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ABSTRACT

The share of a population living in urban areas, or urbanization, is both an important demographic, socio-economic phenomenon and a popular explanatory variable in macro-level models of energy and electricity consumption and their resulting carbon emissions. Indeed, there is a substantial, growing subset of the global modeling literature that seeks to link urbanization with energy and electricity consumption, as well as with carbon emissions. This paper aims to inform both modelers and model consumers about the appropriateness of establishing such a link by examining the nature of long-run causality between electricity consumption and urbanization using heterogeneous panel methods and data from 105 countries spanning 1971-2009. In addition, the analysis of the time series properties of urbanization has implications both for modelers and for understanding the urbanization phenomenon. We consider total, industrial, and residential aggregations of electricity consumption per capita, three income-based panels, and three geography-based panels for non-OECD countries. The panel unit root, cointegration, and causality tests used account for cross-sectional dependence, nonstationarity, and heterogeneity—all of which are present in the data set. We cannot reject pervasively Granger causality in the urbanization to electricity consumption direction. However, the causality finding that is both the strongest and most similar across the various panels is that of long-run Granger causality from electricity consumption to urbanization. In other words, the employment and quality of life opportunities that access to electricity afford likely encourage migration to cities, and thus, cause urbanization. Also, nearly all countries' urbanization series contained structural breaks, and the most recent post-break annual change rates suggested that nearly all countries' rates of urbanization change were slowing. Lastly, future modeling work on energy consumption or carbon emissions should consider subnational scales of analysis, and focus on measures of urban density or urban form rather than national urbanization levels.

Keywords: urbanization and electricity; long-run panel Granger causality; panel unit roots; cross-sectional dependence; panel heterogeneity.

1. Introduction

Increases in anthropogenic greenhouse gas emissions and concentrations—which predominately result from the combustion of fossil fuels—are believed to have caused most of the recent increases in global average temperatures, i.e., climate change. The increased interest in how energy consumption and its resulting carbon emissions impact climate, coupled with the availability of yearly, national-level data (from sources like the World Bank and International Energy Agency) covering various aggregations of energy consumption and socio-economic variables, has helped spur a substantial number of empirical analyses that estimate the socio-economic drivers of that consumption and emissions. Moreover, urbanization has become an important phenomenon—the level of world urbanization (the share of a population living in urban areas) crossed the 50% mark in 2009, and the United Nations expects that over the next 40 years urban areas will absorb all of the projected 2.3 billion global population growth while urban areas will continue to draw in some rural population; thus, the importance of that phenomenon has led several empirical analyses or models to include urbanization as a potentially key socio-economic driver. Indeed, 13 of the 21 papers listed in Table 1 were published from 2009 forward—Table 1 lists the studies that have examined the link between urbanization and energy or electricity consumption. A similar number of very recent papers have focused on the link between urbanization and energy consumption's resulting carbon emissions, e.g., Knight et al. 2013.

The first of these studies focused on developing countries and found a positive, significant relationship between urbanization and energy consumption (Jones 1989; Burney 1995; Parikh and Shukla 1995). More recent, similar studies have considered developed countries as well, disaggregated energy consumption, and provided additional explanatory variables; and those studies have typically confirmed the positive relationship between urbanization and energy consumption (see the listing in the top panel of Table 1).

The papers shown in the top panel of Table 1 all assumed a one-way causal direction, i.e., urbanization causes energy or electricity consumption; yet, it is possible energy or electricity consumption causes urbanization by motivating rural-urban migration. Studies that test for the possibility of a mutual causal relationship between urbanization and energy or electricity (shown in the bottom panel of Table 1) have focused on single countries or panels consisting of a relatively small sample of countries. In this paper we examine the potentially bi-directional causal nature of the urbanization and electricity consumption relationship considering several different aggregations of electricity consumption, panels of a large number of developed and developing countries, and the long-run panel version of Granger causality recommended by Canning and Pedroni (2008). Our analysis of a large number of countries' urbanization series and our finding of a bi-directional causal relationship between electricity consumption and urbanization (i) have several important implications for modelers; and (ii) suggest that the policy proscriptions derived from models that do not allow for this bi-directional causal possibility may not be so straightforward.

Table 1

2. Urbanization and energy or electricity consumption links

A key reason urbanization tends to accompany economic development is the industrialization process through which the typically rural agricultural labor force migrates to the typically urban manufacturing factories. The co-evolving movement of people from rural to urban areas and from agricultural to industrial employment causes energy consumption to increase in at least three ways: (1) agricultural operations must mechanize as they become less labor intensive; (2) urbanization spatially separates food consumers from food producers, thus necessitating a transport requirement that did not exist under traditional agriculture and settlement patterns; and (3) modern (or industrial) manufacturing uses more energy per unit of output and per worker than does traditional agricultural and manufacturing (Jones 1991).

Beyond employment prospects, development can encourage urbanization through the same rural-urban migration for other opportunities like access to culture, education, and health care, and hence, lead to increased energy consumption. Insofar as urbanization is associated with economic growth (e.g., Wheaton and Shishido 1981), urbanization may lead to greater energy consumption since energy consumption is a normal good. Moreover, cities or urban areas tend to control (or produce) a disproportionate amount of national GDP (Beall and Fox 2009; Liddle 2013a)—in part because of the presence of manufacturing. Hence, urbanization could lead to greater demand for manufactured goods—and, thus, more energy consumption in manufacturing. Lastly, urbanization is often considered a proxy for the amount of people with access to a country's energy or electricity grid—thus, more and wealthier people with such access would lead to more energy and electricity consumption. That driver may be particularly important in developing countries, as Holtedahl and Joutz (2004) argued was the case for Taiwan, Halicioglu (2007) for Turkey, Liu (2009) for China, and Adom et al. (2012) for Ghana.

Of course, causality in the opposite direction may occur, too: rural-urban migration to fill manufacturing jobs means that energy consumption in manufacturing causes urbanization if that consumption reflects employment in the presumably urban manufacturing sector. Moreover, manufacturing labor is more productive than traditional agricultural labor—hence, migrants are attracted to cities by higher wages; and thus, manufacturing energy consumption (a proxy for manufacturing) helps to cause urbanization. Likewise, migration motivated by the improved quality of life that energy and electricity may bring (e.g., space conditioning, refrigeration, and machine washing) also means that energy consumption causes urbanization.

