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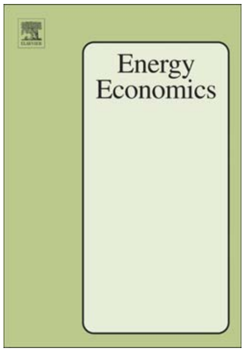

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Energy Distribution and Economic Growth: An empirical test for China

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Abstract

In this paper we consider whether economic growth in China could be constrained by the physical development of the energy distribution network. Specifically, we structurally test Dalgaard and Strulik (2011)'s network theory of electricity distribution using city level data for China. In their paper they argue that the relationship between the size of the economy, measured by capital per capita, and electricity consumption per capita is governed by a simple power law with capital having an exponent bounded between ½ and ¾ depending on the efficiency of the network. We use data for 224 cities in China between 2002 and 2007 to observe whether structural estimates match those of Dalgaard and Strulik (2009) for 50 US states where they find the exponent in the power law connecting capital with electricity to be 2/3. Our results provide an estimate of the power law component to a little higher than the 2/3 found for the US which provides broad support for the model. When we look at different time periods we observe what appears to be a fall in the efficiency of the energy distribution network towards the end of our period.

JEL: O13, Q4, Q43, Q48, P28, P48

Keywords: Energy, Electricity, Economic Growth, China.

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1. Introduction

China's rapid economic growth in the last twenty years has been matched by an equally dramatic growth in the production and consumption of energy. A major concern for Chinese policymakers is whether the current rate of growth will be constrained in the future by physical constraints imposed by a shortage of energy distribution infrastructure. Central to this question is whether China's electricity distribution network will be able to continue to provide the electricity required by China's power hungry consumers and energy intensive manufacturing sector.

To shed some light on the relationship between energy distribution and economic growth we revisit a novel network theory of electricity distribution by Dalgaard and Strulik (2011). The model posits a supply relationship between electricity consumption per capita and the size of the economy measured by capital per capita where the economy is viewed as a transportation network for electricity. The logic is straight-forward. Energy is needed to run, maintain and create capital. Without an electricity supply, any investment in machinery at a particular place or time will not lead to economic growth.

Early attempts to model present how structural characteristics such as population growth and technological change affect the ability of an economy to accumulate capital (Domar 1946 and Solow 1956). The main contribution of Dalgaard and Strulik (2011) is to model the effect of complex electricity supply networks on economic growth using modeling techniques taken from biological sciences. A major innovation is the application of a power law association between consumption per capita of electricity and capital per capita with an exponent assigned to capital bounded between 1/2 and 3/4 with the final exponent dependent on the efficiency of the network. To capture instantaneous aggregate demand for electricity Dalgaard and Strulik (2011) employ an energy conservation equation with the result that they are able to provide a metabolic-energetic founded law of motion for capital per capita. A simple first-order differential equation looking at how capital per capita evolves over time allows them to study the implied dynamics and to be able to characterize the steady-state.[1]

The intuition is straight-forward. The greater the elasticity between consumption per capita and capital per capita the more efficient the network should be. This in turn should mean more electricity is available for final use and hence capital should be accumulated at a greater speed than it would be for countries with less efficient networks. If, as Dalgaard and Sturlik (2011) assumes, that economies are operating at the boundary of physical feasibility, then their model should be testable using data on energy consumption per capita which is directly measureable. When they estimate their model structurally using data for 50 US states from 1960 to 2000 they find that the data fits the model well with a point estimate for the power law linking electricity and capital of 2/3. In addition they find evidence of some β-convergence in electricity consumption per capita across US States.[2]

The contribution of this paper is two-fold. First, we want to see whether Dalgaard and Sturlik (2011)'s structurally estimated point-estimate for the power law holds for a different country to the US but also at a different level of aggregation. In this case we use a panel of 224 Chinese cities for the period 2002 to 2007 instead of US states. Second, we want to better understand the relationship between electricity networks and economic growth in China and how the efficiency of China's electricity network compares to that of the US.

The result of our examination of growth in electricity consumption per capita and associated structural test for China reveals that the data for the model reasonably well with a power law linking electricity and capital a little above 2/3. This suggests that China's energy networks for cities are at least at efficient as those for US states and are arguably more efficient allowing China to accumulate capital at a faster rate. This good news is mitigated by the finding that the efficiency of China's network, although generally good, shows signs of deterioration in recent years no doubt as a result of China's rapid growth straining existing electricity distribution

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[1] The association between energy and growth is not new. The ability to harness energy for the betterment of society and how efficiently it can be deployed was first mentioned by Spencer (1862) First Principles (Dalgaard and Sturlik 2011). To prevent "limits to growth" as a result of energy shortages will require technological change even if the supply of energy increases. The distribution of energy through a network in therefore crucial.

[2] There has been a little written about the social impact of networks. Betterncourt *et al.* (2007) find evidence of a scaling law between city size and city development such as patents, employment and growth rates. They conclude that a city must have a continually accelerating innovation rate to support local economic development because of different mechanisms of material production and citizen welfare.

networks. Overall, China appears to have done a remarkably good job in maintaining the electricity supply to industry although our results suggest that such a performance may be difficult to maintain if China's rate of urbanization and growth continues.

The remainder of the paper is organized as follows: Section 2 briefly outlines Dalgaard and Strulik (2011)'s model of energy distribution and economic growth. Section 3 provides a brief overview of China's electricity network during the period 2002 to 2007. Section 4 discusses our empirical strategy while Section 5 presents our empirical results. Section 6 concludes.

