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Disclaimer

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Abstract

Understanding the relationship between economic growth and electricity use is essential for power systems planning. This need is particularly acute now in China, as the Chinese economy is going through a transition to a more consumption and service oriented economy. This study uses 20 years of provincial data on gross domestic product (GDP) and electricity consumption to examine the relationship between these two factors. We observe a plateauing effect of electricity consumption in the richest provinces, as the electricity demand saturates and the economy develops and moves to a more service-based economy. There is a wide range of forecasts for electricity use in 2030, ranging from 5,308 to 8,292 kWh per capita, using different estimating functions, as well as in existing studies. It is therefore critical to examine more carefully the relationship between electricity use and economic development, as China transitions to a new growth phase that is likely to be less energy and resource intensive. The results of this study suggest that policymakers and power system planners in China should seriously re-evaluate power demand projections and the need for new generation capacity to avoid over-investment that could lead to stranded generation assets.

1. Introduction

Over the last three decades, China's economy has grown on average close to 10% per year. As a result, China's power system has grown 22.7 times in capacity from 60 GW in 1980 to 1,360 GW in 2014, and electricity consumption has grown 18.7 times from 295 TWh in 1980 to 5,523 TWh in 2014, or 9% per year (CEC 2015). However, China's economy has recently entered into a "new normal" phase of transition and rebalancing, featuring slower growth in general, and moving from a growth model driven by investment and exports to one driven by consumption and a larger share of services in the economy (Green and Stern 2015; Xi 2014; Zhang 2015). As such, energy and electricity use have seen much slower growth in the past two years. For the first time, coal use declined in 2014 and electricity use has been growing at its slowest pace in recent years, up only 0.6% in the first half of 2015 (NEA 2015).

Even so, many Chinese and international institutions still project fast growth in electricity use (Hu, Tan, and Xu 2011; Jiang et al. 2013; T. Wang and Watson 2010). Figure 1 provides electricity projections of three recent studies: the International Energy Agency's World Energy Outlook 2014 (IEA 2014), the *2050 China Economic Development and Electricity Demand Study* by the Intelligent Laboratory for Economy-Energy-Electricity-Environment, ILE4 (Hu, Tan, and Xu 2011), and the Energy Research Institute's *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* (ERI, 2015). In these studies, China's electricity consumption is projected to range from 7,584 TWh (~5830 kWh per capita) to 11,154 TWh (~8580 kWh per capita) in 2030.

As the Chinese economy matures, it is important to understand whether such a conventional perspective that China will maintain a high rate of GDP growth with a high elasticity of electricity demand still holds. In this paper, we explore an alternative model in which electricity use will decelerate relative to economic growth and this relationship will continue to fall over time as the Chinese economy shifts to less energy-intensive sectors, and consumption behaviors start to change. Further, we examine the regional pattern of electricity usage to understand the differences between regions in China, as well as use these data to test various relationships between income, economic structure, and electricity use.
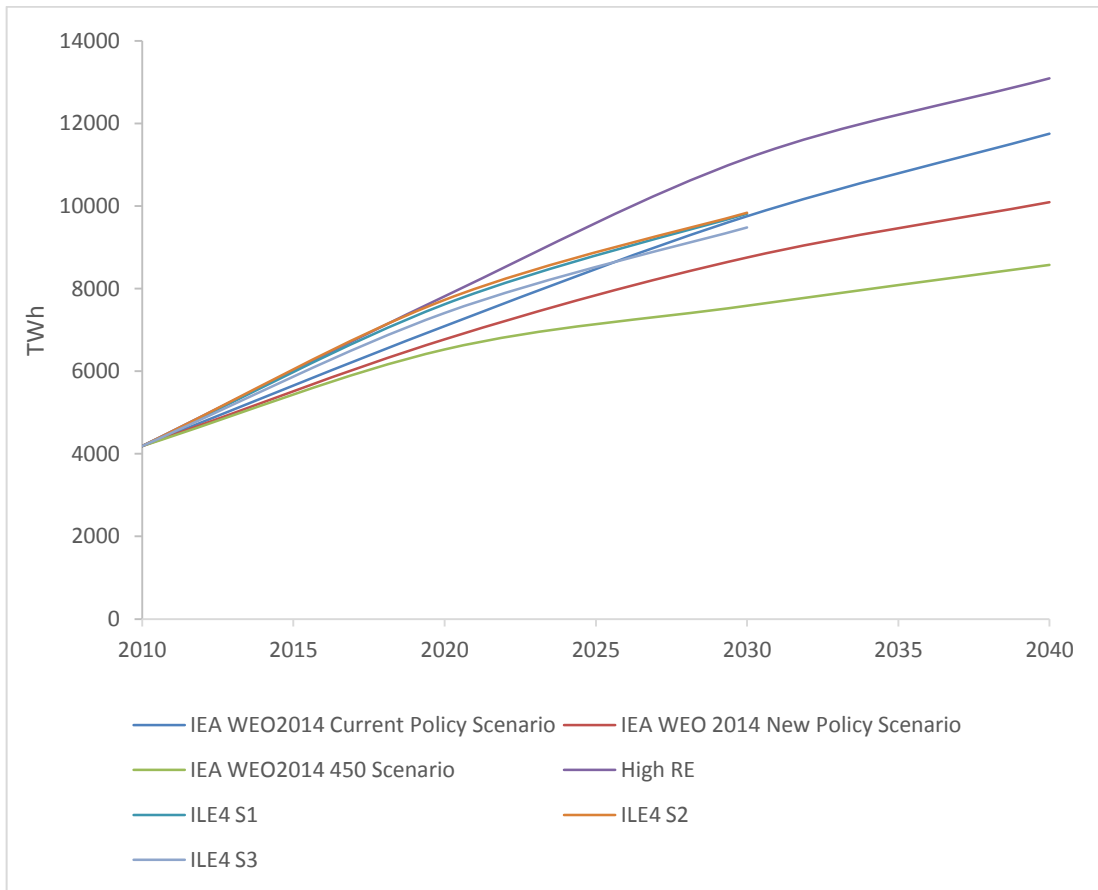

