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Causal Relationship between Fossil Fuel Consumption and Economic Growth in Japan: A Multivariate Approach

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ABSTRACT: This paper explores whether Japanese economy can continue to grow without extensive dependence on fossil fuels. The paper conducts time series analysis using a multivariate model of fossil fuels, non-fossil energy, labor, stock and GDP to investigate the relationship between fossil fuel consumption and economic growth in Japan. The results of cointegration tests indicate long-run relationships among the variables. Using a vector error-correction model, the study reveals bidirectional causality between fossil fuels and GDP. The results also show that there is no causal relationship between non-fossil energy and GDP. The results of cointegration analysis, Granger causality tests, and variance decomposition analysis imply that non-fossil energy may not necessarily be able to play the role of fossil fuels. Japan cannot seem to realize both continuous economic growth and the departure from dependence on fossil fuels. Hence, growth-oriented macroeconomic policies should be re-examined.

Keywords: Fossil fuels; Economic growth; Cointegration; Granger causality
JEL Classifications: Q32; Q43

1. Introduction

There is no doubt that without extensive use of several forms of high-quality energy (for mechanical work, electricity, chemical work and as a source of heat) our modern economy could not support the present prosperity. Because nature has not given us high-quality energy in human-friendly forms with rare exceptions, we need to produce it artificially from low-entropy natural resources. Fossil fuels (coal, oil and gas) have been major sources of energy supply since the Industrial Revolution. They provide over 80 percent of world consumption of primary energy, in spite of our strong anxiety over their dominance. Obviously, any society relying heavily on fossil fuels is unsustainable. Today's heavy dependence on fossil fuels is creating serious environmental problems such as carbon-dioxide emission, ambient air pollution and natural resource degradation. Even so, there are several advantages to using fossil fuels over other primary energy sources. The most notable is the fact - unremarkable but often understated - that fossil fuels are stock-type resources that can be extracted at a rate to suit our desires. On the other hand, renewable energy sources from which preindustrial societies mainly derived their energy are basically of the flow type, and we cannot control the rate of flow as we like. The difference between these two sources, as pointed out by Georgescu-Roegen (1971), should be clearly recognized when explaining the process of economic evolution. We control fossil fuels, while renewables dictate to us. Hence, as a matter of course, fossil fuels and renewables are primarily associated with industry and agriculture, respectively.

Other advantages of fossil fuels are: high energy density, high ERoEI (Energy Return on Energy Invested), low cost, ease of transport and distribution, ease of combustion, and high flexibility in providing several forms of secondary energy, although these are not necessarily independent of each other. In particular, fossil fuels exert a strong influence on the transportation sector. In very few countries in the world do fossil fuels account for less than 97 percent of transportation fuel use (Fulton, 2004). This is because fossil fuels are easily transported, mainly due to their high energy density per mass/volume, and easy to handle and burn, which means heavy equipment need not be installed in transportation containers. In the light of these overwhelming advantages, it seems misleading to suggest that fossil fuels can easily be replaced by other primary energy sources without harming our prosperity. We should not place fossil fuels on the same level as other type of fuels, and should focus more on the relationship between fossil fuel consumption and economic growth.

So far, there have been many studies of the causal relationship between (primary) energy consumption and GDP (or GNP). According to Ozturk (2010), there are four hypotheses related to the energy-growth nexus. Firstly, the "conservation" hypothesis describes the situation where the causality runs from economic growth to energy consumption. If this is the case, it is commonly believed that a decrease in energy consumption would not necessarily hamper economic growth. Secondly, the "growth" hypothesis concerns the situation where there is a unidirectional causality from energy consumption to growth. The presence of this case is interpreted as evidence that economic growth depends on energy. Thirdly, the "feedback" hypothesis, in which bidirectional causality exists, supports that energy consumption and economic growth are interdependent. Finally, the "neutrality" hypothesis means that there is no causal relationship between these variables.

