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The causal relationship between energy resources and economic growth in Brazil

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HIGHLIGHTS

- We model three kinds of clean energy and non-clean energy consumption and real *GDP*.
- There is fossil fuel consumption–economic growth bidirectional causality.
- There is new renewables consumption–economic growth bidirectional causality.
- There is nuclear energy consumption–economic growth bidirectional causality.
- Substitutability exists for new renewables–fossil fuel or new renewables–nuclear.

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ABSTRACT

This study investigates the causal relationship between clean and non-clean energy consumption and economic growth in Brazil over the period of 1980–2009. Clean energy consumption at aggregated level of total renewable energy consumption and disaggregated levels of hydroelectric, new renewables, and nuclear energy consumption are tested within a production function framework. A cointegration test reveals a long-term equilibrium relationship between real output, capital, labor, and renewable and non-renewable energy consumption at aggregated level, and a long-term equilibrium relationship between real output, capital, labor, and hydroelectric/new renewables/nuclear and fossil fuel energy consumption at disaggregated level. The capital, labor, and new renewables elasticities of real output are positive and statistically significant, other energy consumption item's elasticities are insignificant. The results from error correction model reveal the interdependencies between new renewables, nuclear, fossil fuel, and total non-renewable energy consumption and economic growth, the unidirectional causality from hydroelectric/total renewable consumption to economic growth, the substitutability between new renewables and fossil fuel consumption, and the substitutability between new renewables and nuclear energy consumption. Additionally, nuclear and new renewables energy consumption responds to bring the system back to equilibrium. Overall, aggregated analysis may obscure the relationship between different types of clean energy consumption and economic growth.

1. Introduction

According to the 2010 International Energy Outlook released by the US Energy Information Administration (EIA), worldwide renewable energy consumption has been increasing at a rate of 2.6% per year. In 2008, approximately 19% of the global energy consumption was from renewable sources, 13% of which was from traditional biomass (mainly used for heating), 3.2% from hydroelectricity, and the remaining 2.7% from rapidly growing 'new renewables' (e.g., small hydro, modern biomass, wind, solar, geothermal, and biofuels). Renewable energy power generation makes approximately 18% of the global electricity, with 15% from hydropower and 3% from other new renewable energy sources. 'New renewables' technologies are befitting for local electricity generation in rural and remote areas, where the transportation costs for crude oil or natural gas and the transmission costs of electricity are often prohibitively high. Globally, 3 million households are estimated to receive power from small solar PV systems. Micro-hydropower systems configured into village-scale or county-scale mini-grids are emerging in many areas. More than 30 million rural households use family-sized biogas digesters for lighting and cooking. Biomass cookstoves have been used by 160 million households (Wikipedia, 2011). In addition, expected increases in oil prices, increased awareness of the environmental

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damage caused by fossil fuel consumptions, and government incentives for new renewables energy development will continue to foster the global usage of new renewables energy. These 'new renewables' can provide approximately 6% of worldwide electricity by 2030.

Although environmentalists have warned that catastrophic climate change is a real and imminent danger, we still need a large-scale source of around-the-clock electricity to meet our energy needs. Nuclear energy can generate electricity with no carbon dioxide or other greenhouse gas emissions, and it is the only effective option in order to supply the large demand for clean electricity on a global scale. Currently, nuclear power plants supply approximately 6% of the global energy and 14% of the global electricity needs. Nuclear power and new renewables will be urgently needed as partners if the world's enormous demand for clean energy is to be met (World Nuclear Association (WNA), 2011). The use of new renewable energy and nuclear energy is critical to the development of global clean energy economy in the future, due to the continuous depletion of reserve of earth's fossil fuel as well as global warming.

The topic of causal relationship between energy consumption and economic growth has been well-studied in energy economics literature such as Ozturk (2010) and Payne (2010a, 2010b). However, the empirical results may be varied and even conflicted, due to the difference in country′ characteristic, time period, econometric methodology, or proxy variables for energy consumption and income. The causality between energy consumption and economic growth in different directions may have different policy implications. Under the assumption of positive correlation between energy consumption and economic growth, the presence of unidirectional causality from energy consumption to economic growth or bidirectional causality between them would suggest that energy conservation policies that reduce energy consumption may lead to decline in economic growth. In contrast, unidirectional causality from economic growth to energy consumption or no causality in either direction suggests that energy conservation policies will have little or no impact on economic growth (Apergis and Payne, 2013).

Among the literature of energy consumption and economic growth nexus, some studies also examined the relationships between different types of clean energy consumption (renewable or nuclear) and economic growth (Pao and Fu, 2013). Recent researches by Apergis and Payne (2011b, 2011c) focus on the link between both renewable and non-renewable energy consumption and economic growth for sustainable economic development. This paper extends recent works on the energy consumption–growth nexus to analyze the relationships between both the clean and non-clean energy consumption and economic growth in sustainable countries such as Brazil. Brazil is one of the fastest-growing major economies in the world, with an annual growth rate of *GDP* of approximately 5%, and is expected to become one of the world's top five economies in the future. In the past 2 decades, Brazil has achieved a development model that combines social inclusion with sustained economic growth and balanced use of natural resources. This model can maintain high levels of renewable energy to stimulate economic growth and lift millions of people out of poverty, while protecting the country's forests and biodiversity (Secretariat of Social Communication (SECOM), 2012). According to the 2009 EIA, Brazil's renewable energy consumption reached 97% of its total domestic electricity generation, and the growth rate of different types of energy consumption are varies. During the 1980–2009 period, new renewable energy consumption (i.e., non-hydroelectric renewable energy consumption, *NHREC*) with a very high annual average growth rate of 8.72% accounted for 2.89% of the total renewable energy consumption (*TREC*), while hydroelectric energy consumption (*HEC*) with an annual average growth rate of 3.66% accounted for 97.11% of *TREC*. Additionally, nuclear energy consumption (*NUCEC*), with the highest annual average growth rate of 19.65%, accounted for 1.20% of the total non-renewable energy consumption (*TNREC*), while fossil fuel consumption (*FFC*) with the lowest annual average growth rate of 2.85% accounted for 96.67% of *TNREC*. Currently, Brazil is one of the world's cleanest energy matrices. A country with high growth rate or high proportion of clean energy consumption may imply an interdependent relationship between economic growth and clean energy consumption or substitutability between the clean and non-clean energy sources to achieve sustainable economy.

