How Linked are Energy and GDP: Reconsidering Energy-GDP Cointegration and Causality for Disaggregated OECD Country Data.

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ABSTRACT
This study is different from previous energy-GDP cointegration/causality ones by examining whether total energy consumption by industry *causes* total industry GDP (or vice versa), and whether per capita GDP *causes* per capita road and residential sector energy use (or vice versa) for a number of OECD countries. The primary findings are that nearly all of the data series analyzed are not cointegrated, and that by far the most robust result is that of Granger-noncausality; thus, developed economies may be far more flexible in their relation with energy than is often understood, and the price mechanism may be a none-too-costly policy instrument to lower energy consumption.

JEL classification: Q43

Keywords: Energy consumption disaggregated; Economic growth; Granger-causality; Cointegration; OECD countries.

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1. Introduction

Economic growth and energy consumption have been highly correlated historically. This correlation coupled with concerns over energy's environmental costs (e.g., carbon emissions) and security issues (e.g., foreign supply dependence and nuclear technology proliferation) has drawn considerable attention to the relationship between energy and development. Some of the literature dealing with this relationship, beginning in the early 1980s, has used statistical techniques from Granger and Sims to discover the causal direction of the energy-economic growth relationship. More recent advances in the literature have involved improved techniques, like cointegration tests, and updated (and, perhaps, improved) data sets. Taken as a whole, however, the literature on temporal causality between energy consumption and economic growth has offered neither robust results nor convincing rationale. This paper seeks to illuminate the energy-economy relationship by testing data at levels of aggregation for which a causal direction can be theoretically predicted *a priori*. Specifically, I examine the causal link between total industry energy consumption and total industry output in GDP terms and, separately, examine the link between per capital GDP or income and per capita road and residential energy consumption in a number of OECD/IEA countries.

In summarizing the literature there are two general reasons why no clear story has emerged: first, a number of studies focusing on the same countries have produced contradictory results, and second, the few multi-country studies (which look at both developed and developing countries) have found the full spectrum of results, i.e., no causality, bi-directional causality, and both types of uni-directional causality, but without offering an consistent rationale for the differences. For example, in the seminal study on the US, Kraft and Kraft (1978) found causality running from GNP to energy consumption for the US over the period 1947-1974. Subsequently, Akarca and Long (1980) shortened the Kraft and Kraft period by two years, while Yu and

Hwang (1984) lengthened it by four years, and neither later study detected evidence of causality. Both Yu and Choi (1985) and Erol and Yu (1987) also found no causal relationship between GNP and energy for the US. However, none of the early studies tested for cointegration[1]—probably the first *causality* study to test for cointegration for any country was Masih and Masih (1996).[2] More recently, Stern (2000) took a multivariate approach (also considering capital and labor) and found for the US that the variables were cointegrated and that energy consumption causes GDP.

A similar history of often contradictory results also emerged for some of the rapidly developing Asian economies; the most recent studies are summarized below. For Taiwan, Cheng and Lai (1997) failed to find cointegration, but did detect causality running from GDP to energy, while Yang (2000), using slightly updated data, found bi-directional causality (he also found no cointegration). Different still was Masih and Masih (1997), who discovered both cointegration and bi-directional causality for Taiwan by taking a multivariate approach (they also considered the consumer price index). Glasure and Lee (1997) found both cointegration and bi-directional causality for both Korea and Singapore. Masih and Masih (1997), although using a multivariate analysis, found the same for Korea; however, Masih and Masih (1996), detected neither cointegration nor causality for Singapore (this time considering only energy and GDP). Meanwhile, Soytas and Sari (2003), although they detected cointegration for Korea, found only GDP causing energy consumption there.[3] Lastly, Masih and Masih (1996) found cointegration for both India and Indonesia; however, the direction of causality went from energy to GDP in

[1] Two or more nonstationary variables are said to be cointegrated if some linear combination of them is stationary. The finding of cointegration among economic variables is interpreted as evidence of a long-run, equilibrium relationship. More on cointegration follows in the Data and Methodology section.

[2] Yu and Jin (1992) tested whether energy and an index of industrial production were cointegrated for the US; however, they did not test for causality.

[3] Masih and Masih (1997) and Stern (2000) used, quite appropriately for a multivariate analysis, the Johansen test of cointegration. Although both Masih and Masih (1996) and Soytas and Sari (2003) considered only two variables, they also employed the Johansen

India, and from GDP to energy in Indonesia. By contrast, Soytas and Sari (2003) detected neither cointegration nor causality for India and Indonesia.

In a recent, related but still different type of analysis, Coondoo and Dinda (2002) performed Granger-causality tests on per capita GDP and per capita carbon emissions using continent-grouped, panel data. They found emission to income causality for North America and Western and Eastern Europe; income to emission causality for Central and South America; and bi-directional causality for Asia and Africa. Because that study used both a different variable (carbon emissions as opposed to energy) and, particularly, different methods[4] (e.g., panel as opposed to time series data), it is difficult to compare it with the previously mentioned studies. However, it does have in common with the others the pattern of a wide range of results without a very coherent story.

Among the reasons cited for the lack of conclusive or theoretically appealing results are the different data sets, methods for determining lag structure, and statistical techniques (namely, testing for cointegration and whether the analysis considers bi- or multi-variable causality). Still another reason may be the very high level of aggregation of the data analyzed. When considering total energy consumption and total GDP, it is not at all clear what direction causality should be in or how it might evolve temporally. Energy is clearly an input in industrial production; however, in developed countries industry commands a declining share of GDP. Furthermore, a considerable and growing amount of energy consumption in developed countries is for personal

method. Meanwhile, Cheng and Lai (1997), Glasure and Lee (1997), and Yang (2000), used the Engle-Granger test of cointegration, as does this study.

