Energy consumption and economic growth in Italy: A wavelet analysis

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ABSTRACT

This paper investigates the relationship between energy consumption and economic growth with over eighty decades of Italian dataset. The wavelet analysis is applied to decompose series into different time scales whereas the frequency domain technique is used to examine time-specific shocks. Results of both unit root and stationarity tests indicate all series are integrated of order one, however, no evidence of long-run relationship is reported between energy consumption and economic development. We observe that the causal flow from economic growth to energy consumption becomes dominant at lower scales (up to 4 years), while at higher scales the strength of causality from energy use to growth declines. Therefore, the influence of energy consumption on economic growth can significantly be detected only at lower scales. If only original series and lower scales are considered, causal findings lean towards the feedback mechanism, with bidirectional causal relationship. This bidirectional causality is reinforced at all frequency bands, thus, causality from energy consumption to economic growth is observed only at frequencies between 1.3–1.8 (3.49–4.83 years) and 2.2–2.4 (2.61–2.85 years). However, when higher scales are considered, the causality test results are in line with the conservation hypothesis. More precisely, causality from economic growth to energy consumption is reinforced by frequency technique at higher time scales (8–32 years) but only at a frequency more than 0.6 (more than 10.47 years). The differences in the applied results provide alternative policy implications, justifying the use of wavelet approach to decompose time series into various time scales.

1. Introduction

Energy remains a growing factor of production for the last decades, hence, acts as driving force for achieving the sustainable development goals. Energy and its services play a crucial role in improving health (quality of life), socio-economic and human development (Owusu and Asumadu, 2016). The causal nexus between energy and economic growth has been a central theme in economics literature. The analysis of the direction of causality between energy and economic growth provides relevant policy implications for both energy and environmental sustainability.

The causal mechanism between energy and economic growth can be categorized into four different hypotheses namely: (1) growth hypothesis—assumes unidirectional causality from energy to economic growth; (2) conservation hypothesis—assumes unidirectional causality from economic growth to energy; (3)

feedback hypothesis—assumes bi-directional causality between energy and growth; and, (4) neutrality hypothesis—assumes no causal relationship between energy and growth.

If energy Granger-causes economic growth—signifying the growth hypothesis, then, the actual path of economic growth can be negatively affected by conservation policies aiming at protecting the environment. In contrast, if the conservation hypothesis is valid, then, conservation policies will decline long-term carbon dioxide (CO_2) emissions and global warming—without slowing the growth process. Thus, the direction of causality between energy and economic growth is relevant for ensuring sustained economic development and promoting both sustainable energy and environmental policies. The confirmation of a feedback hypothesis implies that energy and economic growth are closely connected, satisfying a complementary association for energy-driven economic development pathways. Contrary, the validity of the neutrality hypothesis indicates the cost of energy may be insignificant and without remarkable effects on economic growth.

However, evidence from existing empirical studies remains controversial and ambiguous—lacking consensus in the literature

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on the direction of causality between energy consumption and economic development (Magazzino, 2018; Sarkodie et al., 2020). Conflicting results can be attributed to differences in data sources, country-specific characteristics, variables selection, and econometric strategies (Ozturk, 2010). In this context, useful overviews of empirical studies covering the connection between energy consumption and economic growth are provided by Shahbaz et al. (2012) and Mutascu (2016).

This paper investigates the causal relationship between energy consumption and economic growth for various time scales while using Italy as case scenario. The Italian case is appealing for developing policy alternatives for countries with similar energy-import-dependent characteristics (Bartoletto, 2013; Vaona, 2012; Bastianelli, 2006; Malanima, 2006). Contrary to reported empirical strategies, we adopt the wavelet filter for decomposing the time in different time scales. The wavelet method has a consistent set of advantages compared to classical time-domains. "First, it offers short-, medium- and long-run frameworks; second, it details the interaction between variables across different frequencies over time; and third, shows the lead–lag and cyclical vs. countercyclical status of the nexus", as reported in Mutascu (2018, p. 444). For each time scale, both time and frequency causality tests are performed to investigate the direction of interaction between energy consumption and aggregate income.

The scientific contributions of this paper are fourfold. First, to the best of our knowledge, this is the first paper that applies wavelet analysis to explore the interaction between energy consumption and economic growth in Italy. Second, this study novelly integrates classical time-domain causality analysis with time–frequency decomposition methods. Unlike classical causality tools, this approach allows the investigation of causality between energy consumption and economic growth at different frequency bands. In other words, this mixed methodology shows not only the direction of causality between energy consumption and growth nexus but also its persistence over time. Third, the results are reinforced by alternative analysis exclusively from the frequency-domain. Such an approach allows the examination of the persistence of causal effects over a period of time without sample splitting. Fourth, unlike the existing studies, this paper clarifies the nature of interaction between energy consumption and growth at business cycle, crucial for policy decisions from both type and time-target perspectives.

The rest of this paper proceeds with a survey of the empirical literature in Section 2. Section 3 provides an overview of the econometric methodology. Section 4 presents the empirical findings and discussion. Section 5 presents the concluding remarks and policy implications.