We test for mutual or bi-directional causality between urbanization and several aggregations of electricity consumption. We focus on industrial and residential electricity consumption, rather than energy consumption, because of electricity's role in the so-called Second Industrial Revolution (Rosenberg 1998) and electricity's unique ability to light and cool buildings and to power appliances. We also consider aggregate electricity consumption--comprised of (i) electricity consumption in commercial buildings, which would have a similar employment-migration story as industrialization, (ii) electricity consumption in residential buildings, (iii) electricity consumption in manufacturing, and (iv) a small amount of electricity consumption in transport (in 2010, transport represented 2% of total electricity consumption in non-OECD countries and 1.2% in OECD countries). For the reasons discussed above, we expect urbanization and those various aggregations of electricity consumption to have a mutually reinforcing causal relationship.

We do not consider road transport energy consumption (as did Poumanyvong et al. 2012), because there is some evidence that national urbanization levels are not a particularly good indicator of transport demand (Liddle and Lung 2010). Indeed, there is a substantial literature using city-based data that has shown a strong negative relationship between urban *density* and transport (e.g., Newman and Kenworthy 1989; Kenworthy and Laube 1999; Karathodorou et al. 2010; Liddle 2013a). Furthermore, national urbanization levels and urban density are negatively correlated (Liddle 2013a). Similarly, we do not consider aggregate transport energy consumption since this measure would include rail (freight and intercity passenger) and air transport, both of which transport modes are likely influenced by geographic factors other than urbanization, like the distance between major cities; and such consideration is beyond the scope of the present analysis. (However, for comparison purposes, we consider aggregate energy consumption in Appendix Table A.2, despite the fact that this measure includes a substantial amount of the previously discussed energy consumption from transport.)

3. Data, pre-testing results, and panel Granger causality testing methods

Urbanization, or the share of people living in urban areas, comes from the World Bank. Per capita total final electricity consumption, per capita industry electricity consumption, and per capital residential electricity consumption are in thousand tons of oil equivalent (ktoe) and are sourced from the International Energy Agency. All variables are converted to natural logs. The data span 1971-2009. To determine whether panel Granger causality varies according to income level, we form three balanced income-based panels (high, middle, and low income). Hence, for total electricity we have three panels of 37, 40, and 28 countries; for industry electricity there are three panels of 35, 37, and 25 countries; and for residential electricity there are three panels of 33, 33, and 25 countries. Lastly, to determine whether there are geographic differences in Granger causality, we divide the non-OECD countries into three geographical-based panels: Africa, Asia (which includes Korea but not Japan), and Latin America and Caribbean (containing 24, 13, and 22 countries, respectively). (Appendix Table A.1 lists the country make-up of each of the panels.)

Figure 1 demonstrates how closely related urbanization and electricity consumption are: it plots the natural log of urbanization and the natural log of per capita total final electricity consumption for 105 countries over 1971-2009. For 63 countries the correlation coefficient between the two series is at least 0.90, and the correlation coefficient is greater than 0.50 for 93 countries. The two series are only marginally correlated (coefficient less than 0.05) for four countries (Democratic Republic of Congo, Haiti, Trinidad and Tobago, and Zimbabwe); whereas, for only five countries are the two series negatively correlated (Egypt, Ghana, Romania, Sri Lanka, and United Arab Emirates). Urbanization is similarly highly positively correlated with residential and industrial electricity consumption per capita with 81 of 91 countries and 70 of 97 countries, respectively, having a correlation coefficient of 0.50 or higher.

Figure 1

3.1 Panel unit root tests: results and implications

The causality tests of Granger (1969) and Sims (1972) assume that the time series analyzed are stationary; hence, the first step is to examine the stationarity properties of the panel data. A nonstationary panel process is one in which its means and/or variances change over time. A nonstationary series is integrated order *d*, denoted *I*(d), if it becomes stationary after being first differenced *d* times. If a series in levels is found to be nonstationary, while in first differences that series is found to be stationary, that series is integrated order 1, or *I*(1).

Several panel unit root tests have been developed to determine the order of integration of panel variables. Many of these tests assume that the cross-sections are independent; yet, for variables like urbanization, electricity consumption per capita, and energy consumption per capita, cross-sectional dependence is likely because of, for example, regional and macroeconomic linkages. Hence, more recently, panel unit root tests have been developed that relax this independence assumption.

The Pesaran (2004) CD test employs the correlation coefficients between the time-series for each panel member to test for cross-sectional dependence (the null hypothesis of the test is cross-sectional independence). Indeed, using the Pesaran (2004) CD test, cross-sectional independence can be rejected for all the variables, and the resulting absolute value mean correlation coefficients are high (results shown in Table 2).

Table 2

Bai and Carrion-i-Silvestre (2009) developed panel unit root tests that take into account possible cross-sectional dependence, and structural shifts of economic conditions by allowing multiple endogenous breaks. Cross-sectional dependence is captured through common factors as described in Bai and Ng (2004) and Moon and Perron (2004). Those common factors can be either stationary or difference stationary, and the automatic selection of the number of factors (with the maximum set at five) is determined by minimizing the Bayesian information criterion. The test is also flexible enough to allow countries to have structural shifts—at different times and with different magnitudes—that affect either the slope or the level. Breaks in trend have been demonstrated to occur in energy consumption series, and, given that urbanization is slow moving, that population agglomerations can be recharacterized, and that some intervening urbanization data points are based on trend modeling, breaks in urbanization series would not be surprising. Hence, the test's flexibility makes it particularly suitable for panel data that contain considerable heterogeneity (such as our data).

The Bai and Carrion-i-Silvestre test produces two sets of three statistics; we report in Table 3 the set of simplified test statistics (of which the P^*_m statistic is best suited for large N panels according to Bai and Carrion-i-Silvestre). The test results provide strong evidence that all four panel series are nonstationary, and that they are $I(1)$ processes: in levels, for no variable is the null hypothesis of a unit root rejected by all three test statistics; but in first differences, for each variable, the null hypothesis of a unit root is rejected by all three tests.

