, 2006). On selecting the optimal lag length, we followed Lütkepohl's (1993:306) procedure where he suggests linking the lag length ($mlag$) and the number of endogenous variables in the system (m) to a sample size (T) according to the formula $m^{*}mlag = T^{1/3}$ (Kónya, 2004). Following Hatemi-J and Irandoust (2000) a combination of AIC, Schwarz's Bayesian criterion (SBC), likelihood ratio (LR) test, and diagnostic testing are used to select the number of lags required in each case. If two different orders of lags are obtained by the AIC and the SBC criteria, we apply the LR test to choose one of these two orders of lags (Pesaran and Pesaran, 1997). We then check to see whether the chosen lag order for each country passes some diagnostic tests. If not, we increase the order of lag successively until the diagnostic tests show better results when we testthe reliability of our models with a number of diagnostic tests, including tests of autocorrelation, normality and hetroscedasticity. In general, we found no evidence of serious violation using all the above tests. Results of the lag selection criteria are presented in Table 1.

Having established the order of integration of the series (d_{max}) and the optimum lag length (k), the next step is to conduct Granger no-causality test and these results are presented in Table 2. The table shows a unidirectional causality running from nuclear energy consumption to economic growth in Japan, Netherlands and Switzerland while the opposite uni-directional causality running from economic growth to nuclear energy consumption is detected in Canada and Sweden. Our results for Japan, Netherlands and Switzerland are in line with the unidirectional causality running from nuclear energy consumption to GDP found for South Korea by Yoo and Jung (2005) and by Yoo and Ku (2009), for India by Hoe et al. (in press) and also for India by Wolde-Rufael (2010). However, our result of unidirectional causality running from nuclear energy consumption to economic growth found for Switzerland is not in line with the bi-directional causality running between economic growth and nuclear energy consumption found for Switzerland by Yoo and Ku (2009). In France, Spain, the United Kingdom and the United States there was a bi-directional causality running between economic growth and nuclear energy consumption. Unlike the unidirectional causality running from economic growth to nuclear energy consumption found for France by Yoo and Ku (2009), we find a bi-directional causality running between economic growth and nuclear energy consumption.[3]

As can be seen from Table 2, the sum of the lagged coefficients of the nuclear energy consumption variable is negative in France, Japan, Netherlands and Switzerland. It is beyond the scope of the paper to thoroughly examine the underlying reasons behind this negative relationship, but it is possible to conjecture that a number of factors may have contributed to the negative relationship between nuclear energy consumption and GDP [(see Squalli, 2007; Bowden and Payne, 2009; Bowden and Payne, in press; Wolde-Rufael, 2009)]. The negative coefficient associated with the uni-directional causality running from nuclear energy consumption to economic growth detected in Japan, Netherlands and Switzerland may be an indication of an inefficient use of nuclear energy in these countries. It is also possible that production is shifting towards less energy intensive sectors or the possibility of excessive nuclear energy consumption in unproductive sectors or capacity constraints may actually reduce output [(Bowden and Payne, in press; Squalli, 2007; Wolde-Rufael, 2009]. Thus, as suggested by Bowden and Payne (in press), within the nuclear energy sector, energy policies such as investment tax credits and the more widespread use of emissions trading markets that promote the use of alternative energy saving technologies may reduce the adverse impact of nuclear energy consumption on real GDP. There is also evidence of negative causality running from GDP to nuclear energy consumption in Spain, Sweden, UK and USA suggesting that increased income could lead to lower nuclear energy consumption.

Our finding of a bi-directional causality running between nuclear energy consumption and economic growth in the USA is not in line with the no causality found by Payne and Taylor (in press) for the United States. The divergence of our results from Payne and Taylor (in press) may be due to the time period covered and the difference in the sources of the data. In contrast, the divergence of our results when compared with Yoo and Jung (2005) and Yoo and Ku (2009) may not only be difference in the time periods covered and the difference in the sources of the time series data but more fundamentally the divergence may be due to the different methodologies used. Moreover, unlike Yoo and Ku (2009) we incorporated more information, and our causal inference may be relatively more reliable than their bivariate case (Loizides and Vamvoukas, 2005).

Table 1
Lag selection criteria.

