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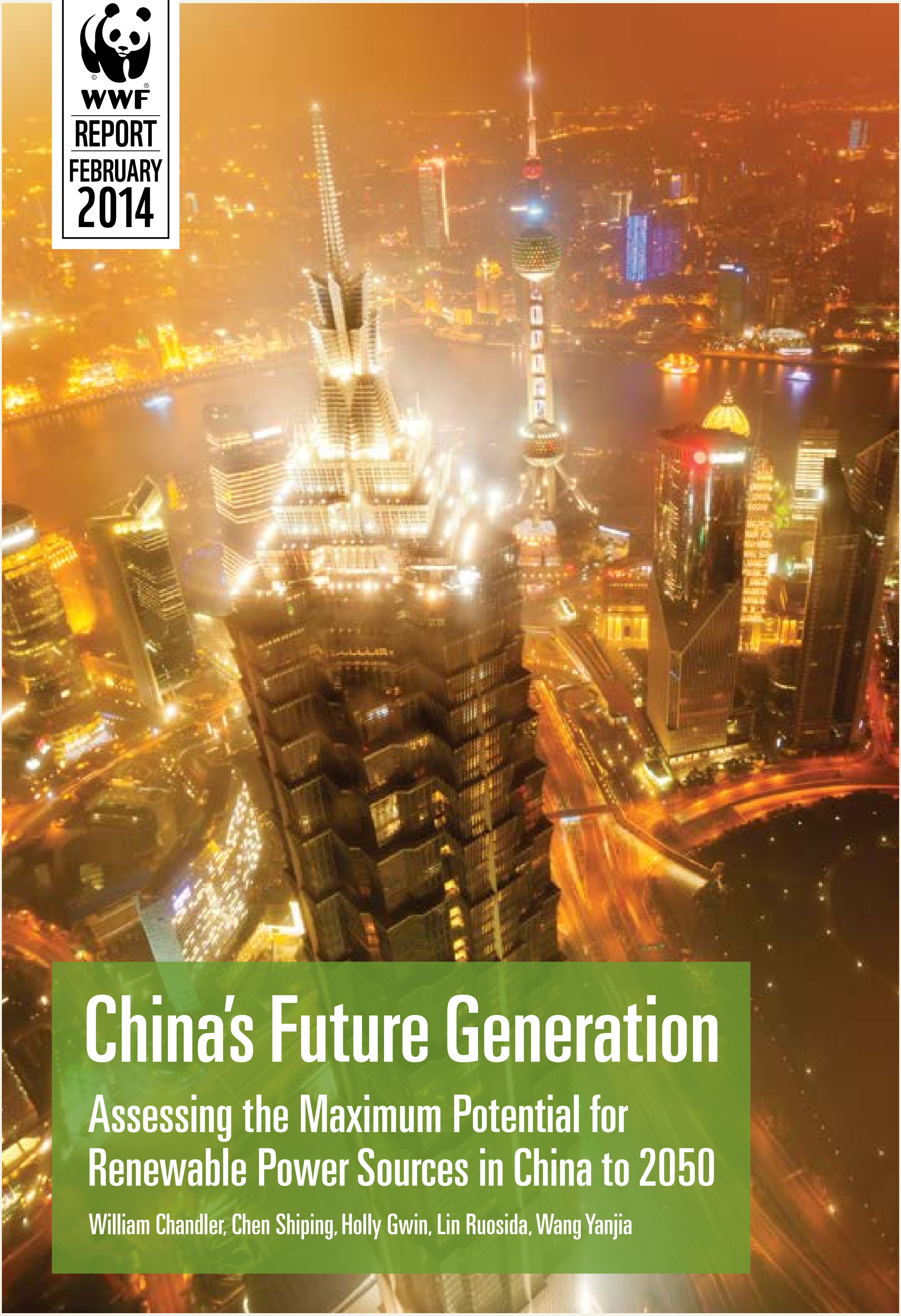

China's Future Generation

Assessing the Maximum Potential for Renewable Power Sources in China to 2050

William Chandler, Chen Shiping, Holly Gwin, Lin Ruosida, Wang Yanjia

Entri

ABOUT WWF

WWF is the world's leading conservation organization. WWF works in 100 countries and is supported by close to 5 million globally. WWF's unique way of working combines global reach with a foundation in science, involves action at every level from local to global, and ensures the delivery of innovative solutions that meet the needs of both people and nature.

WWF CONTRIBUTORS

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ABOUT ENTRI

Entri is a U.S.-based not-for-profit 501(c)(3) corporation created in 2010. The organization builds on decades of its founders' experience in research, institutional development, and technology deployment. The organization is a collaborative international effort with participation of top energy and climate experts from key nations.

ABOUT THE REPORT AUTHORS

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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.

Annapolis, Maryland
January 30, 2014

China's Future Generation

Foreword and Introduction by WWF
Analysis and Report by Entri

BOLD ACTIONS MUST BE TAKEN BY ALL TO MAKE THE CHANGES NECESSARY TO AVOID A FUTURE NO ONE WANTS. LO SZE PING

FOREWORD

With one-fifth of the world's population, China is the fastest- and largest-growing economy—and its global ecological impacts are keeping pace. Whether China can shift to an equitable, environmentally sustainable development pathway will determine not only the future of China but also the future of the entire living planet.

That is why it is critical that the Chinese government reaffirm its dedication to "ecological civilization," an economic pathway brought into harmony with environmental limits.[i]

However, the window to transition is very narrow. Business-as-usual is not good enough, nor is there time for complacency or indifference. Every newly built coal-fired power plant locks us in for 30 more years of carbon emissions and air pollution. Every tree felled reduces the vitality of the forest ecosystem on which many species, such as the tiger and giant panda, depend. Bold actions must be taken by all to make the changes necessary to avoid a future no one wants.

Reducing local air pollution and halting climate change are two of the most important challenges for China. Both are driven heavily by emissions from electricity consumption and require China to make swift, sweeping reforms in the electric power sector, including a shift toward 100 percent renewable electricity. This endeavor will not be possible without collaborative actions taken by key decision-makers in government, the private sector, NGOs, and academia.

As Nelson Mandela said, "It always seems impossible until it's done." WWF is working in China to foster an ambitious renewable energy vision and is dedicated to massively scaling up clean renewables with appropriate legislation and support systems. In the present moment, a green China powered by renewable energy may appear far off, but this report helps us see that it's possible and economically cheaper than a future dominated by fossil fuels. We identified the right path forward and have started on our way; now we must run to reach our goal and not stop until it's done.

Lo Sze Ping
CEO, WWF China

[i] The concept of "ecological civilization" was first coined in 2007 by Hu Jintao while he was general secretary of the Central Committee of the Communist Party of China.

THE PUBLIC IN CHINA HAS BEGUN TO CALL FOR MAJOR ACTION, UNDERSTANDING THAT THE COSTS OF CHINA'S CURRENT ENERGY CHOICES ARE NOT WORTH THE RISKS.

WWF INTRODUCTION

While China's carbon footprint per person is now close to that of the EU, it is still far below those of other countries such as the US, Canada, Australia, and some OPEC counties in the Gulf region. But as the largest greenhouse gas-emitting country in the world, China's current and future contribution to climate change and other global environmental impacts cannot be underestimated.

China has made major development strides in the past 20-plus years, but development has not always come equitably nor without environmental expense. The populous nation of almost 1.4 billion is not only a "developed" country in the main, growing urban centers but also still a poor developing country in the agriculturally dominated rural countryside. For this reason, China will continue to strive for economic growth to pull poor citizens out of poverty. However, continuing on the current fossil fuel-fed development pathway will only deepen the global climate crisis and lead to dangerous levels of local pollution, whether in the water, soil, or air.

Pictures of Chinese cities hidden behind thick curtains of dangerous air pollution were among the most memorable global images of 2013. Red alert pollution days, cancelled airline flights, and school closures brought China's environmental crisis into sharp relief, as city residents searched for sold-out air purifiers and face masks. The public in China has begun to call for major action, understanding that the costs of China's current energy choices are not worth the risks. Coal use in particular is the prime cause of air pollution in China, is reducing the life expectancy of exposed Chinese citizens, and is the largest contributor to climate-changing carbon emissions.

The problem is clear: Chinese citizens, businesses, and government officials alike realize that change must come. In one sense, major change is already occurring. In 2012, China led the world in overall installed renewable energy capacity as well as in installed wind and solar hot water capacity. In 2012, China topped the list of countries investing the most in new renewable energy capacity.[ii]

Even as China positions itself as a leader in renewable energy, it continues to rely heavily on power generation from coal. China's coal consumption has increased for 13 consecutive years, and it currently consumes almost half of the world's coal. Nearly 80 percent of electricity used in China is generated by coal.

Conventional wisdom says that China cannot kick this coal habit, as its massive energy needs are projected to increase in coming years. Transitioning to an energy economy dominated by renewable energy, instead of coal, just isn't possible in the foreseeable future, so many pundits say.

This report shows that the conventional wisdom is wrong. Even under conservative assumptions about the future cost of renewable electricity technology and innovation potential, a renewable power future is within reach.

[ii] Renewables Global Status Report 2013, REN21.

Even accepting projections for substantial increases in energy demand, by 2050 China's energy economy can be dominated by renewable electricity sources, and coal can be completely eliminated from the national electricity mix. And all of this can be accomplished for less than the costs of an energy future dominated by fossil fuels.

WWF asked the Energy Transition Research Institute (Entri), a team of US and Chinese experts, how close China could come to 100 percent renewable electricity by 2050. The analysis shows that with "proven technology,"[iii] around 80 percent of China's electricity generation can be met by renewable sources by 2050 if China immediately begins to implement ambitious energy efficiency measures and reduces the share of its energy-intensive industries while growing its services as a basis for sustainable economic development. Entri finds that coal can be eliminated from China's electricity mix by 2040, provided appropriate regulations or explicit carbon pricing measures are put in place. Just as encouraging, the report shows that the renewable electricity scenario would be more cost-effective than a scenario that does not prioritize renewable energy or energy efficiency. This is without even calculating the external social and environmental costs, which would likely favor renewable energy sources even more. A key prerequisite for effective and continued growth of renewable energy in the power sector is a strong legislative focus on energy efficiency and conservation by mandatory energy efficiency standards for the various appliances.

The Imperative for a Clean Energy Revolution

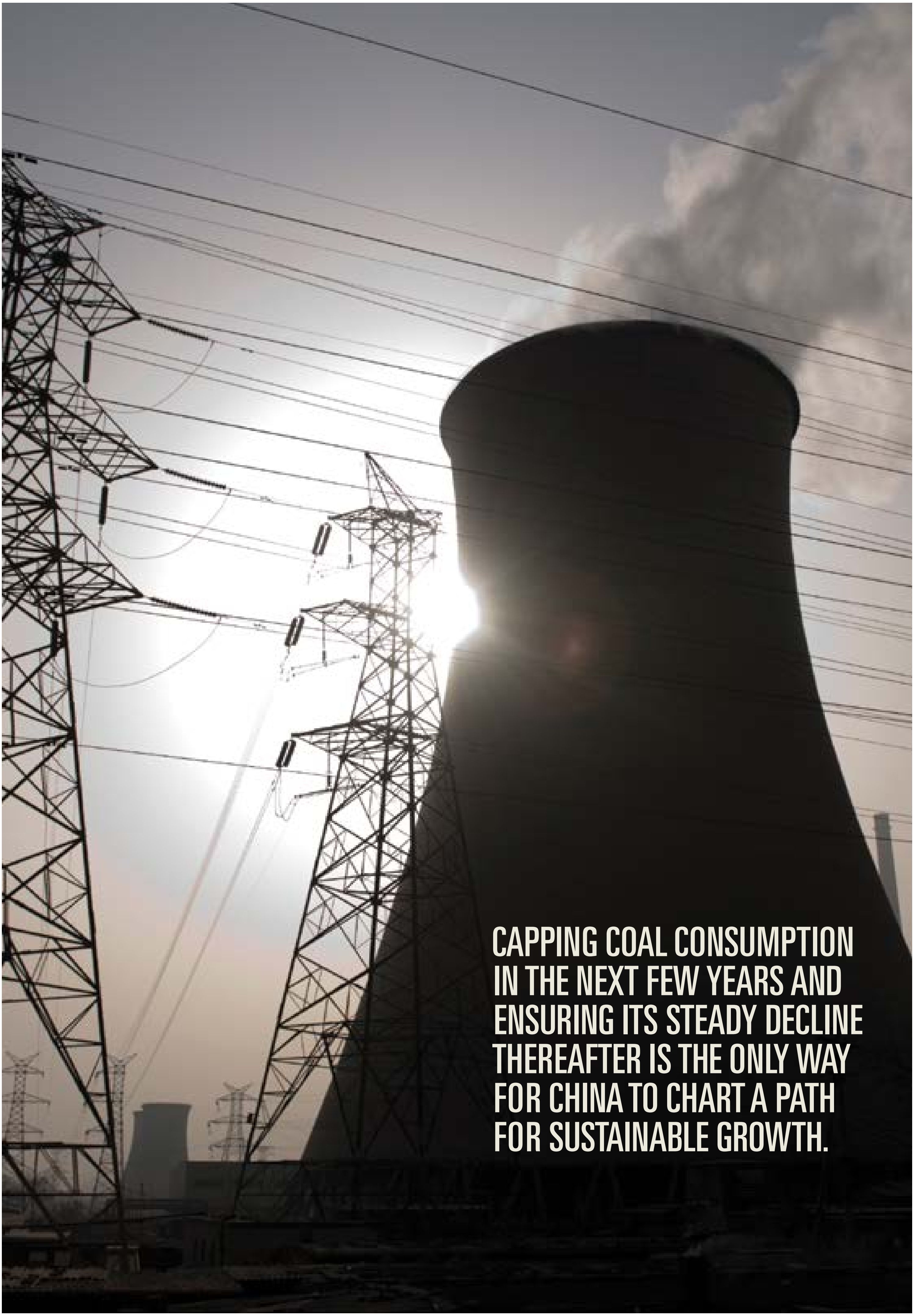
As the world's most populous country with a rapidly growing economy, China currently burns about two times as much coal as the US and four times as much as India. Capping coal consumption in the next few years and ensuring its steady decline thereafter is the only way for China to chart a path for sustainable growth. The ecological and public health impacts are too heavy to continue on the current trajectory.

Most recently this has been evidenced in eastern Chinese cities by levels of particulate air pollution that have exceeded the World Health Organization's definition of "safe" by 30 to 40 times in some cases.[iv] And while scathing public outcry from Chinese urban citizens has thus far focused on air pollution, there will be a growing public focus on the impacts of climate change if the country's carbon emissions aren't soon put in check as well. The scientific community suggests that sea level rise and more powerful storms could impose a heavy cost on eastern Chinese cities and a 2°C increase in average air temperature could decrease rain-fed rice yields by five to 12 percent in China.[v]

[iii] Entri defines "proven technology" as technology in common use that is known to be effective when properly operated and maintained. Entri's China 8760 Grid Model does not incorporate unproven technology, nor does it presume any technology breakthroughs (e.g., in energy storage technologies) nor the availability of carbon capture and storage.

[iv] See http://usa.chinadaily.com.cn/epaper/2013-10/22/content_17050715.htm for more information.

[v] See IPCC Working Group II Fourth Assessment Report (2007) at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch10.html.


CAPPING COAL CONSUMPTION
IN THE NEXT FEW YEARS AND
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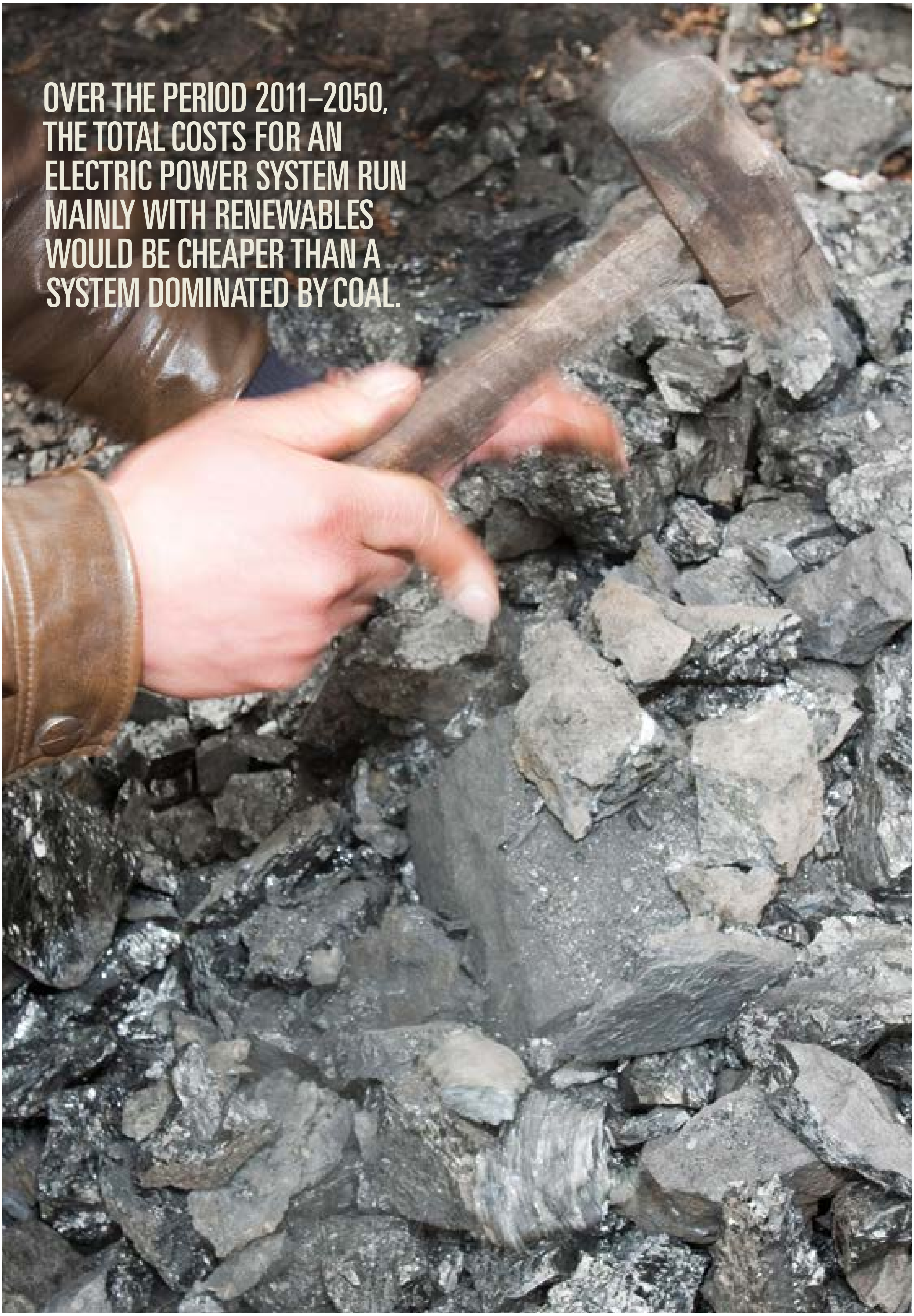
THEREAFTER IS THE ONLY WAY
FOR CHINA TO CHART A PATH
FOR SUSTAINABLE GROWTH.

OVER THE PERIOD 2011–2050, THE TOTAL COSTS FOR AN ELECTRIC POWER SYSTEM RUN MAINLY WITH RENEWABLES WOULD BE CHEAPER THAN A SYSTEM DOMINATED BY COAL.



China's (Possible) Renewable Power Future

Based on Entri's modeling, this report looks exclusively at China's complex electricity sector and asks how close the world's most populous and energy-hungry nation can get to 100 percent renewable power generation by 2050. Incorporating assumptions of only modest technology improvements, the report finds that:

- Around 80 percent of China's electricity generation can be met by renewable sources, if appropriate policies and measures are taken, including—and conditional on—aggressive energy efficiency improvements.
- Coal can be eliminated from the power mix by 2040, but this will require considerable political courage and enabling policies that would regulate or price carbon in the electricity sector at an appropriate level. While there are various methods for pricing carbon such as a national emissions trading system or carbon tax, Entri's research suggests that a carbon emissions performance standard (CO_2/kWh) might be most effective at addressing the full carbon costs from China's power sector.
- The remaining 17 percent of electric generation comes from gas plants, which would serve mainly as backup for the increased amount of variable renewable electricity.
- Over the period 2011–2050, the total costs for an electric power system run mainly with renewables would be cheaper than a system dominated by coal.

