China Power
Benefits and Costs of the “Strong, Smart Grid”

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This report is one in a series of publications dedicated to providing information on the benefits and costs of policy measures in the Chinese electric power sector. Companion reports and data sets can be found at www.etransition.org/chinasmartgrid.

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Few leaders shape the physical world more than those who control the Chinese electric power system, a major impetus of the unmatched growth in the world's second-largest economy. The system emits more carbon than the entire economy of India, its dams impound twice as much river water as Europe's, and its windmills tower over more territory than in any other nation.

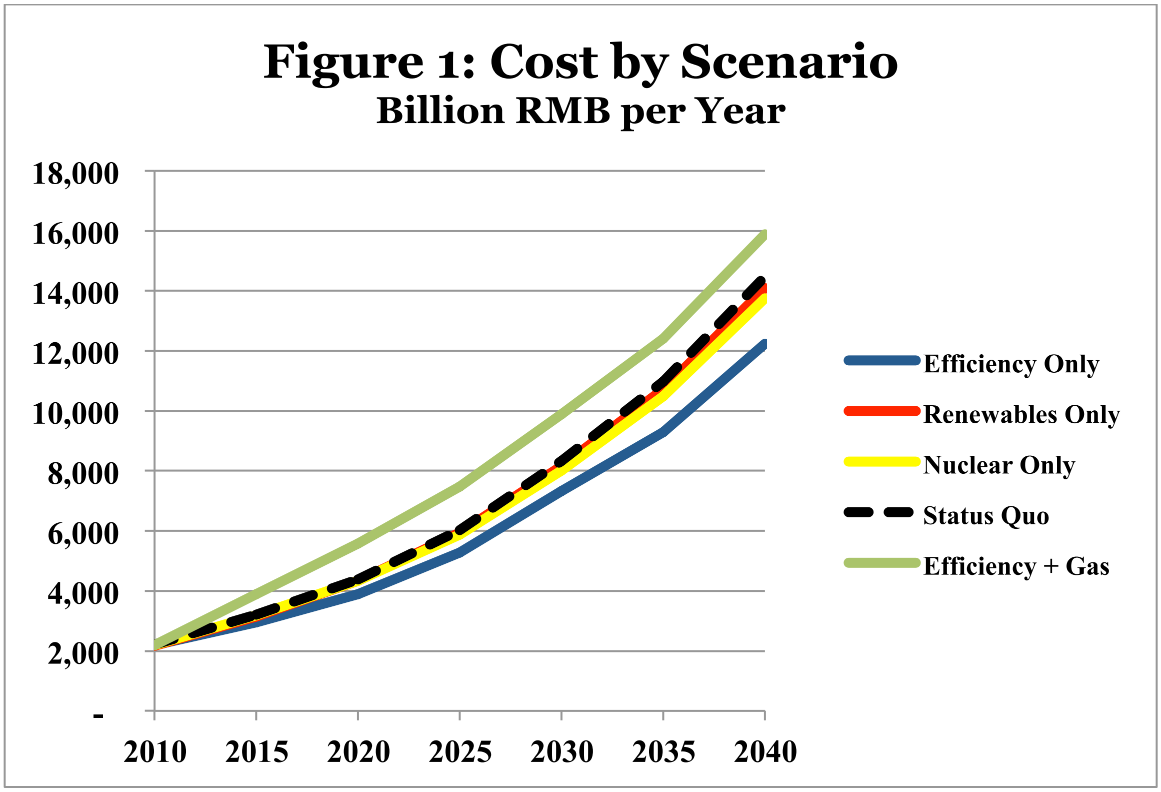
The scale of these comparisons raises questions: What will it cost—in money and resources and global change—to power China's future?[1] What are the benefits and the costs of deploying a "strong, smart grid"?[2]

The State Grid Corporation of China (State Grid), which delivers most of the electric power used in China, first introduced its vision for a "strong, smart grid" in 2009 at a conference on ultra-high voltage power transmission. To date the almost exclusive focus has been on construction of an ultra-high voltage transmission network to serve as the backbone for a system that will incorporate large scale and intermittent power from remote sources. State Grid's published plans barely acknowledge the potential role of the consumer in the electricity demand or supply chain.

Our team spent two years analyzing China's power sector and projecting its future.[3] Our concept of a "strong, smart grid" incorporates all of the technology choices before the power planners, not just transmission, distribution, and information technologies. Our main findings include the following points.

The strong grid envisioned by State Grid will perpetuate the use of coal and encourage expansion of environmentally destructive hydropower projects. Chinese engineers are building a state-of-the art power grid with little apparent attention to consequences outside of the electric power system. Development of long-distance transmission systems can impact surprisingly large areas of relatively undisturbed landscape and encourages widespread, environmentally destructive expansion of power supply technologies. The lines are more likely to connect to coal-fired and large-scale hydropower dams than to less harmful sources.

The smart grid envisioned by State Grid will waste billions of dollars and vastly increase carbon emissions because there is little effort to connect grid and distribution communications and control systems to end users (See Figure 1 and Figure 2). The cost of and emissions from Chinese electric power generation could triple by 2030 unless dramatic new efficiency measures that rely on such connections are developed and implemented. We estimate that the current course of Chinese power sector development will squander 500 billion RMB per year by 2020.