2. Theoretical Background

Research in the natural sciences by West *et al*. (1997 and 1999) and Banavar *et al*. (1999 and 2002) model the energy distribution network as a living organism to verify a statistical finding in biology known as Kleiber's Law.[3] Dalgaard and Sturlik (2011) took this concept and were the first to include something as complex as an electricity distribution network into a macroeconomic model. They argue that applying theories relevant to biological organisms to man-made electricity networks is a valid approach for three reasons. First, that cardiovascular system operates in a similar way to an electricity network by ensuring the distribution of nutrients and electricity respectively around a network. Second, man-made and biological networks are likely to share similar aggregate properties because of the process of development over time as the systems optimize through natural selection in the case of a biological network and constant reworking and upgrading in the case of man-made networks. Third, physicists are applying empirical methods from biological organisms to search for universal scaling laws that will impact on human society. The constant pressure to move to the optimal distribution network means that biological and man-made networks can be expected to share certain characteristics.

Taking electricity consumption per capita (*e*) to be the equivalent to metabolism and capital per capita (*k*) to be equivalent to body mass, the assumption is that the relationship between capital

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[3] Kleiber's Law was named after Max Kleiber's research in the early 1930s when he observed that for the vast majority of animals that the three-quarters power of body weight was the most reliable method for predicting the basal metabolic rate (BMR).

and electricity is concave and log linear. Dalgaard and Sturlik (2011) show how electricity is made available at geographically dispersed sites through the self-organization of an economy. At first, they derive a model depicting characteristics of an energy distribution network from the supply side and draw a basic criteria about the relationship of energy consumption per capita and capital per capita. They state that the energy circulating in the network is different from the energy required by the capital equipment connecting to this network. Banavar *et al.* (1999) present examples of how networks can be designed to best serve electricity demand which we replicate in Figure 1. It is assumed that electricity is generated at a power plant and then distributed via an electricity grid to end users via sites where the distance between a site and the source depends on how many other transfer sites the electricity has to pass through. The most efficient network is when there is a single path to source i as the electricity in each path can be used to operate machines at these sites. Hence, shortages in the provision of electricity may be due to network inefficiencies as well as the demand for electricity of the machines within the network. Likewise, as capital increases, new transfer sites are required and the network then expands.

[Figure 1 about here]

And eventually, given a strong assumption that total energy consumption is proportional to population[4], electricity consumption per capita $e(t)$ should be log-linear correlated to capital stock per capita $k(t)$ at any given time t:

$$e = \varepsilon k^{a} \qquad (1)$$

$$a \equiv \frac{D}{D+x}, x \in [1, D]$$

Parameter D in this model is equal to 3 for a sense of three dimensional space. Note that the parameter x is the measure of the efficiency of energy distribution network which is a crucial benchmark to judge whether an economy is able to afford further economic growth.

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[4] Kűhnert *et al.* (2006) use cross-sectional German city data to confirm this association and Betterncourt *et al.* (2007) find similar evidence from a sample of Chinese administrative units. Dalgaard and Strulik (2011) confirm this relationship using their US State data. We test this assumption empirically in our empirical section.

Given the relationship between capital per capita and energy per capita, Dalgaard and Strulik (2011) further investigate this nexus from the perspective of energy demand. They argue that the demand for energy comes from the requirement of capital operation, maintenance and generation. The steady-state value of energy consumption per capita and capital per capita are given as:

$$k = k^* \equiv [\frac{\mu + nv}{\varepsilon}]^{1/(a-1)}$$

$$\dot{e}(t) = \frac{a\varepsilon^{1/a}}{v} e(t)^{2-1/a} - a(\frac{\mu}{v} + n)e(t) \qquad (2)$$

In addition to predicting a power law relationship between consumption per capita and capital per capita the model also makes predictions about the size of the elasticity between capital and energy consumption and argue that it should fall between ½ and ¾ depending on the efficiency of the network. The implication is that more efficient networks will allow a country or region to accumulate capital and hence grow at a faster rate in the future. Although they derive a steady-state Dalgaard and Sturlik (2011) are quick to point out that technological change is one of the main drivers for pushing the physical limits of electricity production.[5]

3. Electricity Distribution in China

China has experienced rapid economic growth in the last two decades. Annual real GDP per capita between 2002 and 2007 increased from 8,700 RMB in 2002 to 11,000 RMB in 2007 which translates into a per capita income growth rate of 2 percent annually. At the same time, as one of the "Three Carriages of China's Economic Growth" (alongside exports and consumption), fixed investment in China grew at a significantly faster rate than income. The amount of fixed investment per capita in China rose from 338 RMB in 2002 to 1,367 RMB in 2007.

In terms of energy consumption, in 2009 China consumed and produced 3.07 billion tons and 2.75 billion tons of standard coal equivalent (tce) energy respectively (China Statistical Yearbook

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[5] A detailed discussion and exposition of the model is can be found in the original Dalgaard and Strulik (2011) paper.

2010).[6] The manufacturing sector accounts for approximately 66 percent of the total energy consumed. A Statistical Communiqué in 2011 reports that the nation's total energy consumption in 2011 reached 3.48 billion tce up seven percent from 2010.[7] The total volume of coal consumption grew by 9.7 percent; crude oil by 2.7 percent; natural gas by 12 percent; and electric power by 11.7 percent. Imports of coal in 2009 were 125.83 million tons. A figure that rose to 164.78 million tons in 2012. The result is that China now relies on imports for approximately 5 percent of coal consumption, the vast majority of which is used to generate thermal power. China dependence on imports of crude oil is more severe with China importing 239.31 million tons of oil in 2010 accounting for two-thirds of China's crude oil consumption in that year.[8]

Whilst the Chinese government has been making every effort to reduce national energy consumption, the dramatic rate of growth in recent years means that China will need increasing amounts of energy to maintain the current growth trajectory. The emergence of an energy demand-supply gap could seriously damage China's ability to grow at anything like current rates and adversely affect China's ability to meet sustainable development targets.