Starting with this snapshot of China's current electric power system requirements, Entri used its China 8760 Grid Model to develop scenarios for future requirements. Four scenarios are presented in the report:

Baseline Scenario

China implements no specific clean energy or efficiency policies other than the ones currently on the books and does not issue major structural economic reforms that shift China toward having a larger service sector.

High Efficiency Scenario

China successfully implements very aggressive energy efficiency requirements and makes a substantial shift away from energy-intensive manufacturing as the basis for economic growth. Relatively low electricity demand, achievable only through the full-blown commitment to efficiency, is a prerequisite for achieving affordable, low-carbon electric power systems. The demand projections in this scenario form the baseline for the High Renewables and Low-Carbon Mix scenarios.

High Renewables Scenario

Building off of the High Efficiency scenario, China meets its electricity demand with renewable sources if they are available.

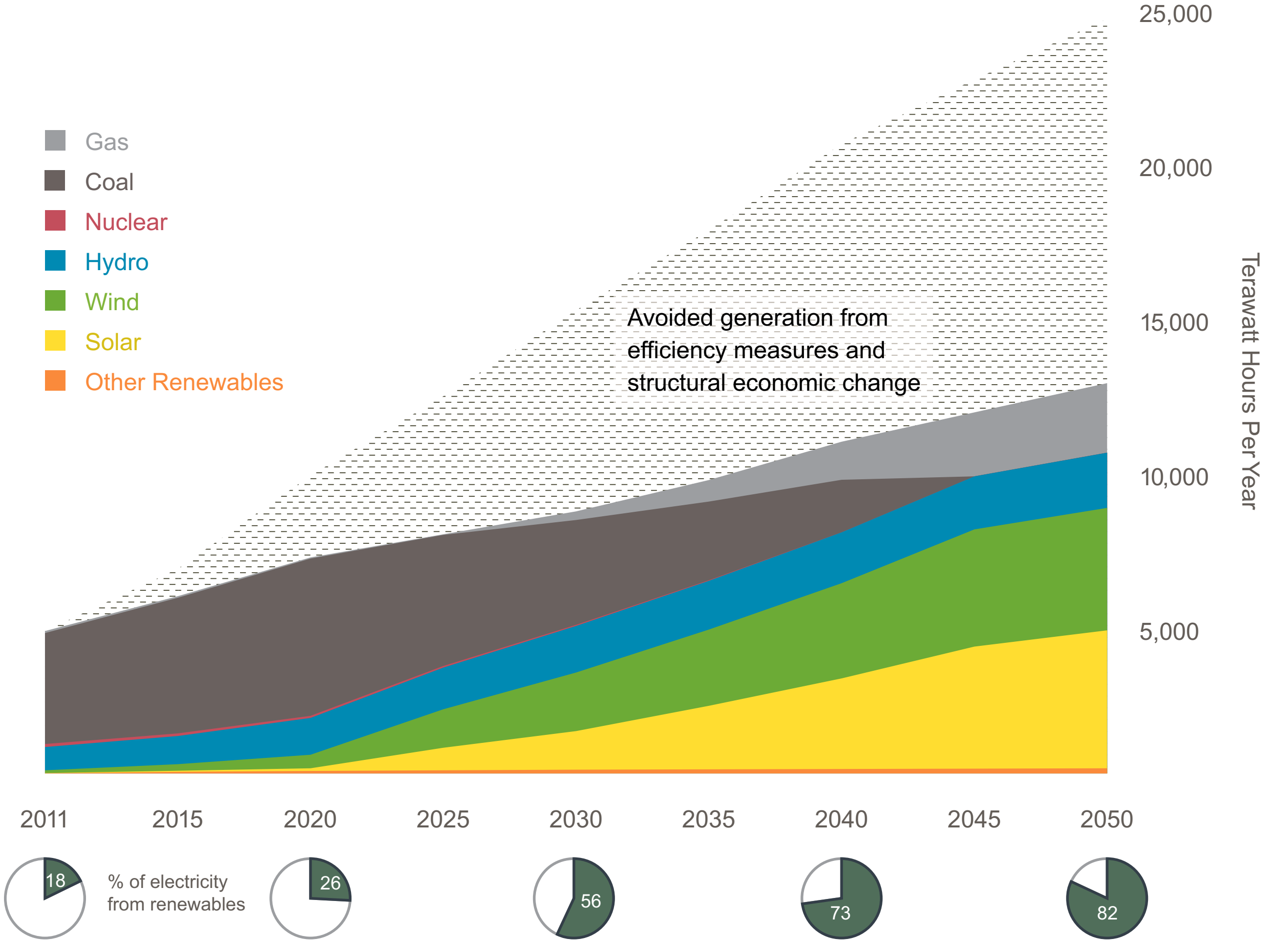
Low-Carbon Mix Scenario

Building off of the High Efficiency scenario, China meets its energy demand with various low-carbon sources available, including renewables, nuclear, and gas.

WWF's Perspective on the High Renewables Scenario

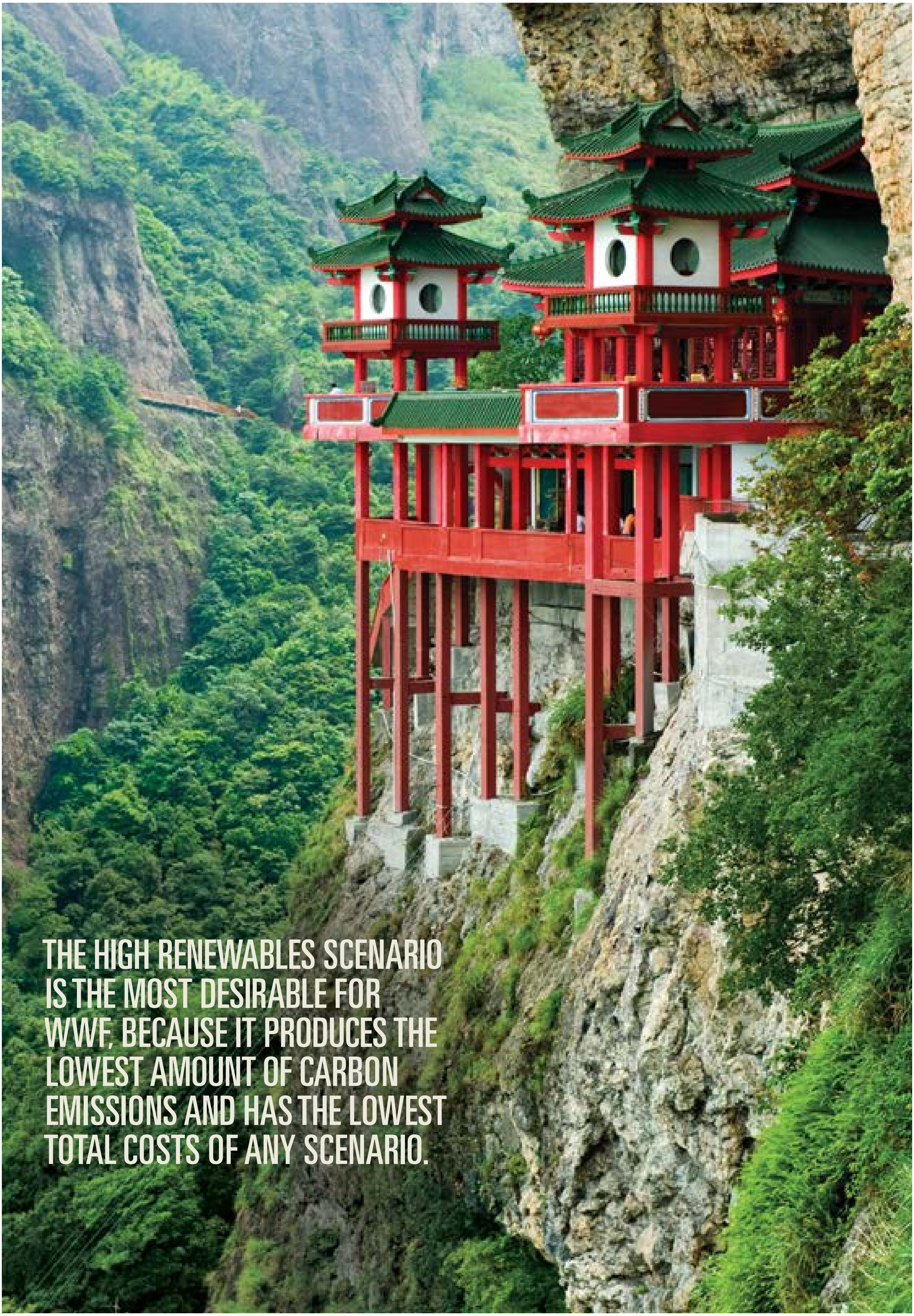
The High Renewables scenario (see chart below) is the most desirable for WWF, because it produces the lowest amount of carbon emissions and has the lowest total costs of any scenario. Renewable energy is sometimes dismissed as "too expensive," but Entri finds that the total cost of the power generation system under the business-as-usual Baseline scenario is more than transitioning to around 80 percent renewable electricity by 2050 under the High Renewables scenario. Phasing out coal will also have major climate and local environmental benefits, which are not calculated in the scenarios. However, care must be taken to avoid potential negative environmental impacts stemming from construction and operations of all sources of power generation, including renewable energy.

Electricity Generation, High Renewables Scenario

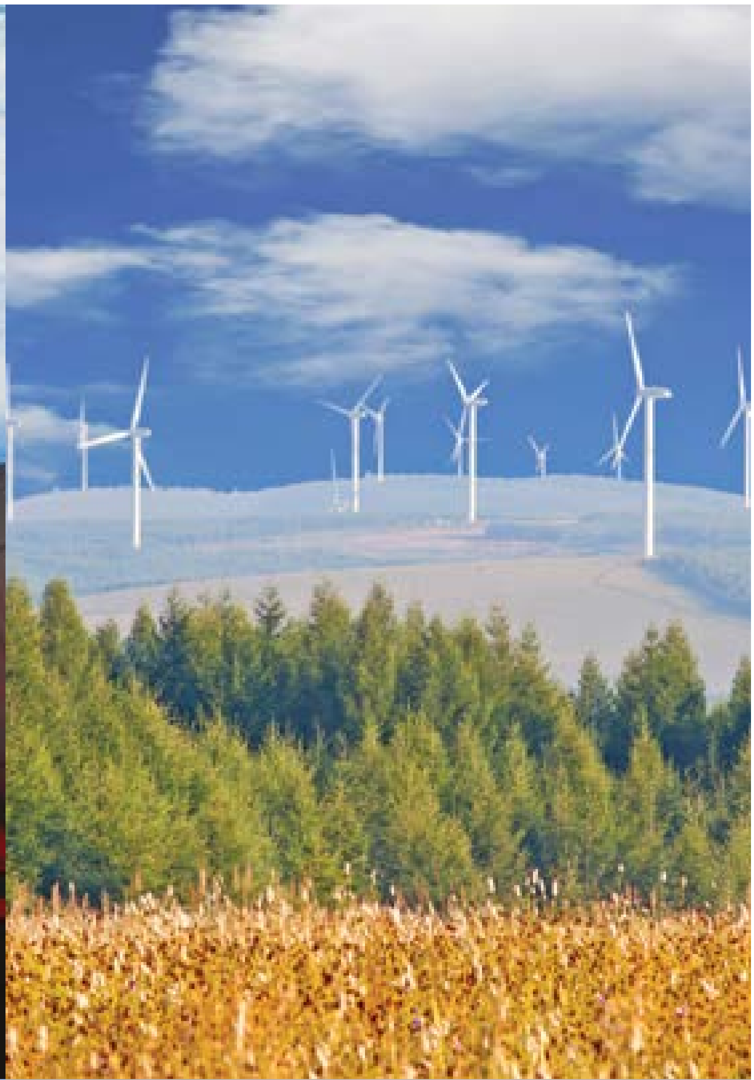


Energy Efficiency and Conservation

To achieve the vision of nearly 100 percent renewable electricity by 2050, China must put in place precedent-setting enabling policies and measures for energy efficiency and conservation. This includes broader economic policies that will be needed to shift China's economy toward a more energy-efficient service



THE HIGH RENEWABLES SCENARIO IS THE MOST DESIRABLE FOR WWF, BECAUSE IT PRODUCES THE LOWEST AMOUNT OF CARBON EMISSIONS AND HAS THE LOWEST TOTAL COSTS OF ANY SCENARIO.

economy. This shift would reduce power demand by 49 percent from projected levels in 2050, making it feasible to supply China's future electricity needs with renewables.

Wind, Solar, and Other (Non-Hydro) Renewables

The High Renewables scenario assumes cost reductions in non-hydro renewable technologies. All of the onshore and offshore wind resources defined as economical by the China 8760 Grid Model are used in the High Renewables scenario, whereas solar power is only constrained by its cost, because of the vast amount of roof space and arid land in western China on which to install photovoltaics. About two-thirds of all power output by 2050 is projected to come from solar and wind power. Geothermal power generation in China plays a very small role in all scenarios in China, since this resource is limited to select regions such as Szechuan Province. The High Renewables scenario does not incorporate much biomass, because of China's prohibition on using agricultural lands for biofuel production. Entri did not analyze the risks or benefits of relaxing this prohibition.

Hydro

To replace the generation that either coal, gas, or nuclear could provide, the High Renewables scenario assumes hydropower expansion that uses all of the economically viable resources. However, if hydropower expansion does not occur in China in an environmentally and socially friendly manner, freshwater ecosystems affected by projects could collapse, and livelihoods of people depending on them could be negatively affected. Because dams can have such a major impact on the long-term sustainability of people and species, significant environmental and social safeguards and assessment tools (such as the Hydropower Sustainability Assessment Protocol[vi] and the Rapid Basinwide Hydropower Sustainability Assessment Tool[vii]) must be prerequisites before hydropower projects are constructed. Siting decisions must consider the effects of the dam itself; the affected areas upstream and downstream of the dam; and any potential and realized cumulative impacts of multiple dams. With the application of best practice standards, China can ensure that only the right dams are built for the right reasons, in the right places.

Coal

The most striking feature of the High Renewables scenario is that coal is completely phased out by 2040. To reach this objective, the China 8760 Grid Model assumes that new coal plants are not built after 2020 and that by 2040 coal power generation is banned. Considering the significant negative consequences of coal combustion and the benefits of switching to renewables, phasing out coal is China's best option for ushering in a truly sustainable economy and ensuring the health of its citizens and the planet.

[vi] See http://www.hydrosustainability.org for more information.

[vii] See http://awsassets.panda.org/downloads/rsat_summary_2013_edition_may_.pdf for more information.

Gas

The High Renewables scenario assumes that the Chinese government's targets for gas expansion are not fully met and that gas remains relatively expensive for some time before seeing significant growth in China. This scenario limits gas to 17 percent of China's electricity mix by 2050, used only to satisfy power demand during peaking episodes. If China sourced all of its gas domestically in this scenario, the country would need to rely on unconventional gas (i.e., shale gas and/or coal bed methane).

Admittedly, including gas in this scenario should raise some concern. While gas emits fewer carbon emissions than coal at the point of combustion, uncertainty about fugitive methane emissions, associated particularly with extraction and shipping of gas to point-of-use, raises valid questions about the climate benefits of gas, particularly in the short run. Concern about fugitive emissions has increased given that the UN Intergovernmental Panel on Climate Change recently revised the potency level of methane showing that it is 34 times higher than CO_2 (on a 100-year time scale).[viii] If fugitive emissions are not sufficiently controlled, the climate benefits would be cancelled out, making gas as environmentally detrimental for the climate as coal, or even more so.

Nuclear

The High Renewables scenario avoids any new build of nuclear, in contrast to the official government targets.[ix] While the speedily growing demand for electric power will tempt China to evaluate expanding nuclear, it should not be part of a long-term sustainable energy system. This is because of its inherent risks, the legacy of highly toxic waste, overall economic costs, and system inflexibility to adjust smoothly with a growing amount of variable renewable power in the context of "smart" grid solutions and high energy efficiency. The High Renewables scenario shows that China need not put itself at risk from nuclear power to achieve a much lower carbon future.

Policy Recommendations

Entri makes the following recommendations for China's leaders to accelerate the pace of change to sufficiently address climate change and local pollution problems in China.

#1 Double down on energy efficiency.

- Issue timely and technology-forcing industrial process standards
- Mandate China's grid companies to achieve high levels of energy efficiency at a consumer level
- Gather lessons learned from the Olympic Peninsula Project
- Clarify the rules for grid companies to recoup demand-side management (DSM) costs

[viii] On a 20-year time scale methane is 86 times worse. See Intergovernmental Panel on Climate Change (2013) at http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf.

[ix] In the 12th Five-Year Plan on Energy Development (40 GW of installed capacity by 2015), the Air Pollution Control Action Plan (50 GW by 2017), and the recently revised mid- and long-term Nuclear Power Development Plan (70 to 80 GW by 2020).

#2 Prioritize low-carbon electricity supply investments.

- Adopt policy that would substantially cut coal power generation, such as a carbon emissions performance standard
- Encourage use of responsibly sourced gas over coal
- Make the grid system flexible and renewable-ready
- Revise current renewables support schemes for effective renewable power delivery

#3 Allow prices to reflect the cost of service.

- Consider a demand charge for commercial and residential consumers
- Redesign power quality demonstration projects

#4 Collect, publish, and analyze the data that matter.

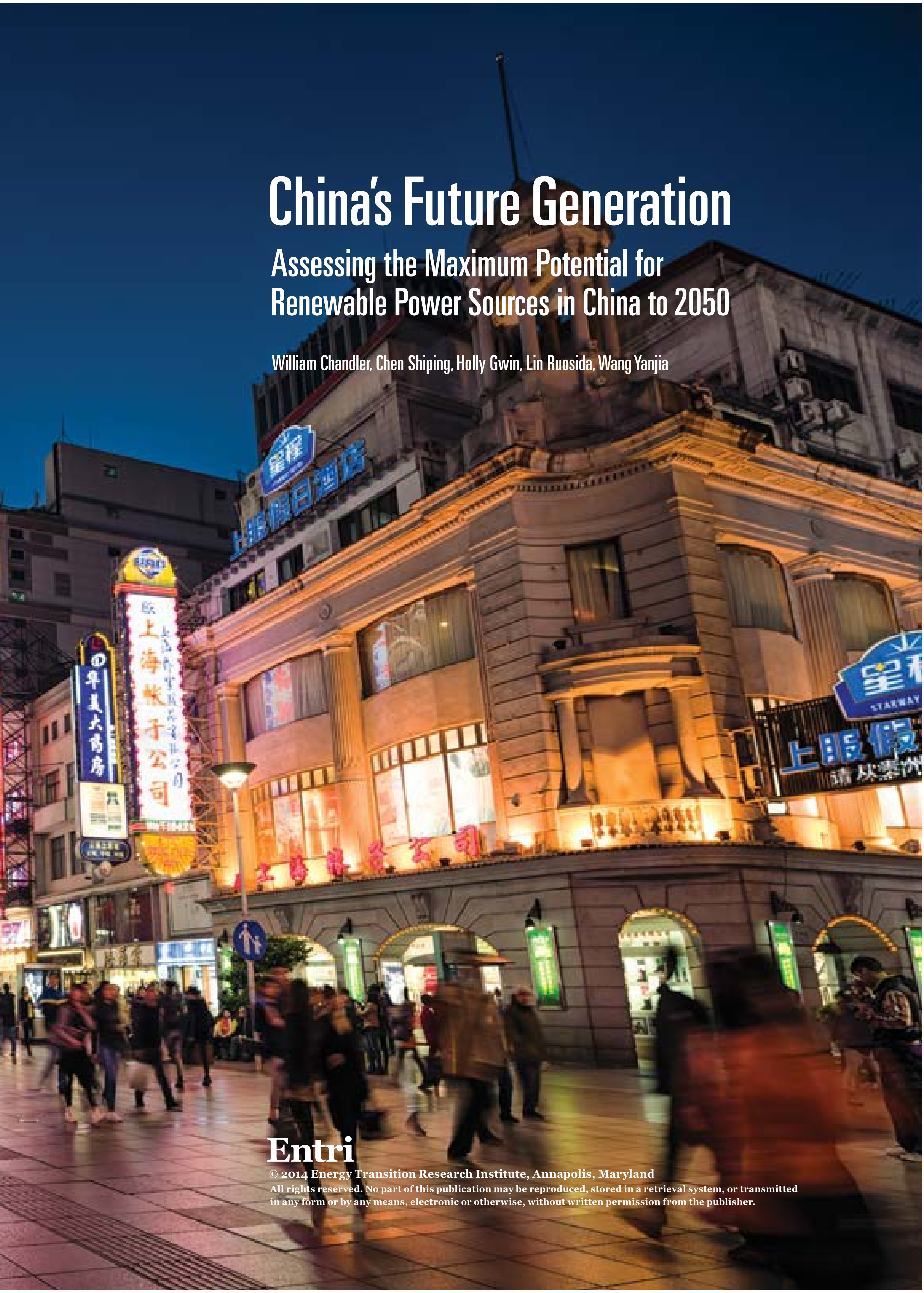
- Improve institutional capacity to operate renewables installations and monitor their performance
- Collect and share appropriate environmental impact data of renewables projects
- Measure success by electricity delivered (kWh), not installed capacity (kW)

Conclusion: Toward 100 Percent Renewable Electricity in China

The Chinese government has been instrumental in having the country embrace renewable energy and become a top global manufacturer of solar and wind energy. Its measures have also helped decrease energy intensity and prioritize the health of China's citizens. But current government policies will not enable the energy transition China urgently needs. In some cases, renewable energy, air pollution, and climate change policies fall short of necessary levels of ambition or have other design flaws that solve one problem while making another worse.[x]

As the detailed analysis in this report shows, a new industrial resource-efficient economy powered by renewable energy in China is not a fantasy, but an opportunity that is within reach. Seizing this opportunity could not come too soon. China is the world's largest current emitter of the greenhouse gases that are driving the climate crisis. WWF believes that China, with a wealth of highly educated engineers and other skilled professionals, has an unprecedented opportunity to solve the current environmental public health emergency in China, set the world on a path to a safer climate future, and lead the world in the coming decades toward a much more sustainable economy. With the 2015 deadline for a global climate agreement quickly approaching, new domestic action in China, such as a cap on coal use, is desperately needed. This report shows that such action is feasible and in China's economic interests.