[4] Performing causality tests with panel data is not standard practice; indeed, Maddala and Kim (2000) argue it is not clear whether even unit root tests are any more powerful with panel data. Finally, Coondoo and Dinda (2002) did not test for cointegration in their data.

transport and use in homes[5]—activities that are “consumptive” in nature, and thus, would be expected to increase with wealth.

Figure 1 shows, for the OECD as a whole, the paths of industrial, road, and residential energy consumption. The figure illustrates that since 1970 industry energy consumption has been fairly constant, fluctuating between a +/- 10 percent band, whereas residential energy consumption has increased and road energy consumption has increased considerably. The patterns for individual OECD countries look quite similar.

For this paper the data are disaggregated so that two separate energy-GDP causality analyses are performed, individually, for a number of OECD/IEA countries. The first set of tests involve total industry GDP and total industry energy consumption; therefore, it is expected that energy (a production factor) will Granger-cause output (GDP). In the second set of tests, per capita GDP and per capita road and residential energy consumption are analyzed; here, one would expect income (per capita GDP) to Granger-cause energy consumption (a normal consumption good). I know of only one other energy-GDP causality paper in which energy is disaggregated according to end use—Hondroyiannis et al. (2002), who focused on Greece.[6] However, Hondroyiannis et al. tested separately for causality between *total* GDP and each of the following: (i) total energy consumption, (ii) *total* residential energy consumption, and (iii) total industrial energy consumption; hence, the direction of causality is still theoretically confusing.

The following section of this paper introduces the data and methodology used. Section 3 presents and discusses the results. The final section summarizes the conclusions and addresses some policy implications.

[5] According to Schipper et al. (2001), space heating followed by electrical appliances account for the greatest share of residential end uses in IEA countries.
[6] They also considered the consumer price index and found cointegration for all three of their aggregations of energy consumption.

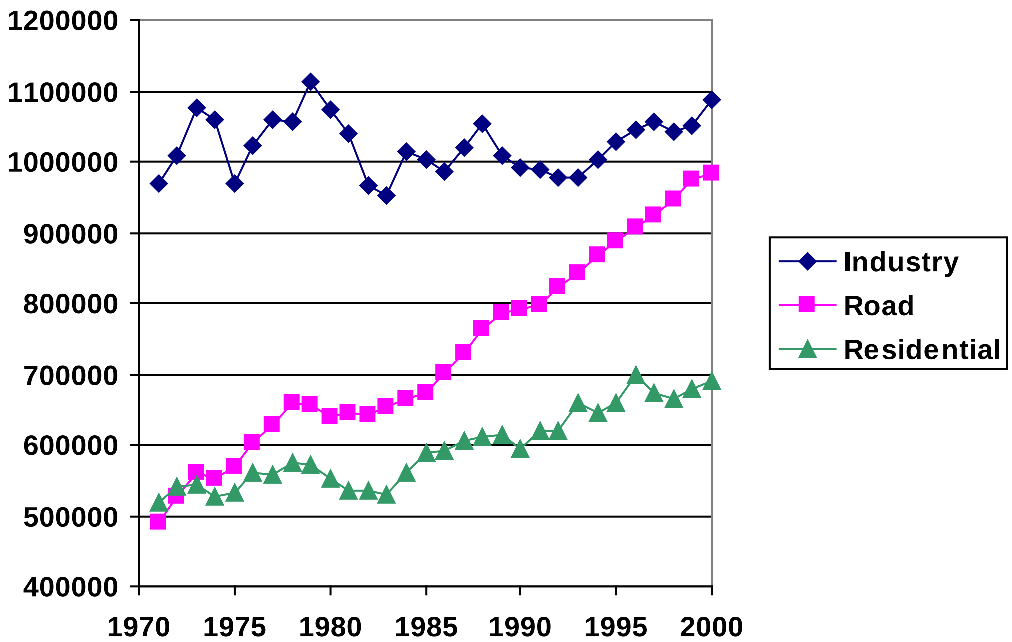

Figure 1. Total energy consumption (in Mtoe) for the OECD as a whole in three different end-use sectors: industry, road, and residential.

2. Data and Methodology

The data used in this study come from the International Energy Agency's Energy Balances of OECD Countries CD-ROM (2002 edition). Again, I examine four data series (all annual and all in natural logs): (1) GDP per capita (in 1995 US$ using PPPs); (2) road and residential energy consumption (in tons of oil equivalent) per capita, in which (i) energy use in road sector includes all fuels used in road vehicles (including military), as well as agricultural and industrial highway use, but excludes motor gasoline used in stationary engines, and diesel oil for use in tractors that are not for highway use[7], and (ii) energy use in residential sector includes all consumption by households, but excludes fuels used for transport; (3) total GDP from industry (also in 1995 US$ using PPPs), calculated by multiplying a country's GDP by its industry's share of value added (this data comes from World Bank Development Indicators); and (4) total energy consumption by industry (also in tons of oil equivalent). The IEA has these data from 1960-2000 (except for energy data for Korea and Mexico, which begins in 1971); however, the World Bank's data on industry's share of value added is incomplete for many of the IEA countries—Appendix Table A1 contains the countries and years for which industry GDP could be obtained.