Because Kraft and Kraft (1978) triggered further studies of this topic, there have been an increasing number of studies regarding the causal relationship between energy consumption and economic growth in both developed and developing countries. However, these studies have yielded mixed results and have not produced a consensus regarding the role of energy in economic growth. For instance, studies finding unidirectional causality running from GDP to energy consumption include Kraft and Kraft (1978) on the US, Lee (2006) on France and Italy, Binh (2011) on Vietnam, Eddrief-Cherfi and Kourbali (2012) on Algeria. On the other hand, studies in favor of a unidirectional causality running from energy consumption to GDP include Asafu-Adjaye (2000) on India and Indonesia, Soytas and Sari (2003) on France, Turkey and Germany, Apergis and Danuletiu (2012) on Romania. In some cases, bidirectional causality between energy and GDP was found. These include Stern (1993, 2000) on the US, Asafu-Adjaye (2000) on Thailand and the Philippines, Kaplan et al. (2011) on Turkey. Finally, there are some cases where no causality was found between energy and GDP. These include Yu and Hwang (1984) on the US, Singapore and the Philippines, Lee (2006) on the UK, Germany and Sweden, Ozturk and Acaravci (2010) on Turkey.

If we look only at Japan, although there are fewer studies, the picture does not change significantly. Erol and Yu (1988) and Zachariadis (2007) found bidirectional relationship between energy and GDP, and Soytas and Sari (2003) found unidirectional causality running from energy and GDP. These studies support the view that a decrease in fossil fuel consumption hampers economic growth. However, Lee (2006) and Lee and Chien (2010) found no causality running from energy to GDP.

Although it is beyond the scope of this paper to reexamine the validity of each study in greater detail, what is clear is that it is not appropriate to judge the causal relationship between fossil fuel consumption and economic growth based on the results of studies on the energy-growth nexus, since in the total consumption of energy, both fossil fuels and non-fossil energy are usually mixed without distinction. If non-fossil energy had essentially the same properties as fossil fuels, both could be virtually treated as the same resource. However, imperfect substitutability between fossil fuels and non-fossil energy reinforces the need for distinguishing between fossil fuels and non-fossil energy, and analyzing the relationship between fossil fuel consumption and economic growth.

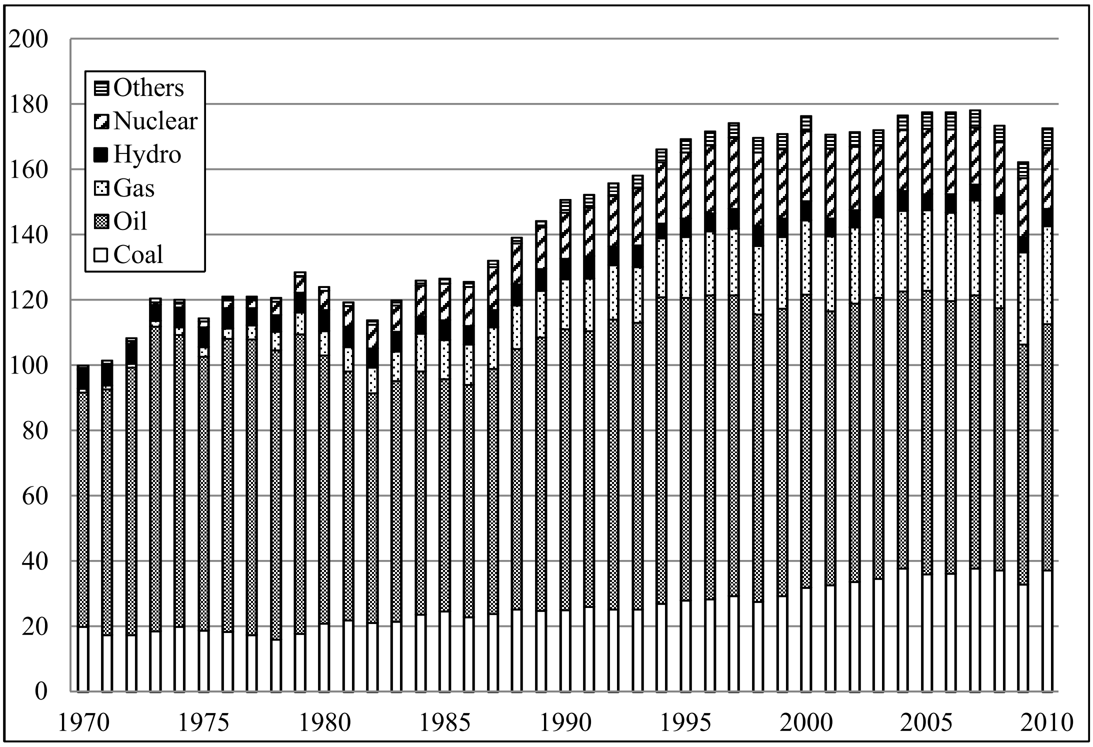
On the other hand, there have been several studies of causal relationships between economic growth and a particular type of fossil fuel, such as oil or coal (Lee and Chang, 2005; Zamani, 2007; Yuan et al., 2008; Yazdan and Hossein, 2012). However, the results of these studies are also insufficient to understand the role of fossil fuels in the economy as a whole. Yet oil, coal, and natural gas have distinctive characteristics, they share the specific advantages of fossil fuels mentioned above. History since the Industrial Revolution has shown that oil, coal and natural gas are, if not perfectly, widely substitutable for each other.