[x] For example, while the Air Pollution Control Action Plan (released in September 2013) would restrict coal plant development in most eastern regions of China, new plants would be allowed in western and northern China. The water-intensive coal plants will further strain already scarce water resources.



China's Future Generation

Assessing the Maximum Potential for Renewable Power Sources in China to 2050

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Entri

The purpose of this study is to assess the maximum potential for renewable electric power sources in China.[1] We used the China 8760 Grid Model[2] to assess the potential for low-carbon power resources, particularly renewable resources, to satisfy China's electric power demand in the year 2050. We found that adoption and enforcement of strong energy-saving policies and regulations and aggressive deployment of energy efficiency and demand-side management technologies could enable China to satisfy much of its electricity demand with renewable power sources. Investment in a very efficient system makes a number of low-carbon power scenarios cost-effective. We conclude that China could build an electric power system that in 2050 uses renewable resources to supply around 80 percent of power demand at a reasonable cost and with confidence that generating capacity and demand could probably be balanced despite the dominance of variable resources.[3]

This result can be placed in perspective by comparing it with countries such as Denmark, Ireland, Portugal, and Spain, which rely on wind power for 15–30 percent of annual power generation today.[4] Projections about the potential for renewables to supply electric power demand in the future, such as the National Renewable Energy Laboratory's *Exploration of High-Penetration Renewable Electricity Futures*, also provide useful context for understanding the challenges presented by rapid and radical change in large electric power systems.[5]

In our assessment of China's power system, grid reliability (the need to avoid excessive interruptions of power supply) constrained the potential of renewable power sources more than cost or resource availability. (For detail on how Entri combined weather data, probabilistic analysis, and assumptions about future technology characteristics and performance, see Appendix IV.) Given this constraint, we also examined ways to achieve lower carbon dioxide emissions (a principal benefit of a high-penetration-renewables system) with less disruption of the status quo in terms of grid operations and reliability. This report presents modeling results primarily in terms of economic costs and carbon emissions reductions. The data that would inform a comparison of the full range of environmental costs and benefits of high-penetration-renewables systems and other low-carbon systems are not available. This is an important issue for data collection and for future analysis.

This report summarizes our methodology, including our key assumptions about how China's economy will grow over the coming decades and how the model accommodates problems of data availability. It describes the economic costs of implementing three technology scenarios, the impact those scenarios would have on carbon emissions, and the environmental problems that could arise as coal is replaced as the primary source of electric power. Finally, it makes some recommendations for policies that would promote a low-carbon future, including policies specific to renewable resources.

Introduction to the Model

The China 8760 Grid Model is a combined econometric and engineering model. Entri developed the model to evaluate power demand and supply for each of the 8,760 hours in a year. The model facilitates assessment of the cost, carbon emissions, land use impacts, and transmission line requirements associated with meeting electricity demand, including the system requirements attributable to the daily and seasonal variability of renewable power supplies. The model incorporates observed trends in human behavior (such as response to price increases), anticipated cost reductions in proven[6] technologies, and known limits on resource availability. Users can generate different scenarios of future electricity supply and demand by changing assumptions (for example, the projected price of various technologies) or by imposing constraints (for example, requiring the addition of a certain type of power generation source).[7]

The model relies on assumptions informed by historical trends in power demand growth in growing economies as well as observations of China's power demand growth over the past decades. Demand for electric power typically responds to changes in income, economic structure, and power price, and we have based our projections of demand on these fundamental relationships. We believe it is possible for China to overcome historical trends, and we include detailed end-use assessments of energy efficiency potential. However, the political will required for such an achievement will be precedent setting. Over the last 10 years, China's electricity demand grew at a rate approximately 15 percent faster than GDP. If that trend continues over the next 40 years as Chinese living standards converge toward those in Europe and North America, demand for power and the costs and pollution associated with its generation could increase five-fold or more. (See Figure 1, page 22)

The model is adapted to the challenges of balancing resources with demand on an electric system dependent on variable power sources. It estimates the daily and seasonal rising and falling of both power (kilowatts) and energy (kilowatt-hour) demand. It uses weather data and probabilistic simulation methods to test the sufficiency of combinations of sun, wind, and water to match supply and demand over every hour of every day for the next 40 years and to identify complementary backup technologies.[8]

China Today

The model starts with the year 2011 and uses actual data for years 2011–2012 where they are available. We used standard references for certain types of assumptions such as demographic data, exchange rates, and discount rates. More information on these details and how the model works is available from Entri in "The China 8760 Grid Model: Methodology and Overview" in Appendix IV (also see Appendices I–III and Box 1, page 26).[9]

China currently has 1,148 gigawatts (GW) of installed power generating capacity. Conventional sources include 837 GW of coal, 223 GW of hydropower, and 15 GW of nuclear power. Onshore wind, at 50 GW, is the largest unconventional source of installed capacity.

The price of electricity is regulated rather than determined by market forces. Chinese residential consumers pay remarkably low rates. Industrial customers, on the other hand, pay slightly more than counterparts in the United States. As is the case in most places in the world, the price system has not adopted marginal cost pricing of generation and demand response, and the costliest power generation is not priced anywhere near its actual cost. As is also the case in most of the world, China subsidizes fossil fuel use throughout its economy,[10] which undoubtedly distorts the price of electricity.

China's annual GDP per capita is US$8,000[11] and power use per capita is 3,100 kWh. Industry uses 75 percent of China's electricity and generates 47 percent of GDP. The services sector generates 45 percent of GDP, and the associated buildings sector is the most rapidly growing electricity consumer.

Electricity Scenario Development

Starting with this snapshot of China's current electric power system requirements, we used the China 8760 Grid Model to develop scenarios for future requirements. In this report, we present four scenarios:

- **Baseline**: This scenario projects a future in which China implements no specific clean energy or efficiency policies other than the ones currently on the books and effects no radical economic changes.
- **High Efficiency**: This scenario projects a future in which China successfully implements very aggressive energy efficiency requirements and makes a substantial shift away from energy-intensive manufacturing as the basis for economic growth. Relatively low electricity demand, achievable only through the full-blown commitment to efficiency, is the sine qua non for an affordable, low-carbon electric power system, and the demand projections in this scenario become the baseline for the next two scenarios.
- **High Renewables**: This scenario builds on High Efficiency demand projections and requires the model to satisfy demand with renewable power sources if they are available.
- **Low Carbon Mix**: This scenario builds on High Efficiency demand projections and requires the model to satisfy demand with low-carbon sources—renewable, natural gas, and nuclear.

The assumptions we made about China's economy and about demand and supply technologies in each scenario are discussed below.

Economic Assumptions

The pace and course of China's economic development will affect future electricity demand. As China transforms its economy from one that generates income from materials and energy-intensive industrial production to one that generates income from services, this structural change will also transform patterns of electricity use. Since 2005, China's economic planners have set a target of increasing the share of the economy generated by services by four percent every five years, but the actual rate of change has been about half that amount.[12]

Structural change will increase the electricity efficiency of the economy. It will do so by increasing the share of higher value-added and lower energy-intensity services. Also, higher value-added and lower intensity manufacturing will increase in share of output compared to the heavy materials industries.

On the other hand, structural change will likely lead to higher long-term economic growth and will offset some of the emissions reduction benefits of restructuring. In addition, an increase in services as a share of the economy will affect the electric grid, because the service sector tends—like the residential sector—to have higher peak and lower off-peak demand for power.

Table 1 shows two sets of GDP assumptions used in the creation of our scenarios. For our Baseline scenario (discussed in more detail below), we assumed that services would contribute less than 30 percent of new GDP growth and so we incorporated the low service/lower growth GDP figures. For our High Efficiency, High Renewables, and Low-Carbon Mix scenarios (discussed in more detail below), we increased the growth of services to 50 percent of new GDP growth and incorporated the high service/high growth GDP figures.[13] Other key assumptions in these projections are presented along with year 2011 actuals in Tables 2 and 3.

TABLE 1 Annual Economic Growth Rate

GDP Assumptions in the China 8760 Grid Model	2010–2015	2015–2020	2020–2030	2030–2040	2040–2050
Baseline scenario *(Low Service, Lower Growth)*	7%	7%	4%	3%	2%
High Efficiency, High Renewables, and Low-Carbon Mix scenarios *(High Service, Higher Growth)*	7%	6%	4%	4%	3%

Note: The share of services in the economy in 2050 would increase from just under 45 percent of GDP in 2012 to just under 60 percent in the Baseline scenario and just under 75 percent in the other technology scenarios in 2050.

Source: Entri

TABLE 2 Key Assumptions for High Efficiency, High Renewables, and Low-Carbon Mix Scenarios

	2011	2050
Population[14] (Million)	1,347	1,300
Urbanization Level[15]	50%	79%
GDP per Capita (Constant 2013 US$[16])	5,725	28,040
Contribution by the Service Sector	43%	75%
GDP Elasticity of Electric Power Demand[17]	1.23	1.23
Price Elasticity of Electric Power Demand[18]	-0.21	-0.21

Source: Entri

Demand Technologies

Our Baseline scenario projects future electricity demand in the absence of any strong new measures to cut power use or to reduce carbon emissions. The scenario incorporates energy intensity and resource portfolio targets established out to the year 2020, but assumes that least-cost supply measures otherwise dominate electric futures. This scenario projects power demand will increase from about 4,000 kWh per capita per year today to more than 17,000 kWh per capita by 2050. Similarly, carbon dioxide emissions from power generation would increase from about 3 billion tons per year to 14 billion tons or more by 2050.[19]

TABLE 3 Key Elements of Each Scenario

Scenario	Reforms Economy	Mandates Efficiency	Mandates Renewables	Expands Nuclear	Regulates Carbon
Baseline	✖	✖	✖	✖	✖
High Efficiency	✔	✔	✖	✖	✖
High Renewables	✔	✔	✔	✖	✔
Low-Carbon Mix	✔	✔	✔	✔	✔

That type of electricity demand growth would be difficult to satisfy with low-carbon energy sources and pose a continuing threat to the health of China's population and of the global atmosphere. Therefore, we adjusted the assumptions used to project demand in our High Efficiency scenario. We assumed the higher rate of structural change (discussed above); and most importantly, we incorporated state-of-the-art efficiency technologies for air conditioning, lighting, and water heating in households, in air conditioning and lighting in the services sector, across the board in industry, and in energy conversion in the power generation sector. We also incorporated price feedbacks on power consumption as future demand and resource constraints drive up the cost of power supply. The question of whether China can generate most of its power from renewable energy in the year 2050 depends more than anything else on the answer to the question of how successful policy can be in driving the uptake of these technologies. If efficiency is not fully deployed, renewable supplies cannot keep up with demand (based on current projections of economically recoverable resources).[20] Even with the above assumptions on income elasticity of demand, we project per capita electricity demand to be about 9,000 kWh per year in 2050 in our High Efficiency scenario.

Figures 1 and 2 compare our projections for China with levels of economic growth and energy consumption in other countries today.

The High Efficiency scenario is the most important technology scenario presented in this study. Unless demand is capped at the level made possible by aggressive efficiency measures, coal will remain an inevitable part of the electricity future. Our recommendations stress the need to focus policy measures on demand reduction to achieve a high-renewables or other low-carbon future.

FIGURE 1 Chinese Electricity Use Per Capita

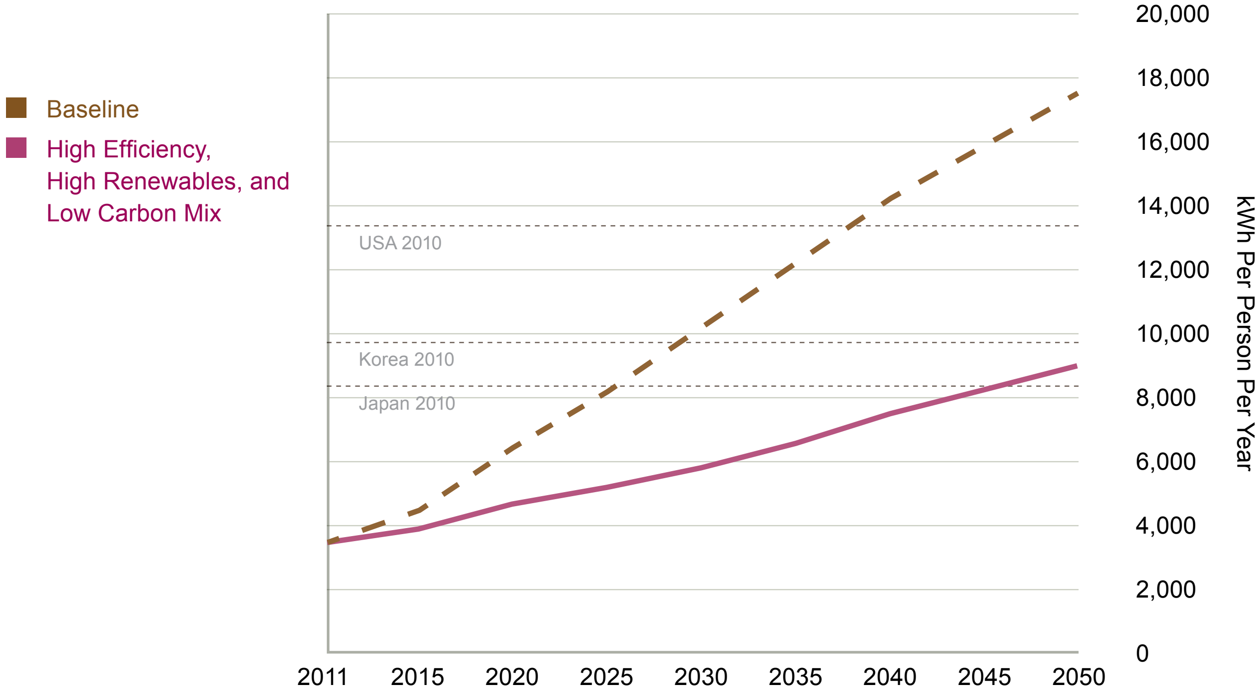
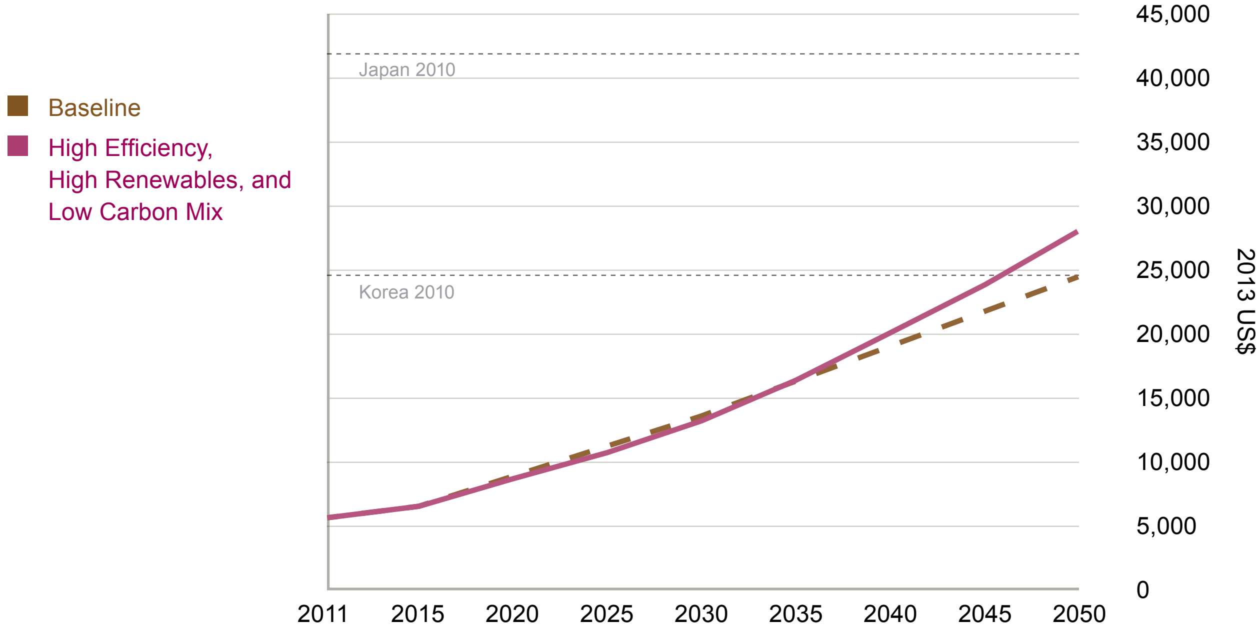


FIGURE 2 Chinese GDP Per Capita



Supply Technologies

The China 8760 Grid Model includes data on fossil (coal, oil, natural gas) and non-fossil (nuclear, wind, solar, hydro, geothermal, biomass) power generation sources. Model users can direct the process-oriented sub-model to select generation sources in three ways: command and control (portfolio standards); competitive choice based on least cost; or a combination of pricing and carbon emissions controls that, for example, encourage non-coal energy use.

The model uses discounted levelized cost analysis to estimate the economic cost of using all power systems included in the model. The discount rate, which is the opportunity cost of money, applied in this study is 10 percent real, meaning inflation plus 10 percent "interest."[21] Data on resource availability caps some of the renewable technologies, and siting issues limit the amount of nuclear uptake. This iteration of the model does not quantify environmental costs of various sources, but we describe some of those considerations below.

Coal. China today relies on coal for three-quarters of its power, and coal-fired power has a major impact on human health.[22] 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 350,000 per year by 2050 in our Baseline scenario.[23] Throughout the timeframe of the model, coal remains available and affordable, and it figures prominently in the supply projections in our Baseline and High Efficiency scenarios. New coal-fired generation can be curtailed by model users through special instructions, which we adopted in the High Renewables and the Low-Carbon Mix scenarios (discussed below).

Natural gas. We assume natural gas remains underdeveloped for a time and costs about US$10 per gigajoule (US$260 per 1,000 cubic meters) in China. Because it is expensive, the model selects gas for new generating capacity only if the model user employs special instructions. Some experts suggest that China may have the world's largest supply of unconventional gas, particularly coal bed methane. If Chinese gas prices were to fall to only US$5 per gigajoule (US$130 per 1,000 cubic meters), natural gas would be a cheaper source of power supply than every other option we modeled, including coal. Gas use could thus unexpectedly alter the economics of Chinese power production.[24] If China develops domestic gas supplies, it will need strengthened environmental controls to avoid problems with fugitive emissions, groundwater contamination, and competing demands for the land necessary for drilling and infrastructure development. Without them, these social and environmental costs could outweigh the economic benefits of switching to gas, and would raise questions about the role of gas in a low-carbon future.