The 2006 Eleventh Five-Year Plan has much to say about the need for China to meet its energy requirements through improvements in energy efficiency and developing domestic energy sources including nuclear and the development of so-called green energy solutions such as solar and wind energy.[9] Nevertheless, it is unlikely that new energy sources will be able to keep up with the demand for energy from a growing economy. Part of the solution will need to include the introduction of energy saving technologies.

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[6] Typically China converts all its energy statistics into "metric tons of standard coal equivalent" (tce). However, a tce unit tends to bear little relation to the heating value of coal actually used in China. One tce equals 29.31 gigajoules (GJ) (low heat) which is equivalent to 31.52 GJ/tce (high heat). Chinese conversion factors for coal and other fuels are low-heat values. Chinese average raw coal contains 20.93 GJ/metric ton (low heat) or 22.51 GJ/t (high heat) assuming that low-heat values for coal are 93% of high-heat values (National Research Academy *et al.* 2000).

[7] The Statistical Communiqué of the People's Republic of China on National Economic and Social Development is an annual report published by National Bureau of Statistics of China and provides a summary of economic and social development in China. There has been a little written about the social impact of networks. Betterncourt *et al.* (2007) find evidence of a scaling law between city size and city development such as patents, employment, and growth rate and so on. They conclude that a city must have a continually accelerating innovation rate to support local economic development because of different mechanisms of material production and citizen welfare

[8] The elasticity of overall energy consumption in China has been greater than unity since 1999 peaking at 16.1 in 2004 before falling back to 3.9 in 2008 and then increasing again from 2009

[9] The previous Tenth Five-Year Plan started in 2001 and ended in 2005 with the Twelfth Five-Year Plan starting in 2011.

The chief input of thermal power generation in China is coal. The electricity generated is supplied to industry and households via a national electricity grid. It is the ability of China's electricity network to deal with increased demand that is the main motivation for this paper. Zhou *et al.* (2010) provide a detailed overview of power transmission systems in China and discuss some of the stability problems that China's power grids face.[10]

Table 1 provides a series of summary statistics for key energy related variables and are discussed in more detail below. A relatively strong assumption of the Dalgaard and Strulik (2011) model is that the distribution network is of the one-source type. Given the disaggregated nature of the electricity network in the US it is hard to argue that such an assumption can hold for the US. However, such a one-source distribution network might be more appropriate when considering the networks that supply individual cities. The electricity networks for Chinese cities are constructed according to the Code of Planning and Design of Urban Electricity Networks published by the State Grid Corporation of China (SGCC). The construction of a city's electricity network consists of two parts: the electricity supply network which includes power stations and subsidiary cables voltages between 220kV and 1000kV and second, the electricity distribution network including substations and cables with lower voltages within the city. Electricity is normally generated by a power station outside of the city limits and is then transported by the cable with high voltage to a ring network that surrounds the city. Electricity is then transported along branches that spread from a ring type network and enters the electricity distribution network which consists of High Voltage, Medium Voltage and Low Voltage distribution networks and subsidiary substations, switching stations and distribution rooms. We believe this city network arrangement can be represented as a simplified one-source distribution network where we treat the ring surrounding the city as the source of electricity.

[Table 1 about here]

Capital accumulation improves local labor's productivity. Capital accumulation in China was often accompanied by city sprawl as new space was required for new construction but also to house the large numbers of migrants from rural areas. In 2002 the area of China considered to

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[10] For further information on the technical operation of China's energy distribution system see Wu (2001), Qi *et al.* (2003) and Zhao (2004).

be part of a city was 25,973 km^2 which had risen to 38,107 km^2 by 2007. Such rapid development had an inevitable effect on city-level energy demand. Electricity consumption per capita also grew rapidly. Per capita consumption of electricity increased three-fold from 126.5 kWh in 2002 to 365.9 kWh in 2007.

An implication from Table 1 is that an energy supply-demand gap is likely to emerge as the nation's economy grows. Traditional energy sources such as coal and oil also causes significant environment damage and contribute to the high levels of pollution. The development of cleaner technologies is relatively rapid (bio-energy, solar power and nuclear power) but any growth in green energy is not sufficient to offset the increase in the demand for total energy that a growing China requires. However, China is changing and modern industries such as finance and software engineering are less energy intensive that the traditional manufacturing sector. However, the transformation of China's economy away from heavy industry is uncertain both in terms of time and magnitude. In the meantime, China must increase its installed capacity which means the construction of more power stations. The total installed gross capacity in 2002 was 356,571 trillion Watts which increased to 718,216 trillion Watts by 2007.[11]

Column (5) of Table 1 shows how installed gross capacity has grown between 2002 and 2007. The amount of electricity supplied to the grid increased from 1,654 billion kWh in 2002 to 32,644 billion kWh in 2007. The supply of electricity can be broken down by cable type. Columns (6) (7) and (8) of Table 1 show the growth in three types of electric cable. Column (6) shows the growth in 500kV cables which are used to construct the outer ring of the electricity distribution network and this has maintained a relatively high annual growth rate. The length of 550kV cable in 2007 was 122,028 km against a 2002 value of 36,745. Growth in 330kV and 220kV cable installation is slower that 500kV but is still significant. What is evident is that China has managed to increase the capacity for electricity production but also to develop the distribution network at the same time

Finally, it is important to consider the reliability of the electricity supply which has implications for productivity. The latest report on electric power reliability shows that by 2011 the average

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[11] Electric Power Reliability Management Center, State Electricity Regulatory Commission. Official Website: http://www.chinaer.org/Default.aspx.

electric power reliability rate of 10 kV clients in cities was around 99.945%. This translates into a fall in power cut off time from 5.07 hours in 2010 to 4.79 hours in 2011. The reliability figure for rural areas is 99.7887% which translates into a decline in power cut off time from 25.06 hours in 2010 to 18.43 hours in 2011. Column (9) of Table 1 presents the reliability data for RS1 and RS3 between 2002 and 2007. Table 2 provides a summary of our main variables (population, population growth and electricity consumption per capita).

