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Disaggregated relationship between economic growth and energy use in OECD countries: Time-series and cross-country evidence

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Abstract: We examine the GDP – energy use nexus in OECD countries over the period of 1960 – 2014. For the first time, energy use and GDP data are both disaggregated into their main components. Panel cointegration techniques addressing heterogeneity and cross-sectional dependence are employed to infer the directions and the signs of long-run cross causalities between GDP and energy components. Results are threefold: first, there is a feedback relationship between total energy use and GDP at the aggregated level, mainly through the public expenditure channel. Second, the feedback relationship is validated between real GDP and transportation energy, residence energy and consumption energy, respectively, mainly through the exports and imports channels. Third,the conservation relationship is found between industrial energy and real GDP for which main transmission mechanisms are consumption, exports and imports.

JEL codes:C23, Q21, Q43

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1. Introduction

This article renovates the classical approach of the energy-GDP nexus and avoids aggregation, by not only decomposing total energy into four components (industrial, transportation, residential and commercial energy), but also by disaggregating economic growth into its five expenditure components that are consumption, public expenditure, investment, imports and exports. It assuredly allows us having some insights into the main disaggregated transmission mechanisms between real GDP and energy use.

Since the pioneering work of Kraft and Kraft (1978), a large stream of literature has been devoted to investigating energy-growth nexus for different countries and regions (see Payne 2008). However, a consensus is still to be reached on the existence of such a relationship or on the direction of the causality between energy consumption and economic growth. While Ozturk (2010) and Bruns*et al*. (2014) interestingly review the subject, Apergis and Payne (2009) categorize the energy-growth nexus into four categories that allow classifying the mixed findings: growth hypothesis, conservation hypothesis, neutrality hypothesis and feedback hypothesis. A major strand of the literature follows the growth hypothesis, which advocates a unidirectional relationship running from energy consumption to economic growth. This hypothesis suggests that energy consumption plays an essential role in economic growth both directly and indirectly in the production process as a complement to labor and capital. Among others, Yu and Choi (1985), Lee and Chang (2005), Narayan and Smyth (2008), Squalli (2007) support the growth hypothesis. On the opposite, the conservation hypothesis states for a unidirectional and positive causality running from economic growth to energy consumption. Examples of studies underlying this finding can be found in Zamani (2007) and Zhang and Chen (2009). Interestingly, while the neutrality hypothesis considers the absence of causality from energy consumption to real GDP (as in Soytas and Sari 2009; Halicioglu 2009), the feedback hypothesis suggests that there is a bidirectional causal relationship between them (as in Masih and Masih 1996; Erdal *et al*. 2008). Despite the use of several alternative theoretical models and empirical strategies for describing the energy-growth nexus, over the last three decades, these contradictory sometimes, or at least dissimilar inferences on the same subject reveals the existence of gaps in the existing literature.

Yu and Choi (1985), Ferguson *et al*. (2000), Toman and Jemelkova (2003) and Karanfil (2008) among others, explain this lack of consensus due to the heterogeneity in climatic conditions, the changing energy consumption patterns, the different structures and stages of economic development within a country and among countries in relationship with the varying quality of indicators measurements (especially GDP), in addition to the diversity of econometric methodologies. However, these explanations refer to a classical way economists have always looked at energy-growth nexus, which leaves the unexplained lacunas in studying the nature and direction of such relationship. In the existing literature, we notice that the specification of the relationship has always been based on aggregate total economic growth, while the approach of energy consumption could have been changed overtime (see for example the classification according to the consumed energy type provided by Tugcu *et al.* 2012).

One way to bridge such gaps is to study the underlying mechanisms of the transmission of impulses from one variable to another. We believe that the black-box of such mechanisms rests in the components of both the energy use and economic growth variables and opening of this black-box should reveal important facts to help solve the puzzle. Therefore the disaggregation of economic growth and energy variables, so far being use at aggregate level (economic growth in all cases) could be the key.

Our approach draws inspiration from a framework that has recently been applied in other macroeconomic domains in trade and on the unemployment-economic growth nexus. In this regard, Anderton and Tewolde (2011), Anderton, Aranki, Bonthius and Jarvis (2014) and Banerji, Lin and Saksonovs (2015) are pioneer studies that disaggregate economic growth into its five main components.