Nuclear. Nuclear power today generates about 2 percent of Chinese electric power. The primary restraint on the uptake of nuclear power in our model is site availability, although public opinion in China on nuclear power has deteriorated considerably since the Fukushima accident in Japan. We limit the total amount of nuclear power in 2050 to 400 GW based on Chinese experts' estimates[25] of the availability of sites in the developed and highly populated north and east of the country (the Baseline and High Efficiency scenarios use only one-quarter that amount and the High Renewables scenario does not use any nuclear power). Capital cost estimates are also at issue. Estimates for nuclear power in China approach only about US$1,600 per kW, far less than the US$7,000 estimated for the Vogtle nuclear plants recently approved for construction in the southern United States. We use an intermediate estimate of US$4,000 per kW for the scenario presented in this assessment.[26] We do not allow additions of nuclear power after 2013 in our High Renewables Scenario, but incorporate the full 400 GW of nuclear power in our Mixed Low-Carbon Scenario.

Renewables. The model includes hydropower, wind, and solar technologies. It also includes biomass and geothermal generation, but only in the small amounts currently employed and anticipated. In 2011, the Chinese power grid had installed capacity of 3 GW of solar, 48 GW of wind, 215 GW of hydro, and 2 GW of biomass and geothermal combined. Published resource surveys indicate that onshore wind, offshore wind, and hydropower could supply up to 2,500 GW, 200 GW, and 400 GW of capacity respectively, and additions to capacity in the model are constrained by these limits, with the exception that we limit on-shore wind to 1,500 GW, based on the recommendations of Chinese renewable energy experts.[27] In our scenarios, we do not constrain solar PV capacity in our model, because the amount of market penetration is well below the space available on rooftops, canopies over paved lots, and western deserts. Note that we do not incorporate electric power imports, which might include hydropower from southeastern Asia and wind and coal power from Mongolia.

As a starting point, we use capacity factors that reflect expectations for improvements in technology: 40 percent for hydropower, 20 increasing to 29 percent for wind, and 15 increasing to 20 percent for solar. These compare to capacity factors of 60 and 90 percent, respectively, for coal and nuclear. However, capacity factors for wind, hydro, and solar vary in the model by quality and quantity of the resource exploited, season, and for solar by time of day. We used published sources of meteorological data for typical wind speeds and rainfall over the period of a year. Hydropower availability was estimated on a monthly basis, but dispatch within each month is permitted on an as-needed basis. Wind availability was estimated based on standard Weibull probability distribution methods as a function of wind resource quality. To deal with the variable nature of wind, we applied a random number generator to vary wind speed (as a function of the measured probability distribution) to simulate resource availability on an hourly basis.

While the term “renewable energy” most often conjures images of wind power, renewable electricity in most countries, including China, is dominated by large-scale hydroelectric dams. The Chinese power grid has been adding 20,000 megawatts of wind generating capacity each year, but today China has seven times more hydro capacity than wind capacity. Even by 2020, the actual power generated by water is expected to exceed the actual power generated by wind by at least a factor of five.

We want to caution that renewable does not always mean environmentally benign. Heavy reliance on large-scale hydropower will completely transform river ecosystems if the Three Gorges Dam is any indicator of China’s approach. The land use impacts of wind and solar power are considerable, although experts disagree on how to value those impacts. We note that for wind power, vast amounts of relatively undeveloped land could be used, and this disturbance could result in a substantial decline in wildlife habitat.

BOX 1 Why Not 100 Percent Renewables?

Our goal in modeling the 2050 China electric power grid for this study was to estimate the maximum share of renewable power generation feasible. We set rules for our supply and demand modeling that included the following requirements:

1. Technologies had to be "proven" (see footnote 6);
2. Power supply and demand had to balance on an hour-by-hour basis without shortages of more than 10 percent of current Chinese demand load, or 100 GW for more than 100 hours per year; and
3. Supply options had to pass standard probability tests for availability.

For example, wind generation by hour was modeled based on actual wind speed data using wind resources in enough regions to meet demand. This involved plotting availability using a "Weibull distribution," with the hour-by-hour occurrence of that distribution based on the wind speed, its variation, and a randomized process to avoid bias in the hour-by-hour generation values.

Readers may wonder whether we made assumptions regarding renewable resources that were too pessimistic or conservative. We have tried to make the rationale for the assumptions transparent. For example, the availability of wind generation (the capacity factor) is lower in our study than one finds using the best new turbines on the tallest towers in the best wind sites. Since our renewables scenario uses all of the estimated wind resource, not just the best wind sites, we adjusted the capacity factor accordingly. Onshore wind alone would total 1,400 GW of generation, and that is more than 20 percent more capacity than the entire electric power generating capacity in existence in China today. The capacity factor assumption pushes the model toward a higher amount of total installed capacity, but does not serve as a constraint on utilization of wind.

We also pushed the envelope of proven technology by utilizing 175 GW of offshore wind. Similarly, we used all of the hydroelectric power generating capacity estimated to be feasible in China, regardless of environmental consequences of doing so. The model does not incorporate much biomass because of China's prohibition on use of agricultural lands for production of biofuels. We did not analyze the risks or benefits of relaxing that prohibition.

Inexpensive, clean power storage systems did not meet our threshold for proven technology. Breakthroughs in those systems by 2030 would fundamentally change electric power planning. We did not assume that a solution would exist for very large-scale deployment, although we did assume 100 GW of storage, far in excess of the amount of pumped-hydro storage sites available in China.

Meeting China's future electric power demand, while even using the large amounts of conservation we assume, is an enormous challenge. That is just the reality of the power planning in China today. Meeting that challenge with an environmentally acceptable outcome, regardless of whether the generating sources are renewable or not, will require far greater attention to the science and values of environmental protection for each and every technology deployed in China's electric power future.

Details about the scenarios given in this report are presented in Appendices I and II. A summary of Entri's methodology is presented in Appendix IV and the full methodology report is available on its website, www.etransition.org. Please contact Entri for information about how to use the China 8760 Grid Model.

Transmission and Storage

We assume for this report that China's transmission and distribution companies make a successful shift from a business model that bases compensation on sales of power to a business model that bases compensation on the most cost-effective delivery of energy services. The model incorporates many of the smart grid technologies that will enable China's transmission and distribution companies to control and aggregate reductions in demand to accommodate fluctuations in power availability. These technologies enable utilities to respond to peak demand or power shortages by, for example, switching off water heaters or limiting how long air conditioners run. The model also incorporates tools such as pricing strategies and contractual arrangements that allow the transmission companies to plan for and respond to variability in power supply. These tools encourage consumers to make behavioral shifts that allow the power system to adapt to supply variability—for example, for homeowners to do laundry at a time of day when electricity is cheaper or for large industrial users to trade planned supply interruptions for lower prices. This shift to a business model that utilizes "dispatchable load"[28] as well as dispatchable generation is not a foregone conclusion, and will require a policy push such as those described in our recommendations.

The model also allows power capacity and generation by each supply option to drive transmission construction and costs. Those costs are based on a formula that relates location of supply options and regional demand and estimates the distances and therefore the capital cost of the indicated transmission line requirements. The remote siting of renewables technologies, particularly the very long distances between the remaining large hydroelectric opportunities in southwest China and demand centers, require massive investment in high-voltage transmission to population centers in the north and east of China.

If the maximum feasible Chinese wind resource of 2,500 GW were exploited, the 1 to 2 million 24-story towers would occupy an area equal to the size of Sichuan Province or half the territory of Inner Mongolia.[29] Therefore, we limit wind power development to a more practicable 1,500 GW based on the advice of Chinese wind power experts. Even so, the territory required for 500,000 to 1 million towers would total as much as one-third of Inner Mongolia. The actual impact of the machines will depend importantly on siting, but unfortunately the more environmentally sensitive areas of a wind-rich province like Inner Mongolia coincide with the best wind resource.[30] It is possible that some economic efficiency could be sacrificed to locate the turbines on bare desert, but we did not make that choice in our model. The model does not currently assign costs to the land occupied by wind farms, solar power sites, or transmission lines. (Model assumptions are provided in Appendix I. Modeling results for capacity, generation, emissions, and land use are provided in Appendix II. The methodology applied is outlined in Appendix IV.)

Storage technology is incorporated to balance supply and demand by storing the power generated off-peak and supplying the power back to the grid during high-demand periods. Storage costs include capital, round-trip efficiency losses, and operating and maintenance. Pumped hydropower, battery, and compressed air storage were all included, but were constrained to total only 100 GW. The decision to limit storage to that amount was a judgment about the commercial availability of technologies other than pumped hydropower. Even the relatively small amount permitted is almost as large as the total global storage capacity extant today, virtually all of which is pumped hydropower. We note that pumped hydro storage construction sites are limited well below such large amounts in China.

Assessing the impact of large-scale electrification of China's automobiles was beyond the scope of this study. We do not anticipate difficulty in meeting the additional power demand due to the official Chinese government target of having 2 million fully electric vehicles on the road by 2020.[31] However, even at the rate of improvement projected in our model runs, the Chinese grid of 2020 might not be equipped with the sophisticated communications and control (smart grid) technologies that can assign electric cars to surplus renewable power generation. Also, non-tailpipe carbon emissions attributable to such cars operated in a power market still dominated by coal could be substantial. As for the storage potential for cars, we believe that automobile batteries would have to compete with grid-scale storage and that the total costs would be comparable.[32]

Hourly load is based on historical load curves compiled from national data provided by the former State Electricity Regulatory Commission and a number of provincial and regional load studies published in academic journals.[33] Peak load is defined as the maximum demand for electric power during the peak days of the peak months each year, typically in late summer. The assumptions in the model are based on national system averages. The peak load-to-valley ratio is peak demand divided by annual average demand as measured in watts. Note that the valley is not the minimum load on the system, but is defined as annual average demand. Note also that the model—reflecting longstanding regulatory policy—requires that installed capacity exceed the maximum annual peak load demand by a factor of 1.2.[34]

The model does not simulate potential exacerbation of the difference between peak and average load as a result of increasing shares of demand coming from the buildings sectors—where demand has daily peaks and valleys that are also affected by seasons—rather from the industrial sector—where demand is steadier. We did not find data sufficient to model this trend. We assumed (we did not test) the Chinese grid's ability to manage power quality under a high-renewables scenario (voltage-amperage reactivity). Technical demonstrations of power quality management with renewables providing more than 30 percent of total demand are too few and modest in scope to allow evaluation at the present time. As China's grid companies experiment with the application of technologies for managing and stabilizing load, these issues will become more amenable to modeling.

Modeling Results

We tested several supply scenarios to examine how various technologies, alone or in combination, could influence the costs and/or reduce the carbon emissions of China's electricity supply system in 2050. We selected two scenarios that are similar in cost to our High Efficiency scenario and go much further in reducing carbon emissions to present here: the High Renewables and Low-Carbon Mix scenarios.

FIGURE 3 Total Cost of the Electric Power System 2011–2050

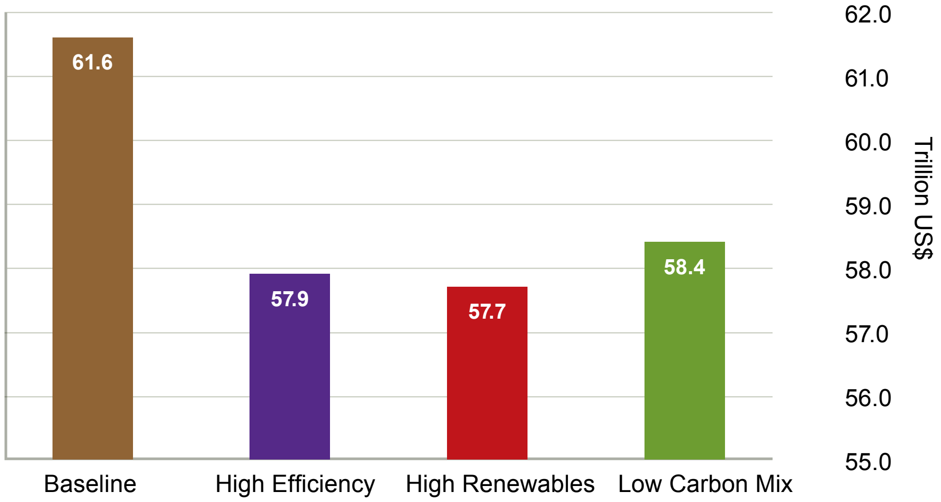
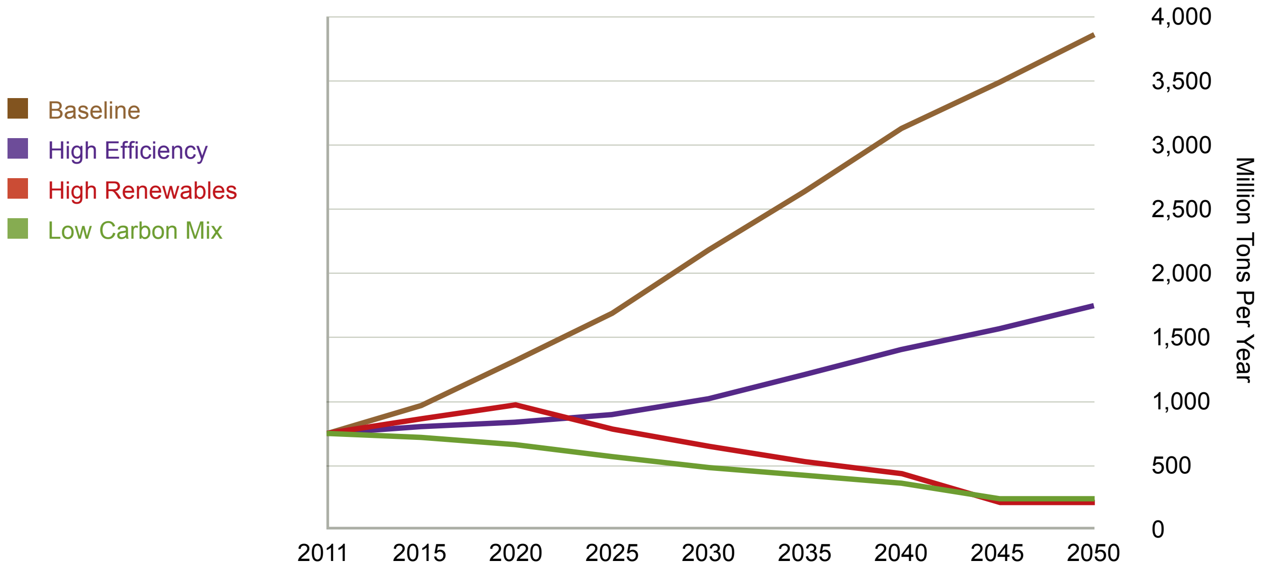


Figure 3 shows total costs of the electric power system for the High Efficiency, Maximum Renewables, and Low-Carbon Mix scenarios.

Figure 4 shows total carbon emissions for each scenario. Note that the "bump" in emissions for 2020 in the renewables case (in comparison with the High Efficiency Scenario case) is due to less use of nuclear power and gas in those scenarios.[35] The High Efficiency scenario assumes the government's existing targets through 2020 for nuclear and gas (as well as for renewables) are met, while the High Renewables and Low-Carbon Mix scenarios assume that the

FIGURE 4 Carbon Emissions



nuclear and gas targets are not necessarily met. Note below that the High Efficiency scenario after 2020 (when the current mandates expire) follows a least cost approach, meaning that more coal is used to meet new demand from 2020 onward.

Note that the costs are similar in all three main scenarios presented here despite the large differences in carbon emissions. There are two main reasons for those results. First, the cost of photovoltaic (PV) and wind systems are assumed to drop dramatically until about 2035 and then to level out after they have become cheaper than conventional sources. Second, although the Low-Carbon Mix scenario uses costs that are higher than in the High Renewables scenario, the higher capacity factors of gas and nuclear greatly reduce the amount of installed capacity required, and therefore offset the higher capital costs. That is, the PV and wind systems become lower cost options on a per kW basis but more kW are required to increase the probability that these variable resources can meet demand.

Please note that carbon emissions in 2050 in our Baseline scenario are more than double the carbon emissions in the High Efficiency scenario and recall that the High Renewables and Low-Carbon Mix scenarios fully incorporate efficiency technologies. Our main conclusion, based on these results, is that by far the most important thing the Chinese government can do to create a sustainable power future is to reduce electric power demand growth. Unless China cuts power growth to about half the rate of GDP growth, the nation has little chance of operating its electric grid with more than 50 percent renewable energy.[36]

High Renewables Scenario

We found that it would be possible to generate around 80 percent of electric power requirements in China from wind, hydropower, and solar resources in 2050, if the government requires it. Left to the market, it would not happen, but that does not mean that a renewable future would be exorbitantly expensive. The cost could be economically affordable, in fact, if expected cost reductions in the capital cost of renewable power sources come to pass (see Appendix I).

The generation mix in the High Renewables scenario is illustrated in Figure 5 (pages 32–33) alongside the Baseline, High Efficiency, and Low-Carbon Mix scenarios.

Seamless integration of renewables in a national electricity grid will be challenging. The amount of generated power available fluctuates from hour to hour and large swings in available capacity are hard to manage. Those swings remain difficult to manage even when wind, hydro, and solar are distributed widely throughout China's large land mass, thus creating a higher probability of availability. That is to be expected considering that it is difficult using PV (which is available mainly from 11 am to 4 pm) and wind (which has a weighted average capacity factor—even using the best wind resources in China—of only about 35 percent) to satisfy historic levels of daily change in power demand. In the High Renewables scenario, the model runs resulted in excessive power shortages (see Box 1, page 26) until we inserted some non-renewable supply to ensure the reliability of the system. This function could be supplied by coal, natural gas, or nuclear power. We used natural gas in the scenario presented here because gas generation plants can be operated on the schedule best matched to the variability in renewable supplies. Please see Appendix III for a scenario balanced with more coal.

We used two "policy like" instructions in the model to generate the High Renewables scenario. First, we required the model to select renewables for new additions to capacity if they were available (the model then picked the least-cost renewable technology). Then, we prohibited selection of coal for new additions to capacity after year 2020 and banned all use of coal (in the power sector) after year 2040.[37]

The prohibition on coal prematurely retires approximately 330 GW of coal-fired plants. They are shut down an average of 10 years early, at a prorated capital cost of about US$250/kW. The total lost value is about US$75 billion, or US$7.5 billion per year for 10 years. If this cost were reimbursed to generators and passed to consumers, it would increase electricity prices by an estimated US$0.001 per kWh over the 10-year period. (This cost is not included in our total cost estimates in Figure 3 (page 29) or elsewhere in the text.)

This carbon cap requires the grid to make an adjustment in generating capacity worth perhaps half a trillion dollars in a short period. Even more significant than the cost is the fact that power generating capacity that works two-thirds of the time predictably is replaced with capacity that—if it is "renewable"—works one-third of the time at best and is predictable only in time frames that are shorter than the time that may be needed to bring backup power sources online (i.e., one to four hours). To ensure relative stability in output, several times the nominal capacity of coal-fired or natural gas-fired capacity must be installed, and instability still remains in the system.

Low-Carbon Mix Scenario

The Low-Carbon Mix scenario adopts the High Renewables scenario policy regarding coal but reintroduces nuclear power to match the Chinese government's stated development goals (400 GW).