2. Literature review

The energy-growth nexus has received much attention among energy economists—due to the importance of energy utilization as the main driver of economic development (Etokakpan et al., 2020a,b). While energy access plays a crucial role in achieving sustainable development, its composition and transformational effect determine both brown and circular economy (Sarkodie and Strezov, 2018). Several existing literature have assessed the long-term effect of intensive energy utilization on economic development and vice versa in South Africa (Bekun et al., 2019); (Saint Akadiri et al., 2019), Turkey (Etokakpan et al., 2020a), Malaysia (Etokakpan et al., 2020b), Nigeria (Ali et al., 2020), Kenya (Sarkodie et al., 2020), Senegal (Sarkodie et al., 2020), Eswatini (Sarkodie et al., 2020), Europe (Adedoyin et al., 2020), and Australia (Sarkodie and Strezov, 2018). These studies outline the pros and cons of energy production and consumption on economic

development and how long-term effects hamper environmental sustainability.

Previous empirical studies lack consensus on the causal relationship between energy and economic development. Table 1 provides a concise summary of the literature on the nexus between electricity consumption and economic growth. These mixed results of causality may be due to heterogeneities in data period, empirical techniques, model specifications, lag-order selection, and differences in country-specific economic development pathways. The available literature on the relationship between energy consumption and economic growth is synthesized in Magazzino (2014), Ozturk (2010), and Payne (2010).

However, few studies have been devoted to the Italian case. Brady and Magazzino (2018) investigated the nexus between renewable energy consumption and economic growth in Italy with decades of data. Long-run estimations reveal a decline in economic development with an increasing share of renewable energy consumption. The Toda and Yamamoto approach showed the existence of unidirectional causal flow from renewable energy consumption to aggregate income, in line with the growth hypothesis. Moreover, these results are confirmed by Granger causality tests. The relationship between energy, real GDP, financial development, and oil prices using the ARDL technique confirmed the long-run effect of real GDP and oil prices on energy consumption (Magazzino, 2018). Moreover, causality tests confirmed the direction of causality from real income to energy consumption. The nexus between renewable energy consumption and economic growth confirmed a unidirectional flow from renewables to real GDP, in line with the growth hypothesis (Magazzino, 2017). Chontanawat et al. (2008) tested for causality between energy consumption and GDP for a panel of 30 OECD and 78 non-OECD countries. The results of causality tests showed evidence in line with the growth hypothesis.

The relationship between CO_2 emissions, energy consumption, and economic growth found no common trend, however, causality analyses validated the neutrality hypothesis of no significant relationship between energy and income (Magazzino, 2016). Similarly, the neutrality hypothesis was confirmed for the case of Italy in a study of G7 countries using the bootstrap panel Granger causality approach (Mutascu, 2016). The cointegration tests for the nexus between energy consumption and GDP revealed a long-run relationship whereas the causal analyses found evidence in favor of the neutrality hypothesis (Magazzino and Giolli, 2014). Vecchione (2011) investigated the relationship between electricity consumption and economic growth for Italy using yearly data covering the period 1963–2007. The results show a unidirectional causality from economic activity to other variables. Lee and Chien (2010) examined the dynamic linkages among energy consumption, capital stock, and real income in G-7 countries from 1960–2001. A unidirectional causal flow running from energy consumption to real income is observed for Italy. Thus, while growth has no impact on energy consumption and vice versa, energy conservation policies have no long-term effects on economic growth.

The relationship between energy consumption and aggregate income showed the existence of a feedback effect between the series (Magazzino, 2015). Magazzino (2012) investigated the relationship between disaggregate energy production and real GDP from 1883–2009. For the post-war sub-sample, a long-run relationship was confirmed between disaggregate energy sources and aggregate income. Also, the Causal tests confirmed the presence of a bi-directional flow, in line with the feedback hypothesis. Soytas and Sari (2006) investigated the relationship between energy consumption and income in G-7 countries and found bi-directional causality, confirming the feedback hypothesis for Italy. Zachariadis (2007) applied bivariate causality tests to total GDP

Table 1
Summary of existing literature on the energy consumption–economic growth nexus for Italy.
Source: Our elaborations.

Author(s)	Study period	Causality flow
Etokakpan et al. (2020a)	1970–2014	Y↔EC
Etokakpan et al. (2020b)	1980–2014	Y→EC
Ali et al. (2020)	1971–2014	Y⇎EC
Saint Akadiri et al. (2019)	1973–2014	EC→Y
Bekun et al. (2019)	1960–2016	EC→Y
Erol and Yu (1988)	1950–1982	Y→EC
Soytas and Sari (2003)	1950–1992	Y→EC
Lee (2006)	1960–2001	Y→EC
Soytas and Sari (2006)	1960–2004	Y↔EC
Zachariadis (2007)	1960–2004	Y↔EC
Chontanawat et al. (2008)	1960–2000	EC→Y
Lee and Chien (2010)	1960–2001	EC→Y
Magazzino (2012)	1883–2009	Y↔EC
Magazzino and Giolli (2014)	1970–2009	Y⇎EC
Magazzino (2015)	1970–2009	Y↔EC
Magazzino (2016)	1970–2006	Y⇎EC
Mutascu (2016)	1970–2012	Y⇎EC
Magazzino (2017)	1970–2007	EC→Y
Magazzino (2018)	1960–2014	Y→EC
Brady and Magazzino (2018)	1970–2007	EC→Y

Notes: Y↔EC: feedback hypothesis holds; Y→EC: conservation hypothesis holds; EC→Y: growth hypothesis holds; Y⇎EC: neutrality hypothesis holds.

and primary energy consumption series for G-7 countries in the 1960–2004 period. For the Italian data mixed results were confirmed. Lee (2006) explored the causality relationship between energy consumption and GDP in G-11 countries and confirmed the conservation hypothesis. The relationship between energy consumption and GDP for 10 emerging markets and G-7 countries found a unidirectional link from aggregate income to energy consumption for Italy (Soytas and Sari, 2003). Erol and Yu (1988) used a 1950–1982 time span, concluding that aggregate income causes energy consumption.