Figure 1 Recent projections of China's electricity demand

Note: S1, S2, S3 are three scenarios presented by ILE4 (Hu, Tan, and Xu 2011). The IEA and High RE reports only provide electricity generation; we subtract transmission and distribution losses (6% assumed) and import/export balances which are negligible in China (Hu, Tan, and Xu 2011; IEA 2014; ERI 2015).

2. Recent trends in China's electricity consumption

Figure 2 presents the growth rate of electricity consumption and the electricity elasticity in China from 1980-2014 (World Bank 2015). It shows that China's electricity demand experienced several boom and bust cycles, which were fairly consistent with economic cycles in the last 25 years. The last major downturn was associated with the Asian financial crisis in 1998, when the electricity growth rate dropped to 3.1%. During the global financial crisis of 2008, electricity growth rate reached 6%, partly due to the huge stimulus package the Chinese government instituted to mitigate the economic downturn at the time.

The growth rate of electricity consumption in 2014 reached a low of 3.8%; the last time electricity growth was this low was 1998. The year-on-year electricity growth rate in the first half of 2015 was reported to be only 0.6% (NEA 2015). Electricity elasticity in 2014 also reached historical low since 1998 at 0.51. While the growth rate of electricity consumption may rebound if economic growth picks up in the future, these recent data, as well as the ongoing economic transition, suggest that a new lower growth phase with lower elasticity may be emerging for electricity demand growth in China (Figure 2).
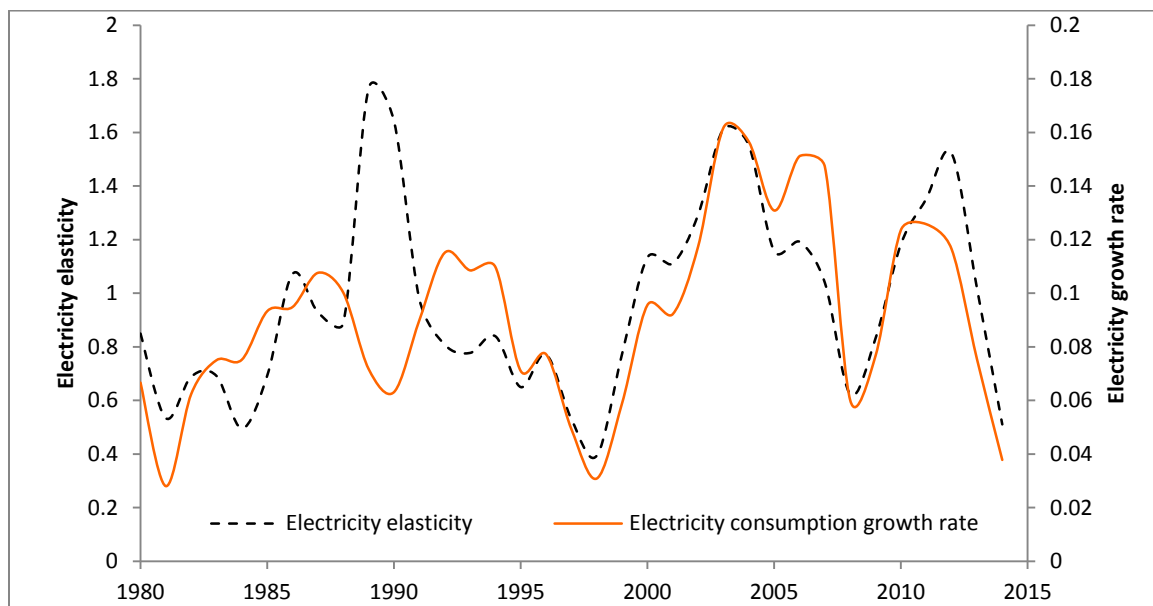
Figure 2 Electricity consumption growth rate and electricity elasticity in China, 1980-2014
Source: World Bank, 2015