Due to the greatly different growth rates of the various types of energy sources, this study focuses on the disaggregated analysis of the causal relationship between clean energy (hydroelectric, new renewables, and nuclear) consumption and economic growth in Brazil over the period of 1980–2009 since aggregated analysis may well mask the differential impact of hydroelectric, new renewables, and nuclear energy consumption on economic growth. The results are compared with the aggregated analysis of the causal relationship between total renewable energy consumption and economic growth. The simultaneous use of clean and non-clean energy consumption in the production function framework intends to distinguish the relative influence of each type on economic growth and to analyze the substitutability between the different types of energy sources. The neo-classical one-sector aggregated production model is adopted where capital, labor, clean energy consumption, and non-clean energy consumption are treated as separate inputs. Within this framework, a vector error-correction model (VECM) is employed to test for multivariate cointegration and Granger causality.

This study is organized as follows. Section 2 provides a brief literature review. Section 3 describes the analytical model and econometric methodology. Section 4 presents relevant energy and economic data and also presents the cointegration and Granger causality results. Section 5 presents the conclusions.

2. Literature review

Since the dawn of the 21st century, the relationships between non-renewable, renewable, or nuclear energy consumption and economic growth have been researched upon (Payne, 2010a, 2010b). Common methodologies include the forecast error variance decomposition analysis model, the bivariate error correction model, the Toda–Yamamoto procedure within a production function framework, and the multivariate error correction model within a production function framework. Using a generalized forecast error variance decomposition analysis, Sari and Soytas (2004) found that different energy consumption items have different effects on real output, where lignite, waste, oil, and hydraulic power are the top four alternative energy sources in Turkey. For the US, Ewing et al. (2007) found that coal, natural gas, and fossil fuel energy sources unexpectedly have the largest impacts on the variation of real output, while several renewable energy sources also exhibit considerable impacts. Using a bivariate panel error correction model, Sadorsky (2009) presented evidence of bidirectional causality between non-hydroelectric renewable energy consumption and economic growth for a panel of 18 emerging economies. Using the Toda–Yamamoto procedure within a production function framework for analyzing data of the US, Payne (2009) found no evidence of a causal relationship between total renewable and non-renewable energy consumption and real *GDP*; Payne (2011b) provided a disaggregated analysis of the causal relationship between fossil fuel (coal, natural gas, and petroleum) consumption and real *GDP*, and their results showed that different energy consumption items have different effects on real output; Payne (2011a) found unidirectional causality from biomass energy consumption to real *GDP*; Bowden and Payne (2010) explored the causal relationship between renewable and non-renewable energy consumption by sector (commercial, industrial, and residential) and real *GDP* in the US, and their results were inconsistent. Using a multivariate panel error correction model within a production function framework, Apergis and Payne (2010a) found evidence of bidirectional short- and long-run causality between non-hydroelectric renewable energy consumption and economic growth for a panel of 20 OECD countries; Apergis and Payne (2010c) found both short- and long-run unidirectional causality from energy consumption to economic growth for a panel of nine South American countries; Apergis and Payne (2010b, 2011a, 2012c) discovered evidence of bidirectional short- and long-run causalities between total renewable energy consumption and economic growth for a panel of 13 Eurasian countries, a panel of six Central American countries, and a panel of 80 countries. Menegaki (2011) found no causality between renewable energy consumption and economic growth for a panel of 27 European countries. Recently, renewable and non-renewable energy consumptions are considered simultaneously in the production model framework in order to differentiate the relative impact of each type in the economic growth process. Apergis and Payne (2011b, 2012b) revealed bidirectional short- and long-run causalities between renewable and non-renewable energy consumption and economic growth for a panel of 25 developed countries, a panel of 55 developing countries, and a panel of 80 countries. Apergis and Payne (2011c) found unidirectional causality from economic growth to renewable electricity consumption in the short-run and bidirectional causality in the long-run, and bidirectional short- and long-run causalities between non-renewable electricity consumption and economic growth for a panel of 16 emerging market economies. Apergis and Payne (2012a) found unidirectional causality from renewable electricity consumption to economic growth in the short-run and bidirectional causality in the long-run, and bidirectional short- and long-run causalities between non-renewable electricity consumption and economic growth for a panel of six Central American countries.

For nuclear power, Apergis and Payne (2010d) found unidirectional long-run causality from nuclear energy consumption to economic growth and bidirectional causality in the short-run for a panel of 16 countries that currently produce nuclear energy. Apergis et al. (2010) found unidirectional short-run causality from nuclear energy consumption to economic growth and bidirectional causality in the long-run for a panel of 19 developed and developing countries. Payne and Taylor (2010) found an absence of Granger causality between nuclear energy consumption growth and economic growth in the US. Wolde-Rufael and Menyah (2010) explored the causal relationship between nuclear energy consumption and real *GDP* for nine developed countries, and their results are inconsistent using the production model framework. Heo et al. (2011) found unidirectional causality from nuclear energy consumption to economic growth without any feedback effect in India. Taking into account the interrelationship among nuclear energy consumption, oil consumption, oil price, and real income in six highly industrialized countries, Lee and Chiu (2011a) found unidirectional causality from real *GDP* to nuclear energy consumption in Japan, bidirectional causality in Canada, Germany, and the United Kingdom, and no causality in France and the United States. They also found unidirectional causality from oil price to nuclear energy consumption except in the United States, and unidirectional causality from oil consumption to nuclear energy consumption in Canada, Japan, and the United Kingdom. They suggested that real *GDP* growth, oil price increases, or oil supply shortages have significant impacts on the development of nuclear energy in highly industrialized countries; Lee and Chiu (2011b) found evidence of unidirectional long-run causality from oil price and economic growth respectively to nuclear energy consumption, no short-run causality between nuclear energy consumption and economic growth, and substitutability between nuclear energy and oil for a panel of six highly industrialized countries. They suggested that the imported-energy-dependent countries should set up long-term income and energy policies for stimulating their nuclear energy development. However, no studies in the literature have explored the causal relationship between clean (e.g., hydroelectric, new renewables, nuclear) and non-clean (e.g., fossil fuel) energy consumption and economic growth in developing countries such as Brazil.