3. Methodology and data

In this paper, we innovatively addressed the causal relationship between energy consumption and aggregate income for several time scales. The causality is explored for both the original frequency and various frequencies. We applied wavelet analysis to decompose the series into different time scales but not centered on the time domain. Wavelets are mathematical instruments able to locate the data in time as well as in the frequency domain. The interest of the study included detecting and quantifying time–frequency dependence between energy consumption and real GDP. To this extent, we used wavelet analysis as the first step to examine the univariate characteristic of the series via the Continuous Wavelet Transform (CWT) (Grossmann and Morlet, 1984; Mallat, 2008) and wavelet power spectrum, which provides information on time and frequency features of the data in parallel. Wavelet analysis reveals the spectral features of a time series—in particular, how periodic components of Italian energy consumption and aggregate income evolve over time. In our empirical analysis, we adopted the Maximal Overlap Discrete Wavelet Transformation (MODWT) since no constraint on the length of the analyzed series is imposed, however, it is non-shift invariant.

According to Ghaemi et al. (2019), the MODWT is based on wavelets coefficients $d'_{j,i} = \frac{d_{j,i}}{2^{\frac{j}{2}}}$ and scaling filters $s'_{j,i} = \frac{s_{j,i}}{2^{\frac{j}{2}}}$. Herein, $d_{j,i}$ and $s_{j,i}$ represent the wavelet coefficients and scaling filters of a Discrete Wavelet Transform (DWT), while i is the filter length ($i = 1, 2, \ldots, I$) and j decomposition level ($j = 1, 2, \ldots, J$).

In this case, the final MODWT wavelet and scaling coefficients $(W'_{j,t}, S'_{j,t})$ for time-series $x_t = 1, 2\ldots, N-1$ are as follows (Zhu et al., 2014):

$$W'_{j,t} = \sum_{i=0}^{j-1} d'_{j,i} x_{t-i \, modN} \tag{1}$$

$$S'_{j,t} = \sum_{i=0}^{l_j-1} s'_{j,i} x_{t-i \, modN} \tag{2}$$

with $I_j = (2^j - 1)(I - 1) + 1$.

After deriving the time scales through the wavelet analysis, we explored the dynamics of both the original series and the scales. Several econometric techniques based on time-series were used. Initially, we investigated the stationarity properties of the series applying the Augmented Dickey and Fuller (ADF, 1979), Leybourne (1995), Dickey and Fuller Generalized Least Squares (DF-GLS), Elliott et al. (ERS, 1996), Phillips and Perron (PP, 1988), Kwiatkowski et al. (KPSS, 1992), Kapetanios et al. (KSSUR, 2003), and Kapetanios and Shin (KSUR, 2008) tests. Then the eventual presence of structural breaks was considered using Zivot and Andrews (ZA, 1992) and Clemente et al. (CMR, 1998) tests. Subsequently, we investigated the presence of a long-run relationship between the analyzed series. The cointegration analyses considered Engle and Granger (1987), Johansen and Juselius (1990), Bayer and Hanck (2013), Boswijk and Doornik (2005), and Banerjee et al. (1998) tests. The causality test adopted in this paper follows a "standard" Granger causality analysis. A time series X_t is said to Granger-cause another time series Y_t if the prediction error of current y declines by using past values of X in addition to past values of Y (Granger, 1969). For bivariate regressions and l lags, the test is as follows:

$$y_t = \alpha_0 + \alpha_1 y_{t-1} + \cdots + \alpha_l y_{t-l} + \beta_1 x_{t-1} + .. + \beta_l x_{t-l} + \varepsilon_t \tag{3}$$

$$x_t = \alpha_0 + \alpha_1 x_{t-1} + \cdots + \alpha_l x_{t-l} + \beta_1 y_{t-1} + .. + \beta_l y_{t-l} + \varepsilon'_t \tag{4}$$

where α_0 is the constant, α and β are the coefficients of x and y reported at moment t and lag l, while ε_t and ε'_t are disturbances. Under the null hypothesis (i.e. x does not Granger cause y or y does not Granger cause x): $\beta_1 = \beta_2 = \cdots = \beta_l = 0$.

Additionally, the test for short- and long-run causality in frequency-domain proposed by Breitung and Candelon (2006) was also employed. In contrast to the classical time-domain Granger causality, the frequency causality test offers important information of causality between two variables at various ranges of frequencies. As such, advantageous in assessing time-dependent shocks at a specific frequency domain (Sarkodie, 2020).