In addition, the average capacity factors of China's power plants have been decreasing generally since 2004, from a peak of 0.62 in 2004 to 0.49 in 2014 (Figure 3), the lowest since 1978 (CEC 2015). China's installed power capacity has been dominated by thermal plants, which in 2014 accounted for 67% of its total 1360 GW capacity and generated 75% of the total electricity production (CEC 2015). In 2014, 95% of thermal capacity was coal-fired, with the balance being natural gas.

Figure 3 China power plant average hours of operation annually
Source: China Electricity Council, 2015

Figure 4 China power investment by fuel source
Source: China Electric Power Yearbook, multiple years

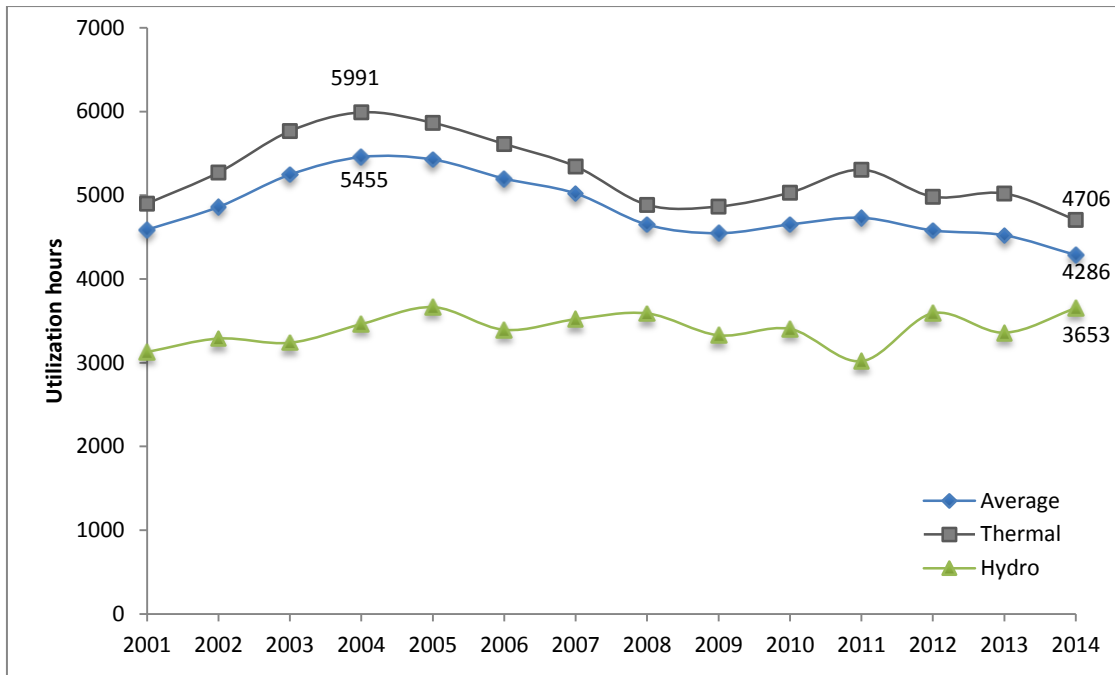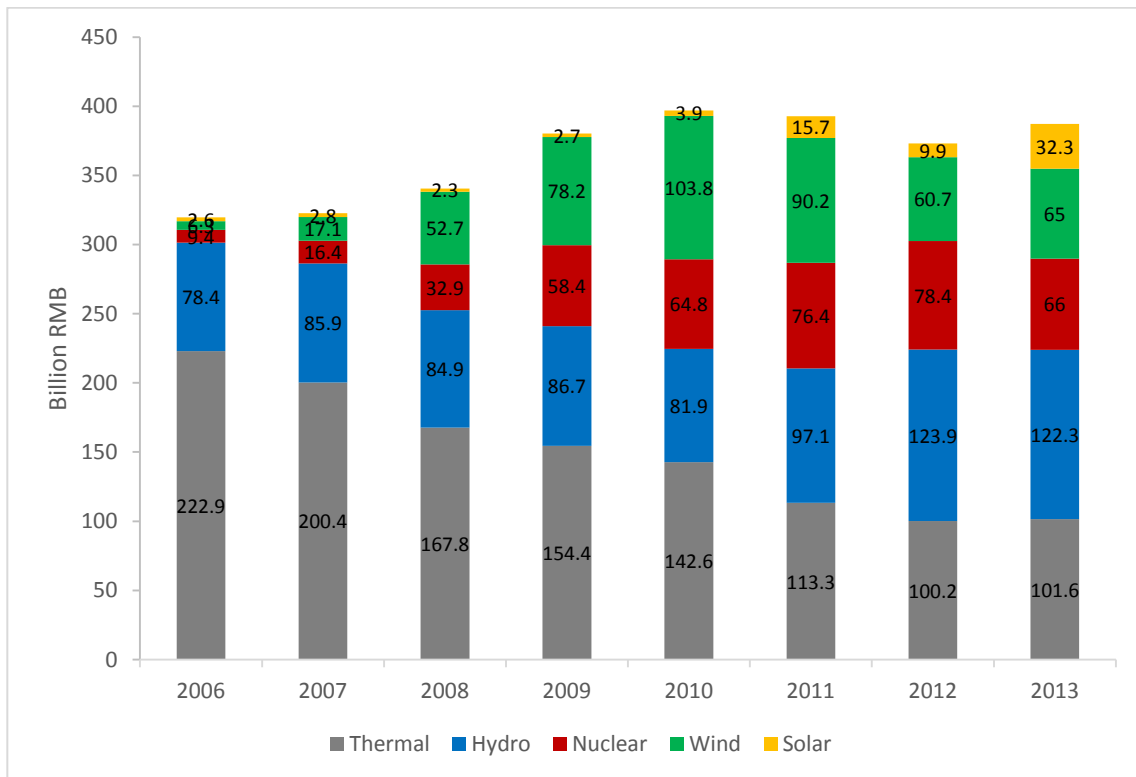The increase in capacity installation has recently overtaken the growth of electricity demand. Over the past decade, the rapid expansion of thermal plants, which are usually run as base load, has led to over-capacity of base-load plants, and the expansion of other competitive power sources such as wind, solar, and nuclear has result in lower capacity factors for existing plants—indicating that the current baseload assets are not fully utilized.