The aim of this paper is to investigate the causal relationship between fossil fuel consumption and economic growth in Japan. After the oil shocks of the 1970s, Japan not only has a strong incentive to lower its fossil fuel dependence in relation to economic growth, but also possesses the advanced technology and abundant capital to develop non-fossil energy. The ability of the Japanese economy to continue to grow without an increase in fossil fuel consumption has important implications for both domestic and international policy. In fact, as shown in Figure 1, fossil fuels accounted for more than 90 percent of the primary energy supply throughout the 1970s, and the share has fallen slightly to about 85 percent in recent years. Most of the increase in non-fossil energy is due to the development of nuclear power plants. Nuclear energy is obtained from uranium ore, which is a stock-type resource similar to fossil fuels. However, we cannot obtain energy from uranium ore as easily as from fossil fuels. Uranium ore cannot be burned with a match, as can fossil fuels. To harness uranium ore as a nuclear fuel, huge and highly complex systems are needed, and still nuclear energy can only supply electricity and heat. Therefore, uranium ore should not be treated as a primary energy source offering the same level of convenience as fossil fuels.

In this paper, I employ a multivariate approach, because standard bivariate causality procedures have been criticized for ignoring the substitution effects between energy and other inputs (Stern, 1993, 2000). Based on the neoclassical approach, I use a multivariate causality framework of GDP, fossil fuels, non-fossil energy, labor and stock.

The remainder of this paper is organized as follows. Section 2 describes the methodology and data used in the paper. Section 3 reports the results of econometric analyses. In Section 4, I discuss the empirical results. Section 5 concludes.

Figure 1. Primary energy supply in Japan (1970=100)



2. Methodology and Data

So far, most studies of the causal relationship between energy and economic activity have used bivariate models. However, the bivariate approach has been criticized for causing bias arising from the omission of variables that could be substituted for energy (Stern, 1993, 2000). Unfortunately, a researcher using the multivariate framework, rather than the bivariate model, faces a difficulty when choosing variables to include in the model. Yet there seems to be no consensus concerning the theoretical framework upon which to base decisions about which variables should be used. Some studies using a multivariate framework have developed a model based on neoclassical production theory, in which primary energy consumption is included as an input factor in the conventional production function of labor and capital stock. Following previous studies, variables in this study are included in the model based on the neoclassical production function

$$Y=g(F, NF, L, K) \quad (1)$$

where Y is output, F is fossil fuel consumption, NF is consumption of non-fossil energy, L is labor, and K is capital stock. Note that this paper treats fossil fuels and non-fossil energy separately, because, as mentioned above, fossil fuels have inherent and particular characteristics that other types of primary energy lack.

The analysis is developed as follows. In the first step, an augmented Dickey-Fuller (ADF) unit root test (Dickey and Fuller, 1979) and Phillips-Perron (PP) unit root test