Table 3

We expected all the variables analyzed here would be $I(1)$ because: (i) they are all highly trending and stock-based, and thus, unlikely to have constant means; and (ii) a substantial number of previous panel analyses have determined these variables or similar ones to be $I(1)$. Indeed, there is a particularly large literature that performs causality tests on GDP and energy or electricity consumption, and these papers have unanimously found energy and electricity aggregations to be $I(1)$ (see Payne 2010 for a survey). Yet, there is some confusion as to urbanization's order of integration. All of the papers listed in the bottom panel of Table 1 concluded that urbanization was $I(1)$, as did Holtedahl & Joutz (2004) and Adom et al. (2012). By contrast, both Poumanyvong & Kaneko (2010) and Martinez-Zarzoso & Maruotti (2011) performed panel unit root tests and concluded that urbanization was $I(0)$. However, those last two studies used tests that did not allow for cross-sectional dependence or structural breaks.

Again, urbanization is clearly stock-based and rarely, if ever, declines (Sri Lanka, for which urbanization levels declined throughout the study period, is an outlier in this respect); also, the potential for breaks in urbanization series was mentioned above, too. Hence, it is possible that those two papers' use of unit root tests that did not take into account cross-sectional dependence and structural breaks led to the potentially erroneous conclusions of $I(0)$. Indeed, Liddle (2013b), considering, separately, cross-sectional dependence and structural breaks, determined the logistic transformation of urbanization to be $I(1)$ for panels of developed and developing countries.

Figure 2 displays a histogram of the timing of the breaks in the urbanization series. The figure indicates the importance of considering breaks when analyzing urbanization since nearly all countries (93%) experienced a break; most countries (78%) had two breaks, and many countries (52%) had three. Yet, most of the breaks occurred at five-year intervals (e.g., 1980, 1985, 1990, 1995, 2000); hence some of the breaks likely represent reassessments of urban areas (as discussed above), and those reassessments apparently are becoming less frequent over time. By contrast, most countries did not have a break in their electricity consumption series, and very few countries had two or more breaks.

Figure 2

If we assume that the change in urbanization since the last break in a country's urbanization series to 2009 is that country's current urbanization path, then the break analysis suggests that urbanization is slowing throughout the world despite the trend toward higher urbanization levels. (Some slowing of urbanization growth is expected *a priori* since urbanization is limited at 100 percent.) The median change in urbanization post-break is less than one-half of one percent per year. Also, for nearly 75% of countries the post-break annual rate of change is less than the annual rate of change for the entire period—indicating that the break in the series represents a slowing down of the urbanization process. Furthermore, for only seven countries is the post-break annual rate of change substantially (i.e., more than one-half of one percent) greater than the annual rate of change for the entire period.

Lastly, many developed countries are fully urbanized (Henderson 2003). Yet, several such countries have stopped urbanizing at substantially different levels. For example, the level of urbanization has changed very little since 1950 for both Austria and Belgium; yet, their current urbanization levels are substantially different, 68% and 97%, respectively. As a further example, if we rank countries according to their post-break annual urbanization change rate, and assume countries in the lowest quartile (i.e., ones with the slowest current rates of change) are fully urbanized, then the ultimate, fully urbanized share of population living in urban areas would have a mean of 76 and standard deviation of 20. In other words, even the achievement of full urbanization is highly heterogeneous.

3.2 Panel cointegration tests

If two variables are integrated order one, a next step is to test for cointegration, i.e., whether there is a long-run relationship between them. Engle and Granger (1987) pointed out that a linear combination of two or more nonstationary series may be stationary. If such a stationary linear combination exists, the nonstationary series are said to be cointegrated. A finding of cointegration between two variables rules out the possibility of no long-run Granger causality.

The Westerlund and Edgerton (2008) panel cointegration test allows for both structural breaks and cross-sectional dependence. As above, cross-sectional dependence is captured through common factors via the Bai and Ng (2004) approach. Break points are estimated following the Bai and Perron (1998) strategy. The Westerlund and Edgerton tests produce two statistics for each of the three endogenous structural break assumptions (break in trend, break in level, and no break). These results, shown in Table 4, reject the null of no cointegration for all three variable pairs.

Table 4

3.3 Panel long-run Granger causality tests

To determine the direction of panel long-run causality we employ the panel adjustments to traditional Granger causality suggested by Canning and Pedroni (2008). A variable, *y*, is said to be Granger caused by another variable, *x*, if *x* helps in the prediction of *y*; hence the definition relies heavily on the idea that the cause must occur before the effect. Thus, Granger causality measures precedence and information content, but does not by itself prove causality, i.e., that *y* is the effect or result of *x*, any more than any statistical test can prove causality. The Granger definition of causality has been widely applied, across many disciplines because it is simple, robust, and extendable even though it does not capture all aspects of causality (e.g., instantaneous causality, or the case in which the forward looking behavior of humans results in an action that is caused by a predictable event but happens before the event—Christmas causes shopping, not the other way around). Important for our purposes, the Canning and Pedroni approach to Granger causality allows for high degree of heterogeneity in long-run causality, unlike the more conventional pooled approach to vector error correction modeling (VECM), which assumes the long-run relationship is the same for all members of the panel.

Since in each country all of the series are individually nonstationary (from the tests reported in Table 3), but the electricity consumption and urbanization pairs together are cointegrated (from the tests reported in Table 4), these series pairs can be represented in a dynamic error correction model (ECM). The first step in the two-step Granger causality procedure is to estimate the cointegrating relationship for each country using fully modified ordinary least squares (FMOLS). (FMOLS is a nonparametric approach in which an initial estimation calculates the serial correlation and endogeneity correction terms that are commonly used to estimate the long-run relationship for nonstationary, cointegrated variables.)

For any country, *i*, the long-run relationship between urbanization, *urban*, and some aggregation of electricity consumption, *elec*, can be described as:

$$urban_{it} = a_i + b_t + \beta elec_{it} + e_{it} \tag{1}$$

where subscript *t* denotes the *t*th time period and *e* is the error term.

In the second step the ECM is estimated:

$$\Delta urban_{it} = c_{1i} + \lambda_{1i} e_{it-1} + \sum_{j=1}^{K_i^1} \varphi_{11ij} \Delta urban_{i,t-j} + \sum_{j=1}^{K_i^1} \varphi_{12ij} \Delta elec_{i,t-j} + \varepsilon_{1it} \tag{2}$$

$$\Delta elec_{it} = c_{2i} + \lambda_{2i} e_{it-1} + \sum_{j=1}^{K_i^2} \varphi_{21ij} \Delta urban_{i,t-j} + \sum_{j=1}^{K_i^2} \varphi_{22ij} \Delta elec_{i,t-j} + \varepsilon_{2it} \qquad (3)$$

where Δ is the first difference operator (which converts the underlying unit root data into stationary process), K is a country-specific lag length, and e_{it-1} is the one period lag of the residuals from the estimated long-run cointegrated regression from the first step (Equation 1).