Annual investment in thermal power capacity has been decreasing, while that in other generation capacity has been expanding since the 2000s. Thermal capacity investment decreased by 50% from 2006 to 2013, while that for solar has grown 12 times, wind 10 times, and nuclear 7 times during the same period (Figure 4). In 2008, investment in non-fossil generation capacity, including nuclear and renewables, surpassed that of thermal generation capacity, and 2013 saw more new non-fossil capacity brought on line than thermal capacity (Wei 2014). As the additional electricity demand will increasingly be met by non-fossil generation – as China strives to meet its 20% non-fossil energy target by 2030 – a continued high level of expansion of coal power plants could result in over-capacity and stranded investments.

Regional disparities appear in the national general trend, however. China is a big country and the regional economic development is highly imbalanced. This can be observed in Figure 5, which shows provincial economic development (real GDP per capita) and electricity consumption (electricity consumption per capita). The data in Figure 5 suggest that Chinese provinces can be categorized into three groups. The first group is composed of Shanghai, Tianjin, and Beijing, high-income municipalities with GDP per capita higher than around 70,000 RMB; for these municipalities, the growth of per capita electricity consumption appears to have plateaued. Qinghai, Xinjiang, Inner Mongolia, Shaanxi, Shanxi, and Ningxia are in a second group, with comparatively lower GDP per