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China's Energy Transition and Economic Growth: A National and Sectoral Level Analyses

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Abstract:
This paper investigates the relationship between economic growth and energy transition in China based on the provincial level panel data for the period 2000 to 2012. The energy transition is measured by the share of low-carbon energy consumption in the total energy mix and per capita GDP is an indicator of economic growth. The stylized facts show that the pattern of China's energy transition varies at different stages of development and varies in terms of different sectors. We apply static models (Fama-MacBeth, OLS, fixed effect) and dynamic models (difference and system GMM) for the national and four sectoral level data- industry, agricultural, service and residential sectors. At the national level, we find a U-shaped curve relationship between energy transition and economic growth; but at the residential level, it is an inverted-U curve. The relationship in the agricultural sector is ambiguous; while in the industry and service sector, energy transition is independent of economic growth. Moreover, energy price, natural resource endowment, environmental policy, and technology are found to influence China's energy transition though to different degrees. The energy transition pattern significantly shifted from 2005 when the National Energy Transition Initiatives launched. It indicates that such industrial policy is effective to promote energy transition and the energy market reform can remove the friction or distortion to facilitate China transitioning to a low-carbon and sustainable development trajectory.

Keywords: Energy transition; Economic growth; EKC, Energy ladder; Carbon lock-in
JEL Codes: Q40; Q48; O13; Q56;

1 Introduction

The transition of China's energy mix, from high-carbon energy to low-carbon energy, has a global impact on tackling climate change as well as sustaining the world economy. As the world's largest developing country and greenhouses gas emitter, China is undergoing grand decarbonization in line with rapid economic growth and structural transformation from an agrarian economy to an industrialized economy and then to a service economy. Such energy transition has been characterized by a significant increase in energy consumption (Crompton and Wu 2005) and production (Wang 2011), and a decrease in energy intensity (Ma and Stern 2008, Wu 2012). in China's success in the energy transition will directly determine the world achieving the target of holding global warming to less than 1.5 degrees (IPCC 2018), and also will demonstrate a pathway for other developing economies such as India or Africa (Sheehan et al. 2014).

However, the relationship between the changing energy mix and economic growth at both national and sectoral levels are still not well understood. In the long history, the energy system evolution can be characterized as moving from carbonization to decarbonization in the context of carbon components in the energy mix. The increasing scale of industrialization mainly drove the first move and the second move was driven by the negative externalities of non-renewable fossil fuels on the environment and economy. The energy transition has occurred in the context of economic development, which is linked to changing economic activities across all provinces but at different levels. In this paper, we will examine the relationship between this energy transition and economic growth to investigate whether such ongoing energy transition follows different patterns at different stages of development and in different sectors.

We find there exists a U-shaped curve between energy transition and economic growth at the national level with the turning point occurring at around 15,350 Yuan per capita GDP, measured in 2010 constant prices. It indicates that the pattern of China's energy transition is similar to the

Environmental Kuznets Curve (EKC) prediction and exhibits increasing returns to scale to economic growth after crossing the turning point. However, the relationship in the residential sector is found to be an inverted-U curve with the turning point occurring at around 39,558 Yuan in 2010 constant prices. It suggests that the energy mix of households would become more carbon-intensive once per capita GDP exceeds such thresholds. Our models show that the energy transitions in the industry and service sector seem to be independent of the level of per capita GDP but perform self-perpetuating evolution patterns. The pattern for the agricultural sector is ambiguous. We also find the natural resource endowments, energy prices and technology affect the energy transition to varying degrees. The price effect becomes particularly significant after 2005 when the nation launched the energy transition policy initiatives. The natural gas abundance would enhance the level of energy transition at the national level and in the industry sector.

In methodology, we adopt a static and dynamic modeling approach based on China 30 provincial data from 2000 to 2012. We conduct the Fama-MacBeth (FMB) regression, Ordinary Least-Square (OLS) regression and Fixed Effect (FE) model for the static models and conduct the difference and system Generalised Method of Moments (GMM) approach for the dynamic models. We compare these approaches in terms of robustness and estimation efficiency and draw the policy implications based on the results.

The paper is organized as follows. Section 2 will review the relating literature on energy transition. We highlight three hypothesized theories -energy ladder, EKC and carbon lock-in in this section. Section 3 will present the stylized facts between energy transition and economic growth. We present both the national level and sectoral level facts in this section. Section 4 will illustrate the models and estimation strategies. Section 5 will explain the variables and describe the data. Section 6 will report econometric results. Section 7 is the conclusion and policy implication.

2 Literature review

Tahvonen and Salo (2001) describe a theoretical model in which the optimal transition path between renewable and non-renewable energy follows a U-shaped pattern at different development stages of an economy. In their model, energy transition may occur even without policy intervention and can be driven by technological change and growth in per capita income. Three well-known evidence-based theories provide distinct insights on energy transition; they are the energy ladder, the environmental Kuznets curve (EKC), and carbon lock-in theories. The energy ladder predicts a linear (one-way) path for energy transition with respect to economic development while the EKC predicts a nonlinear pathway. The carbon lock-in suggests that energy transition may be locked into fossil energy regime by path-dependence factors such as technology or institutional inertia (Unruh 2000).

Grübler (2004) synthesizes the basic facts of energy transition into three dimensions: growth in consumption; change in quality, and change in structure. He defines the transition as evolving from solid to liquid to grid energy, in terms of physical forms; from non-commercial to commercial energy, in terms of economic values; and from a low to a high hydrogen-carbon ratio in the context of the carbon components of energy (i.e., decarbonization). Such energy transitions have been happening for centuries (Kander, Malanima, and Warde 2013, Gales et al. 2007, Smil 2010); for instance, a transition from wood to fossil fuels took place over 200 years ago. Generally speaking, the transition from one type of energy to another takes about 80 to 400 years (Fouquet 2010). In the short run, a transition relies on the availability of energy, its cost, pollution arising from its use and improvements in efficiency arising from economic activity (Solomon and Krishna 2011). Looking at the history of Western Europe, Kander, Malanima, and Warde (2014) show that the share of carbon components in the energy system followed an inverted U-curve from 1870 to 2010, with the peak (80%) appearing in 1940. Its share of coal consumption increased at first and then decreased after 1945. Its share of oil increased dramatically to reach a peak in 1978 and declined thereafter. In contrast, the share of fuelwood followed a U-curve, declining from 70% in 1840 to no more than 10% in the 1970s, but increasing again to almost 30% in 2010.

Gales et al. (2007) find an inverted U-curve of energy intensity[1] for Great Britain, the United States, Germany, France, Japan and some developing countries. Bithas and Kalimeris (2013) surprisingly find that even though energy intensity by total GDP decreased in the last century, energy intensity by per capita GDP increases all the time, and so argue that per capita GDP is a better indicator of energy transition than total GDP. Grübler (2003) captures an inverted U-curve for the worldwide share of coal consumption from 1840 to 2020, with the turning point occurring around 1920. After that, the share of coal consumption stabilizes but the relative share of coal to other energies significantly decreases (Grübler, Nakićenović, and Victor 1999). These studies reveal a universal pattern of energy transition, indicating that coal consumption increased from the time of the Industrial Revolution and decreased after World War II.

Among cross-country studies, Marcotullio and Schulz (2007) find that industrializing countries experience more efficient energy transition in growth - starting at a lower per capita GDP and transiting at a faster rate than the United States. Grübler (2012) emphasizes that such energy transition is underpinned by technological change, but technological change may lead self-perpetuating inertia of fossil technology use, so that energy transition may be locked in by some traditional energies (Arthur 1989). Whether technological change promotes energy transition or locks energy in some high-carbon energy trajectory has not yet been determined, and a better understanding of this phenomenon is needed.

Ma and Stern (2008) find that energy intensity by total GDP in China decreased in the period 1980 to 2003 mainly because of technological change. Palazuelos and Garcia (2008) note that China's energy transition is due to the high rate of economic growth, expansion of transport, and

[1] Energy intensity is total energy consumption in heat content divided by GDP in constant prices.

urbanization. These studies imply that China's energy transition should be in line with economic growth, but the exact pattern is still unclear.

In literature, three well-documented theories have been advanced to explain the relationship between energy transition and economic growth. Evidence shows that individuals tend to switch to modern energy as income increases. This one-way trend of energy transition is called the 'energy ladder' (Hosier 2004). The second theory - the environmental Kuznets curve (EKC) - posits that there is a quadratic relationship between environmental degradation and per capita GDP (Stern, Common, and Barbier 1996). These two theories imply that there is a causal relationship between energy transition and economic growth but the direction of the relationship is ambiguous. A third theory, called the carbon lock-in, states that the energy system may exhibit path-dependent attributes that lock it into fossil energy consumption, driven by technological and institutional increasing returns to scale (Unruh 2000). In this regard, energy transition will be much slower than is predicted. It implies that transition may be more difficult and hindered by exogenous factors.