3. Model and methodology

3.1. Model

To investigate the relationships between the different types of energy sources and economic growth and to analyze the substitutability between clean and non-clean energy sources, based on the production function framework, this paper extends the recent research of Apergis and Payne (2011b, 2011c, 2012a, 2012b) as follows:

$$Y_t = f(K_t, L_t, CE_t^S, FFC_t) \quad (1)$$

where the subscript t is time. Y denotes the real *GDP*; K represents real gross fixed capital formation; L is total labor force; CE represents the consumption of clean energy by type S: total renewable, hydroelectric, new renewables, and nuclear; *FFC* represents the non-clean fossil fuel energy consumption. Capital and labor variables were included to avoid estimation bias (Lütkepohl, 1982). All variables are in natural logarithms.

According to the 2009 EIA, Brazil boasts high growth rates of 12.53% and 10.94% respectively in *NUCEC* and *NHREC* for the 10-year period. However, in the past five years, *NUCEC* shows the lowest growth rate of 1.14% while *NHREC* has the highest growth rate of 12.76%. Thus, the production function framework, which investigates the substitutability between new renewables and nuclear energy consumption, is given as follows:

$$Y_t = f(K_t, L_t, NHREC_t, NUCEC_t). \quad (2)$$

Analyses of the long-run relationship and Granger causality between variables in Eqs. (1) and (2) are crucial for a clean energy economy.

3.2. Econometric methodology

In this paper, empirical analysis tests the existence of a long-run relationship among the variables in Eqs. (1) and (2) while using the vector error-correction model to capture the Granger causality between variables. A three-step procedure is performed by first checking the integration order of each variable. The three standard unit root tests Augmented Dickey–Fuller (ADF) (Dickey and Fuller, 1981), Phillips–Perron (PP) (Phillips and Perron, 1988), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) (Kwiatkowski et al., 1992) are employed to investigate the stationarity and the integration order of the variables. The null hypothesis of ADF or PP is that a series is $I(1)$, while KPSS is that a series is $I(0)$. To obtain robust results, this paper uses KPSS to complement the widely used ADF and PP tests. However, Perron (1989) argued that in the presence of a structure break, the standard unit root tests are biased toward the non-rejection of the null hypothesis. Zivot and Andrews (1992) (hereafter referred to as ZA) developed a unit root test with an endogenous structure break, which allows a break at an unknown point in either the intercept, the linear trend, or in both. Taking the structure break into account, ZA unit root tests are also employed for each time series.

Next, when all of the series in Eqs. (1) or (2) have the same integration order, the Johansen maximum likelihood method (Johansen and Juselius, 1990) is used to test the co-integration relationship among the variables in Eqs. (3) or (4) as follows:

$$Y_t = \beta_{10} + \beta_{11}K_t + \beta_{12}L_t + \beta_{13}CE_t^S + \beta_{14}FFC_t + u_{1t}, \tag{3}$$

$$Y_t = \beta_{20} + \beta_{21}K_t + \beta_{22}L_t + \beta_{23}NHREC_t + \beta_{24}NUCEC_t + u_{2t} \tag{4}$$

The existence of cointegration indicates that (1) the parameters estimated by OLS are super-consistent (Alves and Bueno, 2003); (2) there are long-run equilibrium relationships among the variables; and (3) Granger causality exists among the variables in at least one direction (Engle and Granger, 1987; Oxley and Greasley, 2008). The coefficient β_{jk} can be interpreted as elasticity estimate.

For the last step, if all of the variables are $I(1)$ and cointegrated, the vector error correction model (VECM) is used to explore the long- and short-run causality between variables. The VECM for Eq. (2) is specified as follows:

$$\Delta Y_t = \gamma_{10} + \sum_{k=1}^{p} (\gamma_{11k}\Delta Y_{t-k} + \gamma_{12k}\Delta K_{t-k} + \gamma_{13k}\Delta L_{t-k} + \gamma_{14k}\Delta NHREC_{t-k} + \gamma_{15k}\Delta FFC_{t-k}) + \delta_1 ECT_{t-1} + \mu_{1t} \tag{5a}$$

$$\Delta K_t = \gamma_{20} + \sum_{k=1}^{p} (\gamma_{21k}\Delta Y_{t-k} + \gamma_{22k}\Delta K_{t-k} + \gamma_{23k}\Delta L_{t-k} + \gamma_{24k}\Delta NHREC_{t-k} + \gamma_{25k}\Delta FFC_{t-k}) + \delta_2 ECT_{t-1} + \mu_{2t} \tag{5b}$$

$$\Delta L_t = \gamma_{30} + \sum_{k=1}^{p} (\gamma_{31k}\Delta Y_{t-k} + \gamma_{32k}\Delta K_{t-k} + \gamma_{33k}\Delta L_{t-k} + \gamma_{34k}\Delta NHREC_{t-k} + \gamma_{35k}\Delta FFC_{t-k}) + \delta_3 ECT_{t-1} + \mu_{3t} \tag{5c}$$

$$\Delta NHREC_t = \gamma_{40} + \sum_{k=1}^{p} (\gamma_{41k}\Delta Y_{t-k} + \gamma_{42k}\Delta K_{t-k} + \gamma_{43k}\Delta L_{t-k} + \gamma_{44k}\Delta NHREC_{t-k} + \gamma_{45k}\Delta FFC_{t-k}) + \delta_4 ECT_{t-1} + \mu_{4t} \tag{5d}$$

$$\Delta FFC_t = \gamma_{50} + \sum_{k=1}^{p} (\gamma_{51k}\Delta Y_{t-k} + \gamma_{52k}\Delta K_{t-k} + \gamma_{53k}\Delta L_{t-k} + \gamma_{54k}\Delta NHREC_{t-k} + \gamma_{55k}\Delta FFC_{t-k}) + \delta_5 ECT_{t-1} + \mu_{5t} \tag{5e}$$

where

$$ECT_{t-1} = Y_{t-1} - \alpha_0 - \alpha_1 K_{t-1} - \alpha_2 L_{t-1} - \alpha_3 NHREC_{t-1} - \alpha_4 FFC_{t-1}; \tag{5f}$$

Δ is the first-difference operator; k is the lag lengths determined by the Akaike's information criteria (AIC); and μ_{jt} (j=1,2,3,4,5) is the serially uncorrelated error terms. Note that the time series in the first difference of the natural logarithm can be interpreted as a growth rate of this variable. Short-run Granger causality is examined by testing H_0:$\gamma_{lmk}=0$, $\forall k$, using χ^2-statistics, where l, m=1,…,5, with $l \neq m$. Long-run Granger causality is examined by testing H_0:$\delta_j=0$, using t-statistics, where j=1,2,3,4,5. The adjustment parameter δ_1 measures the speed at which Y returns to the long-term equilibrium levels after violating the long-term equilibrium relationship. Similar tests can be examined to test the short- and long-run Granger causalities in Eqs. (5b)–(5e).