The Low-Carbon Mix scenario provides similar carbon emissions reductions at a similar price to the High Renewables scenario. Some Chinese policy makers consider nuclear as an alternative to hydro.[38]

FIGURE 5a Electricity Generation, Baseline Scenario

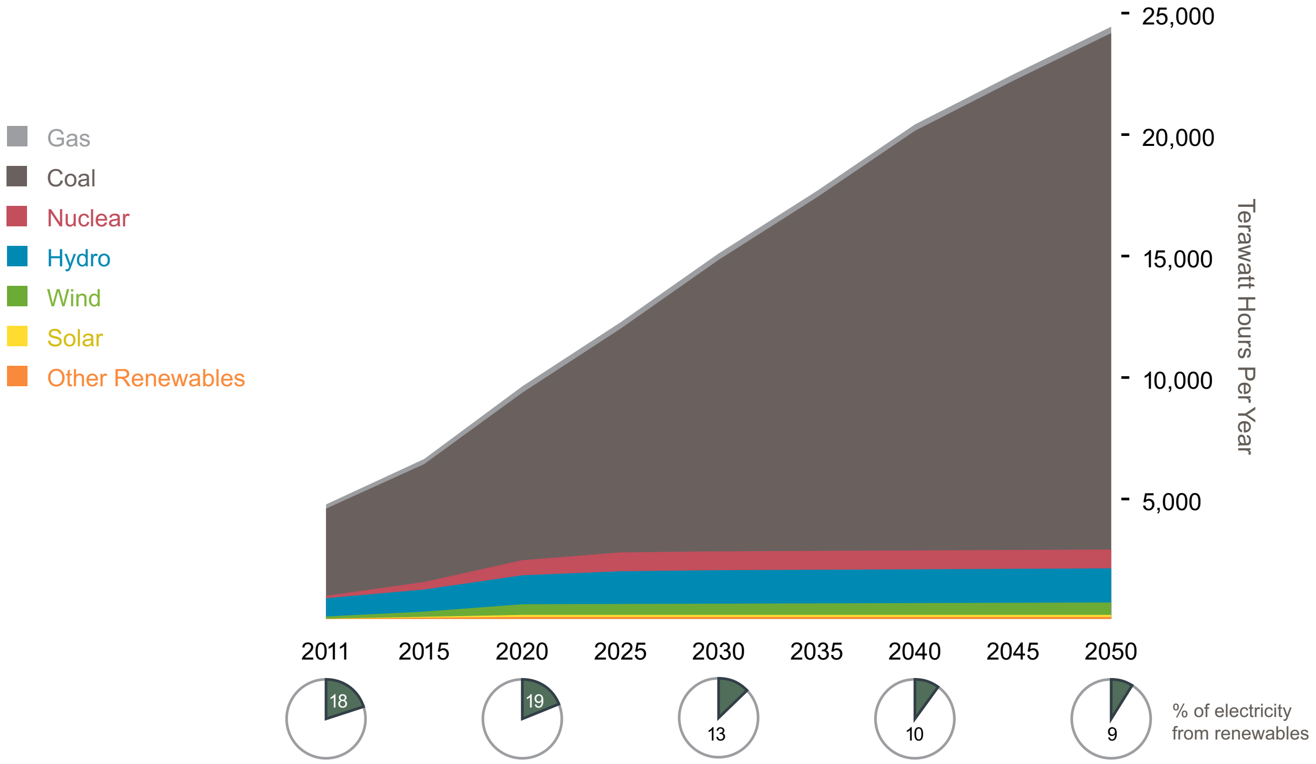


FIGURE 5b Electricity Generation, High Efficiency Scenario

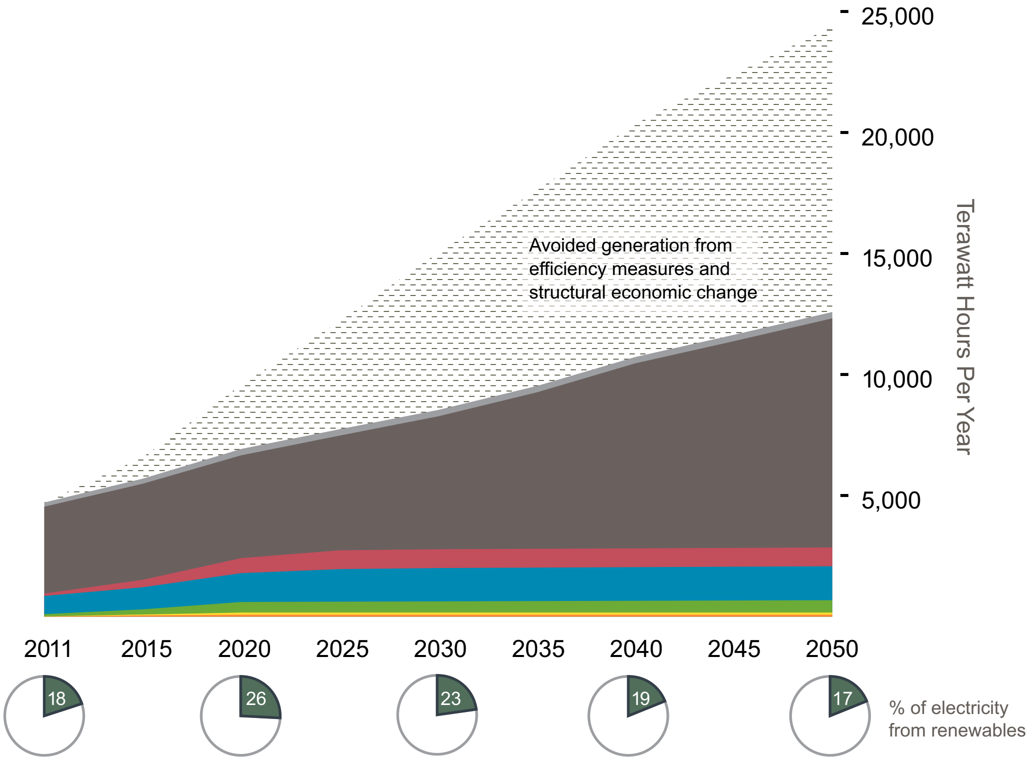


FIGURE 5c Electricity Generation, High Renewables Scenario

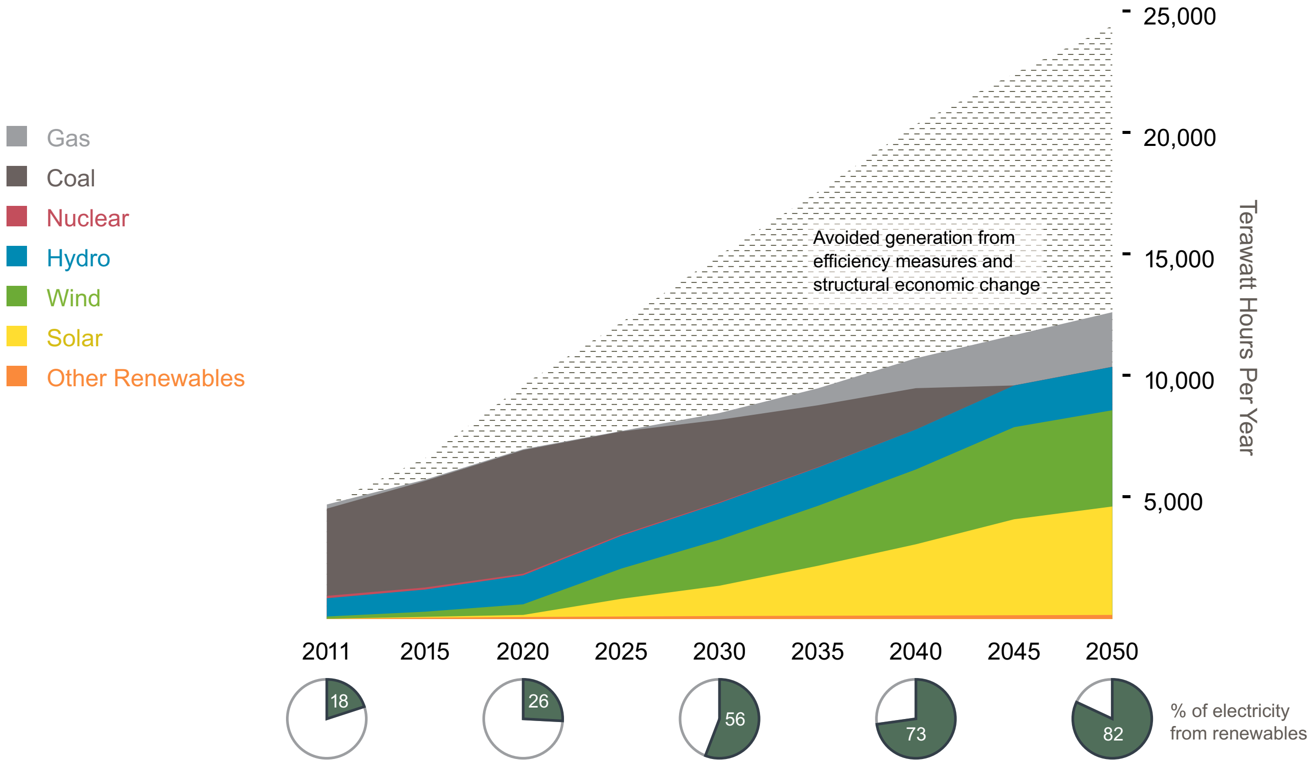
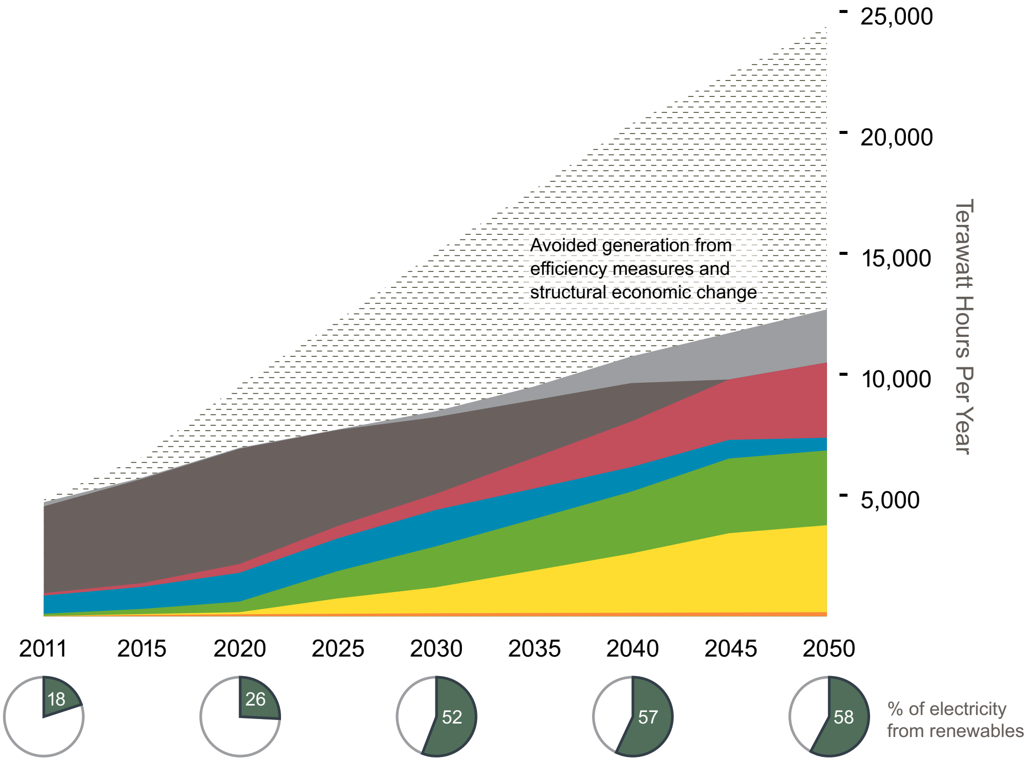


FIGURE 5d Electricity Generation, Low-Carbon Scenario



Shifting to Low-Carbon Electricity in China

The shift towards low-carbon electricity will not happen through business as usual or natural market forces alone. Barriers to this transition include:

- Incomplete separation of generation, transmission, and distribution functions, leading to monopolistic practices.
- Electricity prices that do not reflect the full costs of generating and delivering electricity.
- Lack of clear rules governing generation and transmission of electricity and inefficient administration and enforcement of the rules that currently exist.
- A collection of incentives for fuels and generation technologies that range from being internally inconsistent to being in conflict with stated goals for carbon emission reductions.

In some respects, the Chinese government has demonstrated serious intentions to move toward a low-carbon electricity future, including specific preferences for energy efficiency and renewable power sources. In other respects, the government has neglected problems that will likely undermine these intentions.

Signs of Good Intentions

The Chinese government has ambitious goals for promoting energy efficiency and reducing energy demand throughout its economy. The 12th Five-Year Plan (2011–2015) established an energy intensity target—a 16 percent reduction compared to 2010—and a goal of reducing carbon intensity by 17 percent over the same period. This high-level rhetoric applies to the electricity sector and has produced some specific implementation plans to slow the growth of demand for electricity.

For example, the State Council issued a detailed workplan defining energy efficiency targets for industries and for provinces.[39] The government also issued, in 2010, demand-side management (DSM) regulations that call for its electric grid companies to achieve specific energy savings targets and to facilitate energy efficiency investments in factories, businesses, and homes.[40] The regulations describe requirements for integrated resources planning; identify potential funding sources for energy efficiency investments; and encourage monitoring and verification of energy savings. This DSM framework could serve as a springboard for the more aggressive energy efficiency measures that will be needed to underpin a renewables future.

Several pilot programs for carbon emissions trading will run during the 12th Five-Year Plan to prepare for launch of a national program in 2015.[41] Depending on how the pilots are implemented, substantial investments in reducing electricity demand in industry, generally, and in reducing coal use by electricity generators could result.[42]

The Chinese government's rhetoric and regulations also promote renewable technologies for the electric power sector. The government aims for renewable energy to supply 15 percent of primary energy consumption by 2020, and has specific targets for growth in installed capacity of proven and developing renewable generation technologies.[43] The Renewable Energy Law[44] has stimulated several administrative measures to establish a stable market for the non-hydro renewable generators, including auctions, feed-in tariffs, mandatory purchase requirements, and, more recently, consideration of a mechanism similar to renewable portfolio standards. The Chinese government has also used investment subsidies and tax incentives to encourage development of domestic renewables technologies manufacturers and deployment of renewable electric generation technologies.[45]

In 2007, the Chinese government began to consider an "energy saving" dispatch rule that would help integrate renewable technologies in the electric grid.[46] This rule (written for trial implementation) would require the grid companies to use renewable resources first, whenever it is available to meet demand on the system, and only then take power from non-renewable sources. On one hand, this rule should encourage rapid penetration of efficient, renewable generation technologies. On the other hand, the financial implications of such a rule for generators invested in the traditional base-load plants have made it difficult to implement.[47]

Signs of Difficulties Ahead

Rapid economic growth, accompanied by rapid growth in energy consumption, created the need and the wherewithal for the Chinese government to show unusual foresight in developing its current plans for decreasing energy intensity and weaning itself from coal. Rapid growth also made it more difficult for Chinese leaders to govern from the center and highlighted characteristics of its electric system that undermine progress toward efficiency or low-carbon supplies.

The state-owned enterprises (SOEs) that control all transmission and distribution and most generation operate as unregulated corporate monopolies.[48] The leaders of the SOEs are appointed by the central government but conduct their business at the provincial and local levels. They increasingly form alliances with regional political leaders, who control much of the non-state-owned power sector, and, together, find ample reasons to resist the mandates of the central government. The central government has no independent regulatory agency to oversee the activities of the SOEs and guide them toward national rather than corporate goals.[49]

The National Development and Reform Commission (NDRC) exercises most of the central government's authority over China's electric system. NDRC formulates energy policy, approves new technologies, and sets technical and quality standards. Its Energy Bureau formulates power sector policy, conducts power sector planning, and approves all power sector investment. Its Price Department regulates electricity prices. NDRC recently assumed all of the powers of the short-lived State Electricity Regulatory Commission, which had the responsibility, though little authority, to approve market entry, set service obligations and standards, enforce laws, establish balancing areas, and regulate safety. This long list of responsibilities represents a small fraction of NDRC's overall economic planning duties. In the end, competing interests often overwhelm issues important for the power sector in an agency that generally implements decisions through consensus-based, rather than rule-based, processes.

We conclude that this organizational morass will impede China's progress toward a low-carbon future. It has dispensed with the one power sector reform universally endorsed by advocates of economic efficiency and environmental sustainability: an independent regulatory agency. A competitive power market is most likely to integrate new technology options. However, this competitive power market will not develop without clear rules and an expectation that those rules will be fairly enforced.[50]

Recently the Chinese State Council and Ministry of Environmental Protection issued a new plan intended to reduce China's air pollution. Actions contemplated in this plan could either increase or decrease the carbon intensity of China's economy.[51] Key measures in the plan include:

1. Moving development of coal-fired power plants to China's western region.
2. Banning development of new coal-fired power plants in China's eastern region, except for Shandong Province and in combined heating and power applications.
3. Developing a natural gas substitute from coal gasification.
4. Prohibiting development of new natural gas power plants except for peak load and distributed power generation.
5. Accelerating development of nuclear power.

Measures 1 and 3 above are likely to overwhelm the emissions reduction impact of the others and therefore greatly increase the overall carbon intensity of the Chinese primary and electric energy markets.

Policy Recommendations

China's leaders seem to have an unusually high appreciation of the role that energy policy, including electricity policy, can play in building a sustainable economy. The many challenges of leading their population to higher standards of living can make it difficult to convert interest into action, however. Leaders in the global environmental community who hope to mitigate climate change need to help China's leaders sustain that level of interest and match it with strong and aggressive action to promote energy efficiency and low-carbon sources of energy. Strengthening goals for and governance of the electric power system should be a top priority. We make the following recommendations.

Double down on energy efficiency. Most optimistic projections about the potential role of renewable resources in electricity supply assume that all cost-effective measures for demand reduction have been incorporated in the system.[52] Our High Renewables scenario is not an exception. Achieving that goal, which would require unprecedented cooperation and coordination among electricity regulators, suppliers, and users, requires action on several fronts.

China's regulators should issue timely and technology-forcing industrial process standards. We found in our modeling that the only plausible scenarios for China's electric power future, from an environmental as well as an economic perspective, depend on adoption and enforcement of strong energy-saving policies and regulations and aggressive deployment of energy efficiency and demand-side management technologies. Reaching the profound level of efficiency that underpins a renewable-based or other low-carbon future will not happen through any realistic pricing or incentive scheme. It must be accomplished through standard setting.[53] (See the recommendation "Allow Prices to Reflect the Cost of Service," page 42. Also, see Box 2.)

BOX 2 Stringent Standards to Manage Chinese Power Demand

Chinese power demand could quadruple by 2050 unless China implements strict new equipment standards. Even with standards, demand will likely double or triple. Our High Efficiency, High Renewables, and Low-Carbon Mix scenarios depict the following demand projection broken down by sector as a percentage of the total economy:

Sector	2010	2050
Industrial	69%	55%
Commercial	15%	28%
Residential	13%	16%
Other	2%	1%

In these three scenarios, we adopted the following guidelines:

- Efficiency standards for industry will be vital, because even in 2050 power demand will be dominated by the industrial sector. To account for this, we model that industrial processes are mandated to improve electricity utilization efficiency at three percent per year.
- Electric water heaters are limited to providing no more than 15 percent of residential hot water supply. Only water heater heat pumps are permitted and must have an "energy factor" of 2.35 by 2040, compared to 0.86 for standard electric water heaters today. Peak demand is managed partly by limiting water heater capacity to 1.5 kW, compared to the US average of about 4 kW today.
- Residential and commercial sector air conditioning would be required to increase their "Seasonal Energy Efficiency Ratio" (SEER) from 14 today to 30 by the year 2040.
- Residential lighting in 2040 would be required to have the efficiency of the best LED lights today, using only 5 watts per bulb for 60 watt equivalent lumens. That improvement compares to compact fluorescent lights (CFLs) used in China today with a power consumption rate of about 15 watts when turned on.

The central government plans to issue strengthened standards for manufacture of appliances and equipment starting in 2013 and continuing through 2020. There will also be new and reissued standards for industrial processes, including electricity use standards. These standards need to be reviewed and adapted as frequently as necessary to keep up with (or exceed) international best practice. The government and the utilities must look ahead to 2050, determine the size of the contribution appliances and equipment will need to make to an energy-efficient future, and work with manufacturers to develop, test, and deploy products that meet those requirements.

China's leaders should direct the State Grid Corporation and the South China Grid Company to treat end-use efficiency as a service obligation commensurate with system reliability and security. The China 8760 Grid Model employs efficiency technologies to save 205,000 terawatt hours of electric power over the next 40 years. We found in our modeling that the path specified by China's current DSM regulations—a 0.3 percent annual improvement in efficiency gauged by sales volume and another 0.3 percent annual improvement in efficiency gauged by maximum load—means that the grid companies are being encouraged to go after just 10 percent of the efficiency potential. We conclude that China needs efficiency improvements to occur at a rate of 3 percent per year, and it should increase the share of responsibility it assigns to its grid companies.

China's grid companies should replicate the essential elements of the "Olympic Peninsula Project" in China's electricity sector. (See Box 3.) The grid companies' smart grid experts currently emphasize investment in long-distance transmission[54], giving inadequate attention to the "smart grid" information technologies that help consumers understand and control their energy demand. These technologies deserve far more attention. The restructuring that is essential to the future of the Chinese economy will cause additional stress on the power grid unless smart grid communications and controls are fully utilized to level and manage load swings. Around the world, governments and utilities are using creative financing mechanisms and working with energy service companies to deploy technologies to reduce electricity demand.