The energy ladder theory relates to energy transition to per capita GDP. It states that the transition towards modern energy is driven by rising incomes (Hosier and Kipondya 1993, Barnes and Qian 1992, Leach 1992, 1999, 1996, Leach 1988). Brown (1954) initially hypothesized that households would choose efficient and less polluting energy and abandon traditional energy as their income rises. Empirical evidence shows that countries with higher per capita GDP tend to use higher quality energy (Brown 1956, Burke 2013, Hosier 2004). Hosier and Dowd (1987) present evidence from Zimbabwe based on survey data and find that fuelwood and kerosene consumption decrease and electricity consumption increases as household incomes increase. Hosier (2004) notes that both micro and macro data provide evidence of an energy ladder. Heltberg (2004) analyses household survey data from eight developing countries and shows that the uptake of modern fuels positively relates to per capita income. The energy ladder relates to a change in the quantity of separate energy consumption, rather than indicating structural changes in the energy mix directly. A criticism of this model is that it is one-sided, providing a snapshot of only one segment of a trend. For instance, Masera, Saatkamp, and Kammen (2000, 2083-2103) find that in Mexico, people do not switch fuels but adopt multiple fuels because traditional energy is rarely abandoned. Similarly, Van der Kroon, Brouwer, and van Beukering (2013, 504-513) used a meta-analysis to show that energy ladder is not observed in empirical studies; instead, a multiple fuels energy portfolio is the best description of energy transition in developing countries, in both urban and rural households.

The EKC theory suggests an inverted U-curve relationship between pollution and per capita GDP. According to Stern (2004), EKC is a hypothesized relationship between energy use, economic growth and the environment. It assumes that the environmental degradation indicator is an inverted U-shaped function against per capita GDP. This can be explained by behavioral or preference changes, by institutional, technological, or structural changes, and by international reallocation of polluting industries (Kijima, Nishide, and Ohyama 2010). Andreoni and Levinson (2001) argue that the inverted-U is rooted in the increasing return to the scale of an economy.

Grossman and Krueger (1991) were the first to investigate EKC empirically. Their study, based on cross-sectional data from 42 countries, finds an inverted U curve relationship between sulfur dioxide and per capita GDP. Several studies have investigated this relationship in developed countries (e.g., List and Gallet 1999, Panayotou 1993). Other studies have provided supporting evidence in developing economies (Dasgupta et al. 2002), including China (Wang and Wheeler 2003, Zhang 2000). However, the results in most circumstances are mixed.

Although most EKC studies are not directly concerned with energy transition, it is undeniable that fossil fuel consumption causes pollution. Long-run studies have shown that fossil fuel emissions (Schmalensee, Stoker, and Judson 1998) and the share of coal consumption (Grübler 2012) both follow an inverted U-shaped relationship with economic growth. The EKC model may indicate a quadratic relationship between energy transition and economic growth in the context of the energy mix.

The carbon lock-in theory generally posits that people's present fuel choices depend on what they have chosen in the past. In this context, the energy transition is path-dependent. The theory suggests that the degree of energy transition depends on some exogenous factor such as institution, technology or infrastructure. Arthur (1989) comments that carbon lock-in occurs when a carbon-intensive technology is scaled-up. Some studies show that countries with large fossil fuel reserves tend to change their energy structure slowly -a natural endowment effect (Burke 2013, Burke 2010). Others argue that energy transition can be locked into several interrelated factors such as the dominant technology and policy interventions. They regard energy, technology and institution as a co-evolutionary system (Rio and Unruh 2007). Differing from the energy ladder and EKC, the carbon lock-in theory postulates that energy transition may be hindered even though per capita GDP is growing. It is a more pessimistic view of energy transition compared to the other two.

Each of these three theories provides a different perspective on energy transition. To investigate what pattern China did follow and which theory would explain China's energy transition well, we first review stylized facts about China's energy transition in the next section.

3 Stylized facts

In this paper, we measure China's energy transition by the share of low-carbon energy in total energy consumption. The fuel type choice and the calculation process can be seen in the Appendix.

Figure 1 graphs the cross-sectional distribution of energy transition against per capita GDP in 1995, 2006 and 2012. Per capita GDP is measured at the 2010 constant price.[2] The level of energy transition is seen to rise over time. When per capita GDP is below 20,000 Yuan, the transition curve followed an inverted U curve in 1995 but it changed to a standard U-curve in 2006 when most provinces achieved a per capita GDP of nearly 20,000 Yuan and moving towards 40,000 Yuan. In 2012, per capita GDP in most provinces was between 20,000 to 40,000 Yuan, with some exceeding

[2] We use GDP deflator issued by World Bank http://data.worldbank.org.cn/indicator/NY.GDP.DEFL.ZS, based year is 2010.

40,000 Yuan (Beijing, Tianjin, Shanghai, Jiangsu). The relationship between energy transition and per capita GDP after 2006 shows an upward linear trend, suggesting that the relationship between energy transition and economic growth may change at different stages of development.

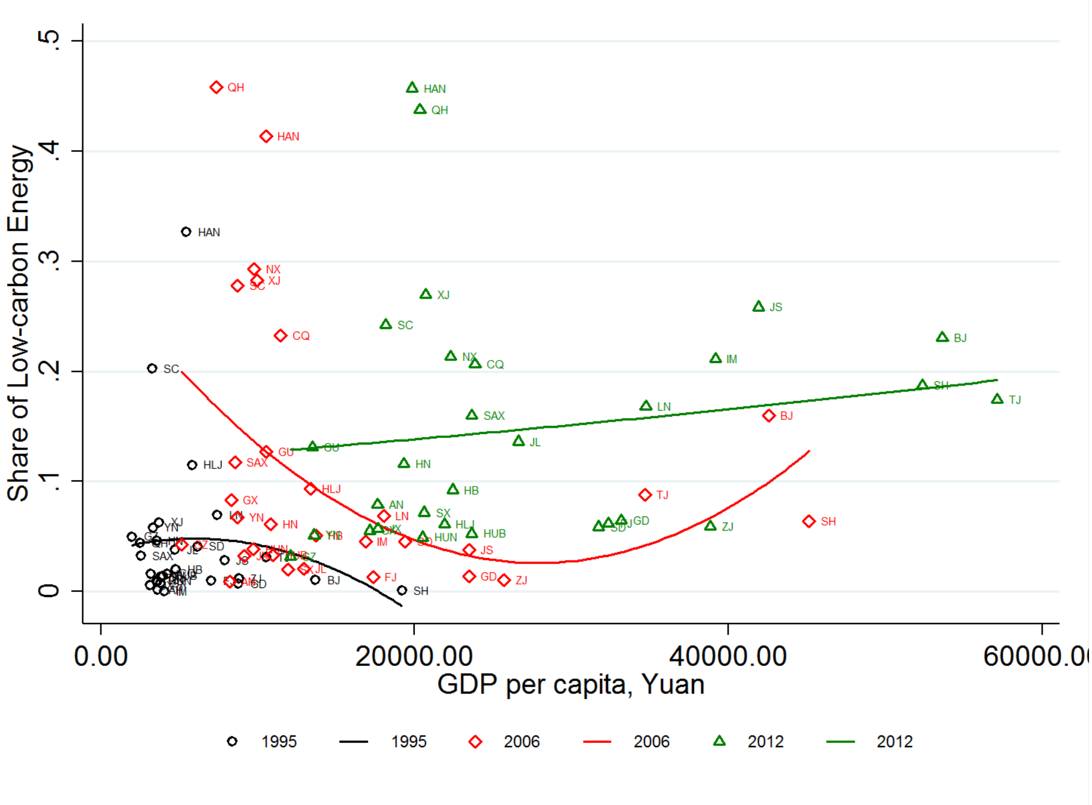

Figure 1 Relationship between the share of low-carbon energy and GDP *per capita* (national level, three years of cross-sectional data for 1995, 2006, 2012)

The sectoral level data are presented in Figure 2. The patterns of the industry sector and service sector are almost linear and flat with time. It may suggest the energy transition in this sector has no bearing with per capita GDP. All three curves of the agricultural sector have negative slopes, suggesting a negative relationship between energy transition and economic growth. In other words, the agricultural sector tends to consume high-carbon energy rather than low-carbon energy during economic growth. In the residential sector, the curves are linear and the slops are becoming flattered over the years; Figure 2 suggest that the causal relationship between energy transition and economic growth differs across sectors.

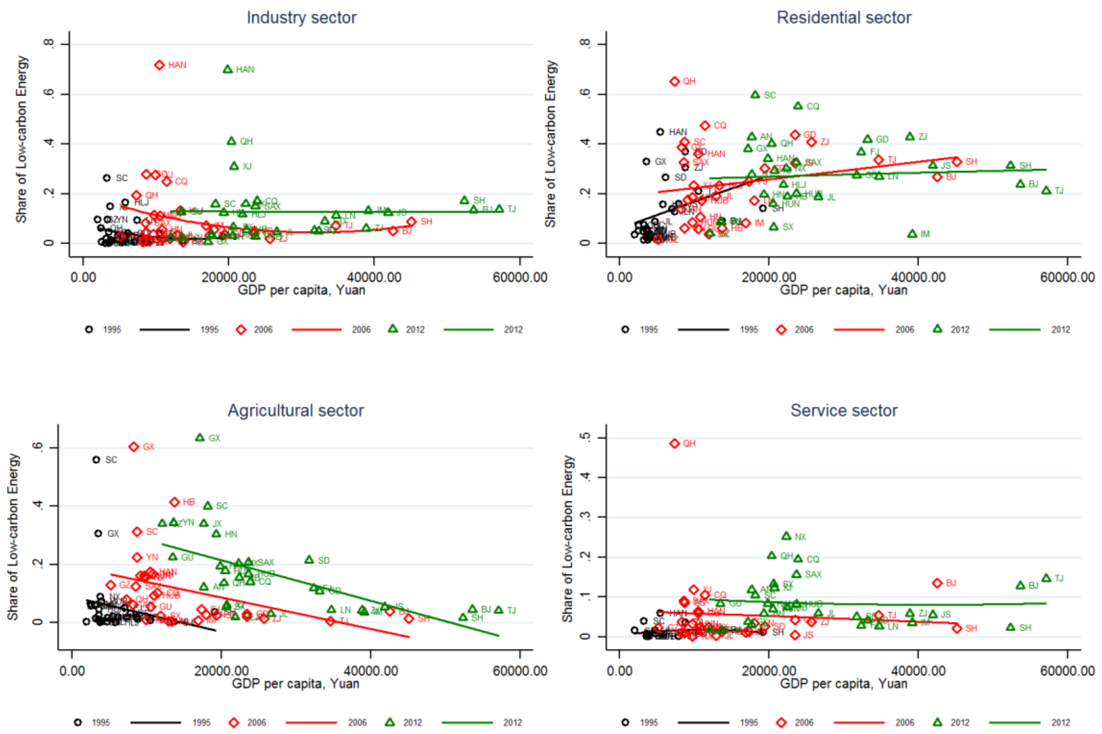

Figure 2 Relationship between the share of low-carbon energy consumption and per capita GDP (sectoral level, three years of cross-sectional data for 1995, 2006, 2012)