In Eq. (5), the *NHREC* variable is replaced by *TREC*, *HEC*, or *NUCEC* to investigate the causal relationship between total renewable, hydroelectric, or nuclear energy consumption and economic growth as well as to analyze the substitutability between clean energy consumption and non-clean consumption. Furthermore, the *FFC* variable in Eq. (5) is replaced by *NUCEC* to analyze the substitutability between new renewables and nuclear energy consumption.

4. Data and empirical findings

4.1. Data analysis

Annual data for Brazil's real *GDP*, real gross fixed capital formation (*K*), and labor force (*L*) from 1980 to 2009 were obtained from the World Development Indicators (WDI). Data for *HEC*, *NHREC* (sum of consumption of wind, biomass, and waste in Brazil), *TREC* (sum of *NHREC* and *HEC*), *NUCEC*, *FFC* (sum of consumption of petroleum, coal, and nature gas), and *TNREC* were extracted from the Energy Information Administration (EIA), where *HEC* and *NHREC* accounted for respectively 97.11% and 2.89% of *TREC* and *NUCEC* and *FFC* accounted for respectively 1.20% and 96.67% of *TNREC*. Note that the net consumption does not include the energy consumption of generating units. All different types of energy sources are measured in quadrillion BTU. Both real *GDP* and the real gross fixed capital formation are measured in US dollars at the year 2000 prices. The total labor force is measured in millions. Table 1 displays the summary statistics associated with the nine variables mentioned above for the actual data.

Fig. 1 shows the time series of Brazilian data in natural logarithms, which have all confirmed growth. As shown in Table 1, nuclear and new renewables energy consumption demonstrate the largest coefficient of variation (120% and 75%). Table 2 shows the average growth rate of the nine variables, where the 15-year (1994–2009), 10-year (1999–2009), and five-year (2004–2009) growth rates are calculated to respectively demonstrate the long-term, medium-term, and short-term growth trends. *NUCEC* has the highest growth rates, which are more than 12% and 38% respectively for the long-term and medium-term periods, while it has the lowest short-term growth rate of 1.14%, higher than the world short-term growth rate of −0.36%. As shown in Table 2, the 10-year growth rate of 12.53% in *NUCEC* is nearly 6.92 times higher than the growth rate of 1.81% in *FFC*. In 2009, nuclear energy accounts for about 3% of Brazil's electricity.

Brazil is the third-largest country for electricity consumption in the Western Hemisphere because of an abundant supply of inexpensive electricity. In 2009, over 90% of Brazil's total electricity generation came from hydroelectricity, which was hypothesized to impact Brazil's economic growth; the share of hydroelectricity in Brazil's renewable electricity generation was approximately 94.35% and the remaining 5.65% was from new renewables (wind,

Table 1
Summary statistics for actual data, 1980–2009.

	Y (US$ Billions)	*K*	*L* (Million)	*TREC*	*HEC*	*NHREC* (quadrillion BTU)	*NUCEC*	*TNREC*	*FFC*
Mean	586.58 (132.63)	102.27 (19.26)	73.18 (16.90)	2.60 (0.76)	2.52 (0.71)	0.08 (0.06)	0.05 (0.06)	4.29 (1.39)	4.15 (1.30)
CV (%)	22.61	18.83	23.09	29.31	28.18	75.00	120.00	32.45	31.33

Notes: Figures in parentheses are standard deviations. CV represents the coefficient of variation. *K* and *L* are real gross fixed capital formation and labor force, respectively. *TREC*, *HEC*, *NHREC*, *NUCEC*, *TNREC*, and *FFC* are, respectively, total renewable, hydroelectric, non-hydroelectric renewable, nuclear, total non-renewable, and fossil fuel energy consumptions.

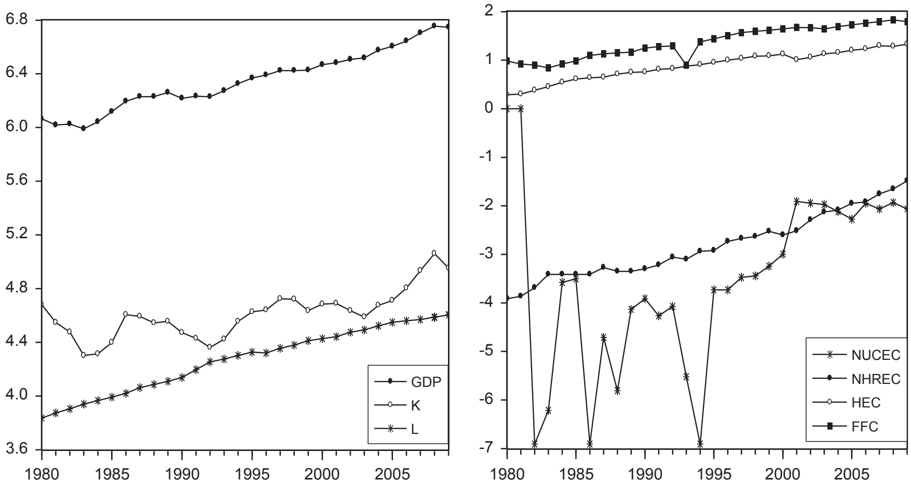

Fig. 1. Time series plots in natural logarithms of real *GDP*, real gross fixed capital formation, labor force, hydroelectric, non-hydroelectric renewable, nuclear, and fossil fuel energy consumption from 1980 to 2009.

Table 2
Average growth rates (%) in 2009 over 5-, 10-, and 15-year periods.