The ECM is estimated individually for each country. A t-test on the point estimate for λ_{1i} (from Equation 2) would be a test on long-run Granger causality from *elec* to *urban*, and accordingly, a t-test on the point estimate for λ_{2i} (from Equation 3) would be a test on long-run Granger causality from *urban* to *elec*. However, the reliability of those point estimates and associated t-tests for any one country are likely to be poor because of the data's relatively short time span. Hence, Canning and Pedroni (2008) proposed two panel-based statistical tests created from those country-by-country ECM estimations. The group mean 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 Granger causal effect for the panel. The lambda-Pearson test is based on the p-values associated with each of those individual country t-tests. That test statistic has a chi-square distribution under the null hypothesis of no long-run Granger causal effect for the panel.

When the group mean test fails to reject, but the lambda-Pearson test does reject the null of no causality, we have evidence that Granger causality is heterogeneous in the panel. In other words, although Granger causality was rejected for the panel as a whole, Granger causality was not rejected pervasively throughout the panel (e.g., λ_{1i} is on average zero, but it is not pervasively zero). The interpretation of these two panel statistics reflects an important, but perhaps seemingly paradoxical point regarding heterogeneous panel analysis. Panel analysis can produce plausible estimates even when individual country estimates can be nonsensical or difficult to interpret (e.g., Boyd and Smith 2002; Mark and Sul 2003)—this is particularly true when the time dimension is relatively short (as in the present analysis). Heterogeneous methods are preferred over homogeneous ones because if one mistakenly assumes that relationships are homogeneous, when the true coefficients of a dynamic panel indeed are heterogeneous, then all of the panel parameter estimates will be inconsistent (Pesaran and Smith 1995). Yet, heterogeneous panel analysis seeks to understand relationships that are likely true for groups of countries by generalizing from individual country relationships; it does so rather than seek to understand the specific situation in a particular country or to understand why relationships might differ among countries—hence, we focus our Granger causality analysis primarily on the results of the group mean test. Lastly, given the predominance of a strong, positive correlation between urbanization and electricity consumption (discussed above and demonstrated in Figure 1), we assume that, at least at the panel level, any causal relationship between the two variables will have a positive sign.

4. Discussion of panel long-run Granger causality results

Table 5 shows the results for the three income-based panels. Considering those results for all three electricity aggregations (total, industry, and residential), that electricity consumption Granger *causes* urbanization is much more supported than that urbanization Granger causes electricity consumption. The group mean test cannot reject that the average value for λ_2 is zero, i.e., we cannot reject the null hypothesis that urbanization does not Granger cause electricity consumption on average, for each aggregation of electricity and for each income group. By contrast the group mean test does reject the null hypothesis of no Granger causality from electricity consumption to urbanization for several aggregations and income groupings. Hence, it is likely the employment and quality of life opportunities that access to electricity afford do encourage migration to cities, and thus, cause urbanization.

For all electricity aggregations and income groups, however, the lambda-Pearson tests strongly indicate that the long-run Granger causal effects are pervasively non-zero in both directions for countries individually. Hence, in each panel there is some evidence of Granger causality from urbanization to electricity consumption and from electricity consumption to urbanization.

Table 5

The results for total energy consumption (shown in Appendix Table A.2) are similar to the results presented in Table 5 in that (i) no Granger causality from urbanization to energy consumption is never rejected, but (ii) the lambda-Pearson tests always reject that Granger causality from urbanization to energy consumption is pervasively zero. However, there is less evidence that energy consumption Granger causes urbanization—the group mean test rejects no Granger causality only for the high income panel and only at the 10% significance level. The lack of any strong Granger causality evidence for total energy consumption likely reflects that transport energy consumption contributes substantially to total energy consumption, and as discussed above, the causal link between transport energy consumption and urbanization is tenuous at best.

Table 6 displays the Granger causality results for the three geography-based panels. The results are mostly similar to those for the income-based panels. Again, a long-run Granger causal effect is evidenced on average only for electricity consumption Granger causes urbanization since the group mean statistic is significant only for those tests (although it is not always significant). However, as before, Granger causality from urbanization to electricity consumption could not be pervasively rejected since the lambda-Person test is always significant.

Table 6

For the most part, the results are similar across the three geographic panels, except that an average long-run effect was never significant for electricity consumption Granger causes urbanization for the Latin America and Caribbean panel. Latin America and Caribbean urbanized much earlier than either Africa or Asia, and currently has much higher average levels of urbanization than Africa or Asia, which may explain the lack of a Granger causality finding for Latin America and Caribbean on average.

While we consider as large a group of countries as data availability (for balanced panels) allows, our sample of countries is neither a random sample nor a comprehensive grouping of all countries. Yet, the results show a high degree of consistency—particularly with respect to (i) the non-rejection of no Granger causality from urbanization to electricity consumption, and (ii) the finding that Granger causality in either direction could never be pervasively rejected—across panels comprised of countries of different income levels and different geography; such consistency suggests that selection bias is unlikely to influence the results.

Finally, to further consider the heterogeneity of the Granger causality results, we count the number of countries for which the null hypothesis of no Granger causality was rejected at the 10% level for at least one direction (from urbanization to electricity consumption or from electricity consumption to urbanization). For total, industry, and residential electricity consumption 82 of 105, 67 of 97, and 70 of 91 countries, respectively, exhibited Granger causality—a substantial and highly statistically significant number (under the null hypothesis of no causality, the *percentage* of countries rejecting that null hypothesis at the 10% significance level has an expected value of 10 and a standard deviation of $30N^{-1/2}$, where N is the number of countries). The countries that failed to reject no Granger causality in both directions were comprised of high, middle, and low income countries in proportions similar to the overall make-up of the panels with two exceptions. A disproportionate number of countries that failed to reject no Granger causality for industry electricity were low income (13 of 30), and a disproportionate number of the countries that failed to reject no Granger causality for residential electricity were high income (10 of 21). Perhaps the most common characteristic among countries that failed to reject no Granger causality was that they did so for more than one electricity aggregation: 18 countries failed to reject no Granger causality for two of the three electricity aggregations and four countries (Argentina, Austria, Germany, and Morocco) failed to reject no Granger causality for all three aggregations. Again, there were no obvious similar characteristics among the countries with multiple no Granger causality results: they came from all three income groupings, and roughly a quarter of them were in the lowest quartile for the post-break urbanization annual rate of change (i.e., the presumed fully urbanized countries). Hence, the lack of Granger causality in both directions among some countries appears to be a result of country specific, idiosyncratic factors.