4 Methodology

4.1 Model specification

A full version of a static model is constructed as:

$$S_{i,t} = \beta_1 \left(lnGDP_{i,t}\right)^2 + \beta_2 lnGDP_{i,t} + \boldsymbol{\gamma lnX_{i,t}} + u_i + \varepsilon_{i,t} \qquad (1)$$

The dependent variable is the energy transition measured by the share of low-carbon energy in total energy consumption. The independent variables include the linear and quadratic terms of per capita GDP and other control variables are in vector ***X***. It is a semi-log regression with all independent variables are transformed in logarithm forms. β_1 , β_2 and vector $\boldsymbol{\gamma}$ are parameters to be estimated; i indicates provinces and t indicates year. u_i is a province-specific factor that is time invariant and assumed to be homoscedastic across provinces. ε_{it} is an error term which is independent and identically distributed.

The quadratic and linear terms of per capita GDP capture the potential relationship between energy transition and economic growth. It measures the 'income effect' or 'growth effect' on energy transition. Per capita GDP determines both the quantity and quality of energy consumption, as well as which types of energy end-use conversion devices are affordable to consumers (Grübler 2004). Parameters β_1 and β_2 are used to test if the observed relationship corresponds to the energy ladder hypothesis (linear relationship) or the EKC hypothesis (U relationship). If either β_1 or β_2 is significant, energy transition is consistent with the energy ladder's prediction: that is, energy transition is linearly dependent on economic growth. If β_1 is significant but β_2 is not, the energy ladder model applies again. If they are both significant, a quadratic relationship between energy transition and per capita GDP exists. In this case, the EKC model will be more powerful in explaining the energy transition. If β_1 and β_2 have different signs, this indicates either a U or inverted U-shaped relationship. The turning point is given by $\exp^{-\frac{\beta_2}{2\beta_1}}$. The elasticity between energy transition and per capita GDP is given by $\beta_1 \ln(GDP) + \beta_2$, which assumes that the marginal effect of economic growth on energy transition is not determined by parameters $\beta_1$and β_2 only, but also by changes in economic growth. The quadratic term allows economic growth to have a diminishing or increasing effect on energy transition at the margin.

The vector $\boldsymbol{X}$ contains all control variables and lock-in effects.[3] We consider three types of lock-in effects: potential technology path-dependence for coal-fired generation, institutional barriers, and natural endowments. We also control for the prices of all types of energy as well as the incentive of policy intervention from local government by a proxy for environmental degradation. The detailed summary and interpretation of all control variables are presented in the Appendix.

[3] We compute the correlation matrix for all explanatory variables to see if significant multicollinearity exists. The results show that all correlation coefficients are below 0.6.

The current state of energy transition may depend upon past conditions of itself: persistence, consumption behavior formation, partial adjustment, and so forth. Therefore, we include the lagged term of the dependent variable in the dynamic model:

$$S_{i,t} = \beta_0 S_{i,t-1} + \beta_1 \left(lnGDP_{i,t}\right)^2 + \beta_2 lnGDP_{i,t} + \boldsymbol{\gamma lnX_{i,t}} + u_i + \varepsilon_{i,t} \tag{2}$$

where β_0 is the parameter of the first-lagged dependent variable and the rate of convergence can be expressed as $1 - \beta_0$, which implies the speed of adjustment. If $\beta_0 = 0$, the dependent variable does not depend on the previous period's state. If $\beta_0 = 1$, there is no dynamic adjustment process because the energy transition is in the steady state in every period. Given the model dynamics, $\frac{\boldsymbol{\gamma}}{1-\beta_0}$ captures the long-run effect of $\boldsymbol{X}$ on energy transition.

4.2 Fixed effect

The fixed effect term u_i in equations (1) and (2) captures all unobservable time-invariant effects across provinces. The fixed effect can result from typical social norms regarding energy transition or fuel-consuming patterns within a province. These factors are highly variable across China's provinces as there are distinct features of development across provinces. The Hausman test is used to choose between the fixed effect and the random effect models.[4]

For robustness and comparison, we also estimate the model using the Fama-MacBeth (FMB) model and ordinary least squares (OLS). The OLS estimator is biased and inconsistent in the presence of fixed effects. The Fama–MacBeth two-step procedure (Fama and MacBeth 1973) is implemented in two steps: first we estimate cross-sectional regression by OLS for every single year; later we

[4] Differences within time series and between individuals have long been discussed since Baltagi and Griffin (1984) in literature. Generally, Panel data involves two types of variation: the differences between provinces (between variations) and the differences over time within provinces (within variation). Firstly, we proceed to the Ordinary Least-Squares (OLS) estimator, fixed-effect (FE) estimator and random-effect (RE) estimator for model choice. The rejection from the likelihood ratio test indicates FE is superior to OLS. Breusch and Pagan Lagrangian multiplier test shows that RE estimator are better than OLS too. We finally adopt FE on basis of rejection of Hausman test between FE and RE. In this case, RE model is biased.

average coefficient estimates from the first step using Zellner's seemingly unrelated regression (SUR) estimation. This procedure allows us to include the over-year variation in coefficients. For T $\rightarrow\infty$, these averages will provide consistent estimators for the population. The standard errors are computed from the sample standard deviations of estimated coefficients, treating them as independent drawings from a common pool. The standard error calculation allows for arbitrary cross-sectional correlation and heteroscedasticity in residuals. The Fama–MacBeth procedure can provide a heteroscedasticity-consistent estimation in the absence of serial correlation. However, given the existence of a serial correlation, in this case, we adjust it via Newey and West (1987) standard error estimates with a lag length of two periods.

4.3 Generalized method of moments

The dynamic model might give rise to 'dynamic panel bias' because the lagged dependent variable may be positively correlated with fixed effect so that the OLS estimator is inconsistent and overestimates the true autoregressive coefficient β_0 (Nickell 1981). Given that the lagged term exists, the FE is inconsistent because the within transformed lagged dependent variable is correlated with the within transformed error. Given the finite time period *T* and provinces *N*, FE model underestimates the true autoregressive coefficient β_0 (Verbeek 2012, 396).

To deal with this potential endogeneity problem, we use the generalized method of moments (GMM) to estimate the dynamic model. This method is particularly suitable for a dynamic model with a few years and large groups. Anderson and Hsiao (1981) propose difference GMM to remove fixed effect by first-difference transforming data as follow:

$$\Delta S_{i,t} = \alpha \Delta S_{i,t-1} + \beta_1 \Delta (lnGDP_{i,t})^2 + \beta_2 \Delta lnGDP_{i,t} + \boldsymbol{\gamma} \Delta \boldsymbol{lnX_{i,t}} + \Delta \varepsilon_{i,t} \quad (3)$$

GMM does not require that the error term is independent and identically distributed over provinces and years, but the consistency of estimators assumes that $\varepsilon_{i,t}$ does not exhibit autocorrelation.

Difference GMM still has potential endogeneity problems, since the lagged dependent variable is still potentially endogenous with the changes of disturbance by way of $S_{i,t-1}$ in $\Delta S_{i,t-1}$ is correlated with $\varepsilon_{i,t-1}$ in $\Delta\varepsilon_{i,t}$. In addition, some predetermined explanatory variables may not be strictly exogenous as they are correlated with $\varepsilon_{i,t-1}$. Therefore, we instrument $\Delta S_{i,t-1}$ by $S_{i,t-2}$ or further lagged terms.

Arellano and Bond (1991) note that difference GMM does not employ all the necessary moment conditions. Thus, if some independent variables are not strictly exogenous but are predetermined, difference GMM does not always guarantee efficiency estimates by applying instrument variables. More important, Blundell and Bond (1998) point out that the first difference GMM may suffer from finite sample biases, particularly in a situation where the dependent variable shows high persistence; that is, α is close to one. In other words, past levels convey little information about future changes. In such situations, the instruments are weak because they provide very little information on the parameters of interest. Blundell and Bond (1998) introduce the system GMM method that uses moment conditions based on both levels and first-differences equations. The significant advantage of system GMM is that it avoids losing information by differencing the fixed effect. In this paper, we employ both difference and system GMM methods for our dynamic model estimations.

5 Variables and data

The detailed data source and the summary of variables are presented in the Appendix.