	Y	*K*	*L*	*TREC*	*HEC*	*NHREC*	*NUCEC*	*TNREC*	*FFC*
5-year growth	3.52	5.70	1.67	3.90	3.49	12.76	1.14	2.01	2.05
10-year growth	3.27	3.22	1.95	2.77	2.45	10.94	12.53	1.90	1.81
15-year growth	2.85	2.68	2.04	3.10	2.85	10.15	38.12	2.91	2.81

biomass, and waste) electricity generation. After a drought crisis in early 2000, Brazil's government actively diversified in order to reduce the country's reliance on hydropower. In low rainfall/dry seasons, Brazil's wind power is used to supplement water power. As shown in Table 2, the 10-year growth rate of 10.94% in *NHREC* is nearly 4.5 times higher than the growth rate of 2.45% in *HEC*.

Additionally, Brazil's real *GDP* enjoys a growth rate of 3.52%, which is higher than the world growth rate of 3.43% for the short-term period and its growth trend is expected to continue in the next decade. This study empirically investigates the causal relationship between clean energy use and economic growth in Brazil over the period of 1980–2009. Aggregated level of total renewable energy consumption as well as disaggregated levels of hydroelectric, new renewables, and nuclear energy consumption are tested.

4.2. Cointegration test results

This analysis begins with the unit root tests. Table 3 for the standard unit root tests and Table 4 for the ZA unit root tests show that all of the time series are integrated at order one (i.e., *I* (1)). Next, the Johansen cointegration test is used for the variables in Eqs. (2) and (3). The results of Panels A–E in Table 5 indicate the existence of at least one cointegrating vector for respectively the (*Y*, *K*, *L*, *TREC*, *TNREC*), (*Y*, *K*, *L*, *HEC*, *FFC*), (*Y*, *K*, *L*, *NHREC*, *FFC*), (*Y*, *K*, *L*, *NUCEC*, *FFC*), and (*Y*, *K*, *L*, *NHREC*, *NUCEC*) combinations at a 5% significant level. Thus, the OLS estimated coefficients shown in Table 6 for Eqs. (3) and (4) are non-spurious regression results. The values of both R^2 and the Jarque and Bera (JB) statistics (Jarque and Bera, 1980), shown in Table 6, indicate that Eqs. (3) and (4) are adequate. Therefore, real *GDP*, real gross fixed capital formation, labor force, *FFC*, and each of the three clean energy consumption items share common long-term trends. The cointegrating vectors shown in Table 6 are (1, 0.40, 0.49, 0.20, −0.04), (1, 0.36, 0.54, 0.08, −0.03), (1, 0.41, 0.54, 0.16, −0.04), and (1, 0.41, 0.74, 0.0004, −0.04) for Eq. (3), and (1, 0.35, 0.51, 0.08, −0.0008) for Eq. (4). The long-term coefficients for *K*, *L*, and *NHREC* are positive and statistically significant at a 1% level, while *TREC*, *TNREC*, and the other different energy consumption items are statistically insignificant. The findings suggest that new renewables energy consumption is sensitive to real output, while the impacts caused by total renewable, total non-renewable, hydroelectric, nuclear, and fossil fuel energy consumption on real output are insignificant.

Table 3
Results of unit roots tests, 1980–2009.

	ADF		PP		KPSS	
	Level	1st difference	Level	1st difference	Level	1st difference
Y	0.6960	−4.4384***	0.5399	−5.0891***	0.7025**	0.1329
K	−1.7697	−3.7613***	−0.6826	−4.0333***	0.5541**	0.1907
L	−2.6173	−4.0425***	−2.5225	−4.0425***	0.7061**	0.0998
TREC	−1.57	−5.38***	−1.92	−5.38***	0.71**	0.22
HEC	−1.7582	−5.3878***	−2.4711	−5.3867***	0.7080**	0.2533
NHREC	0.6177	−5.5776***	−1.3994	−5.5900***	0.7140**	0.2221
NUCEC	−0.6076	−6.1653***	−0.9744	−6.9152***	1.1324***	0.1607
TNREC	−0.75	−7.49***	−0.48	−14.10***	0.69**	0.36
FFC	−0.7193	−7.6040***	−0.5054	−14.2658***	0.6836**	0.36

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

Table 4
Results of the ZA unit root tests with a structural break.

	Level	Break	First difference	Break
Y	−4.43 (C)	1990	−5.75*** (A)	2004
K	−4.26 (C)	1990	−5.18** (C)	2001
L	−3.10 (B)	1994	−4.84*** (B)	1992
TREC	−4.09 (C)	2001	−7.15*** (C)	2003
HEC	−4.10 (C)	2001	−7.23*** (C)	2003
NHREC	−3.31 (B)	1993	−7.17*** (B)	1986
NUCEC	−4.86 (C)	1995	−7.45*** (C)	1995
TNREC	−4.68** (B)	2001	−8.21*** (C)	1994
FFC	−4.68** (B)	2001	−7.67*** (B)	1986

Notes: The letters in parentheses indicate the Models A, B, and C of Zivot and Andrews (1992). Model A allows for a change in the level of a series; Model B allows for a change in the slope of the trend of a series, while Model C combines both of the changes.

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

Thus, disaggregated levels such as *HEC*, *NHREC*, *NUCEC*, and *FFC* are appropriate for exploring the relationship between clean energy use and economic growth. However, aggregated total renewable energy consumption may very well mask the differential impact of hydroelectric and new renewables energy consumption on economic growth. Table 6 also shows that Brazil's economy is highly dependent on investment and labor. A 1% increase in real gross fixed capital formation increases real *GDP* by more than 0.35%, a 1% increase in the labor force increases real *GDP* by more than 0.49%, and a 1% increase in new renewables energy consumption increases real *GDP* by 0.08%.

4.3. Granger causality results

The VECM-based causality tests are performed in this last section. The causal relationships between economic growth and both clean and non-clean energy consumptions are presented in Table 7 from estimating Eq. (5). Clean energy consumption at both aggregated level of total renewable energy consumption and disaggregated levels of hydroelectric, non-hydroelectric renewable (new renewables), and nuclear energy consumptions are tested. The relationships between total renewable and total non-renewable energy consumption and economic growth are shown in Panel A of Table 7. Panels B–D show the relationships between clean and fossil fuel energy consumption and economic growth, while three disaggregated levels of clean energy consumption are being tested. The substitutability between new renewables and nuclear energy consumption is presented in Table 8. A significance level of 5% is in general assumed in this study.