5. Conclusions

Over half of the world's population now lives in cities, and by the century's end, every country will be at least three-quarters urban (UN Population Division 2004). Yet, the analysis of the time series properties of urbanization, including the calculation of most recent post-break annual rates of change for the 105 countries considered here suggested (i) that the urbanization process is slowing—most recent rates of urbanization are lower than the overall (1971-2009) rates, and (ii) that countries achieve full urbanization at substantially different levels.

Our most substantial evidence on the long-run causal relationship between aggregations of electricity consumption and urbanization was that electricity consumption Granger causes urbanization in the long-run--and not the other way around—for panels based on both income and geography. Since rural-urban migration is an important contributor to the increased share of populations that live in cities (i.e., urbanization), the drivers of urbanization are similar to the drivers of that migration. Thus, our results suggest that electricity consumption is at least a proxy for, if not a cause of, both modern (i.e., nonagricultural) employment and improved quality of life opportunities (like lighting, space conditioning, communication technologies) attributable to access to electricity that help to encourage (or cause) rural-urban migration.

Yet, a Granger causal relationship could not be pervasively rejected in either direction (from urbanization to electricity consumption or from electricity consumption to urbanization) for any of the aggregations of electricity (total, industry, or residential), nor for any of the panels (high-, middle-, or low-income, or Africa, Asia, or Latin America and Caribbean). Hence, there was evidence of Granger causality for at least some countries in each direction. However, Granger causality or average long-run effects for a panel could be established only in the direction of electricity consumption to urbanization (i.e., the only cases in which the group mean statistic was significant).

Urbanization has been used as an explanatory variable in a substantial and growing number of particularly recent studies that seek to explain energy and electricity consumption or their resulting carbon emissions. This paper provides evidence of two challenges for modelers who wish to include urbanization in their models. First, urbanization series themselves present several statistical challenges: (i) they contain structural breaks; (ii) they are likely nonstationary; and (iii) they are highly cross-sectionally correlated (i.e., they are not independent); despite (iv) exhibiting a high degree of heterogeneity in, for example, number and timing of breaks, post-break rates of change, and ultimate level of full urbanization. Second, the urbanization-electricity causal relationship may be bi-directional—i.e., electricity consumption should not be modeled as a simple one-way function of urbanization; indeed, the causal relationship may be primarily in the direction of electricity consumption causing urbanization. To address these issues one might employ time-series based methods and account for possible endogeneity or mutual causality via cointegration and vector error correction modeling (as done here and in the papers in the lower panel of Table 1). However, we would recommend avoiding the urbanization (share of population living in urban areas) variable altogether. Rather, we recommend that future work focusing on the urbanization phenomenon (the increasing number of the world's people who live in urban areas) and energy consumption or emissions consider subnational scales of analysis, like metropolitan areas. Again, there is already a substantial literature (perhaps beginning with Newman and Kenworthy 1989) that uses urban form or density to explain transport energy consumption and emissions. However, there are relatively few papers that analyze urban form's or density's impact on other aggregations of energy or electricity consumption or on levels of greenhouse gas emissions (exceptions are Lariviere and Lafrance 1999 and Marcotullio et al. 2012, respectively).

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Table 1. Summary of urbanization-energy/electricity consumption analyses.

Studies testing for an assumed urbanization causes energy or electricity consumption relationship

Study	Dependent variable	Method	Country/ies (period)	Urbanization results
Jones (1989)	Modern energy per capita	OLS	59 developing countries (1980)	+ 0.45
Burney (1995)[a]	Electricity consumption per capita	OLS	93 countries (1990)	+0.01
Parikh & Shukla (1995)	Energy consumption per capita	FE OLS	78 developed & developing countries (1965-1987)	+ 0.28
Holtedahl & Joutz (2004)	Residential electricity per capita	Cointegration, ECM	Taiwan (1955-1995)	+ 1.61
Liddle (2004)[a]	Road energy use per capita	FE OLS	23 OECD countries (1960-2000, 10-yr intervals)	-0.47
York (2007a)	Total energy consumption	Prais-Winsten regression	14 EU countries (1960-2000)	+ 0.53
York (2007b)	Total energy consumption	Prais-Winsten regression	14 Asian countries (1971-2002)	-0.22 (level); 0.37 (quadratic)
Jorgenson et al. (2010)	Total energy consumption	FD OLS	57 less developed countries (1990-2005)	+ 0.37
Liddle & Lung (2010)	Total residential electricity consumption	FD FE OLS	16 OECD countries (1960-2005, 5-yr intervals)	+ 1.92
Poumanyvong & Kaneko (2010)	Total energy consumption	FD FE OLS	99 countries (1975-2005)	+0.91 (HI); +0.51[b] (MI); -0.12[b] (LI)
Adom et al. (2012)	Total electricity consumption	ADRL, ECM	Ghana (1975-2005)	+ 0.62
Poumanyvong et al. (2012)	Total road transport energy use	FE OLS	92 countries (1975-2005)	+1.33(HI); +0.37(MI); +0.81(LI)
Fang et al. (2012)	Total primary energy use	FD system GMM	94 countries (1981-2007)	-0.01 (HI); NS (LI)

Studies testing for possible bi-directional causality between energy or electricity consumption and urbanization

Study	Dependent variable	Method(s)	Country/ies (period)	Causality	Urbanization elasticity
Halicioglu (2007)	Residential electricity consumption per capita	ADRL, ECM	Turkey (1968-2005)	No causality	0.04[b]
Liu (2009)	Total energy consumption	ADRL, ECM	China (1978-2005)	Urbanization→ energy (+)	NS
Mishra et al. (2009)	Energy consumption per capita	Panel cointegration & Granger causality	9 PIC (1980-2005)	Urbanization→ energy (+)	2.41
Gam & Ben Rejeb (2012)	Electricity consumption	Cointegration, error correction, & Granger causality	Tunisia (1976-2006)	Urbanization ←→ electricity (+)	NS
Michieka & Fletcher (2012)	Coal consumption;	Toda & Yamamoto version of Granger causality	China (1971-2009)	No causality	NA
	Electricity production from coal sources			Urbanization →electricity (+)	
Shahbaz & Lean (2012)	Energy consumption per capita	ADRL, Granger causality	Tunisia (1971-2008)	Energy → urbanization (+)	0.87
Al-mulali et al. (2013)	Energy consumption per capita	Granger causality, DOLS	20 MENA countries (1980-2009)	Energy ←→ urbanization	0.57
Solarin & Shahbaz (2013)	Electricity consumption per capita	ADRL, Granger causality	Angola (1971-2009)	Urbanization ←→ electricity	NA