A reconstructed Vector Autoregressive (VAR) between x and y is the core of the test, expressed as:

$$x_t = \alpha_1 x_{t-1} + \cdots + \alpha_l x_{t-l} + \beta_1 y_{t-1} + .. + \beta_l y_{t-l} + \varepsilon_t \tag{5}$$

The optimal lag l is selected according to the Akaike information criterion (AIC) and VAR(l) employed model. Based on Geweke (1982) null hypothesis *(M)* that $M_{y \to x}(\omega) = 0$, where the frequency $\omega \epsilon (0, \pi)$, and adjusted null hypothesis *(H)* can be formulated as:

$$H_0 : R(\omega)\beta = 0 \tag{6}$$

with β denoting the vector related to y coefficients and

$$R(\omega) = \frac{\cos(\omega)\cos(2\omega)\ldots\cos(l\omega)}{\sin(\omega)\sin(2\omega)\ldots\sin(l\omega)} \tag{7}$$

The null hypothesis (no predictability) posits that Y does not cause X at frequency ω_0. For validation, Breitung and Candelon (2006) suggest 5% critical values for all frequencies in the interval $(0, \pi)$. Frequency ω is related to period t as $t = 2\pi/\omega$.
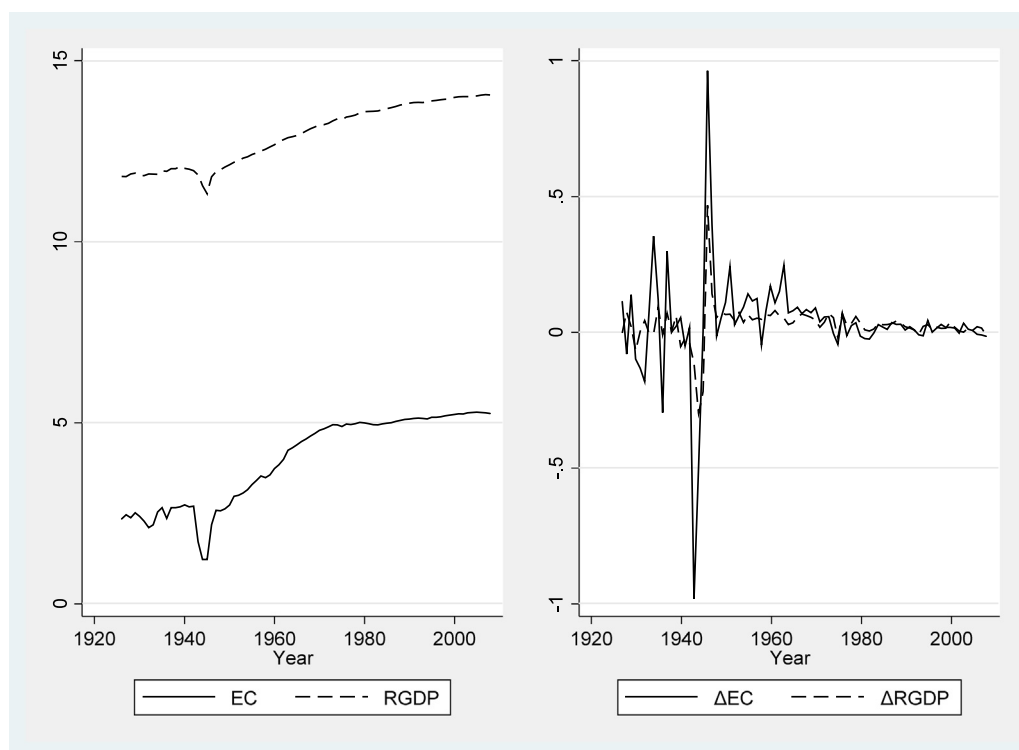
Fig. 1. Real per capita GDP and primary energy consumption for Italy (1926–2008, logs for the left panel, first differences for the right panel).
Source: ISTAT data.

Table 2
Exploratory data analysis.
Source: Our calculations on ISTAT data.

Variable	Mean	Median	Standard Deviation	Skewness	Kurtosis	Pseudo Std. Dev.	IQR	10-Trim
RGDP	12.94095	13.0612	0.8436	−0.1516	1.4897	2.7406	1.7576	12.9600
EC	3.9642	4.5433	1.2308	−0.4868	1.7383	4.0736	2.3892	4.0640

The empirical analysis uses yearly data of real GDP and primary energy consumption from 1926–2008. The time span is constrained by data availability. Both variables were retrieved from the ISTAT data source. Per capita GDP (RGDP) is measured in constant 2005 US$, and per capita energy consumption (*EC*) is measured in tons of oil equivalent. Natural logarithms of the series are used in the analysis. Fig. 1 illustrates the evolution of the variables from 1926 to 2008. From both panels, we observe a negative peak at 1943, which was due to the effects of WWII. In the second post-war period, an upward trend emerges in the log-series. Contrary to the trends of the original series, we observe that *EC* presents more oscillations than *RGDP*, which is confirmed by inspection of Fig. 2.