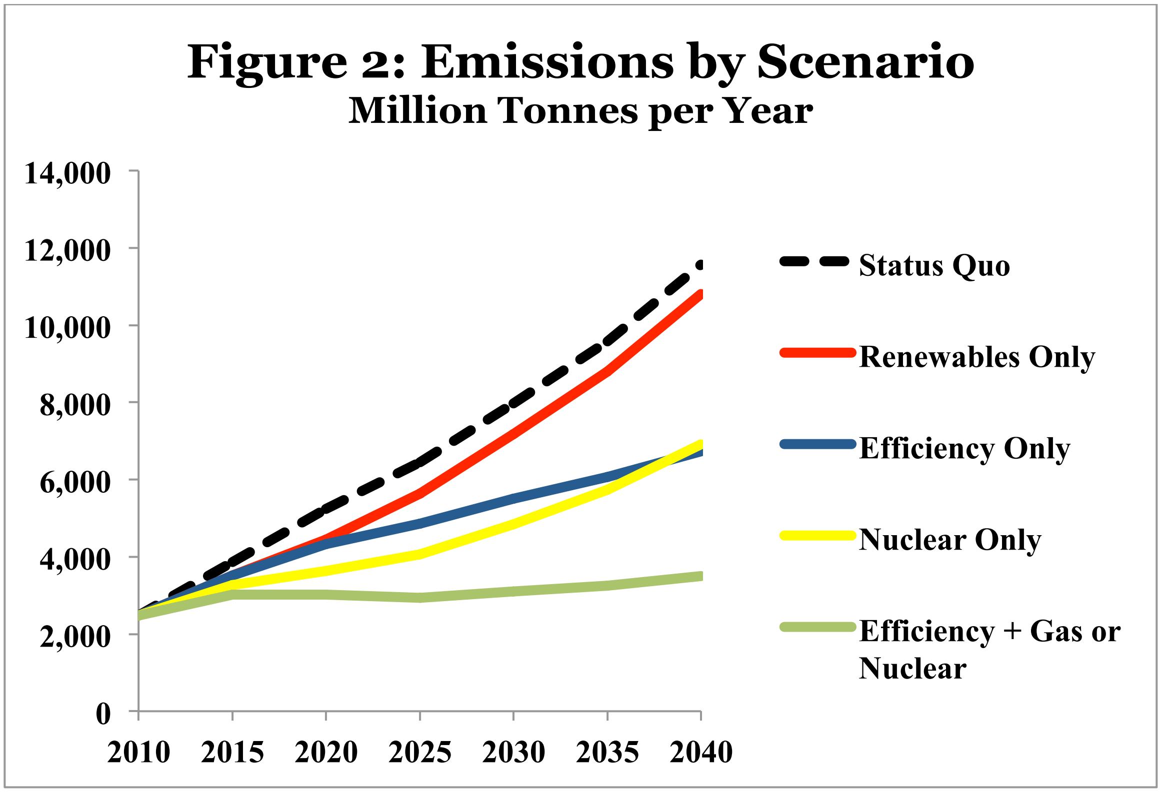


Squaring China's economic, environmental, and national security goals with its power system development plans will require an independent regulatory agency. China's power system plans do too little to incorporate cleaner, cost-effective alternatives to the slow-motion catastrophe of coal. The lack of transparency in the system suggests little effort to undertake the type of full cost-benefit analysis that would support such planning. Portfolio mandates, such as China's commitment to renewables, cannot supplant the role of careful planning, but that appears to be happening in China because there is no effective oversight of State Grid. The costs of this lack of good governance will be enormous for China's economy and the global environment.

The highest priority reforms for the Chinese power sector should:

- Mandate more-aggressive energy intensity reductions in industry and buildings sector energy-using devices. This action would have far more impact on reducing costs and carbon emissions than large scale deployment of renewable technologies.
- Restructure economic development incentives to favor services and light manufacturing
- Regulate carbon emissions to limit construction of new coal-fired plants
- Establish a power planning agency whose organizing mandate includes environmental and economic goals, not just power generating goals.

- Give environmental regulators the power to control the impact of hydroelectric and other "renewable" energy sources.[4]



Growing Demand and Rising Costs

China's electric power system is developing without market mechanisms and regulatory measures bold enough to meet the compound challenges of growing demand, rising costs, and sustainability targets. Power demand could over the coming decade surge to developed country levels. This prospect represents a grave threat to the Chinese economy and environment. Power consumption per capita in China today ranks far below developed nation levels despite the large power requirements of China's heavy industrial sector (see Table 1), and if Chinese consumer behavior mimics U.S. or European—or even Japanese levels—the result could be expensive, particularly if power continues to be supplied primarily by coal.

What is to keep Chinese per capita use from climbing to Korean or even U.S. levels? Certainly, recent trends could take consumption levels that high. Chinese GDP and power use have grown in a nearly one-to-one relationship since 1994. Econometric research suggests that for every one percent of GDP growth, power use would—all other things equal—grow by nearly 1.3 percent. Fortunately, the price of power, the structure of the industrial economy, and strong energy-efficiency mandates have increased just enough to limit power demand growth to the same rate as that of the economy. Still, none of those trends can be taken for granted going forward.

Two factors are key to the future of Chinese power demand growth.[5] The first is an expectation that industrial power growth and GDP growth will slow from the exuberant rates of the past decade. We believe GDP growth will slow to 6-7 percent over the next 10 years. At the same time, the share of GDP generated by services instead of heavy

Table 1: GDP and Power Use Patterns, 2010

Indicator	China	USA	Japan	S. Korea
GDP (2010 $ in PPP/person)	$8,000	$48,000	$35,000	$14,700
Power (kWh/person)	3,100	13,700	8,100	8,850

Sources: Chinese State Electricity Regulatory Commission; Chinese National Bureau of Statistics**;** World Bank; International Energy Agency. Power data refer to end use consumption. PPP stands for Purchasing Power Parity.

industry will increase. Services account for just under 45 percent of GDP now, but could grow to almost 60 percent over the next decade, and probably 80 percent by 2040. This assumption matters a lot: every 1 percent increase in the share of GDP provided by services reduces power demand growth by 0.59 percent.

The second is the near-universal truth that income and power price significantly affect electricity demand. Since 1980, for every one percent increase in China's GDP, electricity use increased 1.24 percent, and for every one percent increase in electricity price, electricity use declined 0.22 percent. In the absence of skyrocketing prices or strict demand-side regulations, power demand in China will grow to levels like those in the developed world. Chinese will naturally increase their personal use of power as their incomes rise, as did Koreans, Europeans, and Japanese (see Figure 3 and note that it includes a high rate of structural change).

None of this is to say that residences or even the commercial service sector will come to dominate electricity consumption. Industry today uses three-quarters of Chinese electricity and even after major structural change will remain responsible for 50-60 percent of power demand in China, even up to the half-century mark.

We project that without changes in Chinese policy, power demand would probably reach 5,400 kWh per capita by 2020. That *status quo* outlook contrasts with that of the leading energy modeler in China, Jiang Kejun of the Energy Research Institute, who expects per capita consumption to be only 4,000 kWh in 2020. If so, China per capita power use would be less than half the present Korean per capita level.[6] The lower number can be achieved technically, but not without new, aggressive, and broad-based efficiency measures for electric power conservation.

Fortunately, the Chinese central government has in the recent past taken a strong stance in favor of efficiency: it closed tens of thousands of inefficient factories, imposed reasonable appliance efficiency standards, and brought power prices up to nearly the

Table 2: Where will the *status quo* lead?