4. Empirical Strategy

This paper uses data for 224 Chinese cities between 2002 and 2007.[12] Following Dalgaard and Sturlik (2011) we also use electricity consumption to represent the law of motion. For the theory to be valid a number of strong assumptions need to be tested. The main prediction from network theory is that the scaling parameter a should be between ½ and ¾. However, the first stage of our empirical strategy is to test the linearity assumption between total electricity consumption and local population size. Following Dalgaard and Strulik (2011) we use OLS on a year by year basis as well as panel fixed-effect with robust standard error to estimate the following specification for each of our seven years for each Chinese city i:

$$log(E_i) = a_0 + a_1 log(P_i) + \varepsilon_i$$

If this assumption is satisfied, the coefficient on log population size a_1 should be approximately 1.

In the second stage we use Chinese city-level data to test the main predictions of the Dalgaard and Strulik (2011) model. The first step is to log-linearize Equation (2) under steady-state conditions where $e = e^* \equiv \varepsilon[\frac{\varepsilon}{\mu + nv}]^{a/(1-a)}$.

Hence;

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[12] The original sample of cities was 256 but certain cities were dropped due to a lack of electricity consumption data (17 cities) and population data (8 cities). A small number of cities were dropped for problems with population growth data. The final sample was 224 cities. We are confident that these cities are not concentrated in certain provinces and does not introduce selection bias.

$$\ln[e(t)] = \ln[e(0)]\exp(-\lambda t) + (1-\exp(-\lambda t))[\frac{1}{1-a}\ln(\varepsilon) - \frac{a}{1-a}\ln(v) - \frac{a}{1-a}\ln(\frac{n+\mu}{v})] \tag{3}$$

where $\lambda \equiv (1-a)(n+\frac{\mu}{v})$.

We estimate this equation using non-linear least squares (NLS) as the parameter *a* is non-linear. The parameters (μ, *v*) in above equation cannot be obtained directly. However, following the simplification proposed by Dalgaard and Strulik (2011), we can use rate of depreciation to substitute for μ /*v*. We follow Wang (2003) and assume the capital depreciation rate in China during this period is 0.05. It should be noted that this figure is close to the 0.06 used by Dalgaard and Sturlik (2011) who follow Naditi and Prucha (1996) and McQuinn and Whelan (2007). A simple transformation gives:

$$\ln[e_i(T)] - \ln[e_i(0)] = -[1-\exp(-s_1 \cdot (n_i + 0.05) \cdot T)][s_2 + s_3 \ln(n_i + 0.05) + \ln e_i(0)] + u_i \tag{4}$$

The variable s_2 captures the influence from *ε* and *v* although no sign is predicted by the model. Likewise, Dalgaard and Sturlik (2011) argue that if *v*, *ε* and *μ* vary across States this variation can plausibly be considered random. There is no reason to expect Chinese cities to be different in this regard and given the technological nature of these variables it is reasonable to assume the technological advances would be quickly diffused through-out the country.

Since our city-level data covers the period 2002 to 2007, *T* in Equation (3) is equal to five. The average population growth rate is given by *n* (we use annual natural population growth rate). The empirical predictions from Equation (4) are:

$$(1) s_1 > 0,$$
$$(2) s_3 > 0,$$
$$(3) 1 - s_1 = s_3/(1+s_3) = a \in [1/2, 3/4]$$

All three predictions should hold for the Dalgaard and Sturlik (2011) theory to hold otherwise it is rejected.

5. Empirical Results

5.1 Linearity between electricity consumption and population size

Figure 2 presents a graph of the relationship between total electricity consumption and local population size for each year. All seven values suggest a positive relationship between population and energy consumption with a fitted line close to 1. Table 3 presents our simple OLS estimates for each year as well as the fixed-effects estimation for the whole sample period (with White's HAC estimator). The coefficients on log local population size ranges between 0.84 and 1.01 and confirms the proportionality assumption of electricity consumption and local population size. In each case the value of unity lies within the 95 percent confidence interval.

[Figure 2 and Table 3 about here]

5.2 Main results

According to Dalgaard and Strulik (2011) electricity consumption per capita e and capital stock per capita k will reach a steady-state because the electricity distribution network cannot load any more electricity and hence cannot support additional productive capacity. For this reason, electricity per capita consumption and its initial level should follow a β-convergence process. Figure 3 plots electricity consumption per capita growth 2002 to 2007 against the initial (log) of electricity consumption per capita. As predicted by the model the sign is negative and significant.

[Figure 3 about here]

In Table 4 we present our NLS results from the estimation of Equation (13) with and without the restriction that $1\text{-}s_1=s_3/(1+s_3)$. Dalgaard and Strulik (2011) only use one year of data. We present repeated cross-section results for seven years.

[Table 3 about here]

Panel A in Column (1) is estimated from the total city sample with an R^2 of 0.99. The high R^2 can be taken to mean that the model is capturing the cross-sectional variation in electricity consumption per capita for 2002-2007. More importantly, the signs and significance (at the 1% level) of our estimates for s_1 and s_3 meet our predictions. $s_1>0$, and $s_3>0$ and more importantly $1-s_1=s_3/(1+s_3)$ is also satisfied. This implies that our cross-city data support the structure of the model. The fact that $1-s_1=s_3/(1+s_3)$ is satisfied means we can estimate a restricted model. The benefit is that this allows us to obtain a unique estimate for a to compare with the prediction that is must lie between ½ and ¾ (when D = 3) and in our case we can compare the value for Chinese cities with that for US States.