In Table 2, we present some exploratory data analysis. The mean and median values of each variable are positive and quite similar. The two variables exhibit a negative skewness, which implies the distribution is skewed towards the left, with more observations on the right. For each variable, the 10-Trim values are near to the mean, whereas the Inter-Quartile Range (IQR) reveals the absence of aberrant observations in our dataset. Each series is transformed separately through the *s4* wavelet filter and is decomposed into sets of coefficients, associated with a time scale. The time scales obtained from MODWT of the *RGDP* and *EC* series are shown in Fig. 2. As shown in Table 3, the time scale results due to wavelet transformation match with various frequencies.

Table 3
Frequency interpretation of time scales for yearly data.
Source: Our elaborations.

Time scales	Yearly frequency
d1	2–4 years
d2	4–8 years
d3	8–16 years
d4	16–32 years

4. Empirical results and discussion

We applied time-series techniques on stationarity and unit root processes. Table 4 shows the results of unit root and stationarity tests, to determine the order of integration. All tests lean towards the conclusion that both original series (*RGDP* and *EC*) are non-stationary. However, their first-differences can be considered stationary processes. Thus, the energy consumption and aggregate income are integrated of order one, or *I(1)*. This leads to the question of whether these series are cointegrated. Starting from multiple series that are non-stationary, we can discover a linear combination of them that is stationary. This is the case when the original series share a common trend in the long-run.

However, we present in Table 5 the results of unit root tests with structural breaks. For both series, the null hypothesis of a unit root cannot be rejected in levels. While for the first differences of *RGDP* and *EC*, we reject H_0 at 1 percent level of

Table 4
Results for unit roots and stationarity tests.

Variable	Unit root and stationarity tests							
	ADF	Leybourne	DF-GLS	ERS	PP	KPSS	KSUR	KSSUR
RGDP	−0.763	−0.521	0.411	0.141	−0.972	1.980***	0.258	−2.378
	(−2.907)	(−2.334)	(−2.120)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
EC	−2.131	−1.979	−1.958	−1.599	−1.915	0.407***	−0.659	−2.627*
	(−3.469)	(−3.088)	(−3.058)	(−3.176)	(−3.468)	(0.146)	(2.461)	(−2.880)
ΔRGDP	−6.714***	−6.452***	−6.132	−6.687***	−7.170***	0.112	−4.753***	−5.164***
	(−2.906)	(−2.333)	(−2.148)	(−2.178)	(−2.905)	(0.463)	(−2.463)	(−2.926)
ΔEC	−6.705***	−6.305***	−6.517	−4.118***	−6.478***	0.085	−3.938***	−4.012***
	(−2.907)	(−2.333)	(−2.148)	(−2.218)	(−2.905)	(0.463)	(−2.463)	(−2.926)
d1RGDP	−9.419***	−6.559***	−3.501***	−0.641	−21.902***	0.028	−2.779**	−3.164**
	(−2.907)	(−2.334)	(−2.146)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d1EC	−10.244***	−6.068***	−3.763***	−1.373	−21.260***	0.027	−2.885**	−3.728***
	(−2.907)	(−2.514)	(−2.146)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d2RGDP	−9.938***	−4.154***	−5.288***	−9.856***	−5.087***	0.016	−6.160***	−6.029***
	(−2.907)	(−2.514)	(−2.134)	(−2.120)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d2EC	−9.388***	−5.711***	−5.349***	−9.451***	−5.008***	0.017	−5.199***	−5.216***
	(−2.907)	(−2.334)	(−2.134)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d3RGDP	−4.018***	−3.050**	−3.353***	−3.989***	−3.641***	0.023	−3.920***	−3.730***
	(−2.907)	(−2.514)	(−2.134)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d3EC	−4.407***	−3.153***	−3.168***	−4.356***	−3.616***	0.023	−4.205***	−4.097***
	(−2.907)	(−2.334)	(−2.134)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d4RGDP	−3.129**	−2.363**	−2.298**	−2.973***	−2.412	0.090	−4.068***	−3.958***
	(−2.907)	(−2.334)	(−2.134)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)
d4EC	−3.593***	−2.254*	−2.382**	−3.505***	−2.476	0.110	−3.466***	−3.583***
	(−2.907)	(−2.334)	(−2.134)	(−2.175)	(−2.904)	(0.463)	(−2.461)	(−2.926)

Notes: the tests are performed on the log-levels of the variables. Δ: first differences. ADF: Augmented Dickey–Fuller test; DF-GLS: Dickey–Fuller GLS test; ERS: Elliott, Rothenberg, and Stock test; PP: Phillips–Perron test; KPSS: Kwiatkowski, Phillips, Schmidt, and Shin test; KSSUR: Kapetanios, Shin, and Snell test; KSUR: Kapetanios and Shin test. Deterministic component: constant. When it is required, the lag length is chosen according to the SBIC. 5% Critical Values are given in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 5
Results for unit root tests with structural breaks (in intercept or trend) and innovative outlier unit root tests (single structural break).