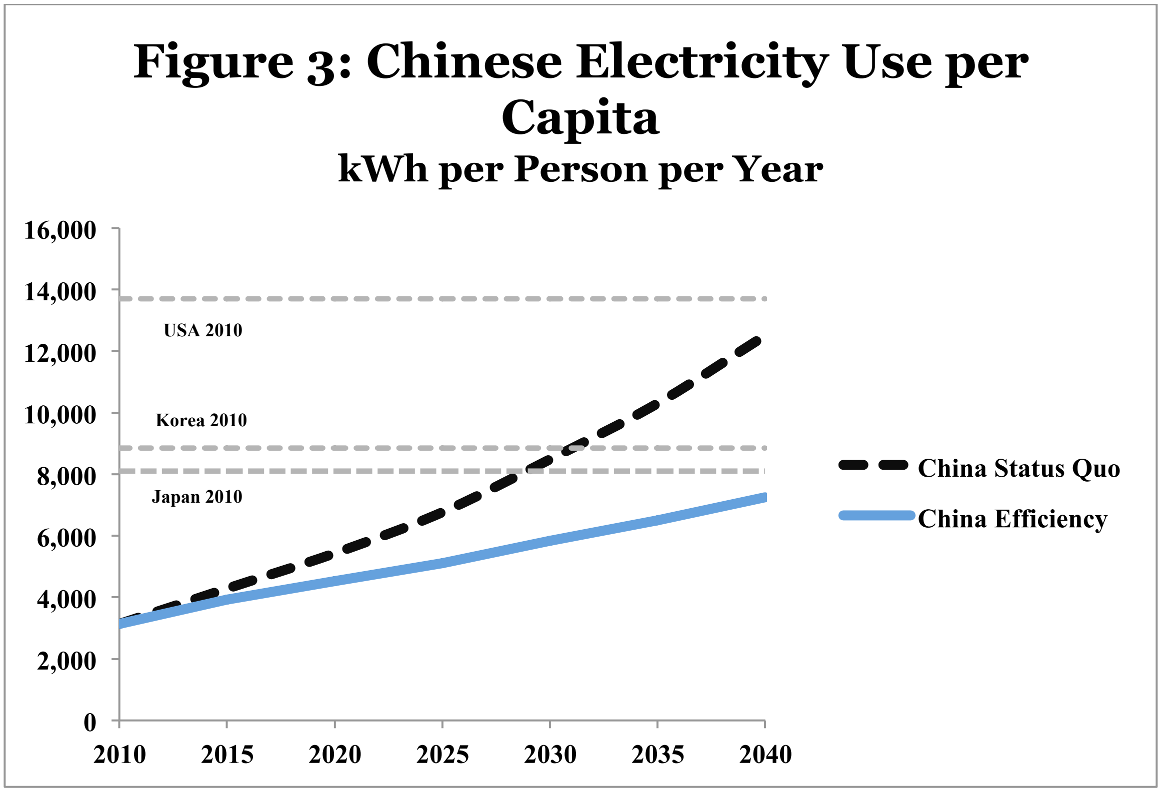
Policy in place...	Because...
Continues rapid economic growth	We assume annual growth slows from the recent rate of about 10 percent to 6-7 percent per year over the next decade, consistent with projections by Jiang.
Includes structural change	Continued rapid economic growth may be impossible without a significant shift from materials intensive manufacturing to light, higher-valued added manufacturing and to services.
Results in much higher demand	We assume that electricity consumption growth in China will resemble regional trends and demand will reach Korea's 2010 per capita demand level by 2030.
Omits energy intensity mandates	China has established efficiency *targets* through 2020, but the specific policies to achieve them have not been set and are not utilities' priority.
Omits a carbon cap	Chinese low carbon *targets* have not yet been translated into policies sufficient to meet the targets.
Omits nuclear	The role for nuclear power is still being debated.
Omits new renewables	We assume that China's renewable portfolio mandates will function primarily as an impetus for increased hydropower because of its status as a known quantity in grid integration.

level of cost. The government also provides purchase incentives and other rewards for early-adopters of efficiency technologies. Significantly, though, these policies operate outside the regulatory functions of the power supply system. The demand-side management (DSM) program within the utilities themselves has a goal only of reducing annual power demand by 0.3 percent.[7]

We conclude that price reform is necessary to rapid deployment of efficiency technologies. The existing power pricing system is distorted and chaotic, with revenues collected by power generation companies rising at a much lower rate than revenues collected by the grid companies. At the retail level, provincial authorities sometimes still utilize power price discounts to encourage energy-intensive industrial growth.[8] We project significant economic losses due mainly to failure to use cost-effective efficiency measures.[9] Choosing the *status quo* over the efficiency only path would in 2020 cost each Chinese household 1,200 RMB per year.

Coal Remains King

None of China's electric power resource options is compelling. Combining the least harmful options can cut health costs and risks, though these hybrid systems have their own challenges and high economic cost. Interestingly, the design and development of China's high-voltage transmission grid may have more influence on supply choices than risk and cost concerns.



China today still relies on coal for three-quarters of its power, and coal-fired power has a major impact on human health.[10] Applying international morbidity rates to Chinese coal-fired power generation suggests that coal-related deaths already exceed 75,000 per year. That level could exceed 300,000 per year by 2040 in our status quo projection.[11]

At the same time, the Chinese government takes seriously the threat of climate change related to coal-fired power generation. The power sector accounts for just over 35 percent of China's carbon dioxide, emitting 675 million tons of carbon-equivalent. That amount exceeds emissions of the entire economy of India. If trends continue, Chinese coal-fired plants are likely by 2025 to emit more carbon than the entire United States does today.[12]

Railway transportation bottlenecks between the north central China coalfields and demand centers in the south and east increasingly constrain coal-fired power plant development. Future coal expansion may well come in the form of remote generating stations connected to population centers by State Grid's "strong, smart grid." The word "strong" was coined by State Grid to convey the sense of security and resilience stemming from a massive network of high-voltage transmission lines. This expansion benefits from the perception that it is a green strategy necessary for the transport of remote renewable resources to the population centers. But new Xinjiang-to-Central China high voltage transmission lines are more likely to handle coal-fired than wind generated electricity.