	Lag Order	Log Likelihood	AIC	SBC	LR test	Optimum lag (k*)
Canada	3	337.455	281.455	240.414		2
	2	323.235	283.235	253.920	28.444[0.028]	
	1	305.991	281.991	264.403	62.923[0.001]	
France	3	385.055	329.055	288.014		3
	2	368.564	328.564	299.249	32.983[0.007]	
	1	345.097	321.097	303.508	79.917[0.000]	
Japan	3	392.567	336.567	295.527		3
	2	367.583	327.583	298.268	49.969[0.000]	
	1	354.063	330.063	312.475	77.001[0.000]	
Netherlands	3	351.118	295.118	254.077		1
	2	338.487	298.487	269.173	25.261[0.065]	
	1	326.079	302.079	284.490	50.079[0.022]	
Spain	3	337.374	281.374	240.333		3
	2	319.865	279.865	250.550	35.020[0.004]	
	1	289.398	265.398	247.809	95.953[0.000]	
Sweden	3	315.217	259.217	218.176		3
	2	293.867	253.867	224.552	42.700[0.000]	
	1	277.474	253.474	235.885	75.486[0.000]	
Switzerland	3	369.191	313.191	272.151		3
	2	349.135	309.135	279.821	40.112[0.001]	
	1	320.844	296.844	279.256	96.694[0.000]	
UK	3	374.532	318.532	277.492		3
	2	348.430	308.430	279.115	52.205[0.000]	
	1	333.219	309.219	291.631	82.626[0.000]	
USA	3	387.092	331.092	290.051		3
	2	370.974	330.974	301.660	32.234[0.009]	
	1	337.870	313.870	296.281	98.443[0.000]	

Notes: AIC and SBC stand for the Akaike and Schwartz Information Criteria, respectively. Term k* is the selected optimal order of the VARs. In the case of conflicting results between the AIC and SBC, we use the AIC results, as suggested by Pesaran and Pesaran (1997), Stock (2004) and Lee (2006).

[2] To conserve space, results are not reported here but are available from the author.

[3] For the rest of the other countries, including, Canada, Japan, Netherlands, Spain, UK and USA, Yoo and Ku (2009) did not carry out causality tests as their two series were not integrated of the same order, hence we could not compare our results with theirs.

Table 2
Granger non-causality test.

	Direction of causality	MWALD χ^2	ρ- value	sum of lagged lnE_t coefficients	sum of lagged lnY_t coefficients
Canada	lnE_t does not cause lnY_t	3.280	0.194	-0.012	1.346
	lnY_t does not cause lnE_t	5.988	0.050**	0.335	0.573
France	lnE_t does not cause lnY_t	15.885	0.001***	-0.068	0.789
	lnY_t does not cause lnE_t	38.814	0.000***	0.818	14.460
Japan	lnE_t does not cause lnY_t	9.915	0.019**	-0.036	1.450
	lnY_t does not cause lnE_t	5.206	0.157	0.635	2.940
Netherlands	lnE_t does not cause lnY_t	4.248	0.039**	-0.019	1.088
	lnY_t does not cause lnE_t	0.050	0.823	0.391	0.649
Spain	lnE_t does not cause lnY_t	10.917	0.012***	0.024	0.073
	lnY_t does not cause lnE_t	24.116	0.000***	1.208	-10.135
Sweden	lnE_t does not cause lnY_t	5.099	0.165	0.027	1.551
	lnY_t does not cause lnE_t	30.545	0.000***	0.027	-5.722
Switzerland	lnE_t does not cause lnY_t	11.744	0.008***	-0.042	0.536
	lnY_t does not cause lnE_t	4.556	0.207	0.119	-6.341
UK	lnE_t does not cause lnY_t	12.469	0.006***	0.018	2.379
	lnY_t does not cause lnE_t	15.081	0.002***	0.920	-4.046
USA	lnE_t does not cause lnY_t	13.290	0.004***	0.138	-0.687
	lnY_t does not cause lnE_t	15.836	0.000***	0.685	-0.047

Notes: *** and ** denote significant at 1% and 5% level.