We introduce the technique of disaggregated GDP and total energy into a bivariate framework, while taking into account cross-sectional dependency and heterogeneity. Cross-sectional dependency implies a variation of the intercept in countries and overtime. While until 2010 the majority of the studies did not consider cross-sectional dependency (Mehrara 2007; Lee and Chang 2008; Huang *et al.* 2008; Narayan and Smyth 2008; Ozturk 2010), a more recent trend of literature underlines the risks of inconsistency and misleading inferences that can affect the exploitation of first generation of commonly used panel unit root tests and cointegration tests, since several of them assume independence (Kapetanios *et al*. 2011). Also, we consider the heterogeneous dynamics which prevails for most aggregate country level data by identifying the existence of structural breaks to obtain consistency in our cointegration analysis. Such an identification beforehand is of utmost importance, for a break introduces spurious unit root behaviour in the cointegration relationship so that the hypothesis of no cointegration is difficult to reject (Gregory *et al.* 1996).

This article proceeds as follows. Section II briefly overviews the hypotheses related to the causal relationships between energy use and economic growth elaborated in the existing literature. Section III describes and presents the data, the pre-tests and their results and the long-run causality methodology. Section IV contains the main empirical results, while the last section concludes.

2. Literature review

The existing literature is evident that researchers commonly infer on the economic relevance of energy by using causality tests (Sims 1972; Hsiao 1979; Engle and Granger 1987; Pesaran and Shin 1999; and Pesaran et al. 2001 among others). Payne (2010) and Ozturk (2010) provide literature surveys of the international evidence on the causal relationship between energy and GDP.

Recently, a new wave of literature attempts to detail more accurately this relationship by disaggregating data, especially on total energy consumption (Tugcu*et al.* 2012; Bowden and Payne 2009; Zachariadis 2007; Thoma 2004).Bowden and Payne (2009) investigate the causal relationship between energy consumption and real GDP for the United States over the period of 1949 to 2006. The authors find that the Toda-Yamamoto (1995) long-run causality between energy consumption and real GDP was not uniform across sectors. The Granger-causality tests indicate no-Granger causality between total and transportation energy consumption and real GDP, respectively, but a bidirectional Granger-causality between commercial and residential energy consumption and real GDP, respectively. The neutrality hypothesis supported by the absence of Granger-causality between total energy and real GDP is also confirmed by Zachariadis (2007), who contradicts the findings of a significant relationship as in Erol and Yu (1989). In a similar manner, the feedback hypothesis implied by the bidirectional Granger-causality between commercial energy and real GDP is in contradiction to the conservation hypothesis found by Thoma (2004). The tests also reveal that industrial energy consumption Granger-causes real GDP, supporting the growth hypothesis. Squalli (2007) obtains the same result. However, to the best of our knowledge, there is no study that attempted to disaggregate both simultaneously the time series on total energy consumption and on real GDP.

This paper aims at filling this gap by disaggregating real GDP into its five main components and energy consumption into its five main components. However, disintegration of time series is not without constraints and therefore, we take into account two limitations identified in the literature while disaggregating time series. According to Zachariadis (2007) and Gross (2012), a discussion on appropriate pairs of variables needs to be undertaken. Statistical problems might appear when the variables do not share the same level of aggregation. In that sense, using national total energy consumption that corresponds to all energy inputs needed for nation-wide production require to systematically use national GDP. Bruns and Gross (2013) specify that another appropriate pair of variables is sectoral total energy and sectoral GDP. Nonetheless, they limit their approach to the national level.

Besides, as underlined by Bruns and Gross (2013) partially-disaggregated studies on one energy type to study the energy-GDP causal relationship might mislead energy researchers in formulating policy recommendations since it does not address potential influences of other energy types. The authors find that disaggregated time series are highly correlated implying that results of causality tests between different types of energy and GDP only reproduce the findings of causality tests between total energy and GDP.

3. Data, pre-tests and long-run causality methodology

3.1 Data

Our sample consists of data on 33 out of the 35 OECD countries[1] spanning 1960 - 2014.We dropped Latvia and Sweden due to data limitations. All our data come from the annual macro-economic database of the European Commission's Directorate General for Economic and Financial Affairs (AMECO).Real GDP (Y) data are used as a proxy for economic growth. We disaggregate real GDP into its main five components: consumption (C), investment (I), public expenditure (G), imports (M) and exports (X). Real GDP and its components are all expressed in per capita of 2005 U.S. dollars. Energy use data are expressed in per 1000 persons. Similarly, we disaggregate total energy (TE) into its four main components: industrial energy (IE), transportation energy (TrE), residential energy (RE), and commercial energy (CE).Industrial energy includes the combined energy usage by manufacturing, forestry, hunting, fishing, construction and mining. Transportation energy refers to part of total energy used by vehicles with the primary purpose of transportation of people and goods. Residential energy represents the use of energy by households, while commercial energy includes service providing facilities of businesses, national and local governments. All variables are converted to natural logs.