While the term "renewable energy" in China most often conjures images of Chinese wind power development, "renewable energy" in fact is dominated by large-scale hydroelectric dams. China has been added some 20,000 megawatts of wind generating capacity each year, but there exists 7 times more hydro capacity in China today than wind. And even by 2020, the actual power (as opposed to capacity) generated by water power is expected to exceed that of wind by at least a factor of five. This prospect is shaped in part by the low availability, or capacity factor, of wind in China, which has averaged only 15 percent in recent years. We assume wind's capacity factor will increase dramatically to 25 percent in the near future, but hydropower, coal, and nuclear power have availability averaging 40, 60, and 80 percent, respectively. Thus, for any given level of capacity, other sources account for much more power. This fact explains in part the relatively low impact of renewable energy can be expected to have on Chinese emissions (see Figure 2).

Hydropower is a sensitive and controversial topic in China, as it is in most countries, in part because it is capital intensive but also because of the social impact associated with population displacement caused by reservoirs. Planners may also want to consider the risk of potentially catastrophic dam failure. It was in China's Henan Province in 1975, after all, where the worst hydropower accident in history drowned 26,000 people when the Banqiao Dam failed in a typhoon. The dam breach drowned 26,000 and contributed to more than a quarter million deaths from disease and famine.[13] Even the worst nuclear accident in history killed only a small fraction as many people.[14]

The relevance of the grid to these choices is clear. Due to the very long distances between the remaining large hydroelectric opportunities in southwest China, hydropower can be developed only by massive investment in high-voltage transmission to population centers in the north and east of China.

Nuclear power today generates only 2 percent of Chinese electric power, less than diesel generators. But nuclear expansion is far less constrained by high voltage transmission development, at least assuming that nuclear power can be developed in the highly populated north and east of the country. Moreover, Chinese regulatory authorities have concluded also that nuclear power is now cheaper than hydropower in China and could play a major role in emissions reductions. The capital cost estimates for nuclear power in China approach only about $1,600 per kilowatt, far less than the $4,000 estimated for the Vogtle nuclear plants recently approved for construction in the southern United States. Uncertainly about cost, as well as a considerable level of public opposition to nuclear power in China, may well determine the future of this resource.

Solar power prospects have been bolstered by recent rapid decreases in the manufacturing costs of photovoltaic cells, but, like wind, is constrained by lack of a means of storage. Hydroelectric power is expected to continue to be the dominant renewable energy source.[15]

China's reluctance to embrace imported pipeline gas or liquefied natural gas leaves the nation with no low-carbon fossil supply options, driving the power sector to riskier hydro and nuclear plants. Striking a balance between concern for the security of indigenous

Table 3: Alternative Electric Futures
New Story Lines

Structural Change	This scenario accelerates service sector growth from less then 30 percent of new GDP growth to half of new GDP growth.
Efficiency + Gas	This "low carbon" scenario maximizes efficiency, prohibits new coal-fired capacity, and uses gas instead of coal. Coal would drop from 60 percent of 2040 capacity to 9 percent.
Nuclear Power	This scenario adds 100 GW of nuclear power every 5 years, starting in 2020. The Status Quo scenario adds no new nuclear capacity.
Renewable Energy	The Renewables scenario mandates addition of 140 GW each of hydro and wind and 10 GW of PV by 2020. The Status Quo scenario includes no subsidies or mandates for PV, wind, and hydro.
Energy Efficiency	This scenario imposes a 2.5 percent per year energy intensity reduction. The Status Quo scenario keeps efficiency requirements at current levels.

Note: Scenarios are evaluated in the "China Electric Power Grid Model," a hybrid econometric-engineering program written by Entri for this project. Scenarios are not additive—results in each are independent of the other scenarios—except for the Efficiency + Gas scenario. This "low carbon" scenario combines demand management, structural change, and low carbon sources including some natural gas and nuclear power. For a detailed mathematical methodology and list of assumptions by scenario, see www.etransition.org/chinagrid/method.

supply and the desire to limit imports on one hand and China's well-publicized concern about global climate change on the other will be one of China's greatest energy challenges in the coming decades.

The high cost of relying on natural gas is a matter of fuel price assumption, which might be expected to remain about $10 per gigajoule in China. That level is as expensive as Russian gas delivered to Europe and imported liquefied natural gas delivered to Japan. In

Table 4: Chinese Power Generation Costs, 2010

	Capital RMB/kW	Fuel Cost RMB/kWh	Busbar Cost RMB/kWh
Solar PV	20,000	-	1.79
Wind Power	8,000	-	0.59
IGCC CCS Coal	11,400	0.26	0.90
Hydropower	10,000	-	0.37
Sub-Critical Coal	4,000	0.26	0.37
Super-Critical Coal	3,675	0.24	0.36
Nuclear Power	10,000	0.16	0.41
Natural Gas	3,250	0.45	0.59

Source: Wang Yanjia (Tsinghua University) and sponsored by the State Electricity Regulatory Commission. See Wang Yanjia, Low Carbon Technology and Policy in China Power Sector, (Beijing: Kwankung Press. ISBN978-988-15498-1-5, 2012).（电力行业应对气候变化技术与政策选择.）

comparison, however, new gas development technology in the United States has driven the price of gas from $10 per gigajoule just a few years ago to only about $2.50 today. Even if Chinese gas prices fell to only $5 per gigajoule, natural gas would be a cheaper source of power supply than every other option we modeled, including coal. Gas use could thus unexpectedly revolutionize the economics of Chinese power production.[16]

Smarter Grid Leadership and Policy

It is almost certainly true that China's electric power grid is technologically more advanced than that of the United States. That does not mean that the Chinese grid is "smart." A smart grid applies communications and control systems to optimize power generation supply and demand. China's grid is stronger and smarter than most, but only in the direction of generator to distributor, not in both directions from end-user to grid as it needs to be. While demand side appliances and factories are heavily regulated for efficiency in China, grid-based encouragement of demand-side and consumer-based peak-load technologies and behavior are not yet part of Chinese grid management.

High-Voltage Authorities

A key problem with the "strong, smart grid" approach in China today is that it focuses disproportionately on increasing long-distance ultra-high voltage transmission of power. This focus by its nature will lead to disproportionate emphasis on—and construction of—large-scale coal and hydropower projects. These plans will benefit energy developers more than they benefit consumers, at least in comparison to lower-cost and cleaner options.

To illustrate the scale of this problem, we used the China Electric Power Grid model to estimate transmission line capacity requirements. These requirements are modeled as a function of generating capacity additions on a regional basis. Long-distance transmission options include 13 long distance combinations between five resource centers in the Northeast, North Central, Inner Mongolia, Northwest, and Southwest grids, and three demand centers in the north, east, and south. Intraregional supply still accounts for a large share of supply and is incorporated in the model.