The first step is to test for unit roots in each series since all variables in a Granger-causality test should be of the same order. It is expected, as others have found, that these series (all of which contain noticeable trends) will be nonstationary in levels, but stationary in first differences. To test for unit roots I use the Elliott, Rothenberg, and Stock (1996) Dickey-Fuller test with GLS detrending (DF-GLS). This test is particularly appropriate for highly trending data; furthermore, Maddala and Kim (2000) argue that DF-GLS tests are more powerful than the (often used) augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The DF-GLS test allows for a constant or a constant and a linear time trend in the test regression. For robustness, I report the results from both types of regression equations in Appendix Tables A2-a and A2-b. The power of unit root tests is sensitive to the number of lagged terms used. To choose the optimal number of lags, for all the unit root tests in this study, I employ Hall's (1994) *general to specific rule*, where one starts with a maximum number of lags, tests the significance of coefficient on the last lagged term, and reduces the number of lags iteratively until a significant statistic is encountered. Following others in the literature, the maximum lag length considered is

[7] In the US, cars and small trucks consumed between 75-80 percent of fuel used on highways from 1980-2000 (data from *National Transportation Statistics 2002*, US Department of Transportation). Data from Schipper et al. (1997) suggests a similar ¾ : ¼ energy

four. Ng and Perron (1995) found that Hall's approach is preferable to more common methods based on Akaike or Schwarz information criteria.

If two series that are each stationary only after differencing have a linear combination that is stationary without differencing, the series are said to be cointegrated. The finding of cointegration implies that two variables have a long-run equilibrium relationship and rules out Granger-noncausality. To test for cointegration, I use the Engle-Granger (1987) method,[8] in which the contemporaneous value of one variable is regressed on the contemporaneous value of the other, and the resulting residuals are tested for a unit root. For example,

$$y_t = \alpha + \delta t + \beta en_t + u_t \quad (1)$$

where *y* is the natural log of the appropriate aggregation of GDP (i.e., GDP per capita or total industrial GDP) and *en* is the natural log of the appropriate energy consumption aggregation (i.e., road and residential sector consumption per capita or total industry sector consumption). If u_t has a unit root (i.e., is nonstationary), then *y* and *en* are not cointegrated; however, if u_t does not have a unit root (i.e., is stationary), then *y* and *en* are cointegrated, and Equation 1 is a cointegrating relationship.

There are a few important additional points on cointegration tests. First, traditional critical values for unit root tests are not valid since the cointegration test is applied to *estimated* residuals. MacKinnon (1991) provides an approximation formula for computing critical values of the ADF and PP tests for all sample sizes. For the unit root test regression, I use *neither* a constant *nor* a trend term and apply both the ADF and PP tests (the DF-GLS test requires the use of at least a constant term; furthermore, I know of no studies that supply the appropriate critical values for use as a cointegration test). Next, the cointegration relationship (Equation 1) can have

consumption breakdown between passenger cars and freight in other IEA countries.

a constant term, constant and linear time trend terms, or neither such terms. I begin with both constant and trend terms, and test the significance of the trend term. Lastly, the results of the cointegration test can be sensitive to the choice of dependent variable in Equation 1; thus, I run the regressions both ways (i.e., with *y* and *en* on either side of the equation) and, following Banerjee et al. (1986), choose the equation with the highest R^2 as the cointegrating relationship. For robustness, I report the results (ADF statistic and R^2) for all four equations (either of two dependent variables with constant and trends or just constant term) in Appendix Tables A3-a and A3-b (the tables do not report the PP statistic since this nearly always agreed with the ADF test).

If two series are cointegrated, then a more comprehensive test of Granger-causality, called an "error-correction model," is used:

$$\Delta y = \alpha_1 + \sum_{i=1}^{l} \beta_{1i} \Delta en_{t-i} + \sum_{i=1}^{l} \gamma_{1i} \Delta y_{t-i} + \eta_{1i} ECT_{t-1} + u_{1t} \qquad (2)$$

$$\Delta en = \alpha_2 + \sum_{i=1}^{l} \beta_{2i} \Delta en_{t-i} + \sum_{i=1}^{l} \gamma_{2i} \Delta y_{t-i} + \eta_{2i} ECT_{t-1} + u_{2t} \qquad (3)$$

where *y* and *en* are the appropriate aggregations of GDP and energy consumption, respectively, Δ is a difference operator, *ECT* refers to the error-correction term derived from the long-run cointegrating relationship (i.e., u_t from Equation 1), and l is the number of lagged difference terms. The ECT term allows for an additional channel for Granger-causality to emerge, namely a long-run equilibrium relationship that is not treated in the standard Granger test. Equation 2 will be used to test causation from energy consumption to GDP, and Equation 3 will be used to test causation from GDP to energy consumption. Short-run causality is tested with an F-test on the sum of the lags of the explanatory variable (β's in Equation 2 or γ's in Equation 3). Long-run causality is tested by a T-test on the ECT term (η). Thus, depending on the outcome of these

[8] Maddala and Kim (2000) argue that there are shortcomings for both the Johansen and Engle-Granger methods, and only in the situation

tests, a relationship can exhibit short-run or long-run, unidirectional, bi-directional, or non-Granger-causality. Granger-causality results are often sensitive to the lag structure in Equations 2 and 3; hence, some studies have used various methods to determine an "optimal" lag structure. However, I am interested in discovering the robustness of causality, and thus, will allow *l* in Equations 2 and 3 to vary from four to one. If two series were found not to be cointegrated, then the standard version of the Granger-causality test (i.e., Equations 2 and 3 without the ECT term) would be performed to determine the direction of short-run causality.

3. Results and Discussion

3.1 unit root tests

For all countries the series natural log of total GDP from industry appears to be nonstationary in levels; the same is true for the log of total energy consumption by industry for most countries—the exceptions are Denmark, Mexico, and the UK, all for the constant only case. (The results of these unit root tests are contained in Appendix Table A2-a.) For the constant only case, the test statistic is just below the 10 percent critical level for Mexico when there are three lags; however, the third lag is just barely significant at the 10 percent level; if two lags are used instead, the statistic (-1.21) is well below the critical value. For the UK (as with Mexico) the trend term is significant, and the statistic is below the 10 percent level when the trend term is included. However, the trend term is not significant for Denmark; thus, we fail to reject that industrial energy consumption is stationary in levels.