To examine the disaggregated economic growth – energy use nexus, the panel regression model specifying this relationship is as follows:

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[1] Australia, Austria, Belgium, Canada, Chili, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea Rep., Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Rep., Slovenia, Spain, Switzerland, Turkey, United-Kingdom and United States.

$$Y_{it} = \alpha_i + \beta_i TE_{it} + \varepsilon_{it} \tag{1}$$

Where $i = 1, \dots, N$ represents each of the 33 OECD countries, and $t = 1, \dots, T$ denotes each year during the period 1960-2014. As we are using the the disaggregating approach Y_{it}represents the vector of all the economic growth components including C, I, G, M and X; and TE_{it} is the vector of all the energy related componentsincluding IE, TrE, RE and CE respectively.

3.2Panel unit root tests

As customary in case of panel data analysis, first, we test the cross-dependence through Pesaran (2004) test for cross-sectional dependence (CD). The CD test is based on an average of all pair-wise correlations of the ordinary least squares (OLS) residuals from the individual regressions in the panel data model. It tests the null hypothesis of zero dependence across the panel members. The CD test statistic is defined by:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \cdot \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \right) \rightarrow N(0,1) \tag{2}$$

Where $i = 1, \dots, N$ represents the cross-section member, $t = 1, \dots, T$ refers to the time period and $\hat{\rho}_{ij}$ is the sample estimate of the pair-wise correlation of the OLS residuals, $\hat{u}_{it}$ associated with equation (2)

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T} \hat{u}_{it} \hat{u}_{jt}}{\left(\sum_{t=1}^{T} \hat{u}^2{}_{it} \right)^{1/2} \left(\sum_{t=1}^{T} \hat{u}^2{}_{jt} \right)^{1/2}} \tag{3}$$

The results (table 1A in appendix) show that the null hypothesis of cross-sectional independence can be rejected for all the variables. For variables like GDP per capita and total energy, and their respective components, cross-sectional dependence was expected, and reasonably so because of the existence of unobserved or omitted common factors (common global shocks and spatial spillover effects between countries, among others) that are likely to be correlated with the regressors. This finding underlines the already mentioned importance of taking into consideration cross-section dependence when analysing the GDP growth-energy use nexus.

Second, we conduct panel unit root tests (URT) to determine the order of integration of panel variables. In the case of no-cross-sectional dependence, we would have used the so-called first generation of URT (Levin *et al.* 2002; Breitung 2000; Im *et al.* 2003; Hadri 2000 among others). However, in our case, the application of these tests would lead to size distortions and low power (Banerjee, Marcellino and Osbat 2000). Therefore, we decide to use second-generation panel URT and to conduct the Bai and Carrion-i-Silvestre (2009) test, which accounts for cross-sectional dependence and for multiple endogenous breaks through a common factors model proposed by Bai and Ng (2004). The common factors approach allows the common shocks to affect countries differently via heterogeneous factor loadings. Hence, the test also takes into account a high degree of heterogeneity across countries. To yield satisfactory results when pooling, the authors define P and P_m statistics that are computed by means of the p-values of the simplified pool modified Sargan and Bhargava (1983) tests for individual time series as:

$$P = -2 \sum_{i=1}^{N} ln\, p_i \rightarrow \chi_{2N}^2 \tag{4}$$

$$P_m = \frac{-2\sum_{i=1}^{N}\ln p_i - 2N}{\sqrt{4N}} \rightarrow N(0,1) \qquad (5)$$

Where $p_i, i = 1, \ldots, N,$ is the individual p-value.

Results in Table 2A in appendix indicate that the null hypothesis of a unit root cannot be rejected for most of our series without any break, with a break in the mean and with a break in the trend. Therefore, taking structural breaks into account do not alter the decision of panel series that has a different order of integration at a different lag order.

3.3Panel cointegration tests

Once confirmed that our variables are integrated of order one, the next step is to examine whether a long-run relationship for each pair of variables exists. For this purpose, we implement the Westerlund and Edgerton (2008) second-generation panel cointegration test that allows for cross-sectional dependency and structural breaks that may be located at different dates for different panel members. Additionally, they allow for heteroskedastic and serially correlated errors, and cross unit-specific time trends. Their test, derived from the Lagrange Multiplier (LM)-based unit root approach, produces two normalized statistics (Z_ϕ and Z_τ) to test for the null-hypothesis of no-cointegration that take the following forms:

$$Z_\phi(N) = \sqrt{N}\left(\overline{LM}_\phi(N) - E(B_\phi)\right) \qquad (6)$$

$$Z_\tau(N) = \sqrt{N}\left(\overline{LM}_\tau(N) - E(B_\tau)\right) \qquad (7)$$