Transmission costs are estimated based on distances between load centers and markets, the share of power transmitted long distance, the capital costs per kilowatt of line types (which vary by voltage), and assumed capacity of the lines. Regional requirements are set as a function of the supply options chosen.[17] For example, hydro plants require long-distance transmission from southwest to central or south China. How many lines and how much right-of-way are needed is determined as a matter of voltage level of the line. That is because ultra-high voltage lines require fewer circuits and less right-of-way per unit of power transmitted.

The results of the grid modeling are striking. The total area to be covered in 2040 by transmission lines in China would amount to an area the size of the U.S. state of Maryland. The difference between relying on renewable sources—with their long-distance transport to load centers—and using either gas or nuclear power closer to demand centers (intraregional transmission) totals an estimated 15,000 square kilometers, an area the size of the U.S. state of Connecticut.[18]

The security of future power supply also depends on the high voltage systems performing up to the levels expected. If the high voltage lines did not perform well, then the cost of rectifying the system would be retrofitting—and adding to the rights-of-way after the fact. Avoiding this cost can alternatively be seen as a benefit of one major aspect of the "strong, smart grid" initiative if, of course, it works.

Policy Reforms That Work

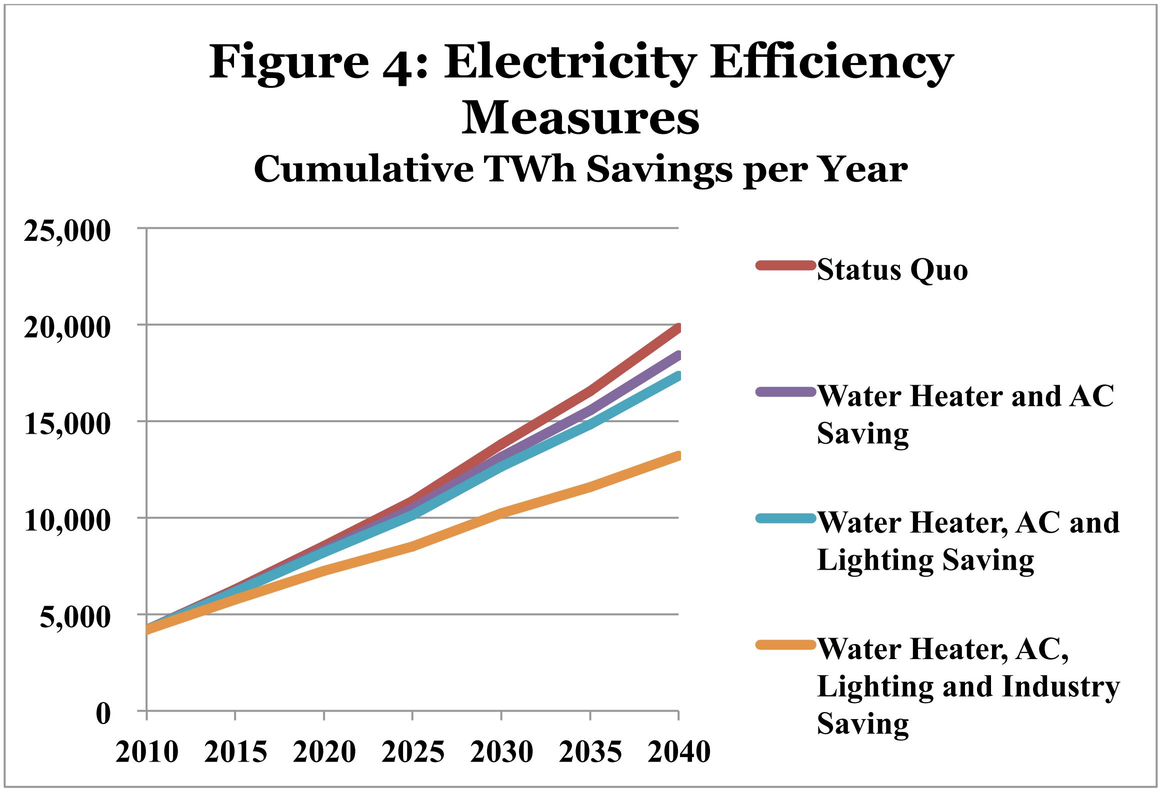
Our research indicates that China's current electricity price regulation system does not yet promote optimal economic outcomes. One key set of problems is that price distortion continues, specifically because of a low wholesale power purchase price for generators. Power prices are not very low in China, and there is evidence that revenues are distributed in such a way that the power generators may be losing money and the grid systems receiving more than their share.

This fact remains in part because of insufficient metering in buildings sector. Carbon tax and demand-side management initiatives are unambitious. Problems remain in part because Chinese grid management is heavily biased toward the supply side for investment and development. More emphasis on demand-side measures would be significantly useful (see Figure 4).

It is often suggested that the utility sector be restructured with decentralized management and wholesale competition. Such an approach could take time and may be unnecessary to implement the measures suggested here. The key will be to shift incentives so that money is made in the power sector not by maintaining ongoing trends but by deploying the technologies and measures that optimize the public interest.

Policy priorities include building power planning tools, including at least two electric sector analytical systems. Those include an economic-technical electricity demand forecasting tool and one for evaluating investment benefit-cost decisions. It would improve decision-making by making these analyses subject to expert and public review.

Sophisticated energy-economic modeling underlies national- and utility-level planning in most countries today. Even as the state-of-the-art improves, however, debate continues among developers and users of the models on the quality of various models and the assumptions that go into them.



A fundamental problem is that decision-making in China's utility sector is opaque. Data and tools for planning appear to be lacking or missing from public view. Utility decision-making is heavily influenced by the corporate bodies which implement policies, and policy-making is divided and distributed across high-level agencies with insufficient human and intellectual capacity to make effective decisions. Overseers could be appointed to provide oversight and guidance by creating and providing to stakeholders public forecasting and policy evaluation tools. In addition, a cross-agency regulatory body is needed with requisite legal and intellectual capacity.

SERC or a comparable organization could develop a model capable of screening research, policy, and investment opportunities. This model would draw on the best available open source models and on the models developed by our U.S. and Chinese partners in this effort. SERC could initiate partnership talks with several institutions, including Tsinghua experts.

The possibility of an inefficient Chinese electric power future is a concern for more than just the Chinese people. China's power plants will, on their present course of development, produce more carbon dioxide emissions in 2020 than the entire United States produces today.[19] The increase would be reasonable to justify because even then China would use half as much power per capita as Americans. Yet for the same money, the nation could hold emissions nearly constant while increasing power generation by 50 percent.