The central government should clarify the rules for grid companies to recoup demand-side management (DSM) costs. China's DSM measures allow recovery of reasonable DSM costs by the grid companies, but the rules for governing recovery of those costs have not been issued. The NDRC needs to make that a top priority since utility executives often cite the absence of clear cost recovery rules as a barrier to DSM. NDRC should give serious consideration to combining those cost recovery rules with rules that cap the grid companies' retained earnings, which would shift their incentives from increasing sales volume to improving profitability by cutting costs.[55]

Make carbon-saving the top criterion for all decisions about electricity supply investment. The transition to a renewable-based electric sector will require transformation of every element of the system, from planning to operations. This transformation will be a formidable challenge in any country, but may prove especially difficult in China, where rapid expansion of the system has been the overriding priority in recent years.

The Chinese central government should adopt policy that would substantially cut coal power generation, such as a carbon standard if it hopes to transform its coal-based electricity supply system to a low-carbon system. There are only a few things government can do to make a pathway to encourage power producers and consumers to use low-carbon sources of power generation and less power in general. Those things include research and development, price reform, incentives for investment (including tax breaks for clean energy and taxes on the use of higher carbon sources), and regulation. Our modeling suggests that a carbon tax of about US$40 per ton of carbon could make new coal-fired power plants non-competitive by 2025, but would not likely lead to the closure of many existing coal-fired power plants.[56]

BOX 3 Olympic Peninsula Smart Grid Demonstration Project

An alliance of utilities, vendors, and research institutions in the northwest United States tested load shifting with residential, commercial, municipal, and even distributed generation customers. They found that they "easily" and predictably reduced load by 20 percent using available technology and innovative incentives.

With residential customers, they used time-of-day usage meters, heating and cooling system thermostats, electric water heater switches, and clothes dryer switches all with built-in ability to communicate with and respond to signals from the local utility. This technology also required broadband Internet service in the home.

The technology works by programming equipment thermostats and switches to respond to signals from the utility in a fashion—defined by contract—chosen in advance by the customers based on their preferences. For example, an air conditioning thermostat can be set to respond to earn the maximum amount of money for a customer or it can be set to ignore utility requests to save power. That is, a home thermostat might respond to a load-shift signal from the utility by allowing a several-degree temperature increase, by allowing only an increase of only a degree, or by not responding at all. If there is a peak load experienced on the power grid, a computer can send a message to the thermostat to ask it how much, if any, it can be asked to save. The response the thermostat makes determines how much money the customer can "earn" from the utility.

The incentive program works based on a contract between the utility and the customer and payments made each month by the utility to the customer's bank account. At the first of each month, the Olympic Peninsula Project deposited US$150 into each participating residential customer's account. This incentive reflected the value to the grid of being able to call on the customer to shift his or her power use to another time. If the customer elected not to respond to the grid computer's enquiry to the air conditioner thermostat, then a sum equal to a prearranged amount would be deducted from the customer's account. Customers who never wanted to have their air conditioning affected would thus earn less than customers who were more flexible—who might not even be home during the day, for example. Other customers who wanted to have complete control over air conditioning could still save by shifting the time of day for drying clothes or washing dishes, for example.

Program support—meaning customer education and marketing—was very important to the success of this program. The researchers following the project noted that many customers did not even know whether their water was heated by electric power or by natural gas. Some did not know whether they had broadband or dial-up Internet service. Participation in the program was thus contingent on participation in an information effort about the peak-shift program and a home visit by a utility representative. Moreover, all equipment was provided free of charge by the utility.

The program effectively created a generally automated market with signals and responses "clearing" every five minutes. More aggressive participation—meaning earning the highest amounts of money—did involve some active interaction in load-shifting behavior.

This program was successful in part because the incentive program takes advantage of a recently proven fact of behavioral science, which is that people are more motivated to avoid losing money they already have than they are to save the same amount of money. By giving the customers money up front and making it theirs to lose, the customers were more motivated to participate. Project reviewers described residential customers as having "eagerly accepted and participated in price-responsive contract options."

Similar programs were developed for heating, cooling, and lighting loads in commercial buildings as well as pumping or other large-scale and flexible loads in municipal governments, utilities, and even distributed generation systems.

Source: D. J. Hammerstrom, *et al,* "Pacific Northwest Gridwise Testbed Demonstration Projects, Part I: Olympic Peninsula Project," Pacific Northwest National Laboratory, October 2007.

Two observations lead us to that conclusion. First, income elasticity of demand for power is high, that is, electric power use grows at a rate close to a country's GDP growth. Second, real-world price reforms or incentives cannot overcome this powerful force, at least not by themselves.[57] That is, relatively high demand growth will overwhelm the relatively low price elasticity of demand unless a carbon tax doubles or triples the price of power.

We recommend the Chinese State Council adopt a standard similar to the Clean Air Act standard in the United States.[58] A clear and enforceable standard to prevent construction of new power sources with high carbon emissions per kilowatt-hour of generation could be very effective, whether it is cast as a ban on coal, an incentive for clean energy, or a human health standard.

An alternative case using coal instead of natural gas as a backup to renewables is presented in Appendix III. In it, emissions increase significantly and total cost increases by about US$100 billion. The scenario assumes (based on current Chinese policy) that coal gasification would be used to produce fuel for backup power. It is possible that carbon capture and storage (CCS) technology could reduce emissions but, even if proven effective, would likely increase total costs by several hundred billion dollars.

The NDRC should invigorate its plans for natural gas. The State Council recently decided the nation will not use natural gas for base load applications around already-polluted cities, but will emphasize gas for peak load and district heating applications.[59] Our scenario analysis suggests that fossil fuels will provide much of China's electric power for several decades, and natural gas has two advantages over coal: It is a lower-carbon fossil fuel; and it works effectively to supply power during peak demand for electricity, so it will respond well to the variability in renewable supply. NDRC will need to work with the grid companies and the generation companies to encourage the use of natural gas; it will also need to ensure improvements in China's natural gas infrastructure and support research on China's reserves of conventional and unconventional gas. Our scenario analysis shows the need for a dispatchable power source such as natural gas in a renewables-dominant future. We emphasize that unconventional gas in China does not necessarily imply "fracking" or shale gas: China possesses potentially 1,500 exajoules of "coal bed methane," enough to run the entire Chinese power sector for decades.[60]

The NDRC should make system flexibility a top priority for the smart grid. The grid companies have declared an interest in the long distance transmission lines that could deliver power over long distances from remote locations. Their interest in the other vital elements of renewables integration—for example, increased connectivity among neighboring and distant regions; improved wind and solar forecasting; and increased use of storage options—is less clear. The grid companies need a keen focus on both the supply and demand sides of electricity service, and NDRC will need to work closely with the grid companies to make sure transmission planning is done proactively with a renewables-dominant future in mind.

The central government should revise its subsidies for renewable power sources to be more effective. China's experience with renewable power subsidies has revealed two major shortcomings: They reward construction without regard for operation; and they fail to reach the power generators in a timely manner.

The issue of "abandoned" or "curtailed" wind illustrates the first problem. Builders of wind turbines receive subsidies on the basis of installed capacity and on generation, not only on the basis of power actually delivered into the transmission grid. Where coordination with the utility is poor, power generated by wind turbines is often wasted. In the eastern part of Inner Mongolia, as much as 30 percent of wind generation may be wasted. China's national average for curtailed wind is 17 percent of generation, which amounted to 20 terawatt hours in 2012.[61] The subsidies need to be redesigned to make them at least partially contingent on efficient delivery of power. At the same time, oversight of the grid companies to ensure that they do not use variability of supply as an excuse will be necessary for the future use of renewable sources of power.

Timeliness of subsidy payments has been a particular problem for solar PV generators in China.[62] This subsidy is based on kWh rather than on kW, but suppliers have sometimes waited over two years for the subsidy payments that they counted on to secure project financing. Some companies have gone bankrupt waiting for subsidy payments to meet their obligations. Precise metering and coordination among NDRC, the Ministry of Finance, and local governments are needed to cure this problem.

Allow prices to reflect the cost of service.

The NDRC should consider a demand charge for commercial and residential consumers.[63] To meet China's long-term environmental goals, industrial, commercial, and residential customers need to see and pay the full costs of electric service. China's industrial electricity consumers already pay a "demand charge"—a charge based on the maximum power (or kW) draw on the grid system over a period of time, typically a year or month, in addition to the rate charged per kWh of demand.

System reliability obligations require the grid companies to acquire the maximum resources needed to meet instantaneous demand on, say, the hottest day of the year when all residential air conditioners are on and factories are still working the busy day shift. China's peak demand typically comes around 4 pm on weekdays in July and August.

For the past 10 years, the average load on the power grid has been about half the full amount that could be produced by installed capacity. Even peak load averages only 75 percent of total output potential. These ratios may deteriorate as the share of demand shifts from relatively steady industrial demand to very "peaky" residential and commercial demand, which tend to reflect the daily living habits of the general population. Demand charges for residential and commercial customers would encourage electricity customers to manage their own demand, or finance utilities to deploy smart grid technologies to reduce the swings in peaks and valleys on the utility load curve.[64]

We estimate that price reform and peak management could reduce capacity requirements in 2050 by more than 60 GW in the commercial sector and 20 GW in the residential sector. That sum is equal to 10 percent of current peak demand and is worth at least US$80 billion in avoided capital costs alone.[65]

The central government should redesign its experiments with competitive wholesale markets.[66] China's early experiments with competitive wholesale electricity markets failed for several reasons, including over-concentration of generation ownership in test areas, over-reliance on a single source of power (coal), and low tolerance for any volatility in electricity prices. The diversity problem is partially addressed by the new emphasis on renewable power supplies, and expansion of the transmission system could help address problems related to over-concentration of generation ownership within a province. It seems timely for China to design new experiments with greater attention to known problems. Ideally, these experiments could expand to include market innovations aimed specifically at promoting energy efficiency and renewable generation. Such innovations could include encouraging competitive delivery of negawatts* sold for baseload or peak dispatch and expanding the customer base that is permitted to buy power directly from the generator of choice.

Collect, publish, and analyze the data that matter. The Chinese government maintains a close hold on much of the data on power resources and system assets essential to rigorous assessment of capabilities and cost-effectiveness. In addition, the government fails to collect (or, at least, report) data that provide a comprehensive view of progress toward building a renewables future. Greater transparency throughout China's government would enable internal and external analysts to contribute to building a more sustainable power system.

China's grid companies should improve their institutional capacity to operate renewables installations and monitor their performance. The more the grid companies can learn from their initial experiments with renewable power, the more likely they are to avoid replicating bad experiments and wasting scarce resources. Efforts like the recent assessment of building-integrated solar technologies[67] should be encouraged throughout the electricity sector. And the State Council should encourage China's schools and businesses to develop the human capital needed to achieve long-term success.

The central government needs to collect and disseminate the data essential to serious environmental impact assessment. All energy supply options have environmental costs, even renewables. Very little of the data necessary to assess those costs is available outside of government circles in China, if it is collected at all. China's nongovernmental organizations (NGOs) should not allow the drive to reduce carbon emissions to overshadow the very real threats posed by many low-carbon energy supplies. The government and NGOs should work together to expand data collection and dissemination.

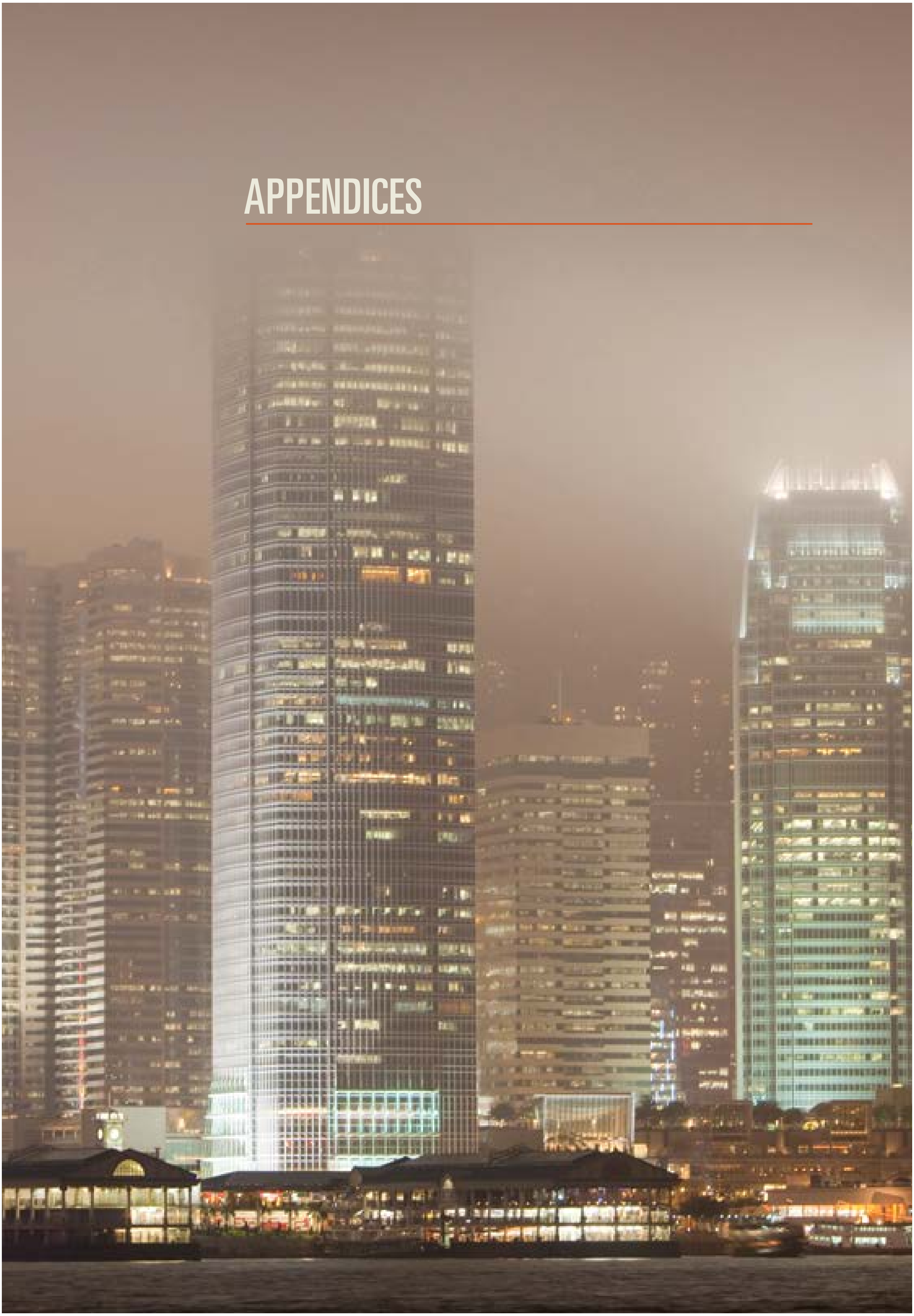
The official process for choosing data for collection also needs improvement. China's environmental impact assessments give short shrift to environmental costs when they fail to consider and report on technological alternatives that could mitigate the environmental costs of specific projects.[68] This failing is particularly egregious in the case of hydropower, which figures prominently in China's near- and longer-term goals for development of low-carbon resources. Despite enormous domestic and international environmental impacts,

* A theoretical unit of energy (measured in watts) that is conserved or avoided.

hydropower in China receives only cursory environmental review.[69] Our scenario analyses suggest there are cost-effective alternatives to hydropower that deserve consideration in the context of China's overall planning efforts and in review of specific construction projects. China should begin to use its existing framework to implement more thorough environmental impact assessment requirements in all energy-related construction projects.

Government policies and reports should reflect data on the amount of electricity generated and delivered (kWh), not just data on installed capacity (kW). The government typically expresses its goals and success stories for renewable energy in terms of installed capacity (kW). This focus has contributed to well-known problems, such as wind generation capacity that never gets connected to the grid, and emerging problems, such as under-investment in the technologies that will ensure system security and reliability as renewable resources increasingly come online. Transparency about the difference between the amount of electricity generated from renewable resources and the amount actually delivered to customers could have a meaningful impact on system development. At the same time, oversight of the grid companies will be essential to ensure that they do not simply refuse to utilize variable power sources, because it requires more work for them to schedule, forecast, and integrate all sources.

APPENDICES



Demographic and Economic Assumptions

DEMOGRAPHIC ASSUMPTIONS	
Population (Millions)	1,347
Population Growth Rates	
2011–2015	0.004
2016–2020	0.003
2021–2025	0.001
2026–2030	– 0.003
2031–2040	– 0.003
2041–2050	– 0.003
Households (Millions)	404
Urban Share of Households	
2011–2015	0.5
2016–2020	0.63
2021–2030	0.7
2031–2040	0.74
2041–2050	0.79
ECONOMIC ASSUMPTIONS	
Exchange Rate	6.25
Discount Rate	0.1

Technology Parameters

Technology	Conversion Efficiency	Historic Capacity Factor	Fuel Cost (RMB/GJ)	O&M Cost (RMB/kWh)	Technology (Year)	Fuel Carbon (kgC/GJ)	Electricity Use Onsite (%)
Solar PV [3 MW]	0.15	0.17	N/A	0.19	20	0	0.8
Concentrated Solar Power	0.15	0.6	N/A	0.19	20	0	0.8
Wind Power, On Shore	1	0.22	N/A	0.07	20	0	0.8
Wind Power, Off Shore	1	0.22	N/A	0.12	20	0	0.8
Hydro, Large Scale	1	0.4	N/A	0.06	30	0	1.5
Hydro, Small Scale	1	0.4	N/A	0.06	30	0	1.5
Geothermal	1	0.5	N/A	0.34	20	0	6
Biomass	0.2	0.46	21	0.11	30	20	17.8
Sub-Critical Coal	0.38	0.6	28	0.05	30	25	7
Sub-Critical Coal w/ Biomass	0.38	0.6	38	0.05	30	20	7
Super-Critical Coal	0.44	0.6	28	0.03	30	25	5.2
Super-Critical Coal	0.44	0.6	28	0.04	30	25	6.3
IGCC CCS Coal	0.39	0.6	28	0.09	20	25	30
Nuclear Power	0.33	0.89	15	0.09	30	0	6.8
Natural Gas, Peak Load	0.49	0.23	62	0.08	20	14	2
Natural Gas, Base Load	0.49	0.6	62	0.04	20	14	2

Technology Expectations (Annual Rates of Change)

Technology	Conversion Efficiency	Capital Cost	Fuel Cost	O&M Cost
Solar PV [3 MW]	0.004	−0.031	N/A	−0.033
Concentrated Solar Power [30 MW]	0.01	−0.021	N/A	−0.017
Wind Power, On Shore [30 MW scale]	0	−0.007	N/A	−0.007
Wind Power, Off Shore [30 MW scale]	0	−0.009	N/A	−0.009
Hydro, Large Scale	0	0.02	N/A	0
Hydro, Small Scale	0	0.02	N/A	0
Geothermal	0.01	−0.008	N/A	−0.012
Biomass [25 MW]	0.01	−0.006	0.02	−0.005
Sub-Critical Coal	0	0	0.02	0.02
Sub-Critical Coal w/ Biomass	0	0.01	0.02	0.02
Super-Critical Coal [1000 MW]	0.01	0.01	0.02	0.02
Super-Critical Coal [600 MW]	0.01	0.01	0.02	0.02
IGCC CCS Coal [1,000 MW]	0.01	0	0.02	0.02
Nuclear Power	0	−0.003	0.02	−0.003
Natural Gas, Peak Load	0.01	0.01	0.02	0.02
Natural Gas, Base Load	0.01	0.01	0.02	0.02

Conservation Assumptions

GENERAL RESIDENTIAL		
Urbanization Level in 2050	0.79	
Occupancy Rate in Urban Areas in 2040	2.55	Persons/Household
Occupancy Rate in Rural Areas in 2040	3.2	Persons/Household
Rate of Growth of Floor Space in Urban Areas per Year before 120 m^2 per Household	0.02	
Rate of Growth of Floor Space in Urban Areas per Year after 120 m^2 per Household	0.01	
Rate of Growth of Floor Space in Rural Areas per Year before 200 m^2 per Household	0.02	
Rate of Growth of Floor Space in Rural Areas per Year after 200 m^2 per Household	0.01	
RESIDENTIAL WATER HEATING		
Capital Cost	300	US$/Unit
Life Time	10	Years
Average Capacity of Electricity Water Heating	1.5	kW/Unit
Electricity Water Heating Share out of Water Heating in Urban Areas in 2040	0.3	
Electricity Water Heating Share out of Water Heating in Rural Areas in 2040	0.3	
Baseline Use of Hot Water in Urban Areas in 2040	70	Liters/Household/Day
Baseline Use of Hot Water in Rural in 2040	70	Liters/Household/Day
Energy Factor of Electricity Water Heating at Policy Scenario in 2040	2.35	
Penetration Rate for Peak Reduction Option in Urban Areas in 2011	0.2	
Growth Rate for Peak Reduction Option in Urban Areas	0.1	
Penetration Rate for Peak Reduction Option in Rural Areas in 2011	0.2	
Growth Rate for Peak Reduction Option in Rural Areas	0.1	
Cost of Peak Reduction Option	100	US$/Unit
RESIDENTIAL AIR CONDITIONING		
Capital Cost	160	US$/Unit
Life Time	15	Years
Average Capacity at Baseline in 2040	2	kW/Unit
Average Capacity at Policy in 2040	1.5	kW/Unit
Seasonal Energy Efficiency Ratio at Baseline in 2040	15	
Seasonal Energy Efficiency Ratio at Policy in 2040	30	
Operation Hours in 2040	1,080	Hours/Year
Capital Cost for Peak Reduction	100	US$/Unit
Switch Rate in 2010	0.1	
Growth Rate of Switch Options per Year	0.05	

Conservation Assumptions, cont.