Notes: [a] used a semi-log model; all other studies took natural logs of all variables; and thus, their coefficients can be interpreted as elasticities. [b] statistically significant at $p < 0.10$; all other reported urbanization coefficients were statistically significant at $p < 0.05$ or higher. ARDL= Autogressive distributed lag; OLS=ordinary least squares; FE=fixed effects; ECM=error correction model; FD=first differences; GMM=generalized method of moments; DOLS=dynamic ordinary least squares; HI=high income; MI=middle income; LI=low income. PIC: Pacific Island countries; NIC: Newly industrialized countries; MENA=Middle East North Africa; NS: not significant; NA: not estimated.

Table 2. Cross-sectional dependence: Absolute value mean correlation coefficients and Pesaran (2004) CD test, 1971-2009.

Variable	CD-test statistic	Absolute value correlation coeff.	Observations
Urban	366.5*	0.88	4095
Total electricity p.c.	333.5*	0.79	4095
Industry electricity p.c.	176.3*	0.59	3781
Residential electricity p.c.	316.7*	0.81	3549

Notes: All variables in natural logs. Null hypothesis is cross-sectional independence. Statistical significance indicated by * < 0.001.

Table 3. Bai and Carrion-i-Silvestre (2009) panel unit root test with breaks and cross-sectional dependence, 1971-2009.

	Variables in logged levels				**Variables in logged first differences**			
	Urban	Total Electricity	Industrial Electricity	Residential Electricity	Urban	Total Electricity	Industrial Electricity	Residential Electricity
Z	50.65**	5.35**	6.76**	3.58**	28.44**	-8.42**	-8.07**	-7.63**
P_m	-0.64	-4.17**	-1.55	-0.94	2.12*	35.15**	35.82**	39.09**
P	198.72	124.51	159.74	163.99	255.58*	930.44**	888.28**	927.70**

Simplified test results shown. Critical values for rejecting the hull hypothesis of unit root (H_0: $\rho_i = 1$ against $\rho_i < 1$) are 2.326 and 1.645 corresponding to ** 1% and * 5% significant levels respectively for both Z and P_m. For P test, chi-square critical values are obtained by using 2N degree of freedom with the corresponding significant levels.

Table 4. Panel cointegration test for urbanization and electricity variables, 1971-2009.

		Total electricity	Industry electricity	Residential electricity
Break options:				
Trend shift	$Z_{\tau}(N)$	-11.91**	-8.12**	-3.60**
	$Z_{\emptyset}(N)$	-7.54**	-6.99**	-2.66**
Level shift	$Z_{\tau}(N)$	-19.35**	-16.07**	-18.54**
	$Z_{\emptyset}(N)$	-19.88**	-15.85**	-19.46**
No shift	$Z_{\tau}(N)$	-15.51**	-13.43**	-14.39**
	$Z_{\emptyset}(N)$	-15.93**	-13.95**	-15.61**

The panel cointegration tests are performed by using Westerlund and Edgerton (2008) second generation test procedures allowing multiple breaks and cross sectional dependence. Z_{τ} and $Z_{\emptyset}$ statistics follow the standard normal distribution. The null hypothesis of no cointegration is rejected at 5% and 1% significant levels, denoted by * and ** respectively.

Table 5. Canning and Pedroni (2008) long-run Granger causality tests and the direction of causality for urbanization and electricity consumption (by end-use and income-based panels), 1971-2009.

		Urban → Electricity		***Electricity → Urban***	
		Test	*p-value*	*Test*	*p-value*
Total					
High (37 countries)	Group mean	-0.37	(0.36)	-1.45	(**0.07**)
	Lambda-Pearson	188.99	(**0.00**)	204.49	(**0.00**)
Middle (40)	Group mean	1.44	(0.92)	-1.05	(0.15)
	Lambda-Pearson	226.12	**(0.00)**	185.57	**(0.00)**
Low (28)	Group mean	1.04	(0.85)	-1.26	**(0.10)**
	Lambda-Pearson	114.81	**(0.00)**	127.08	**(0.00)**
Industry					
High (35)	Group mean	-0.41	(0.34)	-1.80	(**0.04**)
	Lambda-Pearson	157.67	(**0.00**)	249.73	(**0.00**)
Middle (37)	Group mean	0.30	(0.62)	-1.48	(**0.07**)
	Lambda-Pearson	199.36	(**0.00**)	194.56	(**0.00**)
Low (25)	Group mean	0.08	(0.53)	-1.14	(0.13)
	Lambda-Pearson	103.37	**(0.00)**	112.08	**(0.00)**
Residential					
High (33)	Group mean	0.34	(0.63)	-1.74	(**0.04**)
	Lambda-Pearson	159.63	(**0.00**)	236.89	(**0.00**)
Middle (33)	Group mean	1.76	(0.96)	-0.91	(0.18)
	Lambda-Pearson	194.86	**(0.00)**	131.76	**(0.00)**
Low (25)	Group mean	1.31	(0.91)	-0.83	(0.20)
	Lambda-Pearson	213.82	**(0.00)**	135.96	**(0.00)**

Notes: The null hypothesis is no Granger causality. Significant tests (at or below 0.10) in bold. Urban→ Electricity=Urban Granger causes Electricity.

Table 6. Canning and Pedroni (2008) long-run Granger causality tests and the direction of causality for urbanization and electricity consumption (by end-use and geography-based panels), 1971-2009.