For nearly all the series a unit root is strongly rejected in first differences; however, for a few series this is not true in the constant only case. For the constant only case, industry GDP is right at the 10 percent level for Australia when only two significant digits are considered. As for Japan for the same series and case, the statistic is well below the critical level when four lags are used;

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of cointegration tests among three and more variables is the Johansen method clearly preferable.

however, the fourth lag is right at the 10 percent significance level, and when only three lags are used, the statistic is significant at 10 percent. For the first differences of industry energy consumption for Greece and Mexico, a unit root is not rejected in the constant only case, but the trend term is significant for both of these series. More problematic is this same series for Italy and Japan. It is possible these series are order I (2); however, neither the trend nor constant term is statistically significant in the test regression on first differences, and if an ADF test (instead of DF-GLS) is performed without a constant or trend term, a unit root in first differences is rejected at the five percent level for Italy and the 10 percent level for Japan. Thus, I conclude that, with the exception of industry energy consumption in Denmark, all the industry series are of order I (1)—stationary in first differences but not in levels—and will proceed with the cointegration tests.

The null of a unit root was rejected for the GDP per capita series of three countries (results shown in Appendix Table A2-b). For both the US and UK the test statistic and the time trend term were significant in the constant and time trend case, whereas for Ireland the test statistic was significant in the constant only case while the time trend term was insignificant. Thus, stationarity in levels could not be rejected for these countries. On the other hand, there were three countries where it was unclear whether the first differences of GDP per capita were stationary. The test statistic is at the one percent level for Greece in the constant and time trend case, but not significant in the constant only case; however, the time trend term is significant in the test regression. For Spain, the test statistic in the constant and time trend case is just below the 10 percent level and over the 10 percent threshold in the constant only case; furthermore, the time trend term is not significant in the test regression. The case of Australia is less clear. It is possible that Australia is the rare case of GDP per capita being an order I (2) variable. However, in the trend and constant case, the fourth lag was not significant at the five percent level, and without that lag the test ultimately rejects a unit root at the one percent threshold (statistic is –4.98). Furthermore, a number of other unit root tests (PP, ADF, and Ng-Perron) reject a unit root in first differences at the ten percent level or higher for all test models (constant and trend term, constant only, and no constant). Thus, GDP per capita may be stationary in levels for Ireland, UK, and US; however, I will assume it is stationary in first differences for all countries in the sample.

The road and residential energy consumption per capita series appear to be nonstationary in levels for all the countries in the sample (results also shown in Appendix Table A2-b). There were four countries, however, where nonstationarity in first differences was not clearly rejected, most important for the next stage of the analysis are Belgium and Finland (since for Ireland and UK nonstationarity in levels for per capita GDP was rejected earlier). For Belgium, neither the constant nor time trend term is significant in the first difference test regression, and if an ADF test is performed without these terms, a unit root is rejected at the five percent level. For Finland, a unit root is rejected in the constant and time trend case, but not in the constant only case. In the constant only case, the second lag is just significant at the 10 percent level, and with only one lag the test statistic is close to the 10 percent level (-1.44); furthermore, the time trend term is significant in the test regression. Thus, I will assume these series are stationary in first differences for Belgium and Finland and proceed to cointegration tests on the per capita series for all countries except Ireland, UK, and US.[9]

[9] The decision rule for proceeding to a cointegration test with a series that may be I(0) in levels is a matter of debate. Some authors in the energy-GDP causality literature continue with series for which the null of nonstationarity in levels was rejected at the 10 percent level. However, Maddala and Kim (2000) argue that the pre-testing significance levels for cointegration analyses should be *much* higher than the standard 5 percent, perhaps as high as *25 percent*; thus, far fewer series ultimately would be analyzed for cointegration than is currently the case.

3.2 cointegration tests

The results of the cointegration tests for industry GDP and energy consumption are shown in Appendix Table A3-a. Only Belgium and Greece indicate a strong possibility of cointegration. For Belgium the ADF statistic is nearly at the five percent level, while for Greece it is right at the 10 percent level. The cointegrating relationship for Belgium has industry GDP as the dependent variable, while for Greece the independent variable is industry energy consumption. Thus, the error-correction model (Equations 2 and 3) will be used to test for the direction of causality for Belgium and Greece, whereas the standard Granger-causality model will be used for the other countries.

Appendix Table A3-b shows the results of the tests for cointegration between per capita GDP and per capita road and residential energy consumption. The test statistics for Greece and Spain imply cointegration at better than the five percent level, while the statistic is very near the 10 percent margin for Denmark. Thus, the error-correction model will be used to test for the direction of causality for Denmark, Greece, and Spain, whereas the standard Granger-causality model will be used for the other countries.

3.3 causality tests

Displayed in Table 1 are the results of the standard Granger-causality tests between industry GDP and industry energy consumption for lag lengths four through one for the 10 countries for which those series were I (1) and not cointegrated. Again, *a priori*, it was suspected that energy, as an element in the production function, should be found to cause GDP. However, the most robust finding was *no* Granger-causality relation between the two: the case for Australia, Canada, Italy, Japan, Korea, and Mexico. Only Finland displayed the expected relationship, for short lags (one and two). The UK showed by far the most robust causal relationship—although in the unexpected direction, and not readily explained—that GDP causes energy consumption. Turkey indicated a bi-causal relationship at the margins (i.e., the 10 percent level of significance), as did the US, also at the margins, but for high lags only.