Panel B presents our estimates under the restriction that $1-s_1=s_3/(1+s_3)$. The estimate of s_1 is not significantly different to the s_1 estimated in Panel A. The estimate of s_1 implies that the scaling exponent a is 0.689 and confirms the feasibility of the model when the dimensionality D is equal to 3 (Dalgaard and Strulik 2011). Statistically as shown by the 95% confidence intervals we can reject s_1 being below ½ or above ¾.

Our estimates suggest that the electricity distribution network functions with relatively high efficiency (x=1.36, x is equal to $\frac{(1-a)}{a}D$ as Equation (6) suggests). Comparing our results to those of Dalgaard and Strulik (2011) for US States where x=2.00 suggests that Chinese cities have a more efficient distribution network. One explanation is that cross-city data more accurately represents the pattern of electricity distribution as a one source network.

A point made by Dalgaard and Strulik (2011) is that a degree of inefficiency is built into the network as a deliberate backup for emergencies and it should be expected that electricity networks will be less efficient then biological systems. In that sense our results are equally reassuring. A summary of our results is that we support the premise that the scaling coefficient is around 2/3. One implication of this result is that China has been operating close to the feasibility constraint defined in the Dalgaard and Sturlik (2001) model. Given the rapid growth during our period of study this is not a surprising result (it is perhaps more surprising for US states between 1960 and 2000 which includes recessions with the expectation of spare capacity in the electricity network).

Returning to the original theoretical underpinnings it can be argued that any inefficiency is a consequence of a system faced with competing forces of size and the construction of an efficient transportation network. As discussed in Section 3, the most efficient distribution network is the directed spanning tree although this pattern has the drawback that it would not be the most efficient once a network reaches a particular size. In this case, to realize this pattern of connectivity, the work of constructing connecting cables would be very complex and not economic from a city construction perspective. As a city expands, its electricity distribution network would spread but in a pattern stemming from a directed spanning tree. When a city grows without support from technological advances, as the model suggests, the electricity consumption per capita used and the capital accumulation per capita would reach a steady-state (determined by population growth, capital depreciation rate and electricity efficiency as Equation (8) suggests) where the network could not afford even one unit increase of capital accumulation per capita.

In addition to our repeated cross-section results we present a number of robustness checks looking at regional and time differences. We begin with a regional analysis. China's economic growth has tended to be regionally unbalanced. The better-developed areas are mostly located in the eastern coastal part of China. These cities have tended to attract more investment; have greater economic diversity and higher income growth. In contrast, cities in the central and western areas of China have been historically economically poorer and have attracted less foreign investment and subsequently have lower income growth. The theory predicts that their electricity distribution network should be simpler and more direct. Hence, the efficiency of the electricity distribution network is predicted to be higher than those of more developed and rapidly growing cities and provinces. Econometrically, this is allowing the identifying assumption that v and μ are equal across cross-sectional units (cities) to be different across our two groups of cities. Columns (2) and (3) of Table 3 present our results.

Column (2) includes only those cities with below average income growth. The coefficient on s_l in Panel B is positive and significant and the scaling exponent a is around 0.671. The network efficiency x is approximately 1.41 compared to a full sample efficiency x of 1.36. For our sample of cities with above average income growth (Column 3), we find that s_l is larger which implies that the efficiency of the electricity distribution network in these cities is lower than the full sample average (0.657) although the values are still similar. One interpretation is that large cities that are growing rapidly may hinder the development of an efficient electricity distribution network as more and more consumers end up being further away from the original source of energy supply.

As a further sensitivity check we consider a series of smaller time periods within our original time period. In Column (4) in Table 4 we consider the sub-sample 2002-2006 and observe that the estimate of s_1 changes to 0.312 which means that the scaling exponent a falls to 0.688 and the efficiency x decreases to 1.360. This suggests that China's electricity distribution network has deteriorated towards the end of the period possibly as a result of new electricity distribution line construction being unable to keep up with city growth. The downward slope in Figure 3 reflects this trend. Finally, in Table 5 we present the results for a further five sub-samples within our original seven year time period. The results are consistent with earlier periods exhibiting higher s_1 estimates than those for later periods which infers lower network efficiency in later years. However, the short time period means we cannot attach much weight to these higher values and more that Table 5 provides an additional robustness check on the initial results.

6. Conclusions

In this paper, we revisit the novel macroeconomic model of energy distribution and economic growth based on biological sciences and derived by Dalgaard and Strulik (2011). The model is based on strong assumptions and posits a series of predictions that need to hold for the theory not to be rejected. A test for 50 US States between 1960 and 2000 confirms the validity of the model. When we exposed the same model to a battery of tests using Chinese city-level data between 2002 and 2007 we also found similar results and also found a scaling coefficient in the region of 2/3 with and without restrictions.

If we consider the case of China more closely from a city-level perspective it appears that the efficiency of the electricity network in China is likely to be sufficient to support China's economic growth. Our results from a cross-city dataset covering the period 2002 to 2007 suggest that in China the electricity distribution network is relatively direct and efficient. Although our results show that China's electricity distribution network is fairly efficient China needs to be aware of a growing gap between the demand for energy and the ability of China to import enough energy to supply the growing manufacturing sector. Whilst China has done well it will become increasingly difficult for the supply of energy to match an ever increasing demand for energy.

Further investigation shows that in cities with lower income growth the electricity distribution network is more efficient than those in higher income growth cities perhaps because in the former case electricity is transferred more directly to the end user along a simplified distribution network. A more direct distribution pattern implies that these cities are less-developed because as the model suggests, given the population growth, depreciation rate, electricity consumption per capita and capita stock per capita approaches to the steady-state with a path of β–convergence.

However, our results are not conclusive but only suggestive. Further investigation of this model's restriction and its policy implication should be better explored in future research.