		Urban → Electricity		***Electricity → Urban***	
		Test →	*p-value*	*Test*	*p-value*
Total					
Africa (24 countries)	Group mean	1.13	(0.87)	-1.33	**(0.09)**
	Lambda-Pearson	108.57	**(0.00)**	112.83	**(0.00)**
Asia (13)	Group mean	1.15	(0.88)	-1.47	**(0.07)**
	Lambda-Pearson	111.49	**(0.00)**	116.17	**(0.00)**
L A C (22)	Group mean	1.46	(0.93)	-0.90	(0.18)
	Lambda-Pearson	124.59	**(0.00)**	91.87	**(0.00)**
Industry					
Africa (22)	Group mean	0.30	(0.62)	-1.55	**(0.06)**
	Lambda-Pearson	92.26	**(0.00)**	128.56	**(0.00)**
Asia (12)	Group mean	0.58	(0.72)	-1.69	**(0.05)**
	Lambda-Pearson	108.91	**(0.00)**	131.50	**(0.00)**
L A C (22)	Group mean	1.46	(0.93)	-0.97	(0.17)
	Lambda-Pearson	114.28	**(0.00)**	108.83	**(0.00)**
Residential					
Africa (22)	Group mean	1.50	(0.93)	-1.09	(0.14)
	Lambda-Pearson	108.15	**(0.00)**	91.21	**(0.00)**
Asia (10)	Group mean	1.50	(0.93)	-1.09	(0.14)
	Lambda-Pearson	108.15	**(0.00)**	91.21	**(0.00)**
L A C (22)	Group mean	1.50	(0.93)	-1.09	(0.14)
	Lambda-Pearson	108.15	**(0.00)**	91.21	**(0.00)**

Notes: The null hypothesis is no Granger causality. Significant tests (at or below 0.10) in bold. Urban→ Electricity=Urban Granger causes Electricity.

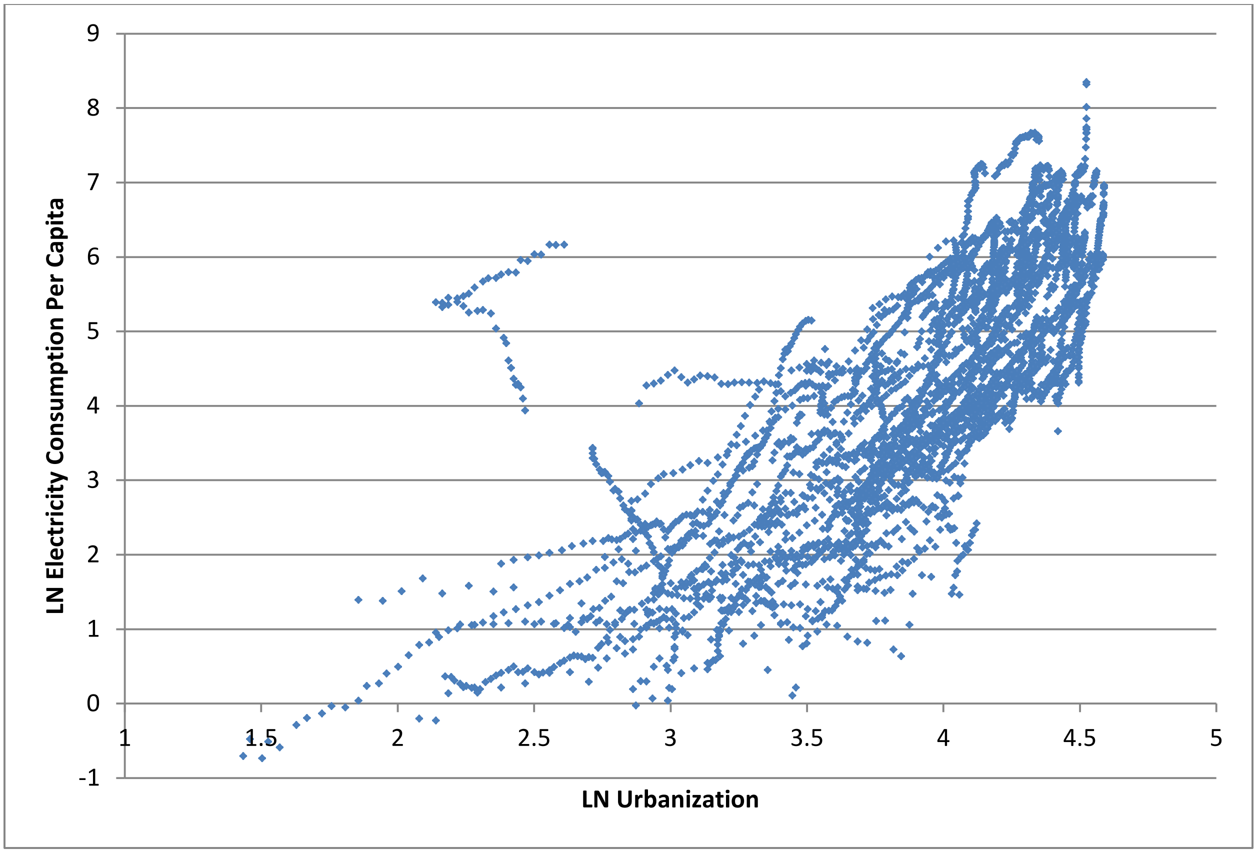

Figure 1. Natural log of urbanization (share of population living in urban areas) vs. natural log of total final electricity consumption per capita for 105 countries, 1971-2009. For only five countries are the two series negatively correlated.

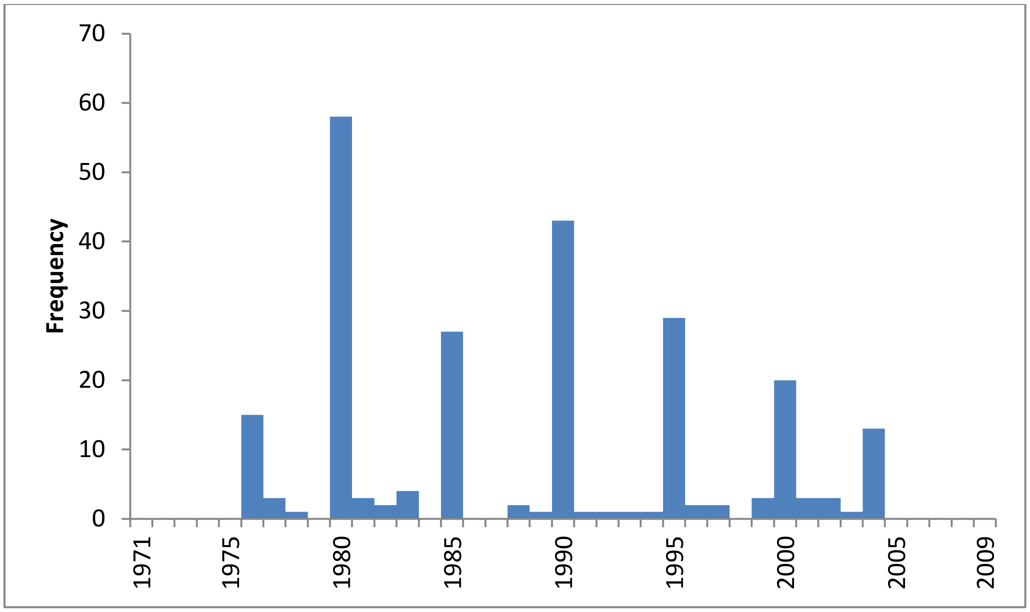

Figure 2. Histogram of the timing of breaks in the urbanization series (1971-2009).