capita but high per-capita electricity consumption, as they are mostly energy extractive provinces with extensive heavy industry. The third group is composed of provinces that fall between these high and low groupings related to per capita income and electricity use.
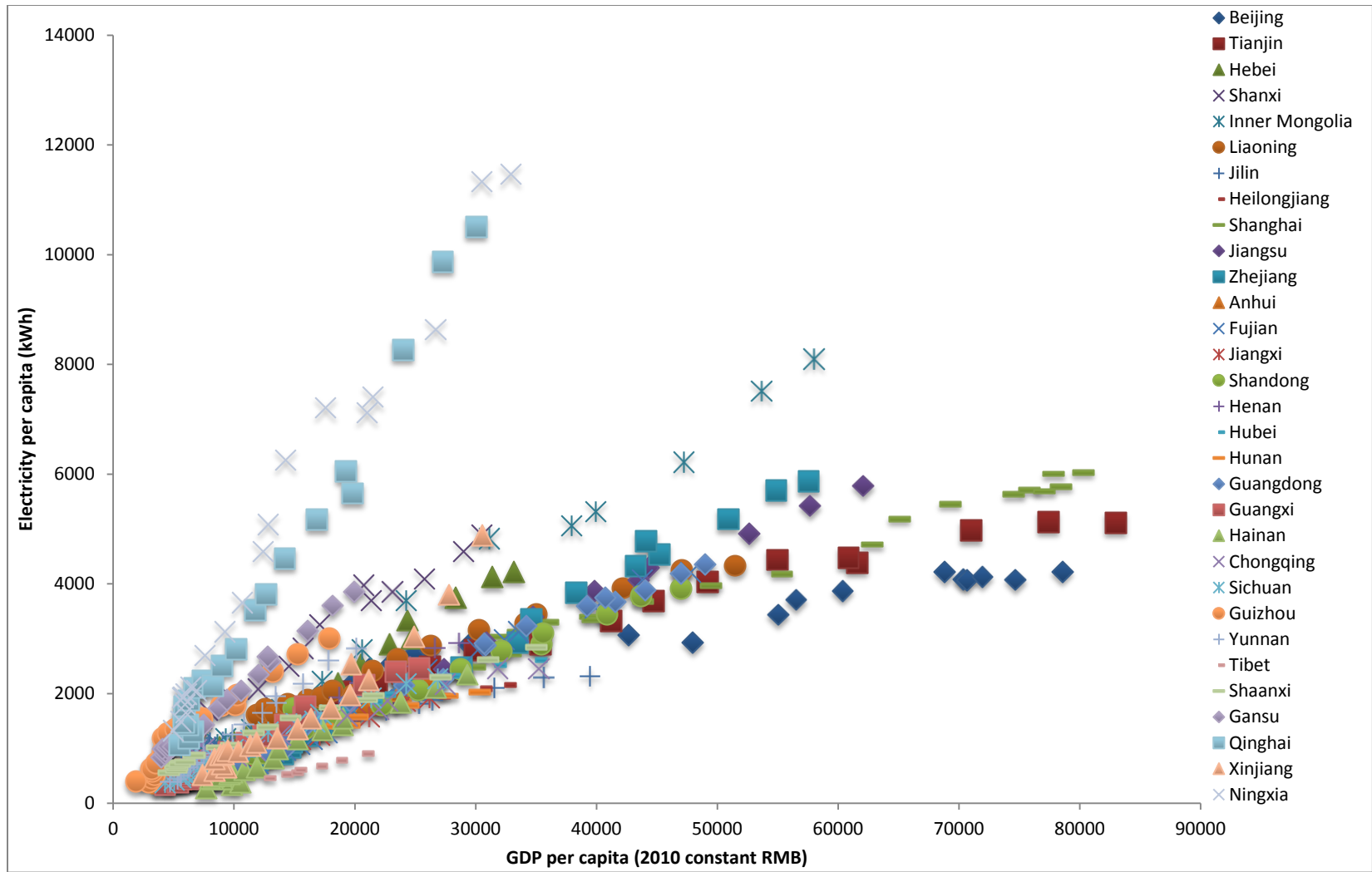
Figure 5 Relationship between electricity consumption and real GDP per capita by province
Sources: China Statistical Yearbook, multiple years; China Electric Power Yearbook, multiple years

3. Literature review

Understanding the relationship between energy—more specifically electricity—and economic development is essential and a component of long-term strategic planning (Smil 2000; Stern and Cleveland 2004; WEF and IHS 2013). However, identifying the relationship between electricity consumption and economic development is difficult given the complex underlying behavioral and structural mechanisms, especially technology, market liberalization, and sustainable development (Tremblay 1994).

There is extensive literature regarding the relationship between electricity consumption and economic growth, with varying regional or national focuses. Generally, studies have found that there could be either a unidirectional relationship from electricity consumption to economic growth, or bidirectional, or even non-causal relationship between electricity consumption and economic growth (Seung-Hoon Yoo and Kwak 2010; Squalli 2007; S. -H. Yoo 2006; Seung-Hoon Yoo 2005; Wolde-Rufael 2006; Altinay and Karagol 2005; Ghosh 2002; Asafu-Adjaye 2000; S. S. Wang et al. 2011).