(Phillips and Perron, 1988) are conducted to check for stationarity of the series. If some variables are nonstationary, there is a possibility that one or more cointegration relationships among the variables exist (Engle and Granger, 1987). Then, in the second step, a cointegration test is conducted based on the Johansen and Juselius (1990) maximum likelihood procedure using a VAR model:

$$X_t=\mu+\sum_{i=1}^{p}\Pi_i X_{t-i}+\epsilon_t \quad (2)$$

where X is a vector of variables, μ is a vector of constant terms, Π are coefficient matrices, p is the number of lags, and ϵ is a vector of the disturbance term with a mean of zero. By reparameterizing Eq. (2), the corresponding VECM is obtained:

$$\Delta X_t=\mu+\sum_{i=1}^{p-1}\Gamma_i \Delta X_{t-1}+\Pi X_{t-1}+\epsilon_t \quad (3)$$

where Δ means first difference, $\Pi=\sum_{i=1}^{p}\Pi_i$ -I ,and $\Gamma_i=-\sum_{j=i+1}^{p}\Pi_j$ .By checking the rank of Π, the existence of a long-run relationship among the variables can be detected. In the third step, a causality test is conducted based on VECM, following Granger (1988). In addition, a generalized impulse response analysis was conducted to reveal the dynamic responses of one variable to another.

This paper uses annual data for Japan for the period between 1970 and 2010. Time series data of real GDP (Y) and capital stock (K) were obtained from the Cabinet Office, Government of Japan, and data for both fossil fuel consumption (F) and non-fossil energy (NF), expressed in terms of joules, were obtained from the Agency for Natural Resources and Energy. Total hours of labor (L) were calculated by multiplying numbers of workers and working time per capita, the data for which were obtained from the Ministry of Internal Affairs and Communications and the Ministry of Health, Labor and Welfare, respectively. All variables are expressed in logarithmic form.

3. Results

The results of the ADF and PP tests are reported in Table 1 and Table 2 respectively. For each variable level, neither test can reject the null hypothesis that there is a unit root. However, after taking the first difference, both tests reject the null hypothesis. The results imply that each variable is nonstationary and integrated of order one.

Table 1. Augmented Dickey-Fuller unit root tests

Variables	With a time trend	Without a time trend
Y	-0.9569(1)	-2.7328(2)
F	-2.3167(0)	-1.7525(0)
NF	-0.7349(0)	-2.1535(0)
L	-1.2337(4)	-1.3641(2)
K	-1.6923(4)	-2.0335(1)
ΔY	-5.1426(1)**	
ΔF	-5.8446(0)**	
ΔNF	-6.8645(2)**	
ΔL	-5.1491(1)**	
ΔK	-3.6299(3)*	

Lag lengths(in parenthesis) are determined by AIC.
* Significant at the 5% level.
** Significant at the 1% level.

Next, to determine the number of cointegrating relationships, the maximum likelihood estimation method of Johansen and Juselius (1990) is employed. The results of cointegration tests are presented in Table 3. Both the maximum eigenvalue and the trace statistics suggest the existence of two cointegrating vectors among the variables.

Table 2. Phillips-Perron unit root tests

Variables	With a time trend	Without a time trend
Y	-0.5080	-1.8695
F	-2.4341	-1.7529
NF	-0.1055	-2.5909
L	-1.2121	-1.3922
K	-1.6728	-2.4620
ΔY	-5.1867**	
ΔF	-5.8185**	
ΔNF	-9.8234**	
ΔL	-4.4715**	
ΔK	-3.7984*	

Lag lengths(in parenthesis) are determined by AIC.

* Significant at the 5% level.

** Significant at the 1% level.

Table 3. Maximum likelihood cointegration tests

Cointegration rank	Trace test		Maximum Eigenvalue test	
	Statistics	Critical value[a]	Statistics	Critical value[a]
None	117.704	88.804	48.830	38.331
At most 1	68.874	63.876	35.225	32.118
At most 2	33.649	42.915	16.886	25.823
At most 3	16.762	25.872	12.462	19.387
At most 4	4.300	12.518	4.300	12.518

[a] 5% Critical value.

The lag structure of VAR is determined by AIC.

Generally, exact identification of r cointegrating vectors requires r restrictions on each vector, one of which is normalization. To solve this problem, I introduce some assumptions as follows: (A) one of the two cointegrating vectors corresponds to a Cobb-Douglas type production function; (B) the other vector corresponds to the fossil fuel supply as a function of the availability of other production factors. It is reasonable to think that the demand for fossil fuels is affected by the supplies of other types of production factors; that is, non-fossil energy, labor and capital stock.