The results in Panels A and B of Table 7 show that the causal relationships between *GDP*, *TREC*, *TNREC*, *K*, and *L* are similar to the causal relationships between *GDP*, *HEC*, *FFC*, *K*, and *L*, because *HEC* and *FFC* account for 94.35% and 96.67% respectively of *TREC* and *TNREC* from 1980 to 2009. The short-run dynamics indicates unidirectional causality from real gross fixed capital formation to non-renewable energy consumption, and bidirectional causality between economic growth and labor force. The statistically significant coefficients of ECT in *GDP*, *TNREC*, *K*, and *L* equations indicate bidirectional long-run causality between economic growth, non-renewable energy consumption, real gross fixed capital formation, and labor force. Note that no statistically significant coefficient in *TREC* and *HEC* equations in Panels A and B indicates that all variables, except for both *TREC* and *HEC*, are confirmed of Granger endogeneity and that there are unidirectional causalities from total renewable energy consumption and hydroelectric consumption, respectively, to other variables. Thus, based on the aggregated analysis, the Granger causality results indicate bidirectional causality between non-renewable energy consumption and economic growth and unidirectional causality from renewable energy consumption to economic growth in the long-run. These findings are partially similar to those reported by Apergis and Payne (2011b, 2011c, 2012a, 2012b) for developed and developing countries, 16 emerging market economies, Central America, and 80 countries, respectively. Their studies reveal consistent results of the bidirectional causality between both renewable and non-renewable energy consumption and economic growth in the long-run, while the relationship between renewable energy consumption and economic growth is inconsistent in the short-run. The positive unidirectional causality from total renewable or hydroelectric energy consumption to economic growth is to be expected because over 97% of Brazil's total electricity generation comes from total renewable electricity generation, as well as the fact that the share of hydroelectricity consumption in Brazil's renewable electricity generation was approximately 94.35% in 2009.

For the new renewables energy consumption, the results in Panel C of Table 7 show that economic growth has negative and statistically significant impact on both non-hydroelectric renewable and fossil fuel energy consumption, and new renewables energy consumption and fossil fuel consumption are negatively affected in the short-run. The statistically significant coefficients of ECT in *GDP*, *NHREC*, *FFC*, and *K* equations indicate bidirectional long-run causality between economic growth, real gross fixed capital formation, new renewables, and fossil fuel energy consumption. Overall, the results of economic growth negative impact on both new renewables and fossil fuel energy consumption in the short-run indicate that economic growth may

Table 5
Results of Johansen's cointegration test.

Eigen value	Trace statistics	5% Critical value	Max Eigen statistics	5% Critical value	No. of *CEs*
Panel A: *Panel A*, *TREC*, *TNREC*, *K*, and *L* variables; no lags					
0.91	117.12***	76.97	69.38***	34.81	$r=0$
0.59	47.74	54.08	25.99	28.59	$r\le1$
Panel B: *Y*, *HEC*, *FFC*, *K*, and *L* variables; no lags					
0.91	118.04***	76.97	69.32***	34.81	$r=0$
0.60	48.72	54.08	26.30	28.59	$r\le1$
Panel C: *Y*, *NHREC*, *FFC*, *K*, and *L* variables; no lags					
0.91	125.30***	76.97	69.09***	34.81	$r=0$
0.55	56.22**	54.08	23.44	28.59	$r\le1$
0.47	32.78	35.19	18.13	22.30	$r\le2$
Panel D: *Y*, *NUCEC*, *FFC*, *K*, and *L* variables; no lags					
0.90	127.42***	76.97	67.11***	34.81	$r=0$
0.60	60.31**	54.08	26.49	28.59	$r\le1$
0.51	33.82	35.19	20.41	22.30	$r\le2$
Panel E: *Y*, *NHREC*, *NUCEC*, *K*, and *L* variables; no lags					
0.91	126.02***	76.97	68.69***	34.81	$r=0$
0.61	57.33**	54.08	27.09	28.59	$r\le1$
0.39	30.24	35.19	14.30	22.30	$r\le2$

r is the cointegration rank.

*** Rejection of a null hypothesis at the 1% level.

** Rejection of a null hypothesis at the 5% level.

Table 6
Coefficients of Eqs. (3) and (4).

	K	*L*	*TREC*	*TNREC*	*HEC*	*NHREC*	*NUCEC*	*FFC*	Intercept	R^2	JB	*p*-Value
Panel A: aggregated level												
Eq. (3)	0.40*** (9.43)	0.49*** (3.53)	0.20 (2.02)	−0.04 (−0.68)				2.29*** (4.15)	0.990	1.64	0.44	
Panel B: disaggregated levels												
Eq. (3)	0.41*** (9.43)	0.54*** (4.05)			0.16 (1.65)			−0.04 (−0.80)	2.06*** (3.90)	0.989	1.60	0.45
Eq. (3)	0.36*** (8.18)	0.54*** (6.10)				0.08*** (2.98)		−0.03 (−0.51)	2.66*** (5.12)	0.991	0.27	0.88
Eq. (3)	0.41*** (8.86)	0.74*** (10.89)					0.0004 (0.12)	−0.04 (−0.74)	1.35*** (4.21)	0.988	1.75	0.42
Eq. (4)	0.35*** (8.99)	0.51*** (7.64)				0.08*** (3.06)	−0.0008 (−0.30)		2.80*** (6.55)	0.991	0.12	0.94

Notes: Figures in parentheses indicate *t*-statistics. JB represents the Jarque and Bera statistics.

*** Rejection of a null hypothesis at the 1% level.

Table 7
Causality tests for clean and fossil fuel energy consumptions and economic growth.