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Figure 1: Alternative network patterns (Bettencourt *et al.* 2007)

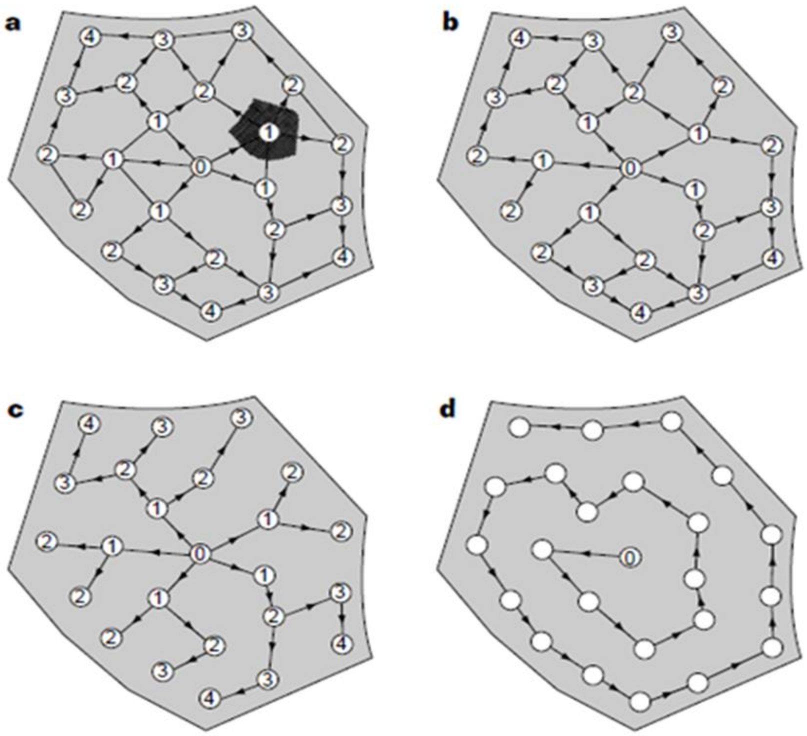

Figure 2: Electricity consumption and local population size for Chinese cities (2002-2007)

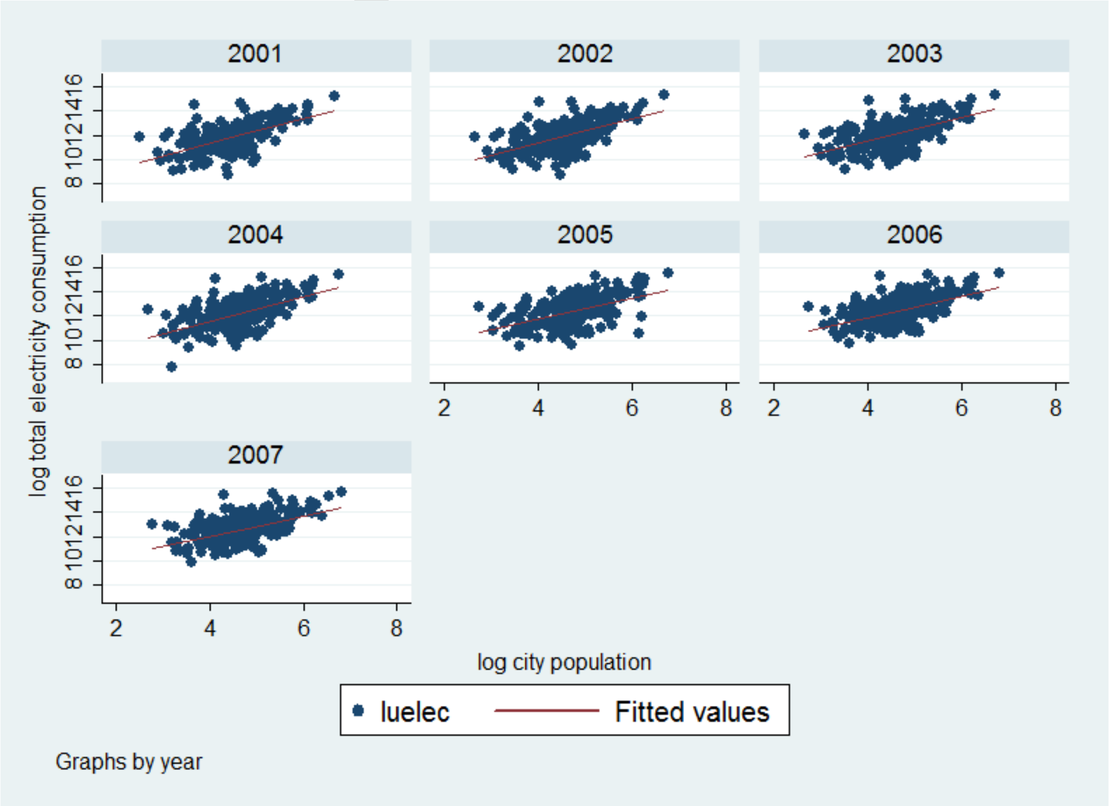

Figure 3: Electricity consumption per capita growth (2002-2007) and initial (log) electricity consumption per capita.