Provinces with large natural endowments of some energy resources are usually reluctant to change consumption habits as this abundant energy is readily available and has low transport costs, especially given the well-developed rails and waterways in China. Such effects have been observed in several cross-country studies (Burke 2010, Burke 2011, 2012, 2013). In modeling, we control for three main types of energy resource endowment: coal, oil and natural gas, to test if energy transition could be locked in by resource abundance. A suitable proxy is needed to measure the amount of natural endowment. Some candidates have been suggested in the literature: for instance, some economists are using export energy data (Sachs and Warner 1995, Davis 1995) while others use resource rent data (Stijns 2006). We adopt Brunnschweiler's (2008) measurement of per capita production as an indicator of the natural endowment.

Energy transition may be locked in by fossil technologies increasing return to scale (Unruh 2000). Large numbers of coal-powered plants may lock a province into using coal for its electricity production. To negate the scale effect of the economy, we use per capita coal-fired power generation capacity (installed) as a proxy to investigate potential technology lock-in.

Urbanization can be regarded as an institutional change during the transition from agrarianism to industrialization. A feature of China's reform and rapid growth during the past decades is internal rural-urban migration, which is partially driven by institutional arrangements such as the Hukou system[5] reform, the social insurance system, urban infrastructure investment, and like human rights related to equality. Herrerias, Aller, and Ordonez (2017) find that the energy mix in urban areas changed when electricity replaced coal, and they consider that urbanization accounts for this, especially in the areas of Hukou reform and the New Urbanisation policy. We use the number of people living in urban areas to indicate this major institutional change: the more people in an urban area, the more sophisticated society becomes and the better is the quality of its institutions. Urban population is measured by the number of people living in towns and city. We use actual residential population rather than registered population.

We control policy effect as a proxy of the lagged term of yearly changes of sulfur dioxide (SO_2) emission as it can measure the tightness of the environmental policy. Sulfur dioxide is one of the main pollutants from the use of coal and oil. It is a major indicator of pollution and is strictly

[5] A Hukou is a record in a government system of household registration required by law in mainland China and Taiwan, and determines where citizens can live. Because of its entrenchment of social strata, especially between rural and urban residency status, the hukou system is often regarded as a form of caste system.

monitored by the Ministry of Environmental Protection and other authorities who use it to assess the performance of the environmental governance of local governments. We use the changes in the logarithm of sulfur dioxide between every adjacent two years to measure the slackness of environmental policy. The underlying assumption is that if an increase in SO_2 emissions were high in last year, the local government would come under more pressure to adopt policy actions on energy transition this year. The policy effectiveness is based on the performance of SO_2 emissions.

6 Results

The consistency of the fixed effect estimator will not guarantee efficiency all the time if the error term is heteroscedastic or displays autocorrelation or cross-sectional dependence. We adopt a modified Wald statistic following Greene (2012, 338) to test for potential province-wise heteroscedasticity in the residuals of the national level model as well as sectoral level models. The null hypothesis is that there is no heteroscedasticity in the model. Tests for autocorrelation, heteroscedasticity and cross-sectional independence and unit roots are reported in the Appendix.

The model residuals may also suffer from autocorrelation; thus estimated parameters will be inefficient but still unbiased. The Wooldridge test is used to test for autocorrelation. The null hypothesis is no series correlation and we reject it at the 5% level in the sectoral level models except for the national level model. Thus, all sectoral level regression performs first-order serial correlation. Under such circumstances, FE is still consistent, but inefficient, and standard error estimates are biased.

We suspect the model residuals are correlated within or between provinces. The Wald test on the FE model is rejected, indicating province-wise heteroscedasticity exists. We are also concerned that provinces may suffer from the problem of spatial dependence (neighborhood effect), which may occur if the social norms or psychological behavior patterns are influenced by neighboring provinces. In theory, Hoechle (2007) suggests this cross-sectional correlation may result from the explanatory variables and disturbance terms containing three components: an individual specific long-run mean, an autocorrelated common factor, and an idiosyncratic forcing term. We conduct the Pesaran test to check this. The null hypothesis is that the residuals are cross-sectionally uncorrelated. The Pesaran test shows that the residuals in the agricultural model present cross-sectional dependence, which implies energy transition could be spatially correlated in the agricultural sector.

To ensure valid inferences, we adopt the Driscoll–Kraay FE estimator (Hoechle 2007) for the agricultural model. With this estimator, we can relax assumptions by allowing residuals to be correlated both within groups and between groups, to take account of spatial correlation in the model. The Driscoll–Kraay estimator also adjusts the standard error estimates by sequencing cross-sectional averages of the moment conditions, which guarantees consistency and independence of cross-sectional dimension N. We adopt Rogers standard errors (clustered standard errors) to compute standard errors for the industry, service and residential sector models (Cameron and Miller 2015). Rogers standard errors allow for residuals that are heteroscedastic and correlated within groups but not between groups.

We estimate the fixed effect model for the whole period and the subperiod after 2005, to investigate if the significance level of some variables changed after 2005 when the national energy transition initiative was launched.[6]

Table 1 and Table 2 are estimations of the national level static and dynamic models, respectively. Sectoral transition estimations are reported in Table 3 to Table 6, for the industry, agricultural, service and residential sectors separately.

[6] China's government has made a commitment that by 2020 non-fossil energy will account for 15 percent of total primary energy consumption, and that CO_2 emission per GDP will be 40–45 percent lower than that in 2005. This is stipulated in *the twelfth Five-Year Plan (2011–2015) for National Economic and Social Development*, and calls for a significant energy transition. Meanwhile, China's economic growth will decouple from energy consumption to some extent. The initial set of China's energy pricing reform started in 2005, with a focus of establishing a market-oriented market to reduce energy price differences in different regions (Guo et al. 2015). A target to improve 20 percent energy efficiency by 2012 was also set in 2005. For the sake of testing this policy effect, we run the subsample before and after 2005 separately.

6.1 National level results

At the national level, a significant U curve relationship is found between energy transition and per capita GDP as can be seen in Table 1. Except for the subperiod before 2005, all the other models' coefficients for per capita GDP quadratic terms are significantly positive and the coefficients for per capita GDP linear terms are significantly negative. The energy transition pattern shifted from 2005 when the National Energy Transition Initiatives launched. However, the turning points are different across the models. Given that the Fama–MacBeth and OLS are biased estimations, the FE models are more robustness and they suggest that the turning point is around 15,000 – 16,000 Yuan.

The FE models for the two subperiods before and after 2005, shown in columns (4) and (5), provide different significance levels. We find the natural gas endowment effect changes from insignificant to positively significant. After 2005, a 1% increase in natural gas production will increase the low-carbon energy share by 0.007 percent point. It could be a result of the natural gas stimulation policy. The price effects became more significant after 2005 too. A 1% increase in the steam coal price will result in 0.093 percent point increase in the low-carbon energy share; 1% increase in residential electricity price will increase the low-carbon energy share by 0.102 percent point; 1% increase in diesel price will increase low-carbon energy share by 0.079 percent point, *ceteris paribus*. These results indicate that price fluctuation is effective to promote energy transition and the deregulation policy reform that decentralizes the energy market would be valid to assist China to get into a low-carbon and sustainable development trajectory (Guo et al. 2015).

Table 1 Results for the national level static model

Model Variable	(1) FMB	(2) OLS_Pooled	(3) FE	(4) FE_before2005	(5) FE_post2005
$ln(GDP)^2$	0.024**	0.018**	0.044***	-0.075**	0.084***
	(0.032)	(0.030)	(0.001)	(0.033)	(0.000)
ln(GDP)	-0.417*	-0.336**	-0.847***	1.454**	-1.634***
	(0.066)	(0.042)	(0.001)	(0.026)	(0.000)
ln(coalgen)	-0.064***	-0.052***	0.041**	-0.004	0.015
	(0.000)	(0.000)	(0.029)	(0.894)	(0.568)
ln(urban)	-0.047***	-0.064***	0.030	0.009	-0.043
	(0.001)	(0.000)	(0.147)	(0.791)	(0.689)
ln(gas)	0.021***	0.019***	0.010***	0.004	0.007*
	(0.000)	(0.000)	(0.006)	(0.509)	(0.055)
ln(oil)	-0.002	-0.003**	-0.001	-0.004	0.000
	(0.280)	(0.027)	(0.863)	(0.545)	(0.964)
ln(coal)	-0.020***	-0.022***	-0.006	-0.021	0.000
	(0.000)	(0.000)	(0.397)	(0.383)	(0.995)
$ln(P_{briquet})$	-0.031*	-0.009	-0.014	-0.044*	0.000
	(0.067)	(0.379)	(0.235)	(0.085)	(0.996)
$ln(P_{steamcoal})$	0.007	0.002	0.019	-0.030	0.093***
	(0.457)	(0.846)	(0.321)	(0.418)	(0.000)
$ln(P_{elecind})$	-0.061	-0.039	0.032	0.044	0.040
	(0.138)	(0.147)	(0.317)	(0.543)	(0.428)
$ln(P_{elecre})$	-0.037	0.053*	0.027	-0.050	0.102***
	(0.359)	(0.091)	(0.534)	(0.486)	(0.010)
$ln(P_{elecag})$	-0.059	-0.006	-0.021	0.036	-0.001
	(0.128)	(0.654)	(0.173)	(0.818)	(0.921)
$ln(P_{elecserv})$	-0.070	-0.102***	0.079**	0.049	0.052
	(0.133)	(0.002)	(0.038)	(0.795)	(0.195)
$ln(P_{petro})$	0.699*	0.233***	0.067	0.183	-0.144
	(0.071)	(0.009)	(0.527)	(0.367)	(0.242)
$ln(P_{diesel})$	-0.164***	-0.040	0.037	-0.200*	0.079*
	(0.002)	(0.151)	(0.368)	(0.085)	(0.092)
$ln(P_{gasind})$	-0.031	-0.041**	-0.031	-0.020	-0.043
	(0.487)	(0.022)	(0.107)	(0.433)	(0.234)
$ln(P_{gasre})$	-0.057	-0.059**	0.013	0.039	0.069
	(0.266)	(0.021)	(0.690)	(0.464)	(0.520)
$dln(SO_2)$	0.055	0.042	0.023	0.004	0.023
	(0.486)	(0.165)	(0.346)	(0.854)	(0.388)
constant	-2.426	0.747	2.837**	-6.557**	8.487***
	(0.511)	(0.527)	(0.045)	(0.041)	(0.000)
N	330	330	330	120	210
R^2	0.919	0.814	0.404	0.415	0.309
Turning point	6062.519	9534.2395	15356.216	16285.513	16146.216

Note: p-values in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. year dummies are eliminated to save space.