Table 4 presents the estimates for cointegrating vectors of adjustment coefficients vectors, normalized to Y for the first cointegrating vector and to F for the second, respectively. From assumption (A), the sum of components, except that for Y in the first cointegrating vector, is -1, and from assumption (B), the second cointegrating vector's component for Y is zero.

Table 4. Cointegrating vectors and adjustment vectors

	Y	F	NF	L	K	$TREND$
β_1	1	-0.177 (-4.843)	-0.052 (-2.039)	-0.480 (-10.513)	-0.291 (-14.439)	-0.011 (-15.524)
β_2	0	1	-0.812 (-3.952)	9.364 (8.589)	-0.812 (-4.141)	0.001 (0.287)
α_1	-0.571 (-2.328)	-0.094 (-0.225)	0.284 (0.306)	-0.105 (-0.649)	0.864 (1.611)	
α_2	-0.010 (-0.403)	-0.126 (-2.973)	0.146 (1.548)	-0.054 (-3.303)	0.096 (1.761)	

T-values are given in parentheses.

Because the coefficient on *NF* in the first cointegrating vector is insignificant, an exclusion test for *NF* from the first cointegrating vector is con-ducted. The likelihood ratio test yields χ^2 (1) = 2.07, which suggests that *NF* can be excluded from the first cointegrating vectors.

Then, in Table 5, cointegrating vectors and adjustment vectors are re-estimated, excluding *NF* from the first cointegrating vector. It is worth pointing out that the results imply that non-fossil energy does not necessarily fulfill the role of fossil fuels, because (1) whereas fossil fuels cannot be excluded from the production function (the first cointegrating vector), non-fossil energy can, and (2) the sign of the coefficient for non-fossil energy in the fossil fuel supply function (the second cointegrating vector) tells us that an increase in the supply of non-fossil energy leads to an increase in supply for fossil fuels. The relationship between non-fossil energy and fossil fuels appears complementary rather than substitutive. Conforming the existence of cointegrating relationships among the variables, I proceed to a Granger causality test based on error-correction models, as follows:

$$\Delta Y_t=\mu_1+\alpha_{1,1}ECT_{1,t-1}+\alpha_{1,2}ECT_{2,t-1}+\sum_{i=1}^{l_1}\gamma_{1,i}\Delta Y_{t-i}+\sum_{i=1}^{l_1}\gamma_{2,i}\Delta F_{t-i}+\sum_{i=1}^{l_1}\gamma_{3,i}\Delta NF_{t-i}+\sum_{i=1}^{l_1}\gamma_{4,i}\Delta L_{t-i}+\sum_{i=1}^{l_1}\gamma_{5,i}\Delta K_{t-i}+\epsilon_{1,t} \quad (4)$$

$$\Delta F_t=\mu_2+\alpha_{2,1}ECT_{1,t-1}+\alpha_{2,2}ECT_{2,t-1}+\sum_{i=1}^{l_2}\eta_{1,i}\Delta Y_{t-i}+\sum_{i=1}^{l_2}\eta_{2,i}\Delta F_{t-i}+\sum_{i=1}^{l_2}\eta_{3,i}\Delta NF_{t-i}+\sum_{i=1}^{l_2}\eta_{4,i}\Delta L_{t-i}+\sum_{i=1}^{l_2}\eta_{5,i}\Delta K_{t-i}+\epsilon_{2,t} \quad (5)$$

$$\Delta NF_t=\mu_3+\alpha_{3,1}ECT_{1,t-1}+\alpha_{3,2}ECT_{2,t-1}+\sum_{i=1}^{l_3}\theta_{1,i}\Delta Y_{t-i}+\sum_{i=1}^{l_3}\theta_{2,i}\Delta F_{t-i}+\sum_{i=1}^{l_3}\theta_{3,i}\Delta NF_{t-i}+\sum_{i=1}^{l_3}\theta_{4,i}\Delta L_{t-i}+\sum_{i=1}^{l_3}\theta_{5,i}\Delta K_{t-i}+\epsilon_{3,t} \quad (6)$$

$$\Delta L_t=\mu_4+\alpha_{4,1}ECT_{1,t-1}+\alpha_{4,2}ECT_{2,t-1}+\sum_{i=1}^{l_4}\lambda_{1,i}\Delta Y_{t-i}+\sum_{i=1}^{l_4}\lambda_{2,i}\Delta F_{t-i}+\sum_{i=1}^{l_4}\lambda_{3,i}\Delta NF_{t-i}+\sum_{i=1}^{l_4}\lambda_{4,i}\Delta L_{t-i}+\sum_{i=1}^{l_4}\lambda_{5,i}\Delta K_{t-i}+\epsilon_{4,t} \quad (7)$$