For China-specific studies, Shiu and Lan (2004) applied an error-correction model to study the causal relationship between electricity consumption and real GDP in China, and found there is a unidirectional relationship running from electricity consumption to real GDP, which means electricity consumption drives economic growth, but not the reverse (Shiu and Lam 2004). Additionally, Yuan et al. (2007) applied the co-integration theory and indicated that there exists Granger causality, a predictive causality, running from electricity consumption to GDP, but such causality does not exist from GDP to electricity consumption (Yuan et al. 2007). However, these studies are based on data from earlier periods that may not offer observation that reflects recent developments in Chinese electricity use and GDP growth.

Given the advances in energy efficiency and renewable energy technologies, as well as the growing concern over energy-related greenhouse gas (GHG) emissions, some have questioned the assumption of a continuing close link between growth in energy consumption and economic development, and have proposed that a sufficient living standard could be maintained without significantly increasing per-capita energy use. Experts have suggested that one kilowatt per capita is sufficient to support basic human needs with an emphasis on energy efficiency improvement and modern energy carriers (Goldemberg et al. 1985). This concept was further developed by the Board of the Swiss Federal Institutes of Technology, and followed by the Swiss Advisory Committee for Energy Research to achieve a "2 kW-society" in Switzerland by 2050 (Haldi and Favrat 2006). If a complete "decoupling", that is maintaining a continued economic well-being with a fixed level of energy or electricity use, is achieved, then future growth in energy or electricity use would taper down over time. In fact, such a decoupling is close to being achieved in some developed regions. For example, California has been able to hold per capita electricity use essentially constant since 1970s (Rosenfeld and Poskanzer 2009).

4. Methodology and data sources

This paper uses twenty years of provincial level GDP and electricity consumption data in China to test the statistical relationships between per capita income and electricity consumption, then projects three scenarios of electricity demand with models derived from the observed data. We argue that the linear model, often adopted by conventional studies, deserves reassessment.

The assumption is that electricity consumption is a function of income and economic structure. To smooth out the impact of population, we use electricity consumption per capita, GDP per capita to represent income levels, and the share of tertiary GDP to represent economic structure. We choose three approaches to estimate the relationship between electricity consumption, income, and economic structure.

Linear model:

$$E_{cap} = a\, GDP_{cap} - b\, Tertiary + c$$

Polynomial model:

$$E_{cap} = a\, GDP_{cap} - b\big(GDP_{cap}\big)^2 - c\, Tertiary + d$$

Logarithmic model:

$$\ln E_{cap} = a \ln GDP_{cap} - b\, Tertiary + c$$

Where:
E_{cap} is the electricity consumption per capita; GDP_{cap} is the real GDP per capita at 2010 constant RMB value; $Tertiary$ is the share of tertiary GDP (point) in total GDP.

The purpose of this analysis is not to identify the best model for capturing the causal relationships but rather to provide alternative modeling approaches that could shed light on the evolving nature of these relationships. We are testing the hypothesis that the relationship between electricity consumption per capita and GDP per capita is evolving as China's economy is shifting to a different phase of growth based on our observation of a plateau effect in China's per capita electricity consumption in high-income provinces. This observation leads us to question the assumption in conventional demand forecasts using linear extrapolation to project future energy and electricity consumption. We have chosen to test two additional functional forms to explore whether these alternatives better explain the evolving relationship between electricity and GDP per capita in China.

The electricity consumption data are extracted from the *China Energy Statistical Yearbook*, and the population, GDP, and tertiary GDP share data are from the *China Statistical Yearbook* (Wei 2014; NBS 2015). All data are reported at the provincial level from 1990 to 2012. The real GDP deflator is obtained from the World Bank GDP deflator database (World Bank 2015).

5. Results

The regression results of the three models— linear, polynomial and logarithmic— are shown below and are summarized in Table 1. There is a positive correlation between electricity consumption per capita and GDP per capita, and the coefficients are statistically significant at 1% level. There is a negative correlation between electricity consumption per capita and tertiary GDP share, and the coefficients are statistically significant at 1% level in the linear and polynomial model, and 10% level in the logarithmic model.