Focusing on the FE model of the whole period (model 3), we find that the coefficient of natural gas production to energy transition is significantly positive (0.010), slightly higher than in the post-2005 model (0.007). It implies a stronger effect of natural gas resource endowment in the long run. The coefficient of coal-fired electricity generation capacity is significantly positive (0.041), suggesting that a 1% increase in coal-fired power generation would increase energy transition by 0.041 percent point, rather than hindering the transition. The seemingly counterintuitive facts can be explained by reviewing the historical stages of development. At early stages of development, when the households directly burn coal for heating or cooking, the burning coal and electricity would be substitutes. Hence, generating electricity, even from coal, could significantly reduce direct coal consumption in a less developed society.

In Table 2, we report the national level dynamic model results. Columns (1) to (4) are the OLS, FE, difference GMM and system GMM models, respectively.[7] All the models suggest a U-curve relationship between energy transition and per capita GDP. The difference and system GMM model suggest that the turning points are about 17,263 or 15,345 Yuan, based on the 2010 constant price. The Sargan and Hansen's tests show that both the difference and system GMM models are appropriate for the selected instruments. As the system GMM model contains more information on the level equation for inference, we are prone to adopt the turning point suggesting by the system GMM model (15,345.213 Yuan). This number is very close to the turning point suggested by the static FE model in Table 1 (15,356.216 Yuan).

Apparently, from the system GMM model, the energy transition performs some pattern of self-persistence with the coefficient of 0.267 and the speed of adjustment is 0.733. We can also observe a significant natural resource endowment effect and price effect. In the long-run,[8] a 1% increase in the natural gas production will increase low-carbon energy share by 0.022 percent point; a 1% increase in petroleum price will increase low-carbon energy share by 0.188 percent point, *ceteris paribus.* On the contrary, a long-run effect of 1% increase in industrial electricity price or industry natural gas price will significantly decrease energy transition by 0.119 and 0.111 percent point, respectively. Apart from these, we find the national energy mix would be locked into the coal-electricity power generation capacity by the long-run coefficient of 0.022 percent point.

[7] As discussed earlier, OLS tends to overestimate the parameter of the lagged term while FE tends to underestimate it. The true coefficient should lie somewhere between them. The estimated coefficients of the lagged transition index in models (3) and (4) lies between those of the OLS and the fixed effect models indicating that the results of the GMM estimation are reliable.
[8] The long-run coefficient of dynamic GMM model is given by $\gamma/(1-\beta_0)$, as illustrated in Equation (3).

Table 2 Results for the national level dynamic model

Model Variable	(1) OLS_lag	(2) FE_lag	(3) Diff_GMM	(4) Sys_GMM
lag S	0.657***	0.224***	0.379	0.267*
	(0.000)	(0.000)	(0.371)	(0.073)
ln(GDP)^2	0.015**	0.041***	0.045*	0.016***
	(0.016)	(0.000)	(0.052)	(0.005)
ln(GDP)	-0.282**	-0.781***	-0.868*	-0.314***
	(0.018)	(0.000)	(0.056)	(0.005)
ln(coalgen)	-0.014**	0.033**	0.069	-0.016
	(0.026)	(0.036)	(0.197)	(0.377)
ln(urban)	-0.023***	0.019	0.071	0.015
	(0.001)	(0.287)	(0.755)	(0.459)
ln(gas)	0.007***	0.008***	0.011**	0.016***
	(0.000)	(0.008)	(0.029)	(0.001)
ln(oil)	-0.001	0.000	0.008	-0.002
	(0.157)	(0.956)	(0.116)	(0.552)
ln(coal)	-0.009***	-0.006	-0.005	-0.027***
	(0.000)	(0.350)	(0.746)	(0.002)
$ln(P_{briquet})$	-0.006	-0.012	-0.045**	-0.027*
	(0.501)	(0.223)	(0.044)	(0.068)
$ln(P_{steamcoal})$	0.005	0.025	0.052**	0.006
	(0.595)	(0.170)	(0.031)	(0.757)
$ln(P_{elecind})$	-0.021	0.025	0.043	-0.087**
	(0.232)	(0.373)	(0.542)	(0.011)
$ln(P_{elecre})$	0.025	0.022	0.002	-0.046
	(0.249)	(0.552)	(0.977)	(0.240)
$ln(P_{elecag})$	-0.000	-0.013	-0.024	-0.026
	(0.964)	(0.347)	(0.515)	(0.309)
$ln(P_{elecserv})$	-0.033	0.062*	0.091	-0.090
	(0.173)	(0.069)	(0.515)	(0.124)
$ln(P_{petro})$	0.015	0.030	-0.005	0.138***
	(0.850)	(0.738)	(0.952)	(0.000)
$ln(P_{diesel})$	-0.011	0.033	0.000	0.038
	(0.625)	(0.288)	(0.999)	(0.131)
$ln(P_{gasind})$	-0.024*	-0.027	-0.060	-0.081***
	(0.059)	(0.116)	(0.183)	(0.001)
$ln(P_{gasre})$	-0.014	0.025	0.059	-0.005
	(0.442)	(0.364)	(0.440)	(0.885)
dln(SO_2)	0.005	0.011	0.014	0.009
	(0.789)	(0.613)	(0.760)	(0.688)
constant	1.544	2.897**		
	(0.116)	(0.013)		
N	330	330	300	330
R^2	0.894	0.436		
AR(1)[1]			0.097	0.003
AR(2)[2]			0.737	0.753
Sargan test			0.369	0.032
Hansen test			0.268	0.340
Instruments			23	26
Adjustment factor			0.621	0.733
Turning point			17263.092	15345.213

*Note: p-values in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01; 1,2. Arellano–Bond test for AR(1) and AR(2)*
Instruments for model 3 include the second lagged to fourth lagged of lag S and the first and second lagged of ln(urban) and ln(coalgen), unless collapsed. Instruments for model 4 include the first to third lagged of lag S and the first and second lagged of ln(urban) and ln(coalgen), unless collapsed.

6.2 Industry sector results

Table 3 reports results for the industry sector. Columns (1) to (3) are for the static models and columns (4) to (7) are for the dynamic models. We can see that except for the FMB in column (1), the quadratic and linear terms of per capita GDP are all insignificant. The lagged terms of energy transition are all highly significant and the magnitudes are relatively high. It suggests a significant self-perpetuating process of energy transition which is independent of GDP per capita in the industry sector. In this case, FMB estimates are inappropriate as errors are likely to be as severely correlated over time as across provinces and GMM can be used to correct the estimates (Cochrane 2001). According to the difference and system GMM model in column (6) and (7), energy transition can be stimulated by 0.009 and 0.012 percent point respectively if the natural gas abundance increased by 1%, which indicates a significant natural resource endowment effect. We can also find in the difference GMM model that the energy transition may be locked in by coal reserve endowment at the margin of -0.014. That is, a 1% increase in coal production will decrease energy transition by 0.04 percent point in the long run. The price effect of petroleum is significant by the margin of -0.074. That is, a 1% increase in petroleum price will decrease low-carbon energy share by 0.2 in the long run. It implies that petroleum price increase would not result in substitution between oil and natural gas; on the contrary, it reversely shifts the energy consumption to coal. It could because coal is easier to access than natural gas in terms of availability and price. We also observe a significant policy effect by the difference GMM model. If the government implements stricter environmental regulations on the factories, it will increase energy transition by 0.11 percent point in the long run.

In the static model, we find that urbanization and natural gas endowments will significantly increase energy transition by 0.048 and 0.01 percent points respectively if they increase 1% at the margin.