Table 1: Westerlund and Edgerton (2008) panel cointegration test allowing for structural breaks and cross-sectional dependence

Pair of variables	No break		Level break		Regime shift	
	$Z_\tau(N)$	$Z_\phi(N)$	$Z_\tau(N)$	$Z_\phi(N)$	$Z_\tau(N)$	$Z_\phi(N)$
Y, C	-11.231***	-22.653***	-3.212***	-6.048***	0.203	-2.271**
Y,I	-12.739***	-24.677***	-4.577***	-7.494***	-4.743***	-7.236***
Y, G	-16.413***	-30.127***	-0.091	-2.589***	-2.737***	-6.459***
Y, X	-14.591***	-27.468***	-2.133***	-4.589***	-2.576***	-6.6***
Y, M	-16.178***	-30.378***	0.704	-1.211	-0.642	-3.897***
Y, TE	-13.232***	-23.973***	-2.826***	-5.808***	-11.887***	-20.541***
Y, IE	-13.971***	-24.712	-4.071***	-7.24	-4.733***	-8.243***
Y, TrE	-12.875***	-23.552***	-1.766**	-4.412***	-1.996**	-5.366***
Y, RE	-11.58***	-21.955***	-2.745***	-5.456***	-4.587***	-8.431***
Y, CE	-9.989***	-19.38***	-2.887***	-5.655***	-2.082**	-5.515***

Source: Authors' calculations

*Notes: Z_τ and Z_ϕ statistics follow the standard normal distribution. The tests are implemented using the Campbell and Perron (1991) automatic procedure to select the lag length. We use three breaks, which are determined by grid search. ***, ** and * denote 1%, 5% and 10% of significance, respectively.*

According to the results shown in table 1 since none of the cointegration tests failed to reject the null hypothesis by all three measures, cointegration is established for all variable pairs. It means that all our cross-relationships between energy components and GDP components move together in the long run as supported in the literature.

3.4 Long-run causality methodology

The cointegration test establishes a long run relationship among the variables, however, the direction and nature of the causality is yet to be determined. We use a two-step Granger-causality procedure which is robust to non-stationarity, cointegrated variables, considering the cross-sectional dependency. First, we estimate a dynamic error correction model (ECM) for each country by using fully modified ordinary least squares (FMOLS) following Canning and Pedroni (2008) methodology.

The dynamic ECM is as follows:

$$\Delta TE_{it} = c_{1i} + \lambda_{1i} e_{it-1} + \sum_{j=1}^{K_i^2} \varphi_{11ij} \Delta TE_{i,t-j} + \sum_{j=1}^{K_i^2} \varphi_{12ij} \Delta \mathrm{Y}_{i,t-j} + \varepsilon_{1it} \tag{8}$$

$$\Delta Y_{it} = c_{2i} + \lambda_{2i} e_{it-1} + \sum_{j=1}^{K_i^2} \varphi_{21ij} \Delta Y_{i,t-j} + \sum_{j=1}^{K_i^2} \varphi_{22ij} \Delta \mathrm{TE}_{i,t-j} + \varepsilon_{2it} \tag{9}$$

Where TE is the total energy use per capita and subsequently each of its components (IE, TrE, RE, and CE), Y is real GDP per capita and also each of its components (C, I, G, X, and M), K is a country-specific lag length, the subscripts i and t denote country i and the tth time period, respectively, Δ is the first difference operator, and e_{it-1} is the one period lag of the residuals from the long-run cointegrated relationship. In this case, e_{it-1} which is estimated by FMOLS represents how far from the equilibrium relationship our variables could be and thereby the error correction mechanism estimates how this disequilibrium causes the variables to adjust towards equilibrium in order to keep the long-run relationship intact. To address cross-sectional correlation, Canning and Pedroni (2008) suggest subtracting out common time effects. Moreover, taking the first difference in equations 8 and 9 minimizes cross-sectional dependence[2].

The adjustment coefficient λ_{1i} (λ_{2i}, resp.) in the dynamic error correction equation for ΔEN (ΔGDP, resp.) equals zero if, and only if, log energy per capita (log per capita GDP, resp.) have no long-run effect on log per capita GDP (log energy per capita, resp.). To overcome the poverty of those adjustment coefficients because of the short time span, Canning and Pedroni (2008) generated two panel-based statistical tests. The mean group (MG) test is based on the panel average of those individual country t-tests and has a standard normal distribution under the null hypothesis of no long-run causal effect for the panel. The Lambda-Pearson (LP) test is based on the p-values associated with each of those individual country t-tests. The LP test statistic has a chi-square distribution under the null hypothesis of no long-run causal effect for the panel (Liddle and Lung, 2015).