Linear model:
$$E_{cap} = 0.0836\,GDP_{cap} - 29.37\,Tertiary + 1546$$

Polynomial model:
$$E_{cap} = 0.133\,GDP_{cap} - 7.67E(-7)\big(GDP_{cap}\big)^2 - 20.77\,Tertiary + 733.4$$

Logarithmic model:
$$\ln E_{cap} = 0.836 \ln GDP_{cap} - 0.00520\,Tertiary - 0.467$$

Table 1 The effect of GDP per capita and tertiary GDP share on electricity consumption per capita

VARIABLES	(1) Linear Electricity Consumption per capita	(2) Polynomial Electricity Consumption per capita	(3) Logarithm Log electricity Consumption per capita
GDP per capita	0.0836***	0.133***	
	(0.00413)	(0.0106)	
GDP per capita square		-7.67e-07***	
		(1.32e-07)	
Tertiary GDP share	-29.37***	-20.77***	-0.00520*
	(8.344)	(7.369)	(0.00291)
Log GDP per capita			0.836***
			(0.0317)
Constant	1,546***	733.4***	-0.467*
	(276.2)	(239.1)	(0.238)
Observations	540	540	540
R-squared	0.528	0.554	0.662
Adjusted R-squared	0.526	0.551	0.661
RMSE	1133	1102	0.414
Robust standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

We can see that the logarithmic and polynomial models fit the historical data better than the linear model as evidenced by a higher R-squared. Applying the GDP level and tertiary GDP share level projected by the World Bank and using population data given by United Nations to calculate the projected GDP per capita (World Bank 2013; United Nations 2015), the projected electricity consumption per capita of three different models is calculated in Table 2 and plotted in Figure 6.

Using polynomial model, electricity consumption per capita in China would peak in 2026 at 5,308 kWh when GDP hits 84,030 RMB and tertiary GDP share accounts for 57.10%, which China would achieve based on World Bank's projections of GDP growth rate and tertiary GDP share (Table 2). We haven't observed any decrease of per capita electricity consumption globally, therefore, we assume per capita electricity consumption will stabilize after peak in the polynomial model. The electricity consumption per capita is projected to be 8,292 kWh and 7,030 kWh in 2030, respectively, using the linear model and logarithm model, which are 2,984 kWh and 1722 kWh higher than that in the polynomial model (Table 2).

We find that there is evidence to support that a "new normal relationship" on electricity use is emerging, and that per capita electricity usage may plateau or peak around 2030. However, under different models of estimation, the level of plateau electricity use in China could differ substantially, by as much as 56%. This could have significant implications for power system planning, investment, and operations in China. If the power system planning approach is not responsive to these emerging trends, there is a significant chance of overbuilding the power capacity in China, with hundreds of billions of dollars of investment potentially stuck as stranded assets.

Table 2 Electricity consumption per capita under three different projections

Period		2011-15	2016-20	2021-25	2026-30
GDP growth rate (percent per year)		8.6	7.0	5.9	5.0
Year	2010	2015	2020	2025	2030
GDP (trillion 2010RMB)	40.15	60.65	85.07	113.30	144.61
Population (million)	1340	1376	1402	1414	1415
GDP per capita (2010RMB)	32765	44079	60676	80130	102196
Tertiary GDP share (%)	43.24	47.60	51.60	56.10	61.10
Electricity per capita (Linear) (kWh)	3015	3833	5100	6593	8292
Electricity per capita (Poly) (kWh)	3370	4117	4906	5300	5308
Electricity per capita (Log) (kWh)	2981	3735	4776	5886	7032