Table 3 Results for the industry sector

Model Variable	(1) FMB	(2) Ind_OLS	(3) FE_ind	(4) IndOLS_lag	(5) FE_ind_lag	(6) Diff_ind	(7) Sys_ind
lag S_{ind}				0.890***	0.486***	0.637***	0.641***
				(0.000)	(0.000)	(0.002)	(0.000)
$ln(GDP)^2$	-0.037***	-0.021	0.022	-0.001	0.009	0.017	-0.001
	(0.001)	(0.202)	(0.121)	(0.782)	(0.360)	(0.247)	(0.698)
ln(GDP)	0.737***	0.403	-0.457	0.017	-0.178	-0.362	0.037
	(0.001)	(0.205)	(0.116)	(0.756)	(0.345)	(0.224)	(0.618)
ln(coalgen)	-0.026**	-0.020	0.010	0.001	-0.005	0.051	-0.017
	(0.021)	(0.374)	(0.726)	(0.868)	(0.799)	(0.200)	(0.170)
ln(urban)	-0.048***	-0.051**	0.048**	-0.010**	0.017	0.077	-0.033
	(0.000)	(0.023)	(0.016)	(0.032)	(0.214)	(0.335)	(0.219)
ln(gas)	0.027***	0.030***	0.010*	0.004***	0.008*	0.009*	0.012**
	(0.000)	(0.000)	(0.071)	(0.006)	(0.057)	(0.095)	(0.031)
ln(oil)	-0.005***	-0.006	0.002	-0.001	0.000	-0.001	-0.002
	(0.002)	(0.104)	(0.671)	(0.262)	(0.989)	(0.868)	(0.316)
ln(coal)	-0.026***	-0.032**	0.008	-0.005*	0.001	-0.014***	-0.009
	(0.000)	(0.013)	(0.425)	(0.064)	(0.798)	(0.005)	(0.162)
$ln(P_{steamcoal})$	-0.016	-0.009	-0.011	0.002	-0.012	-0.014	-0.004
	(0.459)	(0.835)	(0.667)	(0.754)	(0.516)	(0.414)	(0.796)
$ln(P_{elecind})$	-0.121**	-0.115**	-0.024	-0.011	-0.010	0.014	-0.019
	(0.048)	(0.019)	(0.437)	(0.337)	(0.635)	(0.491)	(0.340)
$ln(P_{petro})$	0.522	0.470*	0.098	-0.033	-0.034	-0.074*	0.026
	(0.141)	(0.058)	(0.346)	(0.636)	(0.728)	(0.092)	(0.238)
$ln(P_{diesel})$	0.100***	0.044	-0.061	0.002	-0.031	-0.007	-0.013
	(0.003)	(0.479)	(0.246)	(0.918)	(0.322)	(0.747)	(0.295)
$ln(P_{gasind})$	-0.042***	-0.036	-0.024	-0.005	-0.015	-0.009	0.002
	(0.007)	(0.486)	(0.440)	(0.355)	(0.501)	(0.749)	(0.939)
$dln(SO_2)$	0.013	0.001	-0.010	0.008	-0.002	0.040**	0.008
	(0.883)	(0.984)	(0.670)	(0.739)	(0.942)	(0.016)	(0.676)
constant	-8.394**	-5.681*	1.714	0.223	1.442		
	(0.016)	(0.052)	(0.240)	(0.667)	(0.154)		
N	330	330	330	330	330	300	330
R^2	0.847	0.760	0.264	0.947	0.419		
AR(1)						0.017	0.016
AR(2)						0.447	0.381
Sargan test						0.246	0.125
Hansen test						0.296	0.130
instruments						25	28
Adjustment factor						0.36	0.36
Turning point	21547.938						

*Note: p-values in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Instruments of models 6 and model 7 include the second to the fifth lagged of lag* S_{ind}*, the first to the fifth lagged of ln(coalgen) and ln(urban), unless collapsed.*

6.3 Agricultural sector results

Table 4 reports the agricultural sector results. In the dynamic model, we find a significant self-perpetuating process of energy transition which is similar to the results of the industry sector. The coefficient of the lagged term of the energy transition is 0.837, and all the other variables are insignificant. In the static model, we find an inverted U-curve relationship between energy transition and per capita GDP in the static FE model in column (3).

In contrast, a U-curve relationship is found in the FMB model. We advocate FE result here as, given the presence of heterogeneity of provinces, the standard error estimate from FMB would be too small to be correct in terms of significance level (Petersen 2008). The installed coal-fired electricity generation would increase the energy transition in agriculture by a margin of 0.008 percent point, which could be a result of shifting burning coal to electricity in the rural area. An increase in petroleum and diesel price will decrease the energy transition instead of increasing low-carbon energy consumption such as natural gas, which indicates a potentially reverse energy transition to coal. It could happen in the use of some agricultural and aquaculture facilities, such as greenhouses, sheds, temperature regulation, incubators or in the production of fertilizer. When the oil products become expensive, farmers may use coal to substitute oil consumption as other low-carbon energies are more expensive, or they cannot access the network of natural gas or electricity.

The turning point of FE is 14,952 Yuan, which is very close to the turning points found by the national level model though the patterns are opposite. Whether the energy transition in the agricultural sector is inverted U relationship regarding per capita GDP or it is a solely self-perpetuating phenomenon is still under debate in the literature. For example, Démurger and Fournier (2007) argue that fuelwood in rural areas is a kind of ‘inferior good’ and will decrease as per capita income increases, with the increasing opportunity cost of collecting fuelwood for the wealthier families. On the other hand, Shi, Heerink, and Qu (2009) use a CGE model to find that fuelwood is a normal good in rural Beijing and will increase as income increases. Overall, the energy transition in the agricultural sector is more complex.

Table 4 Results for the agricultural sector

Model Variable	(1) FMB	(2) OLS	(3) FE	(4) OLS_lag	(5) FE_lag	(6) Diff_GMM	(7) Sys_GMM
lag S_{ag}				0.921***	0.673***	0.809***	0.837***
				(0.000)	(0.000)	(0.000)	(0.000)
ln(GDP)^2	0.053***	-0.022	-0.034***	0.004	-0.002	0.011	-0.004
	(0.003)	(0.134)	(0.000)	(0.238)	(0.790)	(0.531)	(0.338)
ln(GDP)	-1.169***	0.333	0.652***	-0.089	0.057	-0.179	0.041
	(0.002)	(0.247)	(0.000)	(0.152)	(0.733)	(0.596)	(0.540)
ln(coalgen)	-0.071***	-0.066***	0.013	0.000	0.019	0.064	0.025
	(0.001)	(0.004)	(0.134)	(0.976)	(0.118)	(0.398)	(0.303)
ln(gas)	0.033**	0.008	0.010	0.001	0.005	-0.095	-0.016
	(0.020)	(0.681)	(0.546)	(0.540)	(0.738)	(0.530)	(0.477)
ln(oil)	-0.006***	-0.007	-0.008	-0.001	-0.005	-0.008	-0.003
	(0.006)	(0.320)	(0.156)	(0.279)	(0.303)	(0.257)	(0.378)
ln(coal)	-0.020***	-0.020**	0.008**	-0.002***	-0.000	-0.004	-0.004
	(0.000)	(0.014)	(0.012)	(0.004)	(0.969)	(0.204)	(0.350)
$ln(P_{steamcoal})$	-0.003	-0.001	-0.002	0.000	-0.001	0.004	0.001
	(0.551)	(0.882)	(0.687)	(0.800)	(0.789)	(0.779)	(0.887)
$ln(P_{briquet})$	0.090***	0.093**	0.042**	0.014*	0.008	-0.007	0.037
	(0.000)	(0.030)	(0.019)	(0.055)	(0.633)	(0.856)	(0.144)
$ln(P_{elecag})$	-0.105***	-0.065	0.006	-0.010	-0.003	-0.024	-0.015
	(0.002)	(0.179)	(0.779)	(0.102)	(0.863)	(0.245)	(0.426)
$ln(P_{petro})$	0.017	-0.001	-0.042**	0.008	-0.015	0.017	0.030
	(0.566)	(0.989)	(0.031)	(0.193)	(0.173)	(0.793)	(0.276)
$ln(P_{diesel})$	-0.364***	-0.265***	-0.025*	-0.024	-0.046	0.024	-0.007
	(0.006)	(0.007)	(0.099)	(0.186)	(0.175)	(0.377)	(0.740)
dln(SO$_2$)	-0.142**	-0.116*	-0.030	-0.008	0.007	-0.008	-0.021
	(0.016)	(0.061)	(0.198)	(0.614)	(0.660)	(0.684)	(0.288)
constant	9.511***	1.336	-3.144***	0.719*	-0.068		
	(0.001)	(0.457)	(0.001)	(0.050)	(0.943)		
N	330	330	330	330	330	300	330
R^2	0.712	0.617		0.955	0.693		
AR(1)						0.013	0.006
AR(2)						0.953	0.778
Sargan test						0.267	0.240
Hansen test						0.136	0.185
instruments						20	23
Adjustment factor						0.19	0.16
Turning point			14952.158				

*Note: p-values in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01. 1,2. Arellano-Bond test for AR(1) and AR(2). Year dummies are eliminated to save space. Instruments of model 6 and 7 include the fourth to the sixed lagged lag S_{ag}, the fifth to the seventh lagged of ln(coalgen) and ln(urban), unless collapsed.*

6.4 Service sector results

Table 5 reports the results for the service sector. There is no significant relationship found between energy transition and per capita GDP across all the models except for the FMB model, which suggests the energy transition of the service sector is independent of per capita GDP. It is consistent with the stylized facts presented in Figure 2. It could be because the scale of the service sector is too small to be observed. The lagged terms of energy transition are significant in all dynamic models, meaning there is a significant self-evolution of energy transition in the service sector.