$$\Delta K_t=\mu_5+\alpha_{5,1}ECT_{1,t-1}+\alpha_{5,2}ECT_{2,t-1}+\sum_{i=1}^{l_5}\nu_{1,i}\Delta Y_{t-i}+\sum_{i=1}^{l_5}\nu_{2,i}\Delta F_{t-i}+\sum_{i=1}^{l_5}\nu_{3,i}\Delta NF_{t-i}+\sum_{i=1}^{l_5}\nu_{4,i}\Delta L_{t-i}+\sum_{i=1}^{l_5}\nu_{5,i}\Delta K_{t-i}+\epsilon_{5,t} \quad (8)$$

Table 5. Restricted cointegrating vectors and adjustment coefficient vectors

	Y	*F*	*NF*	*L*	*K*	*TREND*
β_1	1	-0.175 (-5.881)	0	-0.490 (-8.807)	-0.335 (-20.105)	-0.011 (-14.923)
β_2	0	1	-0.758 (-3.671)	9.438 (8.582)	-0.875 (-4.427)	0.001 (0.284)
α_1	-0.449 (-2.159)	0.030 (0.086)	-0.465 (-0.597)	-0.088 (-0.647)	0.804 (1.809)	
α_2	-0.010 (-0.400)	-0.123 (-2.878)	0.121 (1.280)	-0.055 (-3.334)	0.101 (1.881)	

T-values are given in parentheses.

where ECT_1 and ECT_2 denote error-correction terms assigned to the first and second cointegrating vectors, respectively, μ_j (j = 1, 2, ..., 5) are the intercepts, and l_k (k = 1, 2, ..., 5) are the lag lengths determined using Akaike's information criteria. Table 6 shows the results of diagnostic tests for each equation. The results suggest that every equation supports the standard assumptions.

Table 6. Diagnostic tests of ECM

	ΔY	ΔF	ΔNF	ΔL	ΔK
R^2	0.519	0.391	0.375	0.573	0.587
Adjusted R^2	0.391	0.229	0.197	0.477	0.494
F-value	4.046	2.411	2.104	5.944	6.302
Durbin-Watson	1.696	1.870	1.768	2.045	1.862
Jarque-Bera	0.334	0.098	0.609	1.007	0.095

Table 7 shows the results of the Granger causality tests. The results imply that in the long run there exists unidirectional causality running from fossil fuel consumption to GDP. In the short run, there is a unidirectional causality running from GDP to fossil fuel consumption. The results also imply that there is no causal relationship between GDP and consumption of non-fossil energy. Note that there cannot be long-run causality running from non-fossil energy to GDP through the first error-correction term, because the production function does not have the non-fossil energy variable.

Table 7. Granger causality test results

Dependent variables	F-statistics					t-statistics	
	Short-run					Long-run	
	ΔY	ΔF	ΔNF	ΔL	ΔK	ECT_1	ECT_2
ΔY	-	1.355	2.546	0.782	0.048	-2.186*	-0.384
ΔF	3.430*	-	0.011	0.184	3.020	0.067	-2.884**
ΔNF	0.228	0.393	-	0.299	0.385	-0.475	1.172
ΔL	1.500	3.631*	3.071	-	0.534	-0.699	-3.292**
ΔK	1.241	0.622	5.977*	0.661	-	1.798	1.916

* Significant at the 5% level.
** Significant at the 1% level.

The results of Granger causality tests cannot reveal the importance of the causal impact of each variable on economic growth. To verify this statement, a variance decomposition analysis was conducted. Table 8 shows the results of decomposition of the forecast-error variance for economic growth, on which our interest is focused. Clearly, fossil fuel consumption is more important than non-fossil energy in explaining the variation in GDP, accounting for over 40 percent over 10 periods.