The causality results presented above indicate only Granger causality within the sample period, but they do not allow us to gauge the relative strength of the Granger causality among the series beyond the sample period (Payne, 2002; Shan, 2005). Thus, to complement the above causality tests, we applied the generalized impulse response approach proposed by Pesaran and Shin (1998) that does not require orthogonalization of shocks and is invariant to the ordering of the variables in the VAR. The difference between the orthogonalized and generalized forecast error variance decompositions is that in an orthogonalized forecast error variance decomposition, the percentage of the forecast error variance of a variable which is accounted for by the innovation of another variable in the VAR will sum to one across all variables. In contrast, the generalized forecast error variance decomposition allows one to make robust comparisons of the strength, size, and persistence of shocks from one equation to another (Payne, 2002). The method proposed by Pesaran and Shin (1998) does not evaluate the percentages of the forecast error variance explained by each variable in absolute terms but only in relative terms. Unlike the orthogonalised case, the row values for the generalized decompositions do not sum up to 100 (Payne, 2002; Sari and Soytas, 2007). The generalized version gives an 'optimal' measure of the amount of forecast error variance decomposition for each series (see Payne, 2002; Sari and Soytas, 2007).

In this paper we decomposed the forecast error variance of GDP into proportions attributed to shocks in all variables in the system including itself by estimating the non-augmented VAR in Eq. (1), k lags only. By doing so, we can provide an indication of the Granger causality test beyond the sample period. As we are relatively more interested in the contribution of nuclear energy consumption to economic growth as compared to the other two inputs of capital and labor, we only decompose the forecast-error variance of the output variable (lnY_t) in response to innovations in nuclear energy consumption (lnE_t), capital (lnK_t) and labor (lnL_t). As can be seen from Table 3, the forecast error variance of nuclear energy consumption explains less that 10% of the forecast error variance of GDP in Canada, Netherlands and the USA. In Canada and the USA the forecast-error variance of the nuclear energy variable made the least contribution to the forecast-error variance of GDP. In both countries only 4% of the forecast error variance of GDP was explained by the forecast-error variance of nuclear energy consumption. This indicates that nuclear energy consumption made a modest contribution to GDP growth in these two countries. In France, Spain and Sweden the forecast error variance of nuclear energy consumption explained 10%, 11% and 12% respectively of the forecast error variance of GDP. The forecast error variance of nuclear energy consumption made a

Table 3
Generalized forecast error variance decomposition results.

Horizon	Dependent variable ΔlnY_t				Horizon	Dependent variable ΔlnE_t			
	ΔlnY_t	ΔlnE_t	ΔlnK_t	ΔlnL_t		ΔlnY_t	ΔlnE_t	ΔlnK_t	ΔlnL_t
Canada									
1	95.2	1.8	68.9	70.9	1	1.5	81.1	4.2	3.1
5	89.8	3.7	64.7	68.9	5	2.7	78.6	3.6	4.2
10	89.7	3.8	64.6	68.8	10	2.9	78.2	3.6	4.3
France									
1	88.6	4.3	68.2	57.6	1	22.1	80.7	18.8	23.5
5	73.4	9.7	61.8	52.4	5	19.8	50.0	17.8	28.1
10	71.3	10.0	60.6	50.9	10	19.9	49.1	18.5	28.6
Japan									
1	78.4	12.1	76.6	10.5	1	8.9	98.4	1.4	6.3
5	52.0	30.2	47.4	13.6	5	11.5	85.9	10.3	8.5
10	50.9	28.7	46.6	16.0	10	12.4	84.1	12.0	8.8
Netherlands									
1	81.0	8.7	40.0	2.2	1	15.6	90.3	2.0	5.5
5	73.7	8.7	41.8	3.5	5	15.8	88.7	2.5	5.8
10	73.5	8.7	41.8	3.5	10	15.8	88.7	2.5	5.8
Spain									
1	51.3	3.3	45.1	64.0	1	7.2	79.7	12.5	20.6
5	44.8	10.9	42.4	49.5	5	17.5	55.5	14.2	24.7
10	43.5	10.8	42.3	50.6	10	23.5	49.0	17.7	30.2
Sweden									
1	97.3	7.2	75.4	54.9	1	9.4	83.2	4.2	8.0
5	88.2	11.9	67.7	57.3	5	15.4	66.4	10.6	8.1
10	87.9	12.0	67.6	57.3	10	15.6	64.8	11.1	8.7
Switzerland									
1	77.4	1.3	42.6	53.3	1	2.4	89.3	5.0	14.5
5	47.6	18.4	29.3	50.0	5	4.9	77.5	5.1	20.1
10	45.2	18.4	27.3	50.5	10	5.2	76.8	5.0	20.3
United Kingdom									
1	93.0	4.9	54.1	11.3	1	5.1	71.1	27.4	9.6
5	76.9	17.5	44.4	9.5	5	22.8	50.0	47.3	7.3
10	75.0	17.3	43.9	10.5	10	22.7	49.8	47.1	7.5
United States									
1	89.9	3.8	80.0	60.8	1	2.8	89.2	2.8	0.5
5	85.6	4.1	73.4	59.8	5	9.1	40.3	10.1	27.2
10	85.2	4.0	73.0	59.5	10	10.1	35.5	9.7	23.4