Table 5 Results for the service sector

Model Variable	(1) FMB	(2) OLS	(3) FE	(4) OLS_lag	(5) FE_lag	(6) Diff_GMM	(7) Sys_GMM
lag S_{serv}				0.846***	0.731***	0.779***	0.817***
				(0.000)	(0.000)	(0.000)	(0.000)
ln(GDP)²	0.027*	0.013	0.007	0.001	0.005	-0.000	0.003
	(0.057)	(0.243)	(0.470)	(0.669)	(0.398)	(0.977)	(0.416)
ln(GDP)	-0.504*	-0.262	-0.079	-0.026	-0.054	0.003	-0.067
	(0.068)	(0.245)	(0.658)	(0.671)	(0.561)	(0.989)	(0.439)
ln(urban)	-0.026***	-0.030*	-0.029	-0.003*	0.008	0.109	0.010
	(0.005)	(0.051)	(0.197)	(0.100)	(0.591)	(0.647)	(0.707)
ln(gas)	0.007**	0.007	-0.001	0.000	-0.002	-0.002	0.001
	(0.022)	(0.144)	(0.810)	(0.651)	(0.525)	(0.542)	(0.789)
ln(oil)	0.003**	0.003	0.002	0.001**	0.000	0.002	0.001
	(0.023)	(0.155)	(0.487)	(0.020)	(0.676)	(0.433)	(0.353)
ln(coal)	-0.009***	-0.006	-0.001	-0.001	-0.003	0.007	-0.003
	(0.001)	(0.233)	(0.894)	(0.375)	(0.589)	(0.504)	(0.596)
$ln(P_{steamcoal})$	0.024*	0.015	0.019	-0.000	0.016	-0.003	-0.004
	(0.073)	(0.595)	(0.386)	(0.963)	(0.230)	(0.824)	(0.680)
$ln(P_{briquet})$	0.016***	0.021	-0.019	0.001	-0.007	-0.007	-0.006
	(0.006)	(0.118)	(0.405)	(0.893)	(0.455)	(0.612)	(0.564)
$ln(P_{elecserv})$	0.005	0.005	0.107	-0.010	-0.006	-0.061	-0.030
	(0.847)	(0.898)	(0.221)	(0.345)	(0.798)	(0.217)	(0.553)
$ln(P_{petro})$	-0.117	-0.052	0.150	0.036	-0.000	-0.013	0.032
	(0.578)	(0.743)	(0.189)	(0.194)	(0.989)	(0.835)	(0.206)
$ln(P_{diesel})$	-0.070	-0.072	-0.058	-0.023	0.018	0.024	0.005
	(0.139)	(0.148)	(0.636)	(0.178)	(0.224)	(0.463)	(0.716)
$ln(P_{gasind})$	-0.079***	-0.064**	-0.039	-0.015*	-0.009	0.015	-0.011
	(0.000)	(0.040)	(0.342)	(0.057)	(0.630)	(0.473)	(0.380)
constant	3.982	2.384	-0.361	0.054	-0.120		
	(0.141)	(0.276)	(0.707)	(0.876)	(0.760)		
N	368	368	368	339	339	310	339
R^2	0.615	0.450	0.239	0.843	0.572		
AR(1)						0.045	0.034
AR(2)						0.619	0.720
Sargan test						0.342	0.229
Hansen test						0.487	0.664
instruments						18	20
Adjustment factor						0.22	0.18

*Note: p-values in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Instruments of model 6 include the sixth to eighth lagged of lag S_{serv}, and the first to the fourth lagged of ln(urban); instruments of model 7 include the fifth to seventh lagged of lag S_{serv}, and lagged of ln(urban), unless collapsed.*

6.5 Residential sector results

Results for the residential sector are reported in Table 6. The system GMM model suggests an inverted U-curve relationship between energy transition and per capita GDP, as the quadratic terms of per capita GDP are negative (-0.010) and the linear terms are positive (0.221). It indicates that the low-carbon energy proposition would increase as per capita GDP increases but would eventually decrease in the long-run as economic growth increases. It is pessimistic, but consistent with the stylised facts we have found in Figure 2. The turning point is 39,558.94 Yuan suggested by the system GMM model.

The difference GMM model suggests that oil production has a -0.021[9] percent point effect on energy transition in the long run. It is a sort of natural resource endowment lock-in indicating more oil endowments would decrease energy transition level in the long run. The FE result shows such oil endowments effect would be -0.023 percent point in the static model, which is not far different from the different GMM model.

On the price effect, the system GMM model suggests that diesel oil price has -0.108 percent point effect on energy transition in the long run. On the other hand, the FE model suggests that the marginal effect of petroleum price on energy transition is -0.023 percent point. These findings hint that an increase in such oil product prices seems not decreasing diesel or petroleum consumption in residential sectors. It could be explained by the correlation between the improvement of living standards and an increasingly fueled vehicles adoption. The increase in fuel prices is a consequence of an increase in fueled vehicles consumption rather than a cause of energy transition. It is consistent with what has been observed in other developing countries such as Botswana (Hiemstra-van der Horst and Hovorka 2008). Such evidence shows most households prioritize high-carbon energy consumption rather than shifting to low-carbon fuel use. It could be the underlying reason

[9] As we have explained in equation (2), the long-run effect can be computed by the coefficients of control variables divided by the adjustment factor.

for the inverted-U curve between the energy transition and per capita GDP in the residential sector. Some factors beyond energy price may influence their energy adoption decisions including household characteristics, the reliability of fuel distribution networks and local policies. It has implications for urban development policy design: urban expansion induced by economic growth may work against energy transition contrary to the expectations of policymakers yearning for a transition to low carbon use in the energy mix.

Table 6 Results for the residential sector

Model Variable	(1) FMB	(2) OLS	(3) FE	(4) OLS_lag	(5) FE_lag	(6) Diff_GMM	(7) Sys_GMM
lag S_{serv}				0.934***	0.666***	0.720***	0.666***
				(0.000)	(0.000)	(0.004)	(0.001)
ln(GDP)²	0.027	-0.017	-0.033	-0.002	-0.013	0.007	-0.010**
	(0.321)	(0.460)	(0.114)	(0.748)	(0.310)	(0.786)	(0.041)
ln(GDP)	-0.512	0.359	0.644	0.039	0.295	-0.085	0.221**
	(0.341)	(0.419)	(0.105)	(0.757)	(0.206)	(0.862)	(0.034)
ln(urban)	0.025*	0.013	0.003	0.001	-0.000	-0.105	-0.020
	(0.063)	(0.627)	(0.960)	(0.742)	(0.995)	(0.604)	(0.474)
ln(gas)	0.027***	0.028***	0.009	0.001	-0.004	0.001	0.007
	(0.000)	(0.003)	(0.337)	(0.659)	(0.474)	(0.785)	(0.301)
ln(oil)	0.003	-0.002	-0.023**	-0.001	-0.010***	-0.006*	-0.002
	(0.504)	(0.733)	(0.014)	(0.490)	(0.001)	(0.058)	(0.491)
ln(gas)	-0.052***	-0.045***	-0.010	-0.002	-0.015	-0.014	-0.014
	(0.000)	(0.000)	(0.497)	(0.308)	(0.214)	(0.394)	(0.236)
$ln(P_{briquet})$	0.017	0.030	-0.014	0.005	-0.009	-0.024	0.017
	(0.477)	(0.475)	(0.632)	(0.456)	(0.516)	(0.259)	(0.375)
$ln(P_{elecre})$	-0.043	0.020	0.248*	0.025	0.130**	0.070	0.040
	(0.409)	(0.885)	(0.050)	(0.407)	(0.036)	(0.344)	(0.325)
$ln(P_{diesel})$	-0.311*	-0.132	0.005	-0.020	-0.009	-0.040	-0.036**
	(0.062)	(0.424)	(0.965)	(0.346)	(0.876)	(0.230)	(0.028)
$ln(P_{petor})$	0.331	0.151	-0.105	-0.059	0.014	-0.019	-0.085
	(0.310)	(0.769)	(0.598)	(0.280)	(0.902)	(0.852)	(0.111)
$ln(P_{gasre})$	-0.084***	-0.062	-0.015	-0.024**	0.014	0.056	0.010
	(0.002)	(0.444)	(0.867)	(0.039)	(0.771)	(0.430)	(0.726)
constant	2.091	-2.053	-1.936	0.501	-1.427		
	(0.608)	(0.703)	(0.516)	(0.558)	(0.372)		
N	389	389	389	359	359	329	359
R^2	0.552	0.458	0.251	0.917	0.563		
AR(1)						0.023	0.018
AR(2)						0.181	0.303
Sargan test						0.144	0.212
Hansen test						0.108	0.213
instruments						16	18
Adjustment factor						0.28	0.33
Turning point							39558.94

*Note: p-values in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Instruments of model 6 and model 7 include the second to the third lagged of lag* S_{serv} *and the second to fifth lagged of ln(urban).*

7 Policy implication and conclusion

This study investigates the relationship between low-carbon energy transition and economic growth in China. We use the share of low-carbon energy consumption to measure the degree of energy transition and per capita GDP is an indicator of economic development. The static and dynamic panel data models are based on 30 provinces for the period 2000 to 2012 across four sectors – industry, agriculture, service and residential. We control some factors by the suggestions of three energy transition hypotheses - the energy ladder, the environmental Kuznets curve, and carbon lock-in.

At the national level, we find a U-curve relationship between energy transition and economic development, with the turning point at around 15,350 Yuan at 2010 constant price. It is consistent with Tahvonen and Salo’s (2001) theoretical model and without losing the generality of the Environmental Kuznets Curve theory. According to the China National Bureau of Statistics, all 30 provinces have crossed the turning point so far; thus, generally, China’s energy mix would continuously decarbonize with further increase of GDP per capita. It would shed a positive light on China’s future energy transition to low-carbon development.