Table 2 has the results of the temporal error-correction model for Belgium and Greece. Again, theoretically the finding of cointegration rules out Granger-noncausality; however, for Greece not even the ECT is robustly significant. This result suggests that for Greece, whose cointegration test statistic was at the margin anyway, the two series are in fact not cointegrated, and Greece is another example of Granger-noncausality between industry GDP and energy consumption. On the other hand, for Belgium the ECT was robustly significant when GDP was the dependent variable, indicating the existence of a long-run relationship in which industry energy consumption Granger-causes industry GDP. However, in the short-run the robust finding was, like for so many of the other countries, one of noncausality.

Displayed in Table 3 are the results of the standard Granger-causality tests between per capita GDP and per capita road and residential energy consumption for lag lengths four through one for the 12 countries for which those series were I (1) and not cointegrated. Again, *a priori,* it was suspected that income (or per capita GDP) should be found to cause this "consumptive" type of energy use. However, since these two series are of much higher aggregation than the industry series, e.g., some road energy consumption is part of production, it would not be as surprising to find causality in the other direction as it would for the industry case. Yet, again, by far the majority robust conclusion is Granger-noncausality: the finding for Australia, Canada, Finland, France, Italy, Korea, Mexico, Portugal, and Turkey. Only in the Netherlands does Granger-causality run unambiguously in the expected direction: from income to energy. Both Belgium and Japan indicate bi-directional Granger-causality, although for Belgium, the case that energy causes income appears more robust; whereas for Japan, the case that income causes energy is the more robust.

Lastly, Table 4 shows the results of the temporal error-correction model for Denmark, Spain, and Greece. Here, unlike the case in Table 2, the results reject Granger-noncauality for all countries; however, both the direction and temporal nature of causality is quite different among the three. Both Denmark and Greece show little to no evidence of short-run Granger-causality. In Denmark, the long-run relationship indicates that per capita road and residential energy consumption Granger-cause income, whereas for Greece long-run causality runs in the opposite (expected) direction, i.e., from income to energy consumption. For Spain, the curious result that long- and short-run Granger-causality run in opposite directions is found. The direction of long-run causality is the expected one, i.e., per capita GDP causes road and residential energy consumption; however, in the short-run energy consumption Granger-causes per capita GDP (although, the test statistic is only significant at the 10 percent level for longer lags).

Table 1. Results of the standard Granger-causality tests between industrial output (Δ y) and total industry sector energy consumption (Δ en)[a]

Null hypoth.	Δ y does not Granger cause Δ en				Δ en does not Granger cause Δ y			
Lags	4	3	2	1	4	3	2	1
AUS	2.62*	1.16	0.60	0.14	1.96	0.65	0.74	0.70
CAN	1.12	0.32	0.01	0.01	0.93	1.31	0.55	1.17
FIN	0.11	0.19	0.06	0.33	0.74	1.05	2.82*	3.99**
ITL	0.58	0.73	1.69	1.72	1.27	0.79	0.47	0.06
JPN	2.22*	1.07	0.04	0.60	0.33	0.26	0.66	0.14
KOR	1.90	1.74	0.62	2.16	2.78*	1.17	1.36	1.92
MEX	0.20	0.20	1.28	0.01	1.23	1.39	2.13	1.66
TUR	1.98	2.42*	2.53*	3.16*	2.48*	2.92*	0.24	060
UK	3.91***	4.69***	6.67***	10.44***	0.17	0.15	0.12	0.004
USA	2.70**	2.62*	1.88	2.47	2.18*	0.81	1.79	1.61

[a] Values are the F-statistics testing the null that all the lags of the independent variable are jointly equivalent to zero. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 2. Results of tests for temporal error-correction causality between industrial output (Δ y) and total industry sector energy consumption (Δ en)[a]

Lags	4		3		2		1	
Source of causation	ECT	Short-run Δ y/Δ en	ECT	Short-run Δ y/Δ en	ECT	Short-run Δ y/Δ en	ECT	Short-run Δ y/Δ en
BEL								
Dep Var								
Δ y	-2.36**	0.26	-3.43***	0.23	-3.42***	0.46	-3.14***	1.10
Δ en	-0.98	0.36	-1.06	0.42	-1.28	0.85	-1.09	0.64
GRC								
Dep Var								
Δ y	1.43	0.36	1.19	0.26	1.38	0.067	2.14**	0.082
Δ en	-0.26	0.42	-1.01	0.40	-0.87	0.99	-1.19	1.31

[a] Values beneath the columns labeled "ECT" refer to t-statistics testing the null that the error-correction term is equivalent to zero; "Short-run" column shows the F-statistics testing the null that all the lags of the independent variable are jointly equivalent to zero. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 3. Results of the standard Granger-causality tests between per capita GDP (Δ y) and per capita energy consumption in the road and residential sectors (Δ en)[a]

Null hypoth.	Δ y does not Granger cause Δ en				Δ en does not Granger cause Δ y			
Lags	4	3	2	1	4	3	2	1
AUS	0.45	0.46	0.93	0.92	1.35	1.54	2.06	1.73
BEL	1.41	2.70*	5.03***	3.52*	2.89**	3.95**	6.14***	5.13**
CAN	0.72	0.9	1.32	0.55	0.64	0.79	0.69	0.41
FIN	0.61	0.5	0.22	0.44	0.56	0.6	0.31	0.06
FRA	1.64	0.99	1.03	2.16	1.4	0.88	0.5	0.43
ITL	0.7	1.43	0.69	0.34	1.62	1.87	1.37	0.004
JPN	3.16**	4.68***	7.49***	16.41***	1.58	2.34*	2.04	9.27***
KOR	1.56	0.51	1.09	0.54	1.8	1.05	0.57	1.2
MEX	1.13	0.25	0.07	0.016	0.47	0.49	0.5	0.44
NED	0.49	0.68	0.07	0.1	5.01***	2.58*	5.73***	1.01
PRT	1.01	1.25	2.01	0.55	2.56*	1.84	2.33	1.5
TUR	0.3	0.52	0.94	2.16	0.83	0.92	1.11	0.25