The combination of the MG and LP tests can be particularly informative. When MG does not reject the null hypothesis of no Granger causality, but LM does reject it, we can conclude that there is no Granger causality for the panel as a whole, but a pervasive one throughout the panel.

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[2] Results from Pesaran (2006) test using first difference are available upon request.

Once these estimations obtained, we can determine the multivariate long-run causality with the Pesaran (2006) CCEMG estimator. This panel time series estimator allows for heterogeneous slope coefficients across group members and is also concerned with correlation across panel members. The idea of this estimator is to filter the cross-section specific regressors by introducing cross-section averages of dependent variable and the observed regressors. These cross-sectional averages account for the unobserved common factors and therefore, cross-section dependence can be eliminated (Salim *et al.*, 2014). The CCEMG estimator is defined as:

$$\bar{b}_{CCEMG} = \frac{1}{N}\sum_{i=1}^{N} \hat{b}_i,$$

$$\hat{b}_i = (X_i' \bar{M} X_i)^{-1} X_i' \bar{M} y_i \tag{10}$$

Where $X_i = (x_{i1}, \dots, x_{iT})', y_i = (y_{i1}, \dots, y_{iT})$ and $M = I_T - \bar{H}(\bar{H}'\bar{H})^{-1}\bar{H}'$ with $\bar{H} = (D, \bar{Z})$, where D and $\bar{Z}$ denote the $(T \times n)$ and $(T \times (K+1))$ matrices of observations on d_t and $\bar{z}_t$, respectively.

4. Discussion of causality direction and sign results

Table 2 displays the Canning and Pedroni (2008) panel long-run Granger causality test results for a first level of disaggregation, between real GDP and the four energy components of total energy consumption.

Table 2: Canning & Pedroni (2008) panel long-run causality tests for GDP and energy components

		$\lambda_2: x_{it} \rightarrow y_{it}$		$\lambda_1: y_{it} \rightarrow x_{it}$	
Panels	Test	Estimate	Test	Estimate	Test
TE – Y	MG	-0.05	0.19	-0.2	-1.31*
	LP		87.78*		136.28***
IE – Y	MG	-0.01	-0.14	-0.28	-1.76**
	LP		80.93		194***
TrE – Y	MG	0.03	0.5	-0.19	-1.24
	LP		115.9***		147.09***
RE – Y	MG	0.03	0.58	-0.33	-1.87**
	LP		106.51***		219.31***
CE – Y	MG	0.1	0.74	-0.26	-1.66*
	LP		108.29***		177.81***

Source: Authors' calculations

*Notes: The null hypothesis is no Granger-causality. MG = Mean Group. LP = Lambda-Pearson. ***, ** and * denote 1%, 5% and 10% of significance, respectively. The independent variable Y represents GDP and the dependent variables X are Consumption (C), Investment (I), Governement expenditure (G), Export (X), Import (M), Total energy (TE), Industrial energy (IE), Transportation energy (TrE), Residential energy (RE) and Commercial energy (CE).* $x_{it} \rightarrow y_{it}$ *= energy "Granger-causes" GDP.*

Results show that there is a bidirectional pervasive long-run causality between total energy and GDP. On one side, λ_2 from GDP to total energy indicates that GDP long-run causes and pervasively long-run causes total energy since the two statistics, mean group and lambda-Pearson, are significant. On the other, λ_1 indicates that GDP pervasively long-run causes total energy, but rejects the hypothesis of a long run causality on average. These findings are in line with Erol and Yu (1989) and confirm the feedback hypothesis.

Going deeper into the analysis focusing on the causality between each energy's component and GDP, we find several interesting results (table 2): first, industrial energy does not long-run cause GDP, but real GDP long-run causes industrial energy. This one-way relationship supports the conservation hypothesis, stating that an increase in real GDP causes an increase in energy consumption, and in our case in industrial energy. This result is comforted by those obtained in Zamani (2007) and Zhang and Chen (2009). However, it contradicts Bowden and Payne (2009), whose findings support the growth hypothesis and Zachariadis (2007) who finds support for the neutrality hypothesis. Second, we find bidirectional relationships between real GDP and transportation energy, residential energy and consumption energy, respectively. The feedback hypothesis is validated as we can reject the hypotheses that real GDP (transportation, residential and consumption energy) does (do) not Granger cause transportation, residential or consumption energy (GDP), respectively. The validation of feedback hypothesis for transportation is validated by Gross (2012). On the contrary, earlier studies like Bowden and Payne (2009), Erol and Yu (1989) and Zachariadis (2007) found evidence for the neutrality hypothesis. The result of a feedback hypothesis for residential energy is also found in Bowden and Payne (2008), but is contrary to Erol and Yu (1989) who found that residential energy is not very sensitive to economic activity, and to Thoma (2004) and Zachariadis (2007) who did not find any causal relationship between this pair of variables. Finally, similar to our results, Bowden and Payne (2009) confirm the feedback hypothesis for consumption energy in that real GDP and consumption energy complement each other. However, the conservation hypothesis found support in Thoma (2004).