Dependent variable	Source of causation (independent variables) short-run					Long-run
Panel A: total renewable and total non-renewable energy consumptions and economic growth						
	ΔY	$\Delta TREC$	$\Delta TNREC$	ΔK	ΔL	ECT
ΔY		3.732* (+)	1.311	0.250	8.411***	0.186*** (4.157)
$\Delta TREC$	1.025		0.565	2.599	0.052	−0.092 (−0.951)
$\Delta TNREC$	3.875	0.114		10.706***	2.553	0.851*** (3.664)
ΔK	0.325	0.964	0.792		2.615	0.631** (2.199)
ΔL	6.617**	0.260	2.016	3.981		0.121** (2.775)
Panel B: hydroelectric renewable and fossil fuel energy consumptions and economic growth						
	ΔY	ΔHEC	ΔFFC	ΔK	ΔL	ECT
ΔY		3.740* (+)	1.271	0.266	8.628***	0.194*** (4.311)
ΔHEC	1.242		0.605	3.236	0.104	−0.087 (−0.930)
ΔFFC	5.169	0.508		14.142***	2.580	0.904*** (4.199)
ΔK	0.307	0.870	0.807		2.603	0.627** (2.231)
ΔL	6.065**	0.292	2.120	4.450		0.117** (2.581)
Panel C: non-hydroelectric renewable and fossil fuel energy consumptions and economic growth						
	ΔY	$\Delta NHREC$	ΔFFC	ΔK	ΔL	ECT
ΔY		0.434	2.957	7.93**	3.188	0.027*** (3.946)
$\Delta NHREC$	7.158** (−)		9.528*** (−)	10.272***	1.453	−0.091** (−2.567)
ΔFFC	6.030** (−)	32.317*** (−)		4.542	3.083	0.150*** (7.177)
ΔK	3.539	5.024^{c}	3.618		7.752**	0.140*** (4.086)
ΔL	1.843	1.337	1.417	1.739		−0.008 (−1.090)
Panel D: nuclear and fossil fuel energy consumptions and economic growth						
	ΔGDP	$\Delta NUCEC$	ΔFFC	ΔK	ΔL	ECT
ΔGDP		9.749*** (+)	1.792	0.616	0.652	−0.106 (−1.357)
$\Delta NUCEC$	6.264** (−)		1.948	6.364**	4.533	−12.140*** (−7.231)
ΔFFC	0.281	4.301		4.463**	5.604	−0.138 (−0.593)
ΔK	2.743	3.089	1.402		0.789	−0.333 (−1.041)
ΔL	1.018	5.625**	1.720	0.641		−0.058 (−1.139)

Notes: Wald chi-square tests reported with respect to short-run change in the independent variables. ECT represents the estimated coefficient on the error correction term. Figures in parentheses are *t*-statistics.

*** Rejection of a null hypothesis at the 1% level.
** Rejection of a null hypothesis at the 5% level.
* Rejectin of a null hypothesis at the 10% level.

improve the energy infrastructure and energy efficiency, and therefore lead to a lower energy consumption while reducing fossil fuel and new renewables energy consumption. The finding of long-run bidirectional causalities between new renewables energy consumption, fossil fuel consumption, and economic growth supports their mutual interdependence, suggesting that policies which enhance new renewables and fossil fuel energy consumption have a positive influence on economic growth. Thus, mixing the two types of energy sources is important although fossil fuel consumption affect the environment adversely. These findings are similar to those reported by Sadorsky (2009) for emerging economies and Apergis and Payne (2010a) for OECD countries. They reported short- and long-run bidirectional causalities between non-hydroelectric renewable energy consumption and economic growth. Additionally, the negative bidirectional causality between new renewables and fossil fuel energy consumption reflects the potential substitutability between the two energy sources. The finding suggests that the development of the new renewables sector may provide relief from greenhouse gas emissions generated by fossil fuel consumption. Table 2 shows that the 10-year growth rate of 10.94% in new renewables energy consumption is nearly 6.1 times higher than the growth rate of 1.81% in fossil fuel consumption. The substitutability is similar to the results reported by Apergis and Payne (2010a, 2012a) for 80 countries. With respect to the long-run dynamics, the coefficient of ECT in the new renewables equation is negative and significant, implying that new renewables energy consumption would respond to bring the system back to equilibrium when a shock occurs. The speed of adjustment toward long-term equilibrium is rather slow, due to the fact that electricity generation from new renewables accounted for only 5.51% of Brazil's total electricity generation in 2009.

For the nuclear energy consumption, the results in Panel D of Table 7 show that economic growth has negative statistically significant impact on nuclear energy consumption, and nuclear energy consumption has positive statistically significant impact on economic growth in the short-run. The statistically significant coefficient of ECT in *NUCEC* equation indicates unidirectional long-run causality from respectively economic growth, real gross fixed capital formation, labor force, and fossil fuel consumption to nuclear energy consumption. The results in Table 8 indicate that nuclear and non-hydroelectric renewable energy consumption is negatively affected on each other in the short-run. The statistically significant coefficients of ECT in *GDP*, *NHREC*, *NUCEC*, and *K* equations indicate bidirectional long-run causality between economic growth, real gross fixed capital formation, new renewables, and nuclear energy consumptions. Overall, the finding of bidirectional causalities between economic growth, new renewables, and nuclear energy consumption supports their mutual interdependence, suggesting that limiting nuclear energy use would hamper economic growth. This finding is very similar to the results from Wolde-Rufael and Menyah (2010) for France, Spain, the UK, and the US, Lee and Chiu (2011a) for Canada, Germany, and the UK; and is partially similar to Apergis and Payne (2010c) for 16 countries, Lee and Chiu (2011b) for a panel of six developed countries, and Heo et al. (2011) for India; but differs from the results from Payne and Taylor (2010) for the US, where there is no causal relationship between nuclear energy consumption and real

Table 8
Results of causality tests for the non-hydroelectric renewable energy consumption model.

Dependent variable	Source of causation (independent variables) short-run					Long-run
	ΔY	$\Delta NHREC$	$\Delta NUCEC$	ΔK	ΔL	ECT
ΔY		3.408	9.792** (+)	11.816***	4.894	−0.249** (−2.177)
$\Delta NHREC$	13.316*** (−)		16.927*** (−)	15.700***	8.906***	1.547*** (3.742)
$\Delta NUCEC$	4.106	6.701** (−)		3.950	2.046	−19.536*** (−5.247)
ΔK	3.539	5.024	3.618		7.752**	0.140*** (4.086)
ΔL	1.843	1.337	1.417	1.739		−0.008 (−1.090)

Notes: Wald chi-square tests reported with respect to short-run change in the independent variables. ECT represents the estimated coefficient on the error correction term. Figures in parentheses are *t*-statistics.