RESIDENTIAL LIGHTING		
Capital Cost of LEDs	5	US$/Unit
Life Time	20	Years
Operation Hours in 2040	1,825	Hours/Unit/Year
Growth Rate for Number of Lighting per Household	0.01	
Capacity of CFLs	0.015	kW/Unit
Capacity of LEDs	0.005	kW/Unit
LED Cost Improvement	0	
LED Replace Ratio in 2010	0.1	
Growth Rate for LEDs	0.2	
COMMERCIAL LIGHTING		
Capital Cost	19	US$/Unit
Life Time	20	Years
Electricity Consumption by Lighting in 2040	36	kWh/m^2/Year
Operation Hours in 2040	3,500	Hours/Unit/Year
Average Capacity at Policy in 2040	0.01	kW/Unit
COMMERCIAL AIR CONDITIONING		
Capital Cost	308	US$/Unit
Life Time	20	Years
Electricity Consumption in 2040	42	kWh/m^2/Year
Operation Hours in 2040	3,500	Hours/Unit/Year
Seasonal Energy Efficiency Ratio at Baseline in 2040	13	
Seasonal Energy Efficiency Ratio at Policy in 2040	30	
Capital Cost for Peak Reduction	20	US$/Unit
Switch Rate in 2010	0.1	
Growth Rate of Switch Options per Year	0.05	
INDUSTRY		
Efficiency Improvement Rate per Year	0.03	
Cost of Energy Saved at Particular Efficiency Levels		
Efficiency Rate		
<0.1	0.1	RMB/kWh
0.1–0.2	0.2	RMB/kWh
0.2–0.3	0.3	RMB/kWh
0.3–0.4	0.4	RMB/kWh
0.4–0.5	0.5	RMB/kWh
0.5–0.6	0.6	RMB/kWh
0.6–0.7	0.7	RMB/kWh

Baseline Scenario

	2011[70]	2015	2020	2025	2030	2035	2040	2045	2050	TOTAL
Demand (TWh/Year)	4,693	6,155	8,952	11,413	14,063	16,466	19,028	20,950	22,788	622,538
Installed Capacity (GW)	1,019	1,429	2,097	2,616	3,174	3,679	4,216	4,619	5,004	139,269
Generating Cost (B RMB)	1,708	2,689	4,197	5,548	7,241	9,090	11,328	13,525	15,989	356,577
Cost of Transmission (Billion RMB/Year)	115	194	287	360	441	516	595	655	712	19,377
Cost of Demand/Peak Reduction Measures (Billion RMB/Year)	N/A	0	0	0	0	0	0	0	0	0
Cost of Storage (Billion RMB/Year)	0	0	0	0	0	0	0	0	0	0
Cost of All Measures (Billion RMB/Year)	1,824	2,883	4,484	5,908	7,682	9,606	11,924	14,180	16,701	375,953.9
Population (Millions)	1,347	1,369	1,386	1,393	1,374	1,355	1,337	1,319	1,300	N/A
GDP (2010 USD per Capita)	5,549	6,308	8,737	10,880	13,420	15,927	18,720	21,160	23,687	N/A
Power Use per Capita (kWh)	3,484	4,497	6,459	8,192	10,234	12,149	14,234	15,889	17,523	N/A
Carbon Dioxide Emissions (Million Tons/Year)	2,766	3,638	4,915	6,254	8,087	9,767	11,560	12,901	14,183	370,347.0
Power Demand Growth (GDP Growth)	1.00	1.00	1.04	1.06	1.07	1.07	1.07	1.05	1.04	N/A
CAPACITY (GW)										
Solar PV [3 MW]	3	20	47	47	47	47	47	47	47	N/A
Concentrated Solar Power [30 MW]	0	1	3	3	3	3	3	3	3	N/A
Wind Power, On Shore [30 MW scale]	48	95	170	170	170	170	170	170	170	N/A
Wind Power, Off Shore [30 MW scale]	0	5	30	30	30	30	30	30	30	N/A
Hydro, Large Scale	157	192	265	300	300	300	300	300	300	N/A
Hydro, Small Scale	58	68	75	84	93	95	97	98	100	N/A
Geothermal	0	0	0	0	0	0	0	0	0	N/A
Biomass [25 MW]	2	13	20	20	20	20	20	20	20	N/A
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	N/A
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	N/A
Super-Critical Coal [1000 MW]	707	955	1,357	1,812	2,361	2,864	3,399	3,801	4,184	N/A
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	N/A
IGCC CCS Coal [1,000 MW]	0	0	0	0	0	0	0	0	0	N/A
Nuclear Power	13	40	80	100	100	100	100	100	100	N/A
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	N/A
Natural Gas, Base Load	33	40	50	50	50	50	50	50	50	N/A
TOTAL	1,019	1,429	2,097	2,616	3,174	3,679	4,216	4,619	5,004	N/A
CAPACITY MIX GENERATION (TWh)										
Solar PV [3 MW]	4	30	70	70	70	70	70	70	70	524
Concentrated Solar Power [30 MW]	0	5	16	16	16	16	16	6	16	116
Wind Power, On Shore [30 MW scale]	91	202	373	383	393	404	414	424	435	3,120
Wind Power, Off Shore [30 MW scale]	0	11	66	68	69	71	73	75	77	509
Hydro, Large Scale	549	671	929	1,051	1,051	1,051	1,051	1,051	1,051	8,456
Hydro, Small Scale	203	240	263	294	326	332	338	344	350	2,691
Geothermal	0	0	1	1	1	1	1	1	1	7
Biomass [25 MW]	7	52	80	80	80	80	80	80	80	619
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	0
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	0
Super-Critical Coal [1000 MW]	3,590	4,852	6,896	9,206	11,997	14,549	17,272	19,310	21,258	108,930
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	0
IGCC CCS Coal [1000 MW]	0	0	0	0	0	0	0	0	0	0
Nuclear Power	98	311	622	777	777	777	777	777	777	5,693
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	0
Natural Gas, Base Load	172	210	263	263	263	263	263	263	263	2,221
Percent of Renewables	0.18	0.18	0.19	0.16	0.13	0.11	0.10	0.09	0.09	N/A
TOTAL	4,714	6,584	9,577	12,209	15,043	17,614	20,355	22,411	24,377	132,886

High Efficiency Scenario

	2011	2015	2020	2025	2030	2035	2040	2045	2050	TOTAL
Demand (TWh/Year)	4,693	5,329	6,476	7,238	7,982	8,907	10,028	10,883	11,766	366,510
Installed Capacity (GW)	1,019	1,255	1,576	1,737	1,894	2,087	2,321	2,499	2,683	85,363
Generating Cost (B RMB)	1,708	2,362	3,163	3,693	4,293	5,087	6,120	7,158	8,365	209,754
Cost of Transmission (Billion RMB/Year)	115	169	211	232	254	283	318	345	373	11,505
Cost of Demand/Peak Reduction Measures (Billion RMB/Year)	N/A	171	558	1,188	2,112	3,427	4,597	6,498	7,841	131,967.9
Cost of Storage (Billion RMB/Year)	0	0	0	0	0	0	0	0	0	0
Cost of All Measures (Billion RMB/Year)	1,824	2,702	3,932	5,113	6,659	8,798	11,036	14,001	16,580	353,226
Population (Millions)	1,347	1,369	1,386	1,393	1,374	1,355	1,337	1,319	1,300	N/A
GDP (2010 USD per Capita)	5,549	6,308	8,415	10,381	12,805	15,795	19,484	23,123	27,178	N/A
Power Use per Capita (kWh)	3,484	3,894	4,673	5,195	5,809	6,572	7,501	8,254	9,047	N/A
Carbon Dioxide Emissions (Million Tons/Year)	2,766	3,001	3,099	3,306	3,794	4,430	5,205	5,793	6,400	188,973.1
Power Demand Growth (GDP Growth)	1.00	0.87	0.78	0.70	0.64	0.58	0.54	0.50	0.47	N/A
CAPACITY (GW)										
Solar PV [3 MW]	3	20	47	47	47	47	47	47	47	N/A
Concentrated Solar Power [30 MW]	0	1	3	3	3	3	3	3	3	N/A
Wind Power, On Shore [30 MW scale]	48	95	170	170	170	170	170	170	170	N/A
Wind Power, Off Shore [30 MW scale]	0	5	30	30	30	30	30	30	30	N/A
Hydro, Large Scale	157	192	265	300	300	300	300	300	300	N/A
Hydro, Small Scale	58	68	75	84	93	95	97	98	100	N/A
Geothermal	0	0	0	0	0	0	0	0	0	N/A
Biomass [25 MW]	2	13	20	20	20	20	20	20	20	N/A
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	N/A
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	N/A
Super-Critical Coal [1000 MW]	707	781	836	933	1,081	1,272	1,504	1,681	1,863	N/A
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	N/A
IGCC CCS Coal [1,000 MW]	0	0	0	0	0	0	0	0	0	N/A
Nuclear Power	13	40	80	100	100	100	100	100	100	N/A
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	N/A
Natural Gas, Base Load	33	40	50	50	50	50	50	50	50	N/A
TOTAL	1,019	1,255	1,576	1,737	1,894	2,087	2,321	2,499	2,683	N/A
CAPACITY MIX GENERATION (TWh)										
Solar PV [3 MW]	4	30	70	70	70	70	70	70	70	524
Concentrated Solar Power [30 MW]	0	5	16	16	16	16	16	16	16	116
Wind Power, On Shore [30 MW scale]	91	202	373	383	393	404	414	424	435	3,120
Wind Power, Off Shore [30 MW scale]	0	11	66	68	69	71	73	75	77	509
Hydro, Large Scale	549	671	929	1,051	1,051	1,051	1,051	1,051	1,051	8,456
Hydro, Small Scale	203	240	263	294	326	332	338	344	350	2,691
Geothermal	0	0	1	1	1	1	1	1	1	7
Biomass [25 MW]	7	52	80	80	80	80	80	80	80	619
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	0
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	0
Super-Critical Coal [1000 MW]	3,590	3,968	4,247	4,740	5,493	6,464	7,644	8,540	9,466	54,153
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	0
IGCC CCS Coal [1000 MW]	0	0	0	0	0	0	0	0	0	0
Nuclear Power	98	311	622	777	777	777	777	777	777	5,693
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	0
Natural Gas, Base Load	172	210	263	263	263	263	263	263	263	2,221
Percent of Renewables	0.18	0.21	0.26	0.25	0.23	0.21	0.19	0.18	0.17	N/A
TOTAL	4,714	5,701	6,928	7,743	8,539	9,529	10,727	11,642	12,586	78,109

High Renewables Scenario

	2011	2015	2020	2025	2030	2035	2040	2045	2050	TOTAL
Demand (TWh/Year)	4,693	5,361	6,534	7,232	7,926	8,874	10,034	10,921	11,804	366,900
Installed Capacity (GW)	1,019	1,295	1,639	2,121	2,607	3,230	3,948	4,740	5,063	128,299
Generating Cost (B RMB)	1,708	2,284	2,991	3,810	4,544	5,441	6,391	7,392	8,176	213,419
Cost of Transmission (Billion RMB/Year)	115	179	231	336	420	519	629	739	786	19,774
Cost of Demand/Peak Reduction Measures (Billion RMB/Year)	N/A	173	571	1,184	2,021	3,249	4,364	6,251	7,684	127,492.3
Cost of Storage (Billion RMB/Year)	0	0	0	0	7	7	13	17	18	302.6
Cost of All Measures (Billion RMB/Year)	1,824	2,636	3,793	5,331	6,992	9,216	11,397	14,399	16,664	360,987.7
Population (Millions)	1,347	1,369	1,386	1,393	1,374	1,355	1,337	1,319	1,300	N/A
GDP (2010 USD per Capita)	5,549	6,308	8,415	10,381	12,805	15,795	19,484	23,123	27,178	N/A
Power Use per Capita (kWh)	3,484	3,917	4,714	5,191	5,768	6,548	7,506	8,283	9,077	N/A
Carbon Dioxide Emissions (Million Tons/Year)	2,766	3,247	3,598	2,920	2,456	2,029	1,638	778	836	101,143.8
Power Demand Growth (GDP Growth	1.00	0.87	0.79	0.70	0.63	0.58	0.54	0.50	0.47	N/A
CAPACITY (GW)										
Solar PV [3 MW]	3	20	47	235	388	649	932	1,263	1,377	N/A
Concentrated Solar Power [30 MW]	0	1	3	72	128	207	293	394	459	N/A
Wind Power, On Shore [30 MW scale]	48	95	170	507	759	950	1,147	1,373	1,374	N/A
Wind Power, Off Shore [30 MW scale]	0	5	30	45	60	89	118	146	175	N/A
Hydro, Large Scale	157	192	265	301	337	355	374	392	410	N/A
Hydro, Small Scale	58	68	75	84	93	95	97	98	100	N/A
Geothermal	0	0	0	0	1	1	1	1	2	N/A
Biomass [25 MW]	2	13	20	25	30	33	35	38	40	N/A
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	N/A
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	N/A
Super-Critical Coal [1000 MW]	707	863	1,002	835	668	501	334	0	0	N/A
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	N/A
IGCC CCS Coal [1,000 MW]	0	0	0	0	0	0	0	0	0	N/A
Nuclear Power	13	11	9	7	5	3	0	0	0	N/A
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	N/A
Natural Gas, Base Load	33	26	18	10	140	349	617	1,036	1,126	N/A
TOTAL	1,019	1,295	1,639	2,121	2,607	3,230	3,948	4,740	5,063	N/A
Storage	0	0	0	0	9	9	17	22	23	N/A
CAPACITY MIX GENERATION (TWh)										
Solar PV [3 MW]	4	30	70	350	578	966	1,388	1,880	2,051	7,317
Concentrated Solar Power [30 MW]	0	5	16	379	670	1,089	1,542	2,068	2,412	8,183
Wind Power, On Shore [30 MW scale]	91	202	373	1,143	1,756	2,256	2,794	3,427	3,514	15,557
Wind Power, Off Shore [30 MW scale]	0	11	66	101	139	211	286	365	448	1,626
Hydro, Large Scale	549	671	929	1,055	1,181	1,245	1,309	1,373	1,437	9,747
Hydro, Small Scale	203	240	263	294	326	332	338	344	350	2,691
Geothermal	0	0	1	2	2	3	4	5	7	25
Biomass [25 MW]	7	52	80	100	120	130	140	150	160	939
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	0
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	0
Super-Critical Coal [1000 MW]	3,590	4,387	5,089	4,241	3,392	2,544	1,696	0	0	24,940
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	0
IGCC CCS Coal [1000 MW]	0	0	0	0	0	0	0	0	0	0
Nuclear Power	98	85	68	52	36	20	3	0	0	361
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	0
Natural Gas, Base Load	172	52	36	20	279	697	1,232	2,069	2,249	6,699
Percent of Renewables	0.18	0.21	0.26	0.44	0.56	0.66	0.73	0.82	0.82	N/A
TOTAL	4,714	5,735	6,989	7,737	8,479	9,493	10,734	11,682	12,627	78,086

Low Carbon Mix Scenario

	2011	2015	2020	2025	2030	2035	2040	2045	2050	TOTAL
Demand (TWh/Year)	4,693	5,353	6,510	7,216	7,919	8,869	10,037	10,942	11,858	366,981
Installed Capacity (GW)	1,019	1,288	1,613	2,039	2,468	2,936	3,512	4,161	4,400	117,178
Generating Cost (B RMB)	1,708	2,299	3,059	3,869	4,617	5,591	6,685	7,824	8,841	222,199
Cost of Transmission (Billion RMB/Year)	115	177	223	312	383	453	527	602	623	17,073
Cost of Demand/Peak Reduction Measures (Billion RMB/Year)	N/A	173	566	1,174	2,011	3,220	4,301	6,116	7,464	125,121.9
Cost of Storage (Billion RMB/Year)	0	0	0	0	17	17	0	0	0	169.5
Cost of All Measures (Billion RMB/Year)	1,824	2,649	3,848	5,355	7,028	9,281	11,513	14,542	16,927	364,563.3
Population (Millions)	1,347	1,369	1,386	1,393	1,374	1,355	1,337	1,319	1,300	N/A
GDP (2010 USD per Capita)	5,549	6,308	8,415	10,381	12,805	15,795	19,484	23,123	27,178	N/A
Power Use per Capita (kWh)	3,484	3,911	4,697	5,179	5,763	6,544	7,508	8,298	9,118	N/A
Carbon Dioxide Emissions (Million Tons/Year)	2,766	3,189	3,378	2,743	2,304	1,880	1,526	732	820	96,485.6
Power Demand Growth (GDP Growth	1.00	0.87	0.78	0.70	0.63	0.58	0.54	0.50	0.47	N/A
CAPACITY (GW)										
Solar PV [3 MW]	3	20	47	207	336	560	790	1,062	1,138	N/A
Concentrated Solar Power [30 MW]	0	1	3	62	108	175	242	322	362	N/A
Wind Power, On Shore [30 MW scale]	48	95	170	457	671	806	931	1,091	1,033	N/A
Wind Power, Off Shore [30 MW scale]	0	5	30	45	60	89	118	146	175	N/A
Hydro, Large Scale	157	192	265	301	337	278	219	159	100	N/A
Hydro, Small Scale	58	68	75	84	93	82	72	61	50	N/A
Geothermal	0	0	0	0	1	1	1	1	2	N/A
Biomass [25 MW]	2	13	20	25	30	33	35	38	40	N/A
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	N/A
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	N/A
Super-Critical Coal [1000 MW]	707	848	938	782	625	469	313	0	0	N/A
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	N/A
IGCC CCS Coal [1,000 MW]	0	0	0	0	0	0	0	0	0	N/A
Nuclear Power	13	20	47	66	85	164	243	321	400	N/A
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	N/A
Natural Gas, Base Load	33	26	18	10	122	280	550	960	1,100	N/A
TOTAL	1,019	1,288	1,613	2,039	2,468	2,936	3,512	4,161	4,400	N/A
Storage	0	0	0	0	24	23	0	0	0	N/A
CAPACITY MIX GENERATION (TWh)										
Solar PV [3 MW]	4	30	70	308	501	834	1,177	1,581	1,695	6,199
Concentrated Solar Power [30 MW]	0	5	16	324	570	918	1,272	1,694	1,902	6,702
Wind Power, On Shore [30 MW scale]	91	202	373	1,030	1,552	1,915	2,269	2,723	2,643	12,798
Wind Power, Off Shore [30 MW scale]	0	11	66	101	139	211	286	365	448	1,626
Hydro, Large Scale	549	671	929	1,055	1,181	973	766	558	350	7,031
Hydro, Small Scale	203	240	263	294	326	288	251	213	175	2,253
Geothermal	0	0	1	2	2	3	4	5	7	25
Biomass [25 MW]	7	52	80	100	120	130	140	150	160	939
Sub-Critical Coal	0	0	0	0	0	0	0	0	0	0
Sub-Critical Coal w/ Biomass	0	0	0	0	0	0	0	0	0	0
Super-Critical Coal [1000 MW]	3,590	4,307	4,767	3,972	3,178	2,383	1,589	0	0	23,787
Super-Critical Coal [600 MW]	0	0	0	0	0	0	0	0	0	0
IGCC CCS Coal [1000 MW]	0	0	0	0	0	0	0	0	0	0
Nuclear Power	98	155	365	513	661	1,273	1,885	2,497	3,109	10,555
Natural Gas, Peak Load	0	0	0	0	0	0	0	0	0	0
Natural Gas, Base Load	172	52	36	20	243	559	1,099	1,917	2,197	6,188
Percent of Renewables	0.18	0.21	0.26	0.42	0.52	0.56	0.57	0.62	0.58	N/A
TOTAL	4,714	5,726	6,965	7,719	8,472	9,488	10,737	11,705	12,685	78,103

Alternative High Renewables Scenario: Using Coal Instead of Natural Gas to Backup Renewables

These figures depict an alternative 80 percent renewables scenario. Two key differences distinguish this scenario from the High Renewables scenario presented in the main body of the text. The first difference is an assumption that coal is not phased out after 2040, but the remaining 330 GW of coal-fired plants are allowed to operate for the rest of their useful lives up to the planned age of 30 years. The second difference is that instead of using natural gas to provide almost 20 percent of power as a flexible source to backup renewables, half of that type of power is provided by gas and half is provided by a natural gas substitute from coal. This is, in effect, the same thing as assuming that half of the backup power is provided by Integrated Gasification Combined Cycle plants (IGCC). However, carbon capture and storage technology is not assumed because of high cost and the absence of a proven demonstration of the concept in China (or at full scale). The result is that carbon emissions would double from about 250 million tons per year from power generation in 2050 in the renewables case using all gas for backup to over 500 million tons per year using gas and coal in equal shares for backup.