After disaggregating total energy consumption into its four elements, we disaggregate now GDP and analyze the causal relationship between energy components and GDP components. Findings from this second level of disaggregation are displayed in table 3. The bidirectional pervasive long-run relationship between total energy and real GDP is disaggregated to obtain finer information on the main channels. Our findings indicate a negative Granger-causality from public expenditure (-0.16 at 10% of significance) and from exports (-0.21 at 10% of significance) to total energy. Consumption, investment and imports demonstrate a bidirectional pervasive relationship with total energy at 5% of significance, without any support for Granger causality.

We now reflect on our results for both disaggregated total energy consumption and real GDP. We start by describing the channels for bidirectional relationships. First, regarding the bidirectional relationship between transportation energy and real GDP's components, we find a systematic pervasive long-run causality between all pairs of variables of interest. Similar to total energy, we find a negative Granger causality from public expenditure (-0.17 at 10% of significance), from exports (-0.15 at 10% of significance) and from imports (-0.12 at 10% of significance), respectively to transportation energy.

Second, regarding the bidirectional relationship between residential energy and real GDP's components, results are similar in the fact that there is a systematic pervasive long-run causality between all pairs of variables of interest. Moreover, each GDP's component negatively Granger causes residential energy at 5% of significance, but residential energy fails Granger causing any of them at the 10% of significance.

Third, regarding the bidirectional relationship between consumption energy and real GDP's components, results show that each GDP's component negatively Granger causes consumption energy at 10% of significance, but consumption energy does not Granger cause any of them. The most important channel and most intuitive one is the total consumption channel (-0.28 at 5% of significance).

Finally, regarding the conservation hypothesis for industrial energy, results in table 3 indicate that consumption, exports and imports negatively Granger cause industrial energy (-0.32,-0.30, and -0.26 respectively at 10% of significance), but public expenditure and investment do not Granger cause industrial energy. Moreover, there is no empirical evidence of Granger causality from industrial energy use to any GDP's components.

Table 3: Canning & Pedroni (2008) panel long-run causality tests for both GDP and energy components

		$\lambda_2: x_{it} \rightarrow y_{it}$		$\lambda_1: y_{it} \rightarrow x_{it}$	
Panel	Test	Estimate	Test	Estimate	Test
TE – C	MG	-0.02	0.03	-0.28	-1.17
	LP		105.98***		134.98***
IE – C	MG	0.00	-0.03	-0.32	-1.58*
	LP		108.85***		187.13***
TrE – C	MG	0.03	0.35	-0.31	-1.22
	LP		98.49***		135.77***
RE – C	MG	0.01	0.35	-0.39	-1.60**
	LP		112.08**		229.41***
CE – C	MG	0.08	0.85	-0.28	-1.67**
	LP		138.06***		229.41***
TE – G	MG	0.05	0.97	-0.16	-1.35*
	LP		155.49***		164.03***
IE – G	MG	0.03	0.64	-0.26	-1.72
	LP		101.1**		211.78***
TrE – G	MG	0.06	1.22	-0.17	-1.27*
	LP		135.99***		147.48***
RE – G	MG	0.00	0.56	-0.33	-1.97**
	LP		113.68***		233.99***
CE – G	MG	0.03	0.89	-0.2	-1.52*
	LP		112.95***		162.21***
TE – I	MG	0.12	0.76	-0.18	-1.16
	LP		160.26		169.53***
IE – I	MG	0.02	-0.01	-0.24	-1.51
	LP		148.44***		189***
TrE – I	MG	0.33	1.61	-0.13	-0.96
	LP		255.38***		143.83***
RE – I	MG	0.18	0.77	-0.26	-1.42*
	LP		157***		161.93***
CE – I	MG	0.21	1.32	-0.23	-1.79
	LP		178.87***		259.42***
TE – X	MG	0.04	0.48	-0.21	-1.54*
	LP		76.16		154.08***
IE – X	MG	-0.01	0.05	-0.30	-1.84*
	LP		90.14**		205.37***
TrE – X	MG	0.04	0.54	-0.15	-1.29*
	LP		79.82		132.90***
RE – X	MG	0.10	0.55	-0.38	-2.04**
	LP		80.29		237.38***
CE – X	MG	0.00	0.41	-0.24	-1.69**
	LP		80.38		182.48***
TE – M	MG	-0.01	0.24	-0.18	-1.24
	LP		65.23		133.21***
IE – M	MG	0.00	-0.03	-0.26	-1.67**
	LP		84.01*		192.8***
TrE – M	MG	0.04	0.33	-0.12	-0.95
	LP		67.35		104.01***
RE – M	MG	0.04	0.30	-0.33	-1.99**
	LP		95.04**		242.18***
CE – M	MG	0.05	0.29	-0.21	-1.54*
	LP		95.71**		164.4***