*** Rejection of a null hypothesis at the 1% level.

** Rejection of a null hypothesis at the 5% level.

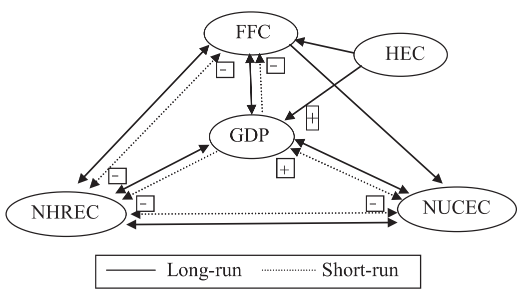

Fig. 2. Granger causality relations for Brazil.

output. Additionally, the negative bidirectional causality between new renewables and nuclear energy consumption reflects the potential substitutability between the two energy sources. This finding suggests that the establishment of partnerships between these two types of clean energy sources would be an urgent need in order to meet the huge demand for clean energy economy in Brazil. In fact, in the past five years, *NUCEC* shows the lowest growth rate of 1.14% while *NHREC* has the highest growth rate of 12.76%. With respect to long-run dynamics, the coefficients of ECT in the nuclear equation is negative and significant, implying that nuclear energy consumption would respond to bring the system back to equilibrium when a shock occurs. Adjustment back to equilibrium takes as little time as 0.2 year. The overall causal relationship between energy consumption and economic growth in Brazil is shown in Fig. 2.

5. Conclusions

In light of the economic and societal growing concerns over global warming caused by fossil fuel, high volatility of energy prices, and high growth of energy needs, clean energy (e.g., hydroelectric, new renewables, and nuclear) has become an important alternative energy source for fossil fuel. Currently, hydroelectric, new renewables, and nuclear energy supply respectively make up approximately 15%, 3%, and 14% of the global electricity needs. The aim of this study is to empirically investigate the causal relationship between clean and non-clean energy use and economic growth in Brazil over the period of 1980–2009. Aggregated level of total renewable energy consumption as well as disaggregated levels of hydroelectric, new renewables, and nuclear energy consumption are tested. The simultaneous use of clean and non-clean (e.g., fossil fuel) energy consumption in the production function framework intends to distinguish the relative influence of each type on economic growth and to analyze the substitutability between the different types of energy sources.

The Johansen cointegration tests reveal that there is a long-term equilibrium relationship between real *GDP*, real gross fixed capital formation, labor force, and renewable and non-renewable energy consumption at aggregated level, as well as a long-term equilibrium relationship between real *GDP*, real gross fixed capital formation, labor force, hydroelectric/new renewables/nuclear and fossil fuel energy consumption at disaggregated level. The real gross fixed capital formation, labor force, and new renewables energy consumption elasticities of real *GDP* are statistically significant at a 1% level and higher than 0.35, 0.48, and 0.08, respectively, while total renewable and total non-renewable energy consumption at aggregated level and hydroelectric, nuclear, and fossil fuel energy consumption at disaggregated level are statistically insignificant at a significance level of 5%. This suggests that in the long term, increases in real gross fixed capital formation and labor force are major drivers behind real *GDP* and that new renewables energy consumption has a lesser and positive impact on real *GDP*, while total renewable, total non-renewable, hydroelectric, nuclear, and fossil fuel energy consumption do not seem to have a very strong impact on real *GDP*. Aggregated analysis may obscure the relationship between renewable energy consumption and real *GDP*.

The results from the vector error correction models show that (1) for the aggregated analysis of renewable energy consumption, the result of long-run interdependence between non-renewable energy consumption and economic growth ($TNREC \leftrightarrow \Delta Y$) affirms the importance of traditional energy sources in the design of energy policy for a more sustainable energy future, although clean energy sources are increasingly important in Brazil. The result of positive unidirectional causality from *TREC* to economic growth ($TREC \rightarrow \Delta Y$) suggests that limiting total renewable energy use would hamper economic growth. This causal relationship is to be expected because over 97% of Brazil's total electricity generation comes from total renewable electricity generation. (2) For the disaggregated analysis of clean energy consumption, the results of bidirectional causality between new renewables, nuclear, and fossil fuel energy consumption and economic growth in the long-run support their mutual interdependence ($NHREC \leftrightarrow \Delta Y$, $NUCEC \leftrightarrow \Delta Y$, and $FFC \leftrightarrow \Delta Y$), suggesting that these three kinds of energy resources are important for the future development of the clean energy economy. The result of positive unidirectional causality from hydroelectric consumption to economic growth ($HEC \rightarrow \Delta Y$) suggests that limiting hydroelectric use would hamper economic growth. In fact, after a drought crisis in early 2000, Brazil's government actively diversified in order to reduce the country's reliance on hydropower, such as the use of wind power to supplement water power in dry seasons and the development of the four largest nuclear reactors to be online by 2025. Furthermore, the share of *HEC* in Brazil's *TREC* was approximately 94.35% in 2009. Thus, there is no reverse causality from *HEC* or *TREC* to economic growth. Yet, to facilitate the expansion of the new renewables energy sector, economic growth is vital to provide the resources for further research and development of new renewables energy technologies and corresponding infrastructure. Additionally, to increase nuclear energy supply investment, the right balance should be struck between the quest for economic growth, nuclear safety, clean energy, and the drive toward making the country relatively energy independent. (3) In the short-run dynamics, nuclear energy consumption's impact on economic growth is positive and the impacts of economic growth on nuclear, new renewables, and fossil fuel energy consumption are negative. These findings suggest that limiting nuclear energy use would hamper economic growth. Economic growth may improve energy infrastructure and energy efficiency, and therefore lead to a lower energy consumption while reducing different types of energy consumption. (4) The presence of substitutability between new renewables and fossil fuel energy consumption provides an avenue for the continued use of government policies that enhance the development of the new renewable energy sector as well as encourage the effective development of carbon markets in Brazil to reduce fossil fuel use. Finally, (5) the presence of substitutability between new renewables and nuclear energy consumption suggests that the establishment of partnerships between these two types of clean energy sources would be an urgent need in order to meet the greener low carbon economy in Brazil. In fact, new renewables technologies are suitable for local electricity and nuclear power is the only effective option to provide for a large demand for clean electricity at a national scale.

To continue the development of new renewables energy sources and renewable energy markets, the Brazilian government should introduce more preferential policies, such as investment subsidies or tax rebates, tax incentives, sales tax, and green certificate trading, to promote the development of a clean energy economy. In order to ensure energy security and stability, minimize the impact of high oil price volatility on macroeconomics, and reduce greenhouse gas emissions, the development of nuclear power is a means, but economic necessity should not outweigh the risk involved. After all, nuclear safety is a global concern that calls for a global solution.

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