On the other hand, the patterns at the sectoral level are diverse. We find an inverted U-curve between energy transition and economic development in the residential sector, with the turning point appearing around 39,558 Yuan at 2010 constant price. We account this for increasing use of fuelled vehicles. In the industry sector and service sector, energy transitions perform a significant autocorrelation of itself. That is, the degree of energy transition largely depends on the conditions of the energy consumption mix in the previous years. However, the pattern of the agricultural sector is ambiguous. The static model suggests an inverted U curve while the dynamic model suggests an autocorrelation process of energy transition. This finding should alert policymakers for the need for more deliberate transition planning and policy design for households' level; in particular, electric cars and natural gas-fuelled vehicles should be encouraged. It also calls for more researches on the agricultural energy transition.

We find that price effect is significantly effective for promoting energy transition, both nationally and at sectoral levels. It suggests that the energy market liberalization would be important for promoting energy transition. After 2005, the price effects became more significant after 2005. 1% increase in steam coal price will result in 0.093 percent point increase in energy transition; 1% increase in residential electricity price will increase energy transition by 0.102 percent point; 1% increase in diesel price will increase low-carbon proportion by 0.079 percent point, *ceteris paribus*.

We can also observe a significant natural resource endowment effect. Suggested by the national level system GMM model, in the long-run, a 1% increase in the natural gas production will increase low-carbon energy transition by 0.022 percent point in the long run; a 1% increase in petroleum price will promote energy transition by 0.188 percent point, *ceteris paribus.* On the contrary, a long-run effect of 1% increase in industrial electricity price or industry natural gas price will significantly decrease energy transition by 0.119 and 0.111 percent point, respectively. Suggested by the industry sector FE and difference GMM models, the natural gas endowment would increase energy transition by 0.010 percent point and the coal endowment would decrease energy transition by 0.012 percent point at the margin.

We find that the energy transition could be hindered by too much coal-fired electricity generation at the national level and the coefficient of 0.016 percent point. Hence, the industrial policy such as reduction coal-fired generation and stimulating renewable electricity would remove such kind of lock-in effect.

Overall, this paper reveals that the pattern of China's energy transition varies according to different levels, different sectors and different stages of economic growth. The marginal effects of control variables and their driving forces are varying due to natural conditions, technology progress or institutional reform. The energy transition policy and other relating industrial policy decision-making should deliberately examine the conditions on a case-by-case basis.

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Appendix

Appendix: Data Supplementary

China's energy transition between low-carbon energy and high-carbon energy is measured by the share of low-carbon energy in total energy consumption:

$$S = \frac{\sum_L \theta_L E_L}{\sum_{L,H}(\theta_L E_L + \theta_H E_H)} \tag{4}$$

where S is the share of low-carbon energy; E is the quantity of energy consumption, L indicates a source of low-carbon energy, and H is a source of high-carbon energy. The term θ represents a conversion factor used to convert all energy types to the coal equivalent.[10] We use the conversion factor sources from the China National Bureau of Statistics.

We consider ten types of energy: coal, diesel oil, gasoline, kerosene, fuel oil, raw oil, liquefied petroleum gas (LPG), natural gas, methane, and non-fossil primary electricity which includes nuclear, hydro, solar and wind as a single unit. Coal and oil products are classified as high-carbon energy and other types as low-carbon energy. All energy quantities are the final consumption by end-users, measured in a heat equivalent unit, tonnes of coal equivalent (TCE). We split energy consumption into four sectors for sectoral level analysis within a province: industry, agriculture, residential and service.

This study is based on a longitudinal dataset of 30 provinces in China from 2000 to 2012 for ten types of energy: coal, diesel oil, gasoline, kerosene, fuel oil, raw oil, liquefied petroleum gas (LPG), natural gas, methane, and non-fossil primary electricity (i.e. nuclear, hydro, solar and wind). All energy quantities are of the final consumption by end-users, measured in heat equivalent units. We split provincial total energy consumption into sectoral levels within each province -the industrial, agricultural, residential (urban) and service sectors. The data are collected from the yearly provincial energy balance sheets from various editions of the *China Energy Statistical Yearbook* and *China Rural Energy Statistical Yearbook.*

[10] The conversion factor can be found in various versions of *China Energy Statistical Yearbook.*

Per capita GDP are from the National Bureau of Statistics and are calculated at constant prices (base year 2010). We adopt the China GDP deflator published by the World Bank. Per capita production data of coal, oil and natural gas are collecting from various editions of the *China Energy Statistical Yearbook*. Per capita coal-fired power generation capacity data are collected from State Electricity Regulatory Commission. The population and urbanisation data are collected from the *China National Population Census* and *China Population and Employment Statistics Yearbook*. We collected Sulphur dioxide emission data from various versions of the *China Statistical Yearbook on Environment*.

We include prices for each type of energy, as these will influence energy adoption, so energy price regulation will be a potential policy lock-in factor for energy transition. China's reform and economic transition is characterised by marketization and deregulation, which has transformed from a central planning economy to a market economy; the energy sector is no exception. Energy prices cannot be used as a market signal unless the industry is deregulated. China's energy prices were controlled by the state before the 'dual-track' pricing reforms[11] introduced in the 1980s; after 1990, price liberalisation was accelerated and deregulation was introduced in the energy sector (Wu 2003).

We collected energy price data from the National Development and Reform Commission, which surveys commodity prices in 36 large cities at ten-day intervals. We used the energy price in the capital city of each province as a proxy for energy prices in each province. The yearly price data was derived by averaging all observations within one year. Other price data were collected from the *China Price Statistical Yearbooks*. All price and per capita GDP data are deflated by 2010 using the GDP deflator issued by World Bank.[12]

[11] In China, the government followed dual-track pricing, known as '*shuangguizhi*' in Chinese. State-controlled (planned) prices, which were lower, accompanied the market prices, which were higher. This was done to ensure stability and gradual opening of markets (instead of a 'big bang' strategy of sudden transformation to capitalism that was followed in Eastern Europe and Russia). However, to provide incentive to the State-owned Enterprises, government allowed selling of the products at market prices after the planned targets had been met. Source: https://en.wikipedia.org/wiki/Dual-track_system.

[12] Source: http://data.worldbank.org.cn/indicator/NY.GDP.DEFL.ZS, based year is 2010.

Appendix-table 1 Summary of variables

	Variable	Label	Unit	Obs	Mean	Std.Dev.	Min	Max
Dependent variables	S	Share of low-carbon energy consumption at national level	%	390	0.106	0.110	9.00e-05	0.565
	S_{ind}	Share of low-carbon energy consumption in industrial sector	%	390	0.101	0.125	0.000168	0.718
	S_{ag}	Share of low-carbon energy consumption in agricultural sector	%	390	0.126	0.147	4.17e-05	0.790
	S_{serv}	Share of low-carbon energy consumption in service sector	%	368	0.0543	0.0680	5.84e-05	0.494
	S_{re}	Share of low-carbon energy consumption in residential sector	%	389	0.241	0.147	0.0150	0.664
Independent variables	GDP	GDP *per capita*	Yuan	390	16291	11200	2662	57132
	coalgen	Coal generation capacity *per capita*	W	390	423.7	370.8	58.17	2567
	urban	Urban population	10^4	390	1912	1259	181	7141
	gas	Natural gas production *per capita*	10^4tce	390	94.24	215.9	0	1145
	oil	Oil production *per capita*	10^4tce	390	0.212	0.420	0	2.566
	coal	Coal production *per capita*	10^4tce	390	2.466	4.986	0	41.84
	$P_{briquet}$	Briquet price	Yuan/100kg	390	35.90	17.52	8.500	99
	$P_{steamcoal}$	Steam coal price	Yuan/ton	390	366.5	181.3	74.10	879.9
	$P_{elecind}$	Industry electricity price	Yuan/kWh	390	0.622	0.147	0.160	0.930
	P_{elecre}	Residential electricity price	Yuan/kWh	390	0.500	0.0704	0.319	0.879
	P_{elecag}	Agricultural electricity price	Yuan/kWh	390	0.418	0.108	0.145	0.748
	$P_{elecserv}$	Service electricity price	Yuan/kWh	390	0.790	0.110	0.502	1.043
	P_{petro}	93# petroleum price	Yuan/ton	390	6190	2273	2898	11247
	P_{diesel}	0# diesel price	Yuan/ton	390	5306	1914	2548	9052
	P_{gasind}	Industry natural gas price	Yuan/ton	390	2.304	0.779	0.730	4.600
	P_{gasre}	Residential natural gas price	Yuan/m^3	390	2.041	0.540	0.920	3.740
	SO_2	SO_2 emission	10^4ton	390	73.75	45.11	2	200.3

Appendix-table 2 Test for autocorrelation, heteroscedasticity and cross-sectional independence

test	National model	Industry sector model	Agricultural sector model	Service sector model	Residential sector model
Wooldridge test for autocorrelation	0.1234	0.0001	0.0000	0.0003	0.0000
Modified Wald for groupwise heteroskedasticity	0.0000	0.0000	0.0000	0.0000	0.0000
Pesaran test for cross sectional independence	0.4271	0.6539	0.0000	0.2172	0.6898
Standard error	White	Roger	Driscoll-Kraay	Rogers	Rogers

p-value