That is not to say that costs and prices will not increase substantially: they will. But a shift in strategy is essential to avoid catastrophic climate change.

Chinese electricity policy would be most effective—meaning it would do more to contribute to overall economic, environmental, and national security goals—if it were shaped to:

- Mandate continued energy intensity reductions in industry and energy-using devices
- Restructure economic development to favor services and light manufacturing
- Regulate carbon emissions to limit construction of new coal-fired plants.
- Fulfill the promise of SERC. China needs a power planning agency with public purpose in mind and interaction with business and environmental groups. SERC could become a window into the electric power governance.
- Give environmental regulators the power to control the impact of hydroelectric and other "renewable" energy sources.

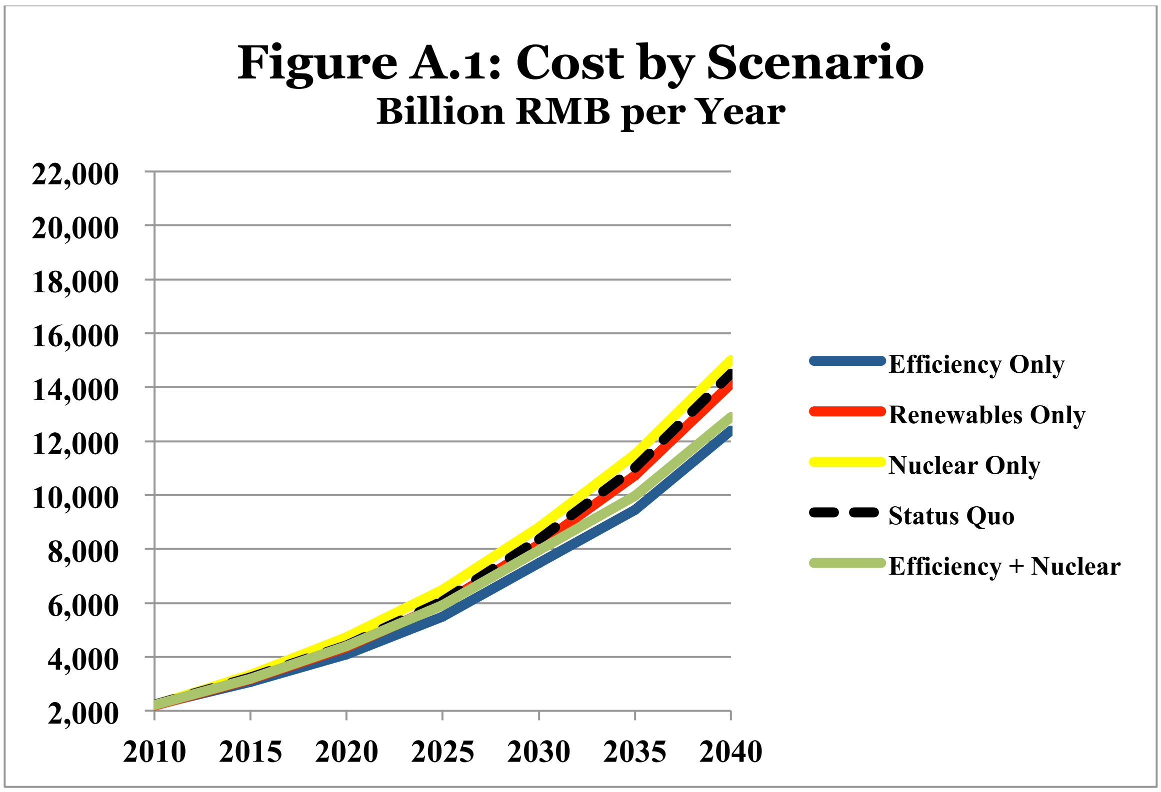
Demand-side policies inherently offer greater cost-saving potential than supply-side measures, and China has achieved remarkable success with energy-efficiency policies. No energy supply future seems to serve China's economic and environmental goals in the absence maximum use of demand side management. Yet, in the electric power sector, demand side management appears to have generally met only resistance outside the State Council and the National Development and Reform Commission (NDRC). The resources committed to "demand-side management" are tiny. The nation's ability to regulate power sector demand is strong but only at the crudest level of regulating access to supply, authority to generate, and prices.

Appendix i

Alternative Scenarios

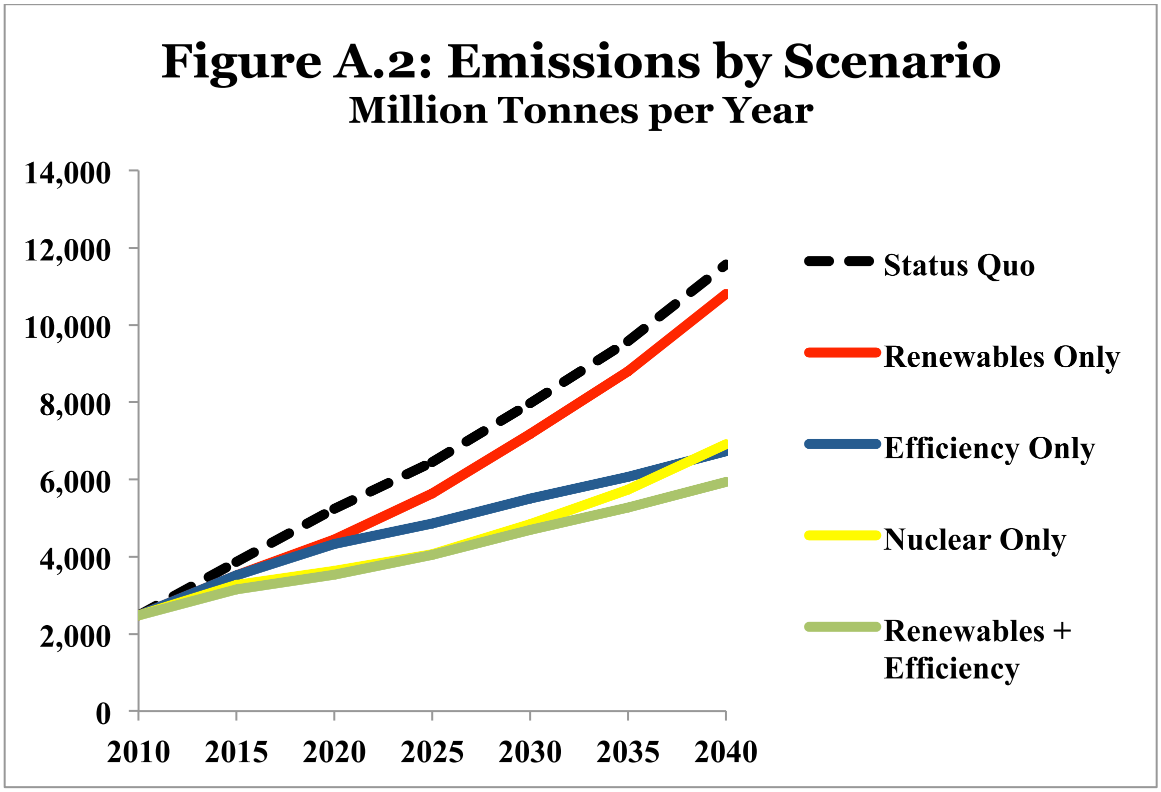
The limits of econometric regression analysis are well known. History is not destiny and there is every reason to think that relationships among economic variables change over time. The Chinese government's information and regulatory campaigns for energy-efficiency over the last decade, after all, increased the price response of electric power consumers. Moreover, lack of transparency in Chinese power use data collection and availability injects more uncertainty than usual into the analysis. 20