ZA tests

Variable	T_b	k	t_{min}
RGDP	1959	1	−3.180
EC	1959	3	−2.934
ΔRGDP	1946	1	−10.200***
ΔEC	1946	2	−8.958***
d1RGDP	1948	3	−9.333***
d1EC	1945	3	−10.247***
d2RGDP	1943	3	−9.878***
d2EC	1954	3	−9.383***
d3RGDP	1949	3	−4.304
d3EC	1952	3	−4.661*
d4RGDP	1977	3	−3.926
d4EC	1966	3	−4.833**

CMR tests

Variable	Optimal break point	k	t-stat
RGDP	1944	2	−5.935***
EC	1943	7	−3.935
ΔRGDP	1944	1	−8.998***
ΔEC	1942	3	−6.406***
d1RGDP	1947	2	−24.060***
d1EC	1947	11	−4.433**
d2RGDP	1933	11	−4.803***
d2EC	1933	12	−6.365***
d3RGDP	1945	12	−4.137*
d3EC	1945	12	−4.025*
d4RGDP	1987	11	−2.735
d4EC	1987	11	−2.969

Notes: Δ: first differences. ZA test refers to the model allowing breaks in the intercept. T_b is the break date endogenously selected. t_{min} is the minimum t-statistic. k denotes the lag length. Critical Values for ZA tests: 1%: −5.34; 5%: −4.80; 10%: −4.58. 5% Critical Values for CMR tests: −4.270. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

significance, therefore, confirming our previous results. Moreover, the panel below in Table 5 indicates that the break detected by the CMR test corresponds to the period of World War II for

both *RGDP* and *EC* and the second oil shocks during the Eighties. Despite the structural break, we cannot reject the null of unit root — nevertheless, when we take the first differences of the series, stationarity emerges. Thus, we can conclude that the series are *I(1)* processes. The results for the CMR test for two breaks confirm previous findings. The empirical findings of several cointegration tests are presented in Table 6. The results of the cointegration tests indicate the absence of any long-run relationship between energy consumption and real GDP. In fact, for both equations and in whichever deterministic component specification, the five selected tests generally agree on the indication of the absence of cointegration. Therefore, the Granger causality tests are conducted through VAR model estimation taking the first differences of *RGDP* and *EC*.

We select the optimal lag-order using the Akaike's Information Criterion (AIC), Schwarz's Bayesian Information Criterion (SBIC), Hannan and Quinn Information Criterion (HQIC), and Final Prediction Error (FPE). For all scales, the order of the estimated VAR is 4, with a stationary model. Diagnostic checks for the estimated VAR clarify that neither autocorrelation nor non-normality emerges in our data. Moreover, we implement additional tests to verify that the VAR models are well specified. Robustness checks indicate the estimated VAR does not violate the normality assumption and no autocorrelation detected in the residuals, thus, the stability condition is not violated. Also, the stability of the estimated coefficients is verified using both CUSUM and CUSUMSQ plots. We observe both plots within the 95% critical bounds, hence, confirming the estimated parameters exhibit structural stability.

The results of causality tests are reported in Table 7. The Granger causality tests indicate that for the first differences of the original series, energy consumption is caused by economic growth and vice versa, thus, confirming a bi-directional causality at *p-value < 0.05*. At *d1*, the very finest scale, we find again a feedback effect, with energy consumption and real GDP that mutually influences each other. Notwithstanding, at *d2* intermediate time scale, it can be observed that the strength of causality vanishes.

Only a marginal effect at 10 percent level of significance from aggregate income to energy consumption is detected. Finally,

Fig. 2. Time scales of *RGDP* and *EC*.

Table 6

Cointegration tests.

Test	Constant	Trend	None
Dependent variable: RGDP			
Bayer–Hanck	10.2826 (21.931)	9.3466 (22.215)	17.9052 (21.352)
Engle–Granger	−2.4651 (0.2915)	−2.7557 (0.3736)	−1.4360 (0.4994)
Johansen	9.3269 (0.3148)	10.3986 (0.4811)	12.8347** (0.0249)
Banerjee	−2.4317 (0.2362)	−2.8587 (0.2668)	0.1648 (0.8600)
Boswijk	6.5726 (0.2699)	10.2835 (0.1948)	11.2515** (0.0121)
Dependent variable: EC			
Bayer–Hanck	14.3761 (21.931)	7.6511 (22.215)	11.8635 (21.352)
Engle–Granger	−2.6278 (0.2230)	−2.8786 (0.3128)	−1.2576 (0.5896)
Johansen	9.3269 (0.3148)	10.3986 (0.4811)	12.8347** (0.0249)
Banerjee	−2.9308* (0.0940)	−2.3495 (0.5106)	−1.2533 (0.4196)
Boswijk	9.1171 (0.1145)	8.9602 (0.2838)	2.8174 (0.4308)

Notes: Constant: include an unrestricted constant in the model. Trend: include a linear trend in the cointegrating equations and a quadratic trend in the undifferenced data. None: do not include a trend or a constant. For the Bayer–Hanck test, 5% Critical Value are presented in parentheses. For Engle–Granger, Johansen, Banerjee, and Boswijk tests, P-Values in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 7

Granger causality test (overall estimated results, P-values).