Notes: ΔlnY_t is growth rate of GDP, ΔlnE_t is growth rate of nuclear energy consumption, ΔlnK_t is growth rate of fixed capital formation and ΔlnL_t is the growth rate of employment. Unlike the orthogonalised case, the row values for the generalized decompositions do not sum up to 100. The generalized version gives an 'optimal' measure of the amount of forecast error variance decomposition for each series (see Sari and Soytas, 2007). The estimates are done without the augmented lags i.e with k lags instead of $k+d_{max}$ lags.

relatively better contribution to the forecast error variance of GDP in Switzerland (17-19%) and the UK (17%). In contrast, the forecast error variance of nuclear energy consumption made the greatest contribution to the forecast error variance of GDP in Japan where it explained around 30% of the forecast error variance of GDP. This confirms the unidirectional causality running from nuclear energy consumption to economic growth found by the Granger causality test. This is also true for Switzerland. In France, Spain and the UK our variance decomposition analysis confirms our earlier finding of bi-directional Granger causality running between nuclear energy consumption and economic growth.

Since in France, Japan, Netherlands and Switzerland increases in nuclear energy consumption were accompanied by decreases in economic growth, the policy implication of our findings is that energy conservation policies that reduce nuclear energy consumption may mitigate the adverse impact of nuclear energy consumption (see Apergis and Payne, 2009). Similarly, in Canada there was a unidirectional positive causality running from economic growth to nuclear energy consumption showing that increases in economic growth caused increases in nuclear energy consumption, thus energy conservation measures that reduce nuclear energy consumption may not have an adverse effect on economic growth. In contrast, in Spain, the UK and the USA, increases in nuclear energy consumption caused increases in economic growth implying that energy conservation policies that adversely impact on nuclear energy consumption may have an adverse effect on economic growth. In Sweden, increases in economic growth caused decreases in nuclear energy consumption and this may be an indication that the Swedish economy is becoming less nuclear energy intensive.

6. Concluding remarks

The aim of this paper was to test the causal relationship between nuclear energy consumption and real GDP for nine developed countries for the period 1971-2005 within a vector autoregressive (VAR) framework by including capital and labour as additional variables to the nuclear energy-economic growth nexus. To do so, we applied two methodologies. First, we used a modified version of the Granger causality test, which is valid regardless of whether a series is I(0), I(1) or I(2), non-cointegrated or cointegrated of any arbitrary order. Secondly, we used the generalized variance decomposition analysis that is invariant to the ordering of the variables in the VAR system. The paper found a unidirectional causality running from nuclear energy consumption to economic growth in Japan, Netherlands and Switzerland while we found the opposite causality running from economic growth to nuclear energy consumption in Canada and Sweden. Unlike Canada, in Sweden nuclear energy consumption was negatively associated with economic growth hence there is a need to make the nuclear energy sector more efficient. In Spain, the UK and the USA, increases in nuclear energy consumption caused an increase in economic growth implying that energy conservation measures taken may negatively affect economic growth. In France, Japan, Netherlands and Switzerland, since increases in nuclear energy consumption caused a fall in economic growth, energy conservation measures may help to mitigate the adverse effects of nuclear energy consumption on economic growth. In Canada and Sweden energy conservation measures taken to reduce nuclear energy consumption may not harm economic growth.

In many countries there is a keen interest in developing nuclear energy as a means of ensuring energy security and stabilising and/or reducing greenhouse gas (GHG) emissions; but economic necessity should not outweigh the risks involved. Nuclear safety is a global concern that needs a global solution. The right balance should be struck between the quest for economic growth, nuclear safety, clean energy and the drive towards making these countries relatively energy independent.

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