Source: 2010 GDP data is from China Statistic Yearbook 2014. GDP growth rate and tertiary GDP share are from World Bank, 2013, *China 2030*. Population projection is from *UN World Population Prospects: The 2015 Revision*, in the medium variant scenario. GDP per capita is calculated based on GDP and population data.
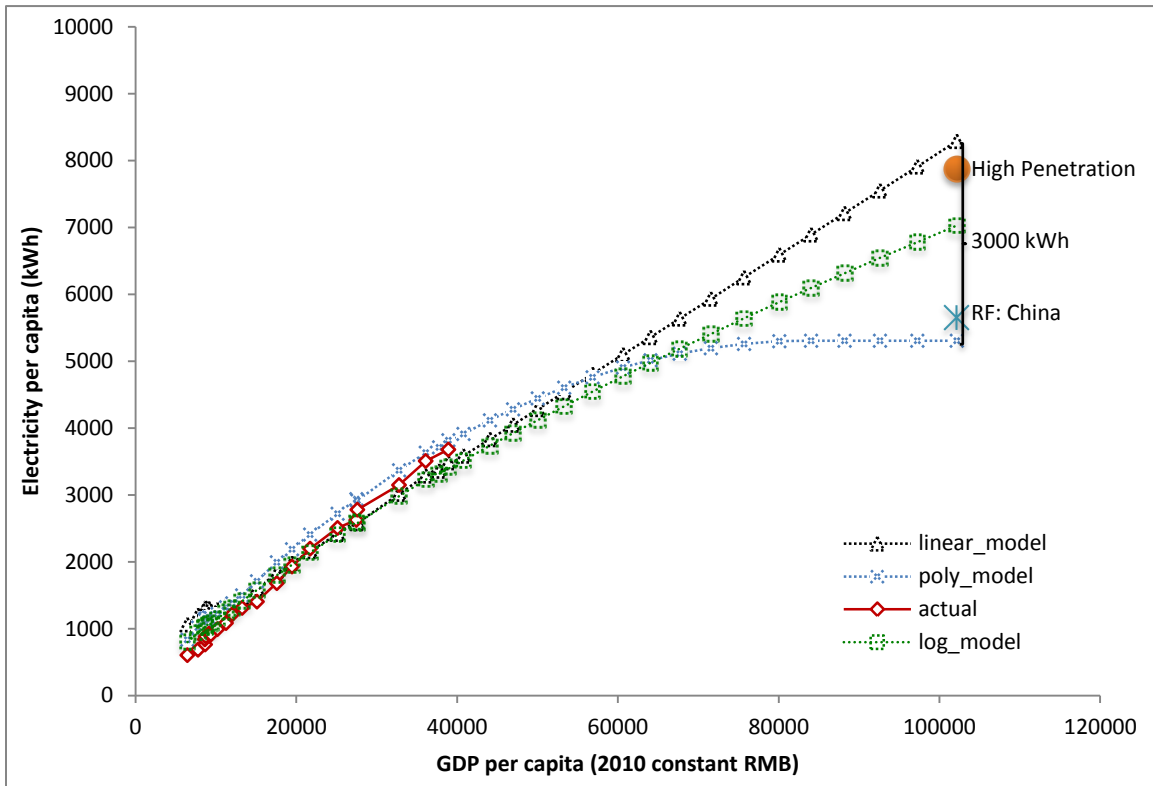
Figure 6 Projections of electricity consumption per capita at different GDP per capita levels

6. Conclusion and policy implications

This study uses 20 years of provincial GDP and electricity consumption data to re-examine the relationship between these two factors in China. We observe a plateauing effect of electricity consumption per capita in high-income provinces as China's economy develops and moves to a more service-based economy. Data presented in Figure 5 suggests that the relationship between per capita electricity consumption and economic development is evolving to a new stage, and that per capita electricity demand is growing only moderately in most Chinese provinces, or even plateauing in the most developed regions, with the exception of a few energy extractive provinces. Using different functional forms, as well as comparing with a few other recent sources, there is a wide range of forecasts, ranging from 5,308 to 8,292 kWh electricity per capita in 2030 (Table 3).

Table 3 Forecasted per capita electricity use in China in 2030

Model	Linear	Logarithm	Polynomial	BNEF	2050 High RE	RF China
Electricity per cap (kWh)	8292	7030	5308	6270	7883	5655

Source: BNEF and 2050 High RE (BNEF 2013); 2050 High RE refers to the *2050 High Renewable Energy Penetration Scenario* study by Energy Research Institute (ERI, 2015); RF China refers to *Reinventing Fire: China*, which a joint study by China's Energy Research Institute, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute; this report is not published yet.

While these different studies have different modeling techniques and inputs, some of the notable difference is likely due to different assumptions used. For instance, in the 2050 High Renewable Scenario, the assumed electrification rate is much higher than that in RF China. However, from a policy planning and investment perspective, such wide variation in projected electricity use raises a serious question about the evolving nature of the relationship between electricity use and economic development. If electricity demand is assumed to grow linearly with GDP, future demand may be seriously overstated, leading to hundreds of billions of dollars of stranded investment.

Despite slowing demand, the investment in coal power plants remains robust in the first half of 2015. It is estimated that by 2030, China's power system will grow by another 1,000 to 1,200 GW in capacity (BNEF, 2015). China's National Center for Climate Change Strategy and International Cooperation (NCSC) estimated 900 GW additional non-fossil capacity is needed between 2014 and 2030 (Fu, Zou, and Liu 2015). Given China's 2030 goal of achieving a 20% share of non-fossil energy, most of the new additions will be renewables or nuclear. It is therefore critically important to assess the evolving relationship between electricity use and economic development, as China transitions to a new growth phase that is likely to be less energy and resource intensive. Policymakers and power system planners can use the observations of this study to reevaluate power demand projections and reexamine the generation capacity expansion plans so as to avoid over investment and stranded assets.

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