Time scale	Integration order		VAR order	Nature of VAR	Results	Null hypothesis	
	RGDP	EC		Stationary		lnRGDP $\nRightarrow$ lnEC	lnEC $\nRightarrow$ lnRGDP
Δ	I(0)	I(0)	4	Stationary	lnRGDP $\Leftrightarrow$ lnEC	0.025**	0.000***
d1	I(0)	I(0)	4	Stationary	lnRGDP $\Leftrightarrow$ lnEC	0.003***	0.000***
d2	I(0)	I(0)	4	Stationary	lnRGDP $\nLeftrightarrow$ lnEC	0.097*	0.158
d3	I(0)	I(0)	4	Stationary	lnRGDP $\Rightarrow$ lnEC	0.044**	0.056*
d4	I(0)	I(0)	4	Stationary	lnRGDP $\Rightarrow$ lnEC	0.003***	0.059*

Notes: Δ: first differences. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 8

Frequency causality test (overall estimated results, P-values).

Time scale	Integration order		VAR order	Nature of VAR	Results	Null hypothesis	
	RGDP	EC		Stationary		lnRGDP $\nRightarrow$ lnEC	lnEC $\nRightarrow$ lnRGDP
Δ	I(0)	I(0)	4	Stationary	lnRGDP $\Rightarrow$ lnEC	No (all frequencies)**	Yes (all frequencies)
d1	I(0)	I(0)	4	Stationary	lnRGDP $\Leftrightarrow$ lnEC	No (all frequencies)**	No, but only for frequencies between 1.3–1.8** and 2.2–2.4**
d2	I(0)	I(0)	4	Stationary	lnRGDP $\Leftarrow$ lnEC	Yes (all frequencies)	No, but only for frequency more than 1.7**
d3	I(0)	I(0)	4	Stationary	lnRGDP $\Leftrightarrow$ lnEC	No, but only for frequency more than 1**	No, but only for frequency more than 1**
d4	I(0)	I(0)	4	Stationary	lnRGDP $\Leftrightarrow$ lnEC	No, but only for frequency more than 0.6**	No, but only for frequency more than 0.4**

Notes: Δ: first differences. **$p < 0.05$.

at 5% level of significance, the real GDP Granger causes energy consumption in both *d3* and *d4* time scales.

Table 8 presents the results of frequency causality tests, while all related plots are presented in the Appendix (Figures A1–A10). All estimations considered an optimal lag of 4, selected in the VAR equations. Unlike the classical time-domain approach, the results of frequency causality seem to be more sensitive under different ranges of frequencies. At first difference, the causality exclusively runs from economic growth to energy consumption at all frequencies. At *d1*, there is two-way causality, but restrictive for 'GDP to energy consumption' direction, more precisely at frequencies between 1.3–1.8 (i.e., 3.49–4.83 years[1]) and 2.2–2.4 (i.e. 2.61–2.85 years). One-way causality running from energy consumption to GDP is registered at *d2*, for more than 1.7 range of frequency, corresponding to more than 3.69 years. Bidirectional causality is found for more than 1 range of frequency (i.e., more than 6.28 years) at *d3*, for both directions. Finally, the same two-way causality is observed at *d4*. Herein, GDP drives energy consumption for more than 0.6 range of frequency (i.e. more than 10.47 years), while energy consumption causes GDP for more than 0.4 range of frequency (i.e. more than 15.71 years).

Comparing with the classical Granger test results, the frequency domain shows the causality is more persistent for superior time scales, generally at business cyclic level, for more than 4–5 years. In essence, Granger causality results confirm a bidirectional flow (feedback mechanism) at lower time scales (Δ and *d1*), as well as a unidirectional flow from real GDP to energy consumption (conservation hypothesis) at higher time scales (*d3* and *d4*). The frequency approach partially confirms the findings at lower time scale (*d1*). Herein, a bidirectional causality is registered at all frequencies, highlighting that the causality that runs from energy consumption to real GDP is validated only at frequencies between 1.3–1.8 (3.49–4.83 years) and 2.2–2.4 (2.61–2.85 years). The Granger causality from real GDP to energy consumption is reinforced by frequency tool at higher time scales (*d3* and *d4*) but only at frequency more than 0.6 (more than 10.47 years).

Therefore, the feedback hypothesis in Italy is fully observed at lower time scales, while the conservation hypothesis is registered at higher time scales. The feedback hypothesis seems to be related to the business cycle as it covers the horizon of 4–5 years. This reveals that the alternation of recession and recovering periods has deep implications on two-way causality between real GDP and energy consumptions. This result is in line with the feedback hypothesis evidenced by Magazzino (2015, 2012) for Italy, Erdal et al. (2008) for Turkey, Lee (2006) for the US, Soytas and Sari (2006) for Italy, Ghali and El-Sakka (2004) for Canada, Paul and Bhattacharya (2004) for India, Glasure (2002) for Korea, Hondroyiannis et al. (2002) for Greece, Yang (2000) as well as Masih and Masih (1997) for Taiwan, and Hwang and Gum (1991) for Taiwan. The homogeneous outputs indicate that there are some similarities between analyzed countries in terms of both energy-growth regulatory mechanisms and business cycle period.