Our reviewers have urged us to illuminate how easily alternative outcomes can be produced by making different assumptions, such as for the cost of nuclear power. Figure A.1 below shows how the order of cost rankings is altered when we assume that the cost of nuclear power in China would be $4,000 per kilowatt (like that assumed for the new Vogtle Plant in the United States), rather than the $1,600 indicated by our sources in China and used in our Status Quo scenario. This one change makes nuclear power the most costly case.



An Efficiency + Nuclear scenario also depicted in Figure A.1 shows that it would be more expensive than an efficiency only scenario, but less costly than the Status Quo scenario.

Other reviewers suggested that we present a comparison of results in which a combination of renewables and energy efficiency as well as nuclear power and energy efficiency be presented to show the effect on emissions reductions. As Figures 2 and A.2 show, the Nuclear or Gas + Efficiency scenario, which would hold carbon emissions at about three billion tonnes per year, would be far more effective than a Renewables + Efficiency scenario.



References and End Notes

1. Note that this paper places Chinese surnames first.

   This report benefitted from an overview of Chinese smart grid policy. See Wu Jiandong, Wu Jiang, Yu Yanshan, “The Smart Grid in China: A Discussion Paper,” Report of the Expert Policy Advisory Group, published by Entri, Annapolis, Maryland, February 2012, in cooperation with the China Center for International Economic Exchanges, Chinese Academy of Sciences and the Policy Research Office of the State Electricity Regulatory Commission.

   For an excellent policy review of the Chinese power sector, see, “Power Sector Policy in China: Next Steps,” The Regulatory Assistance Project, September 2011.

   For an overview of behavioral science and energy using behavior, see Hunt Allcott and Sendhil Mullainathan, “Behavioral Science and Energy Policy,” 2010, Cambridge, Massachusetts (Provided on-line by Harvard University, this article is, according to the authors, “…a longer supporting version of an article in the March 5, 2010 issue of *Science* magazine; see Vol. 327, p. 1204, www.sciencemag.org.) See also Daniel Kahneman, “Maps of Bounded Rationality: A Perspective on Intuitive Judgement and Choice,” Nobel Prize Lecture, Stockholm, December 8, 2002.

2. This term is used by State Grid to describe China’s version of “smart grid.” For excellent studies of smart grid technologies and their impacts, see RG Pratt, PJ Balducci, C Gerkensmeyer, S Katipamula, MCW Kintner-Meyer, TF Sanquist, KP Schneider, and TJ Secrest, “The Smart Grid: An Estimation of the Energy and CO2 Benefits, Revision 1,” Pacific Northwest National Laboratory Richland, Washington, January 2010; and Lisa Schwartz and Paul Sheaffer, “Is It Smart if It’s Not Clean? Smart Grid, Consumer Energy Efficiency, and Distributed Generation, Part II,” Regulatory Assistance Project, Montpelier, Vermont, March 2011.

3. The supply side power generation cost estimates in this study, including capital costs, capacity factors, operations and maintenance costs, efficiency of conversion, and future costs, rely heavily on work by Wang Yanjia (Tsinghua University) and sponsored by the State Electricity Regulatory Commission. See Wang Yanjia, *Low Carbon Technology and Policy in China Power Sector,* (Beijing: Kwankung Press. ISBN978-988-15498-1-5, 2012). （电力行业应对气候变化技术与政策选择.）

   Previous studies include Lin Boqiang, ERD Working Paper No. 37, “Electricity Demand in the People’s Republic of China: Investment Requirement and Environmental Impact,” Asian Development Bank, Manila, Philippines, March 2003.

4. We base our assessment on the China Electric Power Grid Model, which we developed as a combined econometric and engineering model for assessing the costs and benefits of so-called “Smart Grid” measures in the Chinese electric power system. A valid benefit-cost analysis must be based on transparent methods and reproducible results, and there was no model available to us from official or private sector Chinese organizations. We thus developed our own modeling framework in order to project coherently a Chinese electric power future and to consider options that might cut costs and carbon dioxide emissions. We hope our model will serve the community in conducting systematic and reproducible evaluations of electric power policies and technological choices in China. For a detailed description of the methodology of the China Electric Power Grid Model and related, additional analyses, visit www.etransition.org.

5. Population data projected for 2015 and 2020 come from the Population Reference Bureau. See Population Reference Bureau, "World Population Data Sheet 2010," 2011, www.prb.org. Important trend and projections for urbanization were found in Jiang Kejun, “China’s Low Carbon Development Pathways by 2050, Scenario Analysis of Energy Demand and Carbon

Emission," Energy Research Institute, National Development and Reform Commission, Beijing, China, 2011.

6. Jiang Kejun, *Ibid*.

7. Measures for the Electricity Demand Side Management, *National Development and Reform Commission*, Beijing, November 2010.

8. For one example of the draconian nature in recent years of Chinese energy policy, see Keith Bradsher, "In Crackdown on Energy Use, China to Shut 2,000 Factories," *New York Times*, New York, 9 August 2010; and "China orders 2,000 firms to shut overcapacity by end-Sept," *China Daily* (on-line), 8 August 2010.