Table 8. Variance decomposition of GDP

Period	Forecast error	*Y*	*F*	*NF*	*L*	*K*
1	0.013	100.000	0.000	0.000	0.000	0.000
2	0.016	92.936	3.727	3.015	0.130	0.190
3	0.018	64.345	16.917	8.889	6.507	3.339
4	0.020	44.749	33.115	6.814	9.724	5.595
5	0.022	40.764	40.538	5.675	8.430	4.591
6	0.024	37.349	44.641	5.511	7.850	4.648
7	0.028	35.892	42.649	4.765	11.528	5.164
8	0.032	35.126	37.891	4.406	17.214	5.361
9	0.034	32.211	37.575	4.113	20.992	5.107
10	0.036	28.397	41.690	3.615	21.820	4.476

4. Discussion

As shown above, it is clear that fossil fuels are at least one of the important factors spurring economic growth in Japan. Then, our interest moves on to whether non-fossil energy can be substituted for fossil fuels to achieve continuous economic growth. The results of Granger causality tests and variance decomposition analysis imply that non-fossil energy has not played a similar role to fossil fuels in achieving economic growth. The results further imply there are not only quantitative but also qualitative differences between fossil fuels and non-fossil energy, as follows. First, whereas fossil fuel consumption is included in the production function (the first cointegrating vector), non-fossil energy is not. Second, in the second cointegrating vector, non-fossil energy seems to be complementary rather than substitutive with fossil fuels. Third, whereas fossil fuel consumption Granger causes GDP in the long run, non-fossil energy does not. Finally, although both fossil fuels and non-fossil energy are usually treated equivalently as primary energy sources, the results of the variance decomposition analysis show that the impact of fossil fuel consumption on economic growth differs greatly from that of non-fossil energy.

How can we explain such an intrinsic difference between fossil fuels and non-fossil energy? One possible explanation might be that most of the increase in non-fossil energy since 1970 is due to nuclear energy, which depends on fossil fuels for mining, extracting, transporting, processing and enriching uranium ore. Namely, power generation from nuclear energy is not fully independent of fossil fuels. Hence, it is reasonable to obtain results indicating that the relationship between non-fossil energy and fossil fuels is complementary rather than substitutive. The fact that harnessing nuclear energy is fatally accompanied by fossil fuel consumption emphasizes the specialty of fossil fuels as irreplaceable resources.

Some may cast optimistic eyes on the development of solar energy flow such as wind energy, solar power, and biomass energy, which have not been fully harnessed thus far. As Georgescu-Roegen (1971) pointed out, however, there is an intrinsic difference between solar energy flow and fossil fuels. We can extract the stock of fossil fuels at a rate to suit our desires, but cannot control the rate of energy flow from the sun. Most of the significant problems in harnessing solar energy flow are caused by their intermittent nature. There are only two ways to obtain large amounts of stable energy from solar energy flow: back-up through conventional fossil fuel fired systems and storing the energy. The former requires fossil fuel-fired plants in addition to wind or solar power generation systems. Clearly, in this case, the relationship between solar energy flow and fossil fuels is not substitutive, but complementary.

To escape dependence on fossil fuels, we must develop reasonable and economical measures to store large quantities of solar energy flow. One of the important criteria to judge whether a storage system could help us depart from the fossil-fuel age is its energy density. There is no doubt that one of the many reasons that fossil fuels have dominated the energy market is their high energy density. The energy densities of crude oil, natural gas, and coal are about 50 MJ/kg, 55 MJ/kg, and 20–35 MJ/kg, respectively. A fuel with high energy density by mass/volume is easy to transport and store. The abundance of such fuel is a necessary precondition for the viability of its production and transportation around the world. The use of low energy density fuels requires much more energy for its transportation and storage, which could lead to a shortfall in the energy necessary to operate and maintain the existing economy.

Currently, the most conventional way to do that is to pump water into lakes held by dams. However, the relatively very low energy density of pumped water compared with fossil fuels requires very large dam sites and huge volumes of water. The energy required to lift 50 metric tons of water to a height of 100 m is equal to just 1 kg of crude oil. To make matters worse, a pumped storage hydro system requires not only an upper reservoir but also a lower reservoir from which water is pumped up to the upper using excess electricity from wind farms and so on. Therefore, it is more difficult to get a good geologic site for a pumped storage system than for a conventional dam. Using the sea as a low dam leads to the problem of seepage of salt into surrounding soil at the high dam sites (Trainer, 2007). Besides all these, there is no guarantee that both high dam and low dam sites coexist very close to each other. Lengthy distances between upper and lower dams cause problems such as increased construction scale and lowered in-out efficiency. Even if it were achieved, note that pumped water could only supply electricity and it could not replace fossil fuels used in combustion engines installed on transportation machines.