[a] Values are the F-statistics testing the null that all the lags of the independent variable are jointly equivalent to zero. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 4. Results of tests for temporal error-correction causality between per capita GDP (Δ y) and per capita energy consumption in the road and residential sectors (Δ en)[a]

Lags	4		3		2		1	
Source of causation	ECT	Short-run Δ y/ Δ en	ECT	Short-run Δ y/ Δ en	ECT	Short-run Δ y/ Δ en	ECT	Short-run Δ y/ Δ en
DEN								
Dep Var								
Δ y	-3.26***	1.68	-2.65***	1.52	-2.43**	1.28	-2.41**	0.72
Δ en	-.0.099	0.89	-0.203	0.77	0.33	0.99	-0.205	0.46
ESP								
Dep Var								
Δ y	1.24	2.45*	0.61	2.58*	0.53	5.49**	0.74	2.02**
Δ en	-3.86***	1.31	-2.54**	0.46	-2.50**	0.70	-4.25***	0.04
GRC								
Dep Var								
Δ y	-0.48	2.49*	-1.24	1.74	-0.65	1.18	-0.28	0.38
Δ en	-2.01**	0.47	-3.18***	1.81	-3.01***	0.70	-2.23**	0.01

[a] Values beneath the columns labeled "ECT" refer to t-statistics testing the null that the error-correction term is equivalent to zero; "Short-run" column shows the F-statistics testing the null that all the lags of the independent variable are jointly equivalent to zero. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4. Summary, Conclusions, and Policy Implications

Hondroyiannis et al. (2002) also characterized the literature on energy consumption and economic growth causality as producing "neither conclusive results nor persuasive explanations." A reason for this generalization, offered here, is the very high degree of aggregation the previous studies have employed. In industrialized, developed countries energy is an input of production, and thus, could be expected to cause output (total GDP); however, in such countries, energy is also a final consumption good (e.g., in the form of personal transport or the space conditioning of homes), and thus, income (per capita GDP) should cause per capita energy consumption. This paper differs from previous energy-GDP causality studies by dissagregating the data in ways in which the direction of causality would be theoretically clear. Namely, two analyses were performed for a number of OECD/IEA countries: one considering total industrial GDP and total industrial energy consumption, and the other per capita GDP and the sum of road and residential energy consumption, also in per capita terms. The goal here was this level of disaggregation would produce consistent and theoretically convincing outcomes.

The results presented here are fairly robust, and for the most part, theoretically justified. The surprise was that the main, most common finding was of *no* cointegration and *no* causality. For example, of the 12 countries analyzed for industry energy-GDP casualty, only for Belgium was cointegration found (the test statistic for Greece was at the margin, but no statistically significant causality was uncovered by the error-correction model), and in only four additional countries was there a robust determination of short-run causality. Of the 15 countries tested for per capita road and residential energy consumption and per capita GDP cointegration, cointegration was found for only three, and no causality was the robust finding for nine countries. In total, long-run causality (through the error-correction term) was uncovered for only four countries, and short-run causality for only eight (Spain showed signs of both for road and residential energy consumption and per capita GDP). When causality was evident more often than not, it was either bi-directional or in the anticipated direction.

Industry, which of course also employs labor, physical capital, and technology, seems especially more independent of energy. However, it is possible the finding of no cointegration was caused by omitted variables—e.g., labor and physical capital in the case of industry. Stern (2000) performed, for the US, a multivariate analysis of this type—with the important exception that he considered *country-level* not industry-level aggregates—and found cointegration. Ideally, one would want only energy, labor, and capital used in industry along with a measure of industrial output, but much of this industry-specific data is difficult to get for a cross-section of countries. Moving in this direction is an obvious next step, however, the present study is a worthwhile endeavor in its own right by analyzing causality between meaningful aggregations of GDP and energy use for a large subset of developed economies. It also should be noted that the results shown here more complement than contradict those of Stern (2000). After all, short-run Granger-causality was found between industrial output and industrial energy use for the US.[10]

Again, the work closest to this one is that of Hondroyiannis et al. (2002), who considered total industrial and residential energy consumption and total GDP for Greece. Both Hondroyiannis et al. (2002) and this study found evidence of cointegration for Greece. However, it is argued here that cointegration between industrial energy consumption and industrial GDP (not total GDP) may have been spurious since none of the terms in the error-correction model displayed robust statistical significance. Hondroyiannis et al. (2002) also found that total residential energy consumption was cointegrated with total GDP; however, none of the terms in their error-correction model were statistically significant.[11] On the contrary, as reported here, when these series were converted to per capita terms (more appropriate since total residential energy consumption is also a function of total population), there was strong evidence of long-run Granger-causality running from income to energy consumption.[12]

Overall, it appears developed countries have more flexibility with respect to their energy consumption than had been thought. In terms of policy options, price could be a not-too-costly instrument in many developed countries to reduce their energy dependence/use. Of course, there would be a short-run adjustment procedure; however, the finding here of no cointegration for many countries implies these countries would not experience long-run disruptions. Lastly, basing projections of future energy demand on past GDP (or vice-versa) may not be justified for many countries.

[10] Furthermore, per capita GDP and per capita road and residential energy consumption were found to be cointegrated for the US; however, this result was not reported since the possibility that these two series were not of the same order of integration was not rejected at a high enough level.

[11] Hondroyiannis et. al. (2002) described this result as meaning the variables were "weakly exogenous," whereas I have judged a similar result to imply the original finding of cointegration possibly spurious.

[12] The results reported above of course involved the sum of per capita *road* and *residential* energy consumption and per capita GDP; however, a separate analysis (not shown) with just per capita residential energy consumption found it was cointegrated with per capita GDP too.