9. Building sector electricity use data were taken from "Annual Research Report on Energy Conservation Development in Building Sector in China," Beijing, 2010, (in Chinese: 《中国建筑节能年度发展研究报告》; ZHAI Chaoqin, JIANG Yi, XIA Jianjun, "Estimation about National Electricity Consumption by Residential Air Conditioning"; WANG Qingyi, *Research References of Fiscal and Economic Policy for Sustainable Energy Development*, October 2005; JING Yi, "Building Energy Efficiency and Living Patterns," *Architectural Journal*, December 2007; JIANG Yi, LI Zhaojian, "Simplified Calculation Method of Air Conditioning Energy Consumption of Residents in China," *HV&AC*, Vol. 36, November 2006; JIANG Yi, *Building Energy Efficiency Methods in China through* "Comparing Energy Consumption in China and in Other Countries," *China Science Technology Achievement*, Vol. 22, 2007.

10. Electric power sector data generally are adopted from *China Statistical* Yearbooks 1996-2011," National Statistics Bureau; and State Electricity Regulatory Commission, "Electricity Regulatory Annual Report," Beijing, 2006 to 2010 (in Chinese: 电力监管年度报告(2010) 国家电力监管委员会. For an overview of natural gas and electric power generation in China, see "Policy Study: Gas-fired Power Generation in China: Synthesis Report, Energy Research Institute, Beijing (undated). For an update on nuclear power technology, see John M. Deutch, Charles W. Forsberg, Andrew C. Kadak, Mujid, Kazimi, Ernest J. Moniz, John E. Parsons, Du Yangbo, Lara Pierpont, *Update of the MIT 2003 Future of Nuclear Power*, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2009.

11. Coal-fired power morbidity and mortality data were taken from "Uncertainty and Variability in Health-Related Damages from Coal-Fired Power Plants in the United States," Jonathan I. Levy, Lisa K. Baxter, and Joel Schwartz (Harvard School of Public Health), *Risk Analysis*, Vol. 29, No. 7, 2009. See also, Kristin Aunana, Jinghua Fang, Haakon Vennemo, Kenneth Oye, Hans M. Seip, "Co-benefits of climate policy—lessons learned from a study in Shanxi, China," *Energy Policy*, Vol. 32, p. 567-581, 2004; and YI Honghong, HAO Jiming, DUAN Lei, LI Xinghua, and GUO Xingming (Department of Environment Science and Engineering, Tsinghua University, Beijing, People's Republic of China), "Characteristics of Inhalable Particulate Matter Concentration and Size Distribution from Power Plants in China," *J. Air & Waste Manage. Assoc.* 56:1243–1251, 2006; and C. Arden Pope III, Richard T. Burnett, Michael J. Thun, Eugenia E. Calle, Daniel Krewski, Kazuhiko Ito, and George D. Thurston, "Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution," *Journal of the American Medical Association*, 1132 to 1141, 2002; and Sarah Penney, Jacob Bell, John Balbus, "Estimating the Health Impacts of Coal-Fired Power Plants Receiving International Financing, Environmental Defense Fund, New York, 2009.

12. This estimate includes the aggressive "renewable energy" mandates made by the Chinese central government. The general policy framework supporting this modeling approach can be found in: Standing Committee of the National People's Congress, 14th Session, "The Renewable Energy Law of the People's Republic of China," Beijing, China, February 28, 2005. Article 2 specifically includes hydroelectric power. The law gives control of hydroelectric resource development to the State Council. Emissions data taken from Oak Ridge National Laboratory, Carbon Dioxide Information Center, Oak Ridge, Tennessee, USA, 2012. See cdiac.ornl.gov.

13. Wayne J. Graham, “A Procedure for Estimating Loss of Life Caused by Dam Failure,” U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office, Denver, Colorado, September 1999. This paper describes the worst hydropower catastrophe as having occurred in Henan, China in August 1975 at the Banqiao Dam, and attributes failure to overtopping in a typhoon. According to Graham, some 26,000 people drowned immediately and 230,000 “probably died from epidemics and famine.” The dam was 118 meters high.

14. See, generally, Robert E. Ebel, “Chernobyl and Its Aftermath: A Chronology of Events,” The Center for Strategic & International Studies, Washington, D.C., 1994; Richard Stone, “The Explosions That Shook the World,” *Science Magazine*, Vol. 272, 19 April 1996, pp. 352-354; Michael Balter, “Children Become the First Victims of Fallout, Special News Report,” *Science*, Vol. 272, 19 April 1996, pp. 357; Nigel Williams, “Leukemia Studies Continue to Draw a Blank,” *Science*, Vol. 272, 19 April 1996, pp. 358; John Bohannon, “Panel Puts Eventual Chernobyl Death Toll in Thousands,” *Science*, Vol. 309, 9 September 2005, p. 1663.

15. Hydroelectric dams can reverse their turbines as pumps to store water for peak or other power generation uses later. However, the ability to use hydro dams for this purpose can be limited when run of the river water supplies are low due to seasonal conditions or drought.

16. For an overview of natural gas and electric power generation in China, see “Policy Study: Gas-fired Power Generation in China: Synthesis Report, Energy Research Institute, Beijing (undated).

17. A separate demand module is used to estimate capacity requirements based on power demand, average load, and peak load based in turn on total electricity demand and mandatory capacity-to-peak load requirements. The model uses total power demand divided by average capacity factor to get the requisite installed capacity figures. Total demand is provided by the GDP and Demand Module. The average capacity factor is provided as assumed by the model user in a Supply Options Module.

18. We assume that the capacity per power line corridor is 6,000 MW, and the transmission line capital cost is estimated in RMB per kWh for each option. The function to capture these costs includes variables for new installed capacity for each power generation option; capacity per power line corridor; supply-source-to-load transmission distance with a distance appropriate for each supply option.

19. Our Status Quo scenario projects year 2020 Chinese electric power sector emissions to exceed 6 billion tons of carbon dioxide per year, compared to U.S. total emission in 2008 of 5.67 billion tons. The U.S. figure references Tom Boden, Gregg Marland, and Bob Andres, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, 2011 (www.cdiac.ornl.gov/trends) converted by the authors to carbon dioxide using a factor of 3.67.

20. The China Grid Model’s representation of demand varies by scenario. The Status Quo projection stems from a regression function using time series data from 1980-2010. We conducted original research on price response and GDP elasticity of demand and use the results to drive the model. The “Demand Management” scenario modifies the Status Quo by assuming 12th 5-year plan goals are achieved, including reductions in residential and commercial sector electricity consumption.