Another way of storing energy is using batteries. Batteries can store surplus electricity as chemical energy and transform this energy into electricity again. Lead acid batteries are commonly used and have a long history of about 150 years. However, prevailing lead acid batteries can store about 0.1 MJ/kg, which is incomparably smaller than the energy densities of fossil fuels. Even rechargeable lithium ion batteries, which are rapidly becoming popular because of their relatively high energy densities, can store only around 0.5 MJ per kg. Of course, there is room for further improvement in lithium ion batteries since they do not have a very long history. However, lithium ion batteries have a theoretical energy density limit of several MJ/kg, or about 10+ times less than crude oil. Moreover, considering the declining capacity after repeated charge-discharge, actual energy densities of lithium ion batteries will never be close to those of fossil fuels in the future.

Other ways to store energy (hydrogen, compressed air, vanadium batteries, flywheels, etc.) are under development, and so far have no prospect of supplying massive energy to our society without the help of fossil fuels, because construction of power generating and storage systems on a huge scale cannot be implemented without fossil fuels (Ferguson, 2008).

Another traditional way to store solar energy flow is to harvest and store biomass (solid or liquid). However, as the average energy production density of phytomass is very low (Smil, 2008), heavy dependence upon biomass energy to feed a mass-consumption society may lead to fierce competition over finite fertile land for the production of food. In addition, we should remember that conventional agriculture has only come about with huge reliance upon fossil fuels (Patzek, 2008).

Finally, it is important to mention the other factors of production. For capital stock, the sign of the coefficient in the second cointegrating vector implies that the relationship between capital stock and fossil fuels is complementary. From the viewpoint of thermodynamics, it is no surprise that such results are obtained. Low-entropy resources require the agents upon which the resources are consumed, just as gasoline is burned in an internal- combustion engine settled in a vehicle. Soddy (1926) called the former wealth I, and the latter wealth II. Georgescu-Roegen (1971) called the former flow elements, and the latter fund. Both emphasized the differences between these factors of production.

Judging from the sign of the coefficient in the second cointegrating vector, it seems that only can be substituted for fossil fuels. The results of decomposition of the forecast-error variance for economic growth also imply the decent importance of labor in explaining the variation in GDP, accounting for over 20 percent over 10 periods. Needless to say, except in rare cases, human workers are not valued for jobs that machines can do just as well, but rather for physical dexterity and information-processing skills (Ayres and Ayres, 1999). However, even considering labor's high-quality values, the fact remains that its supply is limited by a ceiling. Whether a decrease in leisure time on behalf of economic growth can enrich people's lives is another significant problem.

To summarize, it is unlikely that Japan will achieve both continuous economic growth and a strong departure from fossil fuels simultaneously. Therefore, we should re-examine growth-oriented macroeconomic policies.

5. Conclusion

This paper investigates the relationship between fossil fuel consumption and economic growth in Japan based on a multivariate model of fossil fuels, non-fossil energy, labor, stock and GDP. Using the Johansen cointegration technique, the empirical results indicate two long-run relationships among the variables, one of which corresponds to the production function, and the other to the supply function for fossil fuels. Then, using a vector error-correction model, the study reveals bidirectional causality between fossil fuels and GDP; that is, long-run causality running from fossil fuels to GDP, and short-run causality from GDP to fossil fuels. These results imply that fossil fuels are at least one of the important factors promoting economic growth.

The results also show the non-existence of a causal relationship between non-fossil energy and GDP. The results reveal the intrinsic difference between fossil fuels and non-fossil energy, because the relationship between fossil fuels and non-fossil energy seems complementary. Moreover, the results of variance decomposition analysis show that the impact of fossil fuel consumption on economic growth is extremely different from the impact of non-fossil energy. Above all, non-fossil energy may not necessarily play the part of fossil fuels, which implies that it is difficult for Japan to achieve both departure from dependence upon fossil fuels and continuous economic growth.

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