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Table A1. Range of data availability for industry's share of value added

AUS	1962-1996
BEL	1970-2000
CAN	1961-1993
DEN	1966-2000
FIN	1960-2000
GRC	1960-1995
ITL	1970-2000
JPN	1960-1997
KOR	1960-2000
MEX	1965-2000
TUR	1968-2000
UK	1960-2000
US	1960-1997

Table A2-a. Results from unit root tests on levels and first differences of total industry GDP and energy consumption in the industry sector using Dickey-Fuller with GLS detrending

	Natural log total GDP from industry				Natural log total energy consumption by industry			
	Levels		First differences		Levels		First differences	
	Trend & constant	Constant	Trend & constant	Constant	Trend & constant	Constant	Trend & constant	Constant
AUS	-1.51[4]	0.08[4]	-5.33[0]***	-1.58[3]	-2.46[0]	0.72[0]	-6.37[0]***	-5.95[0]***
BEL	-2.38[0]	-0.41[0]	-6.17[0]***	-6.04[0]***	-1.42[0]	-0.10[0]	-5.45[0]***	-5.37[0]***
CAN	-1.48[1]	-0.34[4]	-5.38[1]***	-3.85[0]***	-1.58[3]	-0.31[3]	-5.63[1]***	-2.67[2]***
DEN	-1.72[0]	0.75[0]	-3.43[4]**	-2.67[4]***	-2.45[0]	-1.68[0]*	-5.21[0]***	-1.68[2]*
FIN	-2.18[1]	0.19[1]	-4.43[1]***	-4.03[1]***	-1.64[0]	0.16[0]	-6.21[0]***	-5.05[0]***
GRC	-0.79[1]	-0.81[1]	-5.10[0]***	-3.31[0]***	-1.09[1]	-0.41[3]	-4.94[0]***	-0.87[4]
ITL	-1.69[0]	-0.62[1]	-4.71[0]***	-4.41[0]***	-1.65[3]	-0.52[3]	-2.01[2]	-1.42[2]
JPN	-0.96[4]	0.005[4]	-3.54[3]**	-0.58[4]	-1.90[3]	-0.67[3]	-1.18[4]	-0.63[4]
KOR	-1.10[1]	-0.84[4]	-4.84[0]***	-2.01[2]**	-1.42[0]	0.37[2]	-4.29[0]***	-3.89[0]***
MEX	-1.63[2]	0.12[2]	-4.98[0]***	-2.27[1]**	-1.11[2]	-1.56[3]	-8.47[0]***	-1.09[1]
TUR	-1.14[0]	0.05[1]	-5.23[0]***	-5.02[0]***	-1.10[0]	-0.31[4]	-5.07[0]***	-4.52[0]***
UK	-2.44[1]	-0.49[1]	-5.45[1]***	-5.35[1]***	-1.96[3]	-1.61[3]*	-5.99[0]***	-5.79[0]***
US	-2.79[1]	0.14[1]	-5.17[1]***	-4.99[1]***	-1.73[0]	-1.34[0]	-5.42[1]***	-5.26[0]***

The Elliott-Rothenberg-Stock DF-GLS test statistic is shown. The numbers in brackets are the optimal lags determined by Hall's general-to-specific procedure. Levels of significance are indicated by ***, **, and *, referring to the 1%, 5%, and 10% levels, respectively.

Table A2-b. Results from unit root tests on levels and first differences of per capita GDP and road and residential sector energy consumption per capita using Dickey-Fuller with GLS detrending

	Natural log GDP per capita				Natural log road & residential energy consumption per capita			
	Levels		First differences		Levels		First differences	
	Trend & constant	Constant	Trend & constant	Constant	Trend & constant	Constant	Trend & constant	Constant
AUS	-1.74[0]	0.32[1]	-1.97[4]	-1.06[4]	-0.90[0]	-0.19[1]	-6.11[0]***	-5.48[0]***
BEL	-1.33[2]	0.57[2]	-5.69[0]***	-2.62[1]***	-2.07[0]	-0.58[0]	-2.12[4]	-1.32[4]
CAN	-1.85[1]	0.34[1]	-4.33[0]***	-4.13[0]***	-1.69[4]	-1.13[4]	-4.77[0]***	-4.51[0]***
DEN	-1.73[3]	0.42[3]	-6.02[0]***	-1.71[2]*	-2.03[1]	-1.37[1]	-5.02[0]***	-4.57[0]***
ESP	-1.51[1]	1.92[3]	-2.75[0]	-1.83[0]*	-2.10[3]	-0.02[3]	-4.31[0]***	-2.04[2]**
FIN	-2.14[1]	0.65[1]	-3.93[1]***	-2.89[0]***	-0.65[2]	-0.29[3]	-5.02[0]***	-0.69[2]
FRA	-1.17[1]	0.43[2]	-4.35[0]***	-2.96[0]***	-2.13[0]	0.65[0]	-6.14[0]***	-6.04[0]***
GRC	-1.57[3]	0.08[3]	-4.94[0]***	-1.23[2]	-1.37[0]	0.23[2]	-4.61[3]***	-3.02[0]***
IRL	-0.82[1]	1.75[1]*	-3.84[0]***	-3.15[0]***	-1.60[0]	0.85[2]	-3.06[1]*	-1.59[2]
ITL	-0.76[1]	0.54[3]	-5.59[0]***	-3.21[0]***	-1.05[3]	0.27[3]	-4.84[0]***	-1.83[2]*
JPN	-1.01[1]	-0.32[3]	-3.77[0]***	-2.01[0]**	-1.29[3]	-0.28[3]	-5.76[0]***	-1.65[2]*
KOR	-2.23[0]	-0.057[3]	-5.54[0]***	-5.13[0]***	-2.37[0]	-0.49[4]	-5.99[0]***	-5.97[0]***
MEX	-1.65[1]	0.17[1]	-4.57[0]***	-4.60[0]***	-2.52[1]	-0.77[1]	-4.01[0]***	-4.00[0]***
NED	-1.99[1]	0.47[2]	-4.19[0]***	-3.40[0]***	-0.77[3]	-0.28[3]	-6.21[0]***	-2.95[2]***
PRT	-1.24[4]	0.17[3]	-3.93[3]***	-3.46[3]***	-2.03[0]	0.57[2]	-5.55[0]***	-5.54[0]***
TUR	-2.40[0]	0.28[3]	-6.48[0]***	-6.29[0]**	-1.70[0[	-0.38[0]	-6.47[0]***	6.31[0]***
UK	-3.92[1]***	0.73[1]	-5.30[1]***	-5.29[1]***	-2.16[0]	0.27[0]	-3.95[3]***	-1.34[4]
US	-3.44[1]**	0.74[1]	-4.91[0]***	-4.77[0]***	-1.86[1]	-0.78[1]	-3.74[0]**	-3.62[0]***