Source: Authors' calculations

*Notes: The null hypothesis is no Granger-causality. MG = Mean Group. LP = Lambda-Pearson. ***, ** and * denote 1%, 5% and 10% of significance, respectively. The independent variable Y represents each of the five*

GDP components Consumption (C), Investment (I), Public expenditure (G), Export (X), Import (M), while the dependent variables X are each of the four components of Total energy (TE), Industrial energy (IE), Transportation energy (TrE), Residential energy (RE) and Commercial energy (CE).$x_{it} \rightarrow y_{it}$*= energy "Granger-causes" GDP.*

The last step of our analysis consists of examining the causality relationship in a multivariate framework. Since the MG statistics rejected panel causality from energy factors to GDP's components, we estimate panel equations by applying the Pesaran (2006) CCEMG estimations with energy components as the dependent variables and GDP's components as the independent variables. Table 4 depicts the main results. Slight changes occur when we consider the simultaneous role of the independent variables. It shows that the panel average elasticity estimations are highly significant and strongly positive. The only exception refers to consumption and investment that do not play a significant role in explaining industrial energy consumption. The results reveal also that in the long run, a 1% increase in consumption, public expenditure and investment will enhance total energy consumption by 4.73%, 4.74% and 2.38%, respectively. Besides, consumption has the largest effect on transportation energy (+2.40), on residential energy (+1.15%) and on commercial energy (+0.84%) while public expenditure and exports have the largest impacts on industrial energy (+0.91% and +0.56%, respectively).

Table 4: CCEMG estimates – multivariate framework

Dep. Variable	Indp. Variable	β	St. Errors	95% C.I.
TE	C	4.73***	1.41	[1.95 7.50]
	I	2.38***	1.68	[1.04 3.72]
	G	4.74***	1.76	[1.67 7.81]
	M	1.89***	0.77	[0.77 3.01]
	X	1.72***	0.51	[0.72 2.73]
IE	C	NS	NS	NS
	I	NS	NS	NS
	G	0.91**	0.39	[0.14 1.67]
	M	0.33**	0.17	[0.02 0.67]
	X	0.56***	0.16	[0.23 0.89]
TrE	C	2.40**	0.99	[0.54 4.44]
	I	1.50**	0.64	[0.23 2.77]
	G	1.34***	0.38	[0.59 2.09]
	M	0.94*	0.36	[0.22 1.66]
	X	0.70**	0.28	[0.15 1.25]
RE	C	1.15***	0.37	[0.42 1.88]
	I	0.46**	0.18	[0.10 0.82]
	G	1.03**	0.40	[0.24 1.83]
	M	0.31***	0.11	[0.09 0.53]
	X	0.30***	0.09	[0.10 0.49]
CE	C	0.84**	0.33	[0.18 1.49]
	I	0.35**	0.15	[0.04 0.65]
	G	0.55**	0.22	[0.12 0.99]
	M	0.28***	0.10	[0.07 0.49]
	X	0.22**	0.09	[0.04 0.40]

Source: Authors' calculations

*Notes: Dep. variable = Dependent variable. Indp. variable = Independent variable. C.I. = Confidence intervals. N.S. = Not significant. ***, ** and * denote 1%, 5% and 10% of significance, respectively.*

5. Conclusion

While there has been a significant amount of research regarding economic growth – energy use nexus, nothing had been done yet regarding the disaggregation of both real GDP and total energy. This study aimed at filling this gap by examining for the first time the cross-relationships between real GDP's components and energy components for 33 OECD countries from 1960 to 2014.

Disaggregating the data within a framework accounting for heterogeneity and cross-sectional dependence allows us to have some insights into the main economic transmission mechanisms between GDP and energy factors in several ways. First, we confirm at the aggregated level a feedback relationship between real GDP and total energy use. The main transmission mechanism at the disaggregated level runs from public expenditure to total energy use. Second, we demonstrate that such feedback relationship is validated between real GDP and transportation energy, residence energy and consumption energy, respectively. From GDP to residence energy (*consumption energy*), the main transmission mechanisms are consumption and exports (*consumption*). For transportation energy, the important transmission mechanisms are public expenditure, exports and imports. Third, in contrast with the other energy factors, the conservation hypothesis is supported by the results between real GDP and industrial energy. While consumption, exports and imports are the main channels from real GDP to industrial energy, investment and public expenditure do not play a significant role.