In the original frequency of the data, the causality from economic growth to energy consumption becomes dominant, while at higher scales the strength of causality from energy consumption to growth declines. In fact, at *d3* and *d4* scales, real GDP affects energy consumption at 5 and 1 percent confidence interval respectively, while the reverse is true only at 10 percent significance level. Thus, at coarser scales, the conservation hypothesis seems to work better in the long-run. This suggests the energy demand for different sectors of the economy raises during the period of rapid economic growth. This finding is in line with results of Magazzino (2018, 2016) for Italy, Wolde-Rufael

(2009) for some African countries, Zhang and Cheng (2009) for China, Ang (2008) for Malaysia, Karanfil (2008) for Turkey, Lee and Chang (2007) for a panel of 22 developed countries and 18 developing countries, Lise and Van Montfort (2007) for Turkey, Mehrara (2007) for 11 oil-exporting countries, Zamani (2007) for Iran, Lee (2006) for Italy and Japan, Soytas and Sari (2003) for 10 emerging markets and G-7 countries, Aqeel and Butt (2001) for Pakistan, Cheng (1998) for Japan, Cheng and Lai (1997) for Taiwan, Abosedra and Baghestani (1989) for the US, Erol and Yu (1988) for industrialized countries, Yu and Choi (1985) for Korea, and Kraft and Kraft (1978) for the US. The reported studies suggest that the policy of conserving energy may be implemented with little or no adverse effect on economic growth, such as in less energy-dependent economies.

The overall results do not confirm the growth and neutrality hypotheses — as heterogeneous tools and datasets are used in literature with different variables and target countries (Magazzino, 2014; Ozturk, 2010; Payne, 2010). The validity of outputs is supported by a battery of tools, working in both time and frequency domains. While the classical Granger method is mixed with wavelet technique to explore the direction of causality at different frequency bands, the pure frequency domain causality tool increases the quality of findings by performing both short- and long-run approaches for the whole time-period without sample splitting. Therefore, in addition to assessing the causality between energy consumption and growth, we test the persistence and its related sensitivity over time. The results have important implications in both economic and environmental fields as direction of growth-energy consumption nexus gradually changes over time. In the short to medium-run, the conservation hypothesis reveals the long-term reduction of gas emissions and control of global warming does not affect the economic growth in Italy. In other words, both energy and environmental adjustments can be done without impacting sustained economic development. In the long-run, the perspective of neutral hypothesis suggests that the business cycle is crucial. Herein, it seems that the alternation of periods with peaks, recessions, troughs, and expansions ensures two-way energy-growth link. Therefore, the results are very useful for political decisions taking into account that the growth is not influenced by control of environment in the short-run, while both environmental and growth corrections influence each other in long-run at business cycle.

Not affecting the quality of the core results, this study has several limitations given the period of data availability. Additionally, the lack of data also restricts the use of more advanced wavelet techniques namely wavelet coherency as well as multiple and partial wavelet coherency. The outputs can be successfully used in policy decisions on both economic and environmental areas, a mix of such policies recommended in long-run at business cycle. Additionally, the findings can also serve individuals, companies as well as non-profit organizations in their eco-environmental analyses. For further research, it is expected that a more complex analysis be done based on an extended dataset by using multiple and partial wavelet coherency methodologies. The approach will help to better isolate the energy consumption — growth interactions, offering more deep insights.

5. Conclusions and policy implications

Using yearly data for Italy spanning from 1926 to 2008, this study investigated the effect of energy consumption on economic growth over different time scales. The results for unit root and stationarity tests show that our variables are integrated of order one, or *I(1)*. However, several cointegration tests reveal the absence of long-run relationship between energy consumption and real GDP. The causality analyses suggest the effect of energy consumption on economic growth varies according to time scales.

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[1] The frequency (ω) represents 2π/cycle length period (T).

In the short-run, a feedback mechanism is found in the time domain, with bi-directional causality. Yet, in the medium and long-run, the impact of real GDP on energy consumption seems to be more present. Therefore, at lower scales, our results empirically sustain the feedback hypothesis, while at higher scales real GDP runs energy consumption.

The short-run effect in the frequency domain shows real GDP causes energy consumption, while in the medium-run energy consumption drives real GDP passing through a bidirectional causality episode. In the long-run, the feedback hypothesis is validated at business cycle, fully matching the time scale results based on the wavelet decomposition.

Corroborating our restrictive validation of tests at 5% level of significance, the main conclusion confirms the business cycle ensures the feedback hypothesis. This emerges in correspondence to bi-directional causality between energy consumption and real income. In the short-run, economic expansion can support energy consumption, which further enhances growth.

In this case, the Italian energy policies oriented towards improvements in energy efficiency may not lead to economic recession, especially at the business cycle level. This difference in the applied results provides alternative policy implications, justifying the use of the wavelet approach to decompose the series into various time scales. As discussed, alternative empirical strategies (Granger tests vs. frequency domain tests) may be conducted to arrive at similar or varying results, which for that matter implies different policy implications.

Through the wavelet theory, we decompose the time series data into various time scales, providing us the identification of the effects of energy consumption on economic growth. Such an influence could not be detected if only the original series were analyzed given that sampling supplies a combination of several frequencies and veils the differences between short- and long-run relationships.

CRediT authorship contribution statement

Cosimo Magazzino: Conceptualization, Methodology, Software, Supervision. **Mihai Mutascu:** Data curation, Methodology, Software. **Marco Mele:** Visualization, Writing - original draft. **Samuel Asumadu Sarkodie:** Investigation, Validation, Writing - reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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