The Elliott-Rothenberg-Stock DF-GLS test statistic is shown. The numbers in brackets are the optimal lags determined by Hall's general-to-specific procedure. Levels of significance are indicated by ***, **, and *, referring to the 1%, 5%, and 10% levels, respectively.

Table A3-a. Results of cointegration tests (Engle-Granger method) between industrial output (y) and total industry sector energy consumption (en)[a]

Dep Var	y				en			
Co-intgrtn Eq.	Trend & constant		Constant		Trend & constant		Constant	
	ADF	R^2	ADF	R^2	ADF	R^2	ADF	R^2
AUS	-2.13[4]	0.892	-1.60	0.727	-3.08	0.877	-1.14	0.727
BEL	-4.04*	0.916	-1.58	0.244	-2.98	0.705	-1.28	0.244
CAN	-1.66	0.973	-1.69	0.957	-1.75	0.958	-2.39[3]	0.957
FIN	-2.49	0.948	-2.60	0.948	-2.77	0.958	-2.71	0.947
GRC	-3.41	0.982	-2.36	0.979	-3.70*	0.986	-2.43	0.979
ITL	-2.12	0.790	-2.23	0.016	-1.95	0.026	-2.09	0.016
JPN	-1.05[1]	0.985	-1.38[2]	0.808	-1.36[4]	0.930	-2.18[2]	0.808
KOR	-1.44	0.985	-1.44[1]	0.948	-1.49	0.967	-1.29[1]	0.948
MEX	-0.89	0.847	-0.14	0.814	-0.59[1]	0.838	-0.16	0.814
TUR	-1.21	0.955	-2.20	0.929	-3.19	0.951	-2.54	0.929
UK	-2.42[1]	0.846	-2.45	0.118	-1.72	0.420	-1.81	0.118
US	-3.12[1]	0.982	-0.21	0.054	-2.46	0.663	-2.03	0.054

For each pair of series, four cointegration equations were tried. The ADF test was performed on only the resulting residuals (i.e., no constant and no time trend in that test equation). See Section 2 for more details. The number in brackets is the optimal lags (when not equal to zero) determined by Hall's general-to-specific procedure. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. For example, with 40 observations, the critical values from MacKinnon (1991) are –3.68, -4.03, -4.74 for significance at the 10%, 5%, and 1% levels, respectively.

Table A3-b. Results of cointegration tests (Engle-Granger method) between per capita GDP (y) and per capita energy consumption in the road and residential sectors (en)a

Dep Var	y				en			
Co-intgrtn Eq.	Trend & constant		Constant		Trend & constant		Constant	
	ADF	R^2	ADF	R^2	ADF	R^2	ADF	R^2
AUS	-2.14	0.985	-0.44	0.874	-1.47	0.885	-1.07	0.874
BEL	-2.49	0.982	-0.84[4]	0.819	-3.74*	0.863	-1.78[4]	0.819
CAN	-3.34[4]	0.985	-0.12	0.393	-1.91	0.778	-1.36	0.393
DEN	-3.57	0.992	-0.12[2]	0.222	-3.35	0.822	-2.48	0.222
ESP	-4.92***	0.980	-4.89***	0.980	-4.25[4]**	0.988	-3.89[1]*	0.980
FIN	-3.41[1]	0.970	-1.22[1]	0.822	-3.10[1]	0.847	-2.92	0.822
FRA	-1.79[1]	0.948	-2.11	0.924	-2.10	0.968	-1.87	0.923
GRC	-2.88	0.953	-2.23	0.927	-4.29[2]**	0.986	-2.23	0.927
ITL	-2.41	0.995	-1.30	0.935	-2.60	0.977	-2.19	0.935
JPN	-2.84	0.994	-2.45	0.992	-2.71	0.992	-2.44	0.992
KOR	-2.21[1]	0.992	-1.82	0.970	-2.13	0.972	-1.92	0.970
MEX	-2.45	0.661	-1.87	0.390	-3.00[1]	0.825	-1.17	0.390
NED	-2.38	0.989	-0.10	0.607	-2.82	0.845	-2.04	0.607
PRT	-2.03	0.957	-2.10	0.952	-2.06	0.988	-1.68	0.952
TUR	-2.84	0.978	-1.62	0.887	-2.00	0.890	-1.82	0.887

For each pair of series, four cointegration equations were tried. The ADF test was performed on only the resulting residuals (i.e., no constant and no time trend in that test equation). See Section 2 for more details. The number in brackets is the optimal lags (when not equal to zero) determined by Hall's general-to-specific procedure. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. For example, with 40 observations, the critical values from MacKinnon (1991) are –3.68, -4.03, -4.74 for significance at the 10%, 5%, and 1% levels, respectively.