Appendix

Table A.1 Make-up of income- and geography-based panels by World Bank country code.

Total Electricity			Industrial Electricity			Residential Electricity			Regions		
High	**Middle**	**Low**	**High**	**Middle**	**Low**	**High**	**Middle**	**Low**	**Africa**	**Asia**	**LAC**
AUS	ALB	AGO	AUS	ARG	AGO	AUS	ARG	AGO	AGO	BGD	ARG
AUT	ARG	BEN	AUT	BGR	BEN	AUT	BGR	BEN	BEN	CHN	BOL
BEL	BGR	BGD	BEL	BOL	BGD	BEL	BOL	BGD	CIV	IDN	BRA
BHR	BOL	CIV	BHR	BRA	CIV	BRN	BRA	CIV	CMR	IND	CHL
BRN	BRA	CMR	BRN	CHL	CMR	CAN	CHL	CMR	COG	KOR	COL
CAN	CHL	COG	CAN	CHN	COG	CHE	CHN	COG	DZA	LKA	CRI
CHE	CHN	EGY	CHE	COL	EGY	CYP	COL	EGY	EGY	MMR	CUB
CYP	COL	ETH	CYP	CRI	ETH	CZE	CRI	ETH	ETH	MYS[b]	DOM
CZE	CRI	GHA	CZE	CUB	GHA	DEU	CUB	GHA	GAB[a]	NPL	ECU
DEU	CUB	HTI	DEU	DOM	HTI	ESP	DOM	HTI	GHA	PAK	GTM
DNK	DOM	IND	DNK	DZA	IND	FIN	DZA	IND	KEN	PHL[b]	HND
ESP	DZA	KEN	ESP	ECU	KEN	FRA	ECU	KEN	LBY	THA	HTI
FIN	ECU	LKA	FIN	GAB	LKA	GBR	GTM	LKA	MAR	VNM[a]	JAM
FRA	GAB	MMR	FRA	GTM	MMR	GRC	HND	MMR	MOZ		MEX
GBR	GTM	MOZ	GBR	HND	MOZ	HUN	IDN	MOZ	NGA		NIC
GRC	HND	NGA	GRC	IDN	NGA	IRL	IRN	NGA	SDN		PAN
HUN	IDN	NIC	HUN	IRN	NIC	ISL	JAM	NIC	SEN		PER
IRL	IRN	NPL	IRL	JAM	NPL	ISR	LBY	NPL	TGO		PRY
ISL	JAM	PAK	ISL	JOR	PAK	ITA	MAR	PAK	TUN		SLV
ISR	JOR	SDN	ISR	LBY	SDN	JPN	MEX	SDN	TZA		TTO
ITA	LBN	SEN	ITA	MAR	SEN	KOR	PAN	SEN	ZAF		URY
JPN	LBY	TGO	JPN	MEX	TGO	KWT	PER	TGO	ZAR[a]		VEN
KOR	MAR	TZA	KOR	MYS	TZA	LUX	PRY	TZA	ZMB		
KWT	MEX	VNM	LUX	PAN	ZMB	NLD	ROM	ZMB	ZWE		
LUX	MLT	YEM	NLD	PER	ZWE	NOR	SLV	ZWE			
NLD	MYS	ZAR	NOR	PHL		NZL	SYR				
NOR	PAN	ZMB	NZL	PRY		OMN	THA				
NZL	PER	ZWE	OMN	ROM		POL	TTO				
OMN	PHL		POL	SLV		PRT	TUN				
POL	PRY		PRT	SYR		SVK	TUR				
PRT	ROM		SAU	THA		SWE	URY				
QAT	SLV		SVK	TTO		UAE	VEN				
SAU	SYR		SWE	TUN		USA	ZAF				
SVK	THA		UAE	TUR							
SWE	TTO		USA	URY							
UAE	TUN			VEN							
USA	TUR			ZAF							
	URY										
	VEN										
	ZAF										

Notes: [a] Not included in the industry or residential electricity consumption panels. [b] Not included in the residential electricity consumption panel.

Table A.2 Canning and Pedroni (2008) long-run Granger causality test and the direction of causality for urbanization and total energy consumption (by income- and geography-based panels).

		Urban → Energy		***Energy → Urban***	
		Test	*p-value*	*Test*	*p-value*
High	Group mean	0.08	(0.53)	-1.45	(0.07)
	Lambda-Pearson	172.91	(0.00)	216.18	(0.00)
Middle	Group mean	0.72	(0.76)	-0.93	(0.18)
	Lambda-Pearson	206.36	(0.00)	181.30	(0.00)
Low	Group mean	0.29	(0.62)	-0.84	(0.20)
	Lambda-Pearson	174.97	(0.00)	174.57	(0.00)
Africa	Group mean	0.22	(0.59)	-1.08	(0.14)
	Lambda-Pearson	114.35	(0.00)	86.86	(0.00)
Asia	Group mean	1.04	(0.85)	-1.24	(0.11)
	Lambda-Pearson	109.12	(0.00)	141.75	(0.00)
L A C	Group mean	1.03	(0.85)	-0.74	(0.23)
	Lambda-Pearson	95.41	(0.00)	113.93	(0.00)

Notes: The null hypothesis is no Granger causality. Urban→ Energy=Urban Granger causes Energy consumption. The natural log of total energy consumption per capita was determined to be I(1) by the Bai and Carrion-i-Silvestre (2009) panel unit root test and cointegrated with urbanization via the Westerlund and Edgerton (2008) panel cointegration test (results not shown but are available upon request).