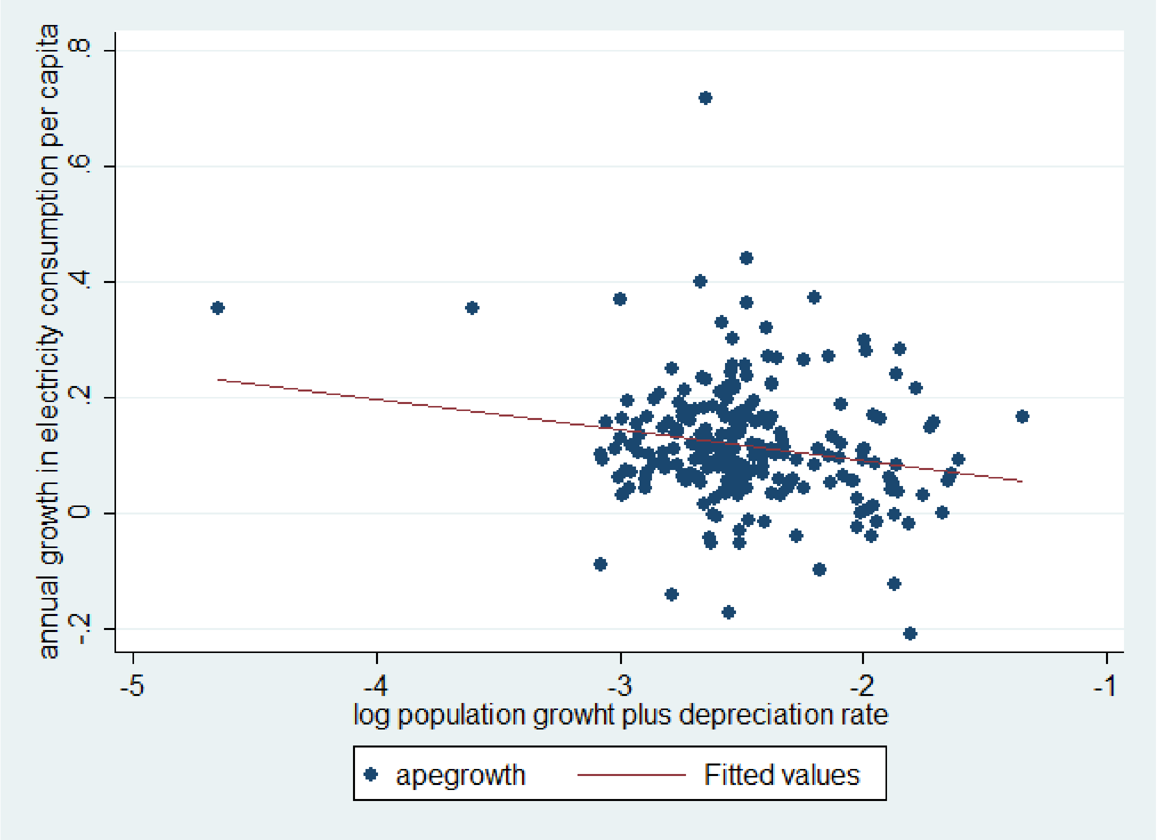

Table 1: Summary of Chinese energy distribution network

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
	Real GDP per capita	Fixed capital investment per capita	City constructed area	Electricity consumption per capita	Installed gross capacity	500kV cable length	330kV cable length	220kV cable length	RS1	RS3+
year	Yuan(2001=100)	Yuan(2001=100)	Km^2	kWh	(trillion Watt)	(km)	(km)	(km)	(%)	(%)
2001	7543	0.29158	24027	126.5	338387	31486	9177	135935	99.897	99.898
2002	8669.742	0.337969	25973	138.3	356571	36745	9612	142362	99.907	99.916
2003	8897.615	0.419896	28308	159.7	391408	43616	10515	147260	99.866	99.929
2004	9517.165	0.501377	30406	184	443287	54705	11061	161010	99.82	99.927
2005	9885.871	0.61794	32521	221.3	517185	62344	13384	178900	99.766	99.845
2006	10267.19	0.750394	33660	255.6	623698	77092	13762	195392	99.849	99.953
2007	11047.75	0.896995	35470	308.3	718216	96574	15493	216159	99.882	99.883

+ RS3 excludes the time caused by systematic shortage supply

Table 2: Summary Statistics for our key variable (2001 – 2007)

Variable	Year	Mean	Std. Dev.	Min	Max
Population (10000 persons)	2001	391.73	231.434	16.10	1122.3
	2002	394.02	232.80	15.97	1136.3
	2003	399.15	234.03	16.37	1148.82
	2004	402.19	237.00	16.76	1162.89
	2005	404.52	237.58	17.22	1180.7
	2006	409.73	242.95	17.61	1197.6
	2007	414.27	246.37	18.14	1213.26
Population Growth (%)	2001	4.84	2.59	-0.39	12.14
	2002	4.76	2.51	-0.31	14.74
	2003	4.60	2.90	-1.58	18.92
	2004	5.12	3.55	-2.52	29.08
	2005	5.11	3.00	-2.49	13.30
	2006	6.36	3.69	-1.14	19.89
	2007	6.36	3.83	-3.29	17.01
Energy Consumption Per Capita (kwh/person)	2001	2424.77	3877.58	76.32	48696.01
	2002	2557.62	3764.67	73.31	43890.71
	2003	2840.58	4260.49	150.94	49857.38
	2004	3104.49	4735.26	92.32	56974.97
	2005	3239.80	3499.13	85.78	24196.61
	2006	3803.33	5420.97	263.79	63265.51
	2007	4273.01	5893.55	291.84	65503.11

Table 3: OLS estimates of Equation (1). Dependent variable is total energy consumption

Year / Variable		2002	2003	2004	2005	2006	2007	Panel Fixed Effect
lpop		1.012***	0.970***	1.000***	0.838***	0.895***	0.838***	0.838***
		(0.0993)	(0.0982)	(0.0988)	(0.0976)	(0.0908)	(0.0894)	(0.160)
Constant		7.326***	7.602***	7.548***	8.385***	8.276***	8.663***	8.321***
		(0.451)	(0.452)	(0.458)	(0.462)	(0.427)	(0.423)	(0.733)
95%	upper	1.21	1.16	1.19	1.02	1.07	1.01	1.15
CI	lower	0.82	0.78	0.81	0.65	0.72	0.66	0.52
Observations		224	224	224	224	224	224	1568
R-squared		0.319	0.305	0.316	0.249	0.304	0.284	0.310

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1;
Panel fixed effect using White robust standard errors.