These findings have several policy implications for OECD countries. First, the feedback relationship between real GDP and transportation energy, residence energy and consumption energy, respectively indicates that energy conservation policies focusing on these energy sectors and aiming at reducing energy intensity, improving energy efficiency or promoting the use of alternative renewable energy sources may be harmful for economic growth.However, a reduction of public spending would significantly reduce total energy use, especiallytransportation energy use. Second, in contrast with the preceding implication, the conservation relationship between real GDP and industrial energy implies that such energy conservation policies like investment tax creditswithin the industrial sector would not have a significant impact on economic growth. On the contrary, a negative demand shock tothe economy would negatively affect the short term consumption and trade activities, and in the long term significantly erode industrial energy use. Finally, future research at such disaggregated level would shed additional light on this nexus to develop more appropriate and efficient energy and environmental policies for OECD countries in theyears to come.

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Appendix

Table A1: Cross-sectional dependence: Average absolute value coefficients and Pesaran (2004) CD test

Panel	*Absolute value coefficient*	*CD stat.*
Y	0.423	58.29*
C	0.281	32.372*
I	0.401	52.585*
G	0.192	12.398*
M	0.590	82.805*
X	0.524	70.406*
TE	0.274	37.708*
IE	0.231	29.451*
TrE	0.188	21.976*
RE	0.212	23.181*
CE	0.153	10.265*

Source: Authors' calculations

*Notes: Null hypotheses are cross-sectional independence. Statistical significance indicated by * <0.001.*

Table 2: Bai and Carrion-i-Silvestre (2009) panel unit root test

MODEL	Test	Y	C	I	G	X	M	TE	IE	TrE	RE	CE
Trend shift	Z	-0.95	0.37	-2.13***	-059	-1.18	-1.56*	0.54	-0.28	-1.46*	0.26	-1.08
	P	52.3	49.81	87.88***	56.2	66.57*	65.94*	55.86	59.32	75.02	53.95	67.29
	P_{m}	0.44	-0.01	3.51***	0.62	1.42*	1.59*	-0.71	-0.41	0.97	-0.88	0.66
Simplified	Z	0.05	3.51	-1.93***	-0.76	-0.77	-1.66**	6.52	2.44	-0.29	1.38	1.29
	P	47.97	37.76	87.63***	53.19	66.08*	66.85*	56.26	58.79	76.74	45.37	47.49
	P_{m}	-0.00	-1.22	3.49***	0.31	1.38*	1.68**	-0.68	-0.46	0.97	-1.64	-1.14
Mean shift	Z	-1.83**	-1.98**	-2.48***	-3.46***	-2.85***	-1.91**	-2.4***	-2.21**	-1.80**	-1.34*	-2.28**
	P	53.40	67.3*	85.76***	120.39***	85.54***	72.66**	76.81	80.01**	85.62**	76.55	69.80
	P_{m}	0.55	1.73**	3.31***	7.04***	3.29***	2.26**	1.13	1.41*	1.91**	1.11	0.89
No break	Z	1.34	0.62	-2.13**	-2.16**	-0.24	-0.54	1.39	0.48	-0.66	1.37	2.12
Trend	P	39.14	42.11	76.46**	67.57**	70.43**	54.92	67.86	64.80	70.24	53.77	43.35
	P_{m}	-0.93	-0.78	2.39***	1.75**	1.80**	0.49	0.34	0.07	0.55	-0.90	-1.51
No break	Z	-1.83**	-1.98**	-2.48***	-3.46***	-2.85***	-1.91**	-2.4***	-2.21**	-1.80**	-1.34*	-2.28**
Constant	P	53.40	67.35	85.76***	120.39***	85.54***	72.66**	76.81	80.01**	85.62**	76.55	69.80
	P_{m}	0.55	1.73**	3.31***	7.04***	3.29***	2.26**	1.13	1.41*	1.912**	1.11	0.89

Source: Authors' calculations

Notes: The Z andP_m *statistics follow the standard normal distribution. Zcritical value is one-tail negative.* P_m*critical value is one-tail positive.* P_m*suits a model with large* N*. The P statistic follows the Chi-squared distribution with* $df = 2n$*. ***, ** and * are statistical significant levels of rejecting unit root at 1%, 5% and 10%, respectively. The number of common factors is estimated using the panel Bayesian information criterion proposed by Bai and Ng (2002).*