Table 4: Empirical Results 2002-2007 (dependent variable total energy consumption)

Estimate of Equation (13)		City Subsample Estimate of Equation (13)				Time Period Subsample 2002-2006 Estimate of Equation (13)	
(1)		(2)		(3)		(4)	
		Cities below the average income growth		Cities above the average income growth			
Panel A: unrestricted model		Panel A: unrestricted model		Panel A: unrestricted model		Panel A: unrestricted model	
s_1	0.313***	s_1	0.322***	s_1	0.365***	s_1	0.317***
	(0.082)		(0.114)		(0.106)		(0.096)
s_2	-5.932***	s_2	-6.746***	s_2	-5.328**	s_2	-5.658**
	(2.351)		(3.116)		(1.924)		(2.167)
s_3	2.210**	s_3	1.500	s_3	2.551***	s_3	2.266*
	(1.223)		(1.687)		(0.768)		(1.174)
$1-s_1$	0.687***	$1-s_1$	0.678***	$1-s_1$	0.634***	$1-s_1$	0.683***
	(0.082)		(0.114)		(0.106)		(0.096)
$s_3/(1+s_3)$	0.688***	$s_3/(1+s_3)$	0.600**	$s_3/(1+s_3)$	0.718***	$s_3/(1+s_3)$	0.694***
	(0.117)		(0.270)		(0.061)		(0.110)
R^2	0.997	R^2	0.998	R^2	0.996	R^2	0.998
Obs.	224	Obs.	112	Obs.	112	Obs.	224
Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$	
s_1	0.311***	s_1	0.329***	s_1	0.343***	s_1	0.312***
	(0.079)		(0.105)		(0.088)		(0.093)
s_2	-9.259***	s_2	-8.492***	s_2	-9.665***	s_2	-9.185***
	(0.671)		(0.515)		(0.857)		(0.754)

$1-s_1$	0.689***	$1-s_1$	0.671***	$1-s_1$	0.657***	$1-s_1$	0.688***
	(0.079)		(0.105)		(0.088)		(0.093)
95% CI for a	(0.534, 0.844)	95% CI for a	(0.465, 0.877)	95% CI for a	(0.485, 0.829)	95% CI for a	(0.390, 0.986)
R^2	0.997	R^2	0.998	R^2	0.996	R^2	0.998
Obs.	224	Obs.	112	Obs.	112	Obs.	224

Table 5: Alternative time period subsamples (dependent variable total energy consumption)

(1) 2002-2005		(2) 2002-2004		(3) 2003-2007		(4) 2003-2006		(5) 2003-2005	
Panel A: unrestricted model		Panel A: unrestricted model		Panel A: unrestricted model		Panel A: unrestricted model		Panel A: unrestricted model	
s_1	0.391**	s_1	0.399**	s_1	0.339***	s_1	0.372***	s_1	0.454**
	(0.157)		(0.184)		(0.090)		(0.105)		(0.175)
s_2	-6.568**	s_2	-7.136***	s_2	-6.618***	s_2	-6.422***	s_2	-7.416***
	(2.440)		(1.762)		(2.271)		(1.918)		(2.269)
s_3	1.361	s_3	1.096	s_3	1.866	s_3	1.784**	s_3	0.866
	(1.178)		(1.100)		(1.112)		(0.907)		(1.006)
$1-s_1$	0.609***	$1-s_1$	0.601***	$1-s_1$	0.661***	$1-s_1$	0.628	$1-s_1$	0.546***
	(0.157)		(0.184)		(0.090)		(0.105)		(0.174)
$s_3/(1+s_3)$	0.576**	$s_3/(1+s_3)$	0.523**	$s_3/(1+s_3)$	0.651***	$s_3/(1+s_3)$	0.640	$s_3/(1+s_3)$	0.464
	(0.211)		(0.250)		(0.135)		(0.117)		(0.289)
R^2	0.996	R^2	0.997	R^2	0.998	R^2	0.998	R^2	0.997
Obs.	224	Obs.	224	Obs.	224	Obs.	224	Obs.	224
Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$		Panel B: restricted model; $1-s_1=s_3/(1+s_3)$	
s_1	0.384**	s_1	0.394**	s_1	0.332***	s_1	0.342***	s_1	0.447**
	(0.152)		(0.186)		(0.094)		(0.104)		(0.168)
s_2	-8.265***	s_2	-8.251***	s_2	-9.268***	s_2	-9.170***	s_2	-8.136***
	(0.679)		(0.848)		(0.633)		(0.692)		(0.671)
$1-s_1$	0.616***	$1-s_1$	0.606***	$1-s_1$	0.668***	$1-s_1$	0.658***	$1-s_1$	0.552***
	(0.152)		(0.186)		(0.094)		(0.104)		(0.168)

95% CI for a	(0.318, 0.914)	95% CI for a	(0.241, 0.971)	95% CI for a	(0.484, 0.852)	95% CI for a	(0.454,0.862)	95% CI for a	(0.223, 0.881)
R^2	0.996	R^2	0.997	R^2	0.998	R^2	0.998	R^2	0.997
Obs.	224	Obs.	224	Obs.	224	Obs.	224	Obs.	224
Note: Heteroskedasticity Robust and Province-clustered Standard Errors in brackets. *** p<0.01, ** p<0.05, * p<0.1									

Highlights:

- We test Dalgaard and Strulik (2011)'s network theory of electricity distribution
- City level data for China between 2002 and 2007 is examined
- Results provide a power law estimate of a little over 2/3
- Some evidence of a fall in network efficiency over time is shown