FIGURE IIIa
Electricity Generation, High Renewables Scenario with Coal Backup

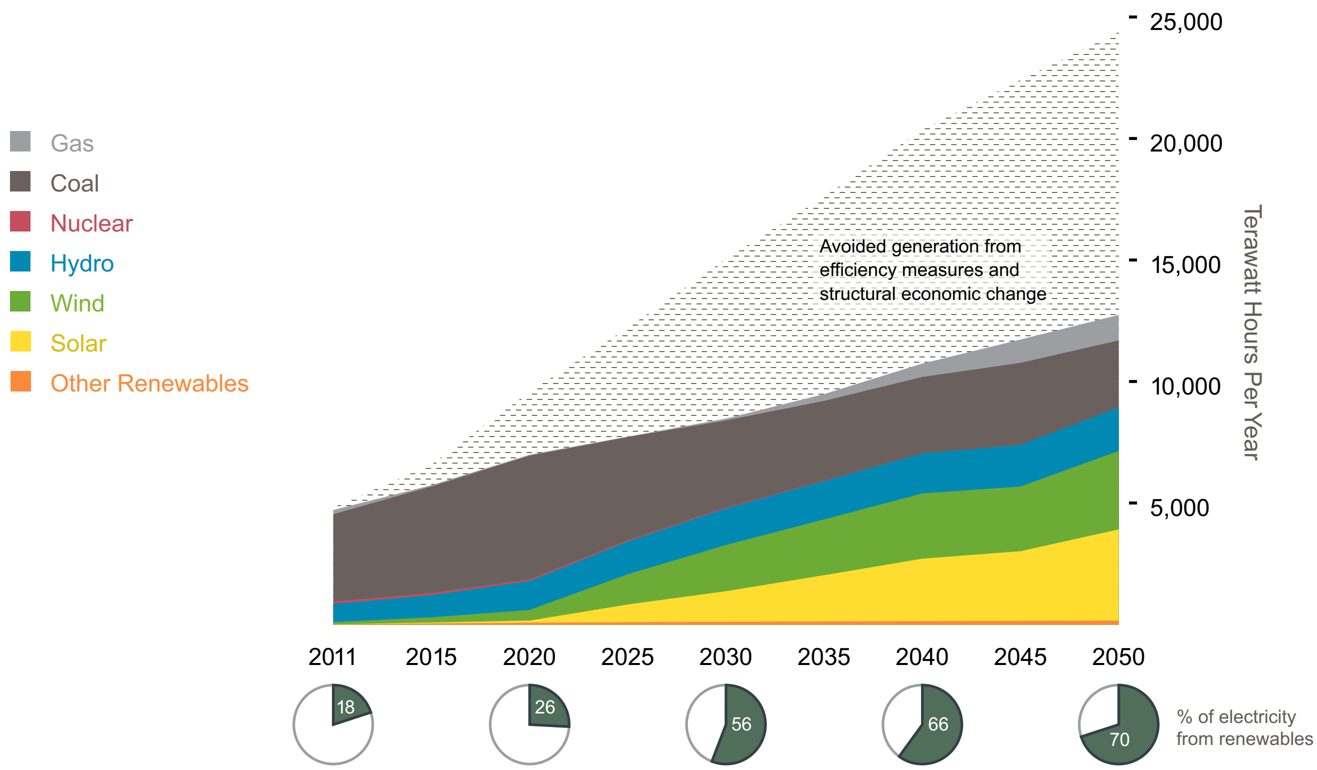
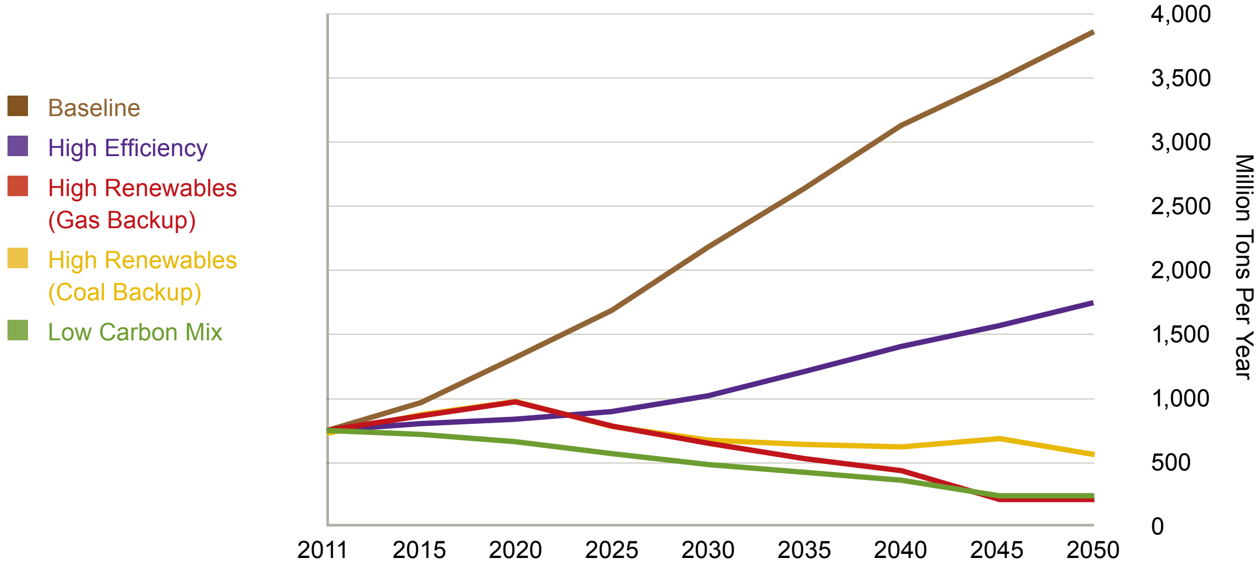


FIGURE IIIb Carbon Emissions



The China 8760 Grid Model: Methodology and Overview

NOTE: This appendix includes only the introduction from a separate methodology paper that presents detailed methods and mathematical formulas for the China 8760 Grid Model. The latest hour-by-hour version of the methodology has been published and is available online at www.etransition.org.

Assessing the Future

The authors developed the China 8760 Grid Model as a combined econometric and engineering model for assessing the costs and benefits of the Chinese electric power system under various scenarios. It simulates hour-by-hour power supply and demand from the present through 2050. It is capable of accurately reproducing actual supply and demand behavior for 2011 based on analyses of power consumption and economic conditions based on the past two decades.[71]

A valid modeling scenario and 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.[72] 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.[73]

Because not all pertinent information is publicly available in China, we also created and recreated data sets on which we could base our modeling. Our goal fortunately was made simpler by the support of the State Electricity Regulatory Commission (SERC). SERC's academic advisors provided key data, advice, and insights. We supplemented official and published data with our own original econometric research, particularly for understanding power sector demand-side behavior.[74]

The China 8760 Grid Model is based on a set of interlocking spreadsheets. This format enables ready access by a wide set of potential users and reviewers. In this way, we hope that our model will serve the community in conducting systematic and reproducible evaluations of electric power policies and technological choices in China.

The model can test policies involving economic behavior or regulatory policies or both. It handles complex technical and end-use detail, and it allows the user to choose a variety of assumptions for economic and planning factors. The model can be used by anyone with a basic understanding of the electric sector to make projections in five-year increments and cost estimates to the year 2050. Although it is a long-term projection tool, it is capable of handling daily and annual power demand and supply variations.

Overview of the Model

The China 8760 Grid Model includes over 100 variables and many thousands of functions or equations. Key variables include: electric power prices (base load and peak); price and GDP elasticities of demand; GDP and income growth; structural change (industry to services); carbon tax (if any); power supply cost for 16 different technologies; and efficiency costs and effectiveness for lighting, air conditioning, water heating, and industrial energy conservation. The model takes account of several additional factors, including: technological change (for each of 16 supply options); capacity factor (for each of 16 supply options); supply and demand balance; a power generating capacity selection (process) model; transmission grid costs; transmission grid geography; transmission grid land-use requirements; and load shifting and smart-load management options. To create a realistic model of how the power sector works, we compiled unpublished and generally unavailable power sector data and conducted original econometric research to estimate power sector demand-side behavior. The model can be used by anyone with a basic understanding of spreadsheets and the electric sector to make demand and supply projections and to estimate overall costs to the year 2050.

The model produces three types of results: costs; emissions; and capacity installed and power generated by supply option.[75] Each scenario result may be compared and contrasted with other scenarios to evaluate the effect of various assumptions or sets of assumptions. The results for costs (total cost of power generation and delivery including capital cost, operation and maintenance, fuel cost [if any], and transmission cost [if any]), for example, are generated according to the following logic:

1. Power demand growth is projected using log-linear Cobb-Douglas-style equation-related assumptions for GDP growth—the main driver—as well as power price and the share of GDP generated by services. Coefficients determine the response of the model to assumptions for GDP growth, price changes, and growth in the share of GDP provided by services.
2. Power demand growth in turn is used to drive changes in hourly demand load and power generating capacity requirements. Assumptions and equations relate GDP to hourly load based on historical load curves and random simulation.
3. Power generating capacity requirements drive a process model that chooses among a dozen power supply options. The process chooses options based on whether renewables are required under a selected scenario. Mandated additions or closures of power generating capacity as well as retirement of obsolete equipment are included in this process.
4. The model next checks whether supplied capacity meets demand load each hour. If not, capacity (or, if chosen as an option, storage) is added to supply the load shortage.
5. Power capacity and generation by each supply option selected in step 3 then drive a transmission construction and cost module. Transmission line locations are associated with location of supply options and demand centers. The module thus estimates the route and cost of the indicated transmission line requirements.
6. A set of load-shifting equations may be used to modify peak and base load demand, with assumptions chosen for the cost and effectiveness of the load-shifting options. For example, storage or peak load pricing may be used to change required system total generating capacity and the distribution over time of power demand.
7. A number of conservation options—driven in part by growing GDP (which is related to the amounts of residential and commercial floor space and the numbers of devices providing light, cooling, and warm water) and changing population totals—can be selected by assumption and used to reduce overall demand as well as make reductions in peak demand.[76]
8. After conservation and peak load reduction measures have been implemented and used to adjust overall power demand, capacity, and generating requirements, overall costs, emissions, capacity, and generation by option type are tabulated.

The functions and algorithms used and inter-linked in the China 8760 Grid Model for incorporating variables, assumptions, and relationships are described in some detail in this methodology paper.

NOTES AND REFERENCES

[1] An excellent assessment of the penetration potential for renewable energy for all energy carriers and not just electricity has been conducted by Jiang Kejun of the Energy Research Institute. For a recent update on his work, see, for example, Jiang Kejun, “Energy Transition in China in a 2 Degree Global Target,” presented at the International Energy Workshop, Paris, 19–21 June 2013 (www.internationalenergyworkshop.org). An advantage of the China 8760 model is its incorporation of an hour-by-hour load curve that permits testing of supply and demand balances for variable electricity sources.

[2] Entri named the model to emphasize the fact that it incorporates data on China’s electricity load curve, which enhances its ability to balance electricity supply and demand during each of the 8760 hours in a year.

[3] We qualify our conclusion because while our analysis did assess the probability that variable renewable sources could satisfy daily peak and off-peak power loads, our analysis did not include an assessment of how well the Chinese grid would be able to manage power quality (voltage-amperage reactivity). Technical demonstrations of power quality management with renewables providing more than 30 percent of total demand are too few and modest in scope to allow evaluation at the present time. See Hannele Holttinen, “Task 25: Power Systems With Large Amounts of Wind, Power,” International Energy Agency, IEA Wind, 2012 Annual Report, p. 2.

[4] See Hannele Holttinen, “Task 25: Power Systems With Large Amounts of Wind, Power,” International Energy Agency, IEA Wind, 2012 Annual Report, p. 2.

[5] *Renewable Electricity Futures Study (Entire Report)*, National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory.

[6] Entri defines “proven technology” as technology in common use that is known to be effective when properly operated and maintained. The China 8760 Grid Model does not incorporate unproven technology.

[7] The China 8760 Grid Model can be used under arrangement with Entri. Please contact China8760@etransition.org.

[8] For an example of this approach, see Cristina L. Archer and Mark Z. Jacobson, “Supplying Baseload Power and Reducing Transmission Requirements by Interconnecting Wind Farms,” *Journal of Applied Meteorology and Climate*, Vol. 46, November 2007, pp. 1701–1717.

[9] William Chandler, Chen Shiping, Holly Gwin, Lin Ruosida, Wang Yanjia, “The China Electric Power Grid Model: Methodology and Overview,” Entri, 20 September 2013.

[10] *Energy Subsidy Reform: Lessons and Implications*, International Monetary Fund, January 2013.

[11] This figure is adjusted for purchasing power parity. All dollar values (except as indicated in the appendices) are converted to 2013 levels. To convert year 2013 dollars to RMB, multiply by 6.1, the average exchange rate in the first half of 2013.

[12] The target as stated here is measured in terms of share of GDP stated in constant RMB values.

[13] We assume in the Baseline scenario that during the period covered by the next Five-Year Plan the Chinese government still intends to try to sustain rapid GDP growth (~7 percent per year) by stimulating more investment. But this growth cannot be sustained after 2020, and the growth rate will drop continuously. We assume in the High Efficiency case that rapid structural change will slow growth slightly, but will accelerate growth in the long run.

[14] Although China’s population is large, it is not expected to grow or shrink markedly during the time periods in the model, and has very little impact on model results. Population figures are included mainly to enable per capita results for comparison purposes. Population data for 2011 come from the National Statistical Bureau, “China Statistical Yearbook 2012,” 2013, Beijing; and Population Reference Bureau, “World Population Data Sheet 2011,” 2012, www.prb.org. For a comparison of population projections to 2050, most of which show a slight decline in total population assuming continuation of current trends, see Peng Xizhe, “China’s Demographic History and Future Challenges,” *Science*, 333, pg. 581, 2011.

[15] Jiang Kejun, Energy Research Institute, National Development and Reform Commission, personal communication, March 2012.

[16] Conversion from base year dollars (generally year 2005 constant US dollars) to mid-year 2013 values were done using the GDP deflator values originally provided by the US Department of Labor, Bureau of Economic Analysis (BEA) from www.bea.gov. During the US government shutdown these data were not available directly from the BEA but were used as reported by the St. Louis Federal Reserve Bank (see http://research.stlouisfed.org). The 2013 dollars were benchmarked to April values.

[17] Based on regression analysis by the authors.

[18] Based on regression analysis by the authors.

[19] All carbon dioxide emissions units in the text are presented as units of carbon dioxide. To convert carbon dioxide emissions values to carbon, divide by 3.66.

[20] The test of whether renewables can satisfy demand adequately is based not only on the condition of meeting total electric energy demand over a yearly period but also on meeting *hourly* capacity requirements. Our test requires that renewables satisfy the hourly load curve, based on year 2011 diurnal and annual variation and projected to each hour in each future year through 2050. Load shedding is permitted but if more than 100 hours per year of shedding of more than 100 GW per hour are required, then "renewables" is concluded to have failed the adequacy test.

[21] The discount rate used here represents the opportunity cost of money based on our best judgment and a considerable volume of economic research literature. See, for example, Nicholas R. Lardy, "Financial Repression in China," Peterson Institute for International Economics. Lardy argues that interest rates in recent years have been artificially suppressed resulting in a real return on deposits of as much as a negative seven percent in 2008. For a discussion on financial returns and clean energy investing, see William Chandler, Holly Gwin, and Chen Shiping, "Financing Energy Efficiency in China: 2011 Update," Energy Transition Research Institute, www.etransition.org, 2011. The authors noted that the hurdle rate required by foreign investors in the clean energy sector often exceeded 20 percent and that in the industrial sector in China, enterprises often require a hurdle rate of 50 percent.

[22] 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《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.

[23] 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.

[24] 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).

[25] Jiang Kejun, Energy Research Institute, National Development and Reform Commission, personal communication, 22 August 2013.

[26] See, generally, 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.

[27] Gao Hu, Center for Renewable Energy Development, Energy Research Institute, Beijing, personal communication, 22 August 2013.

[28] We use the term "dispatchable load" to encompass a range of technologies that enable an electric power provider to reduce or shift demand on the system selectively and predictably.

[29] This assumes spacing of 9-by-7 turbine diameters and average turbine diameter of 80 meters. While the space "occupied" would not be covered over, the "wildlife avoidance" impact or the noise and visual pollution impact of such a massive deployment of industrial machines is difficult to test or predict.

[30] Michael B. McElroy, Xi Lu, Chris P. Nielsen, Yuxuan Wang, "Potential for Wind-Generated Electricity in China," *Science* 325, 1378 (2009)

[31] The goal for electric vehicles was announced in《国务院关于印发节能与新能源汽车产业发展规划》People's Republic of China, State Council, "On the issuance of energy-saving and new energy vehicles industry development plan (2012–2020)," 28 June 2012, Recovered November 2013, http://www.gov.cn/zwgk/2012-07/09/content_2179032.htm.

[32] Patrick Looney, Chair, Sustainable Energy Department, Brookhaven National Laboratory, personal communication, 22 July 2013.

[33] Yu Yanshan, Director, Policy Department, State Electricity Regulatory Commission, personal communication, 7 January 2012. See also, for example, Zhong Lihua, Zhou Shaoyi, Li Yong and Zhang Yuping, Guangxi Electrical Network Power Load Change Characteristic and Temperature Relations and Its Forecast, *Journal of Meteorological Research and Application*, Vol.28 No.1; and Chen Wei, Zhou Feng, Han Xinyang and Shan Baoguo, "Analysis on Load Characteristics of State Grid," *Electric Power Technologic Economics*, Vol.20 No.4, 2008.

[34] Note, however, that we permit "load shedding" of up to 100 GW for as many as 100 hours per year. That limit was not exceeded in any of the scenarios.

[35] The lower use of nuclear power and natural gas in the Low-Carbon Mix and High Renewables cases is due to the assumption that the Chinese central government does not mandate use of those sources in the near term.

[36] Result for the ratio of electric power demand growth to GDP growth deriving from our scenarios are presented in Appendix II. Please note that the GDP elasticity does not itself change in the basic econometric function that drives the model. That coefficient, which can be thought of as a "partial elasticity," is the percent change in power demand for every percent change in GDP *if all other factors are held constant*. In the overall model, of course, the demand side as well as supply side efficiencies are changing in response to exogenous regulatory policy (where specified) and endogenous (cost result) or exogenous price effects (such as from a carbon tax). This effect is illustrated in the following table:

Estimating Total GDP Elasticity

Power demand growth due solely to 1% GDP growth:	+ 1.24 %
Power demand growth due solely to 1% *service* GDP growth:	– 0.58 %
Power demand growth due to 1% power price increase:	– 0.21 %
Combined effect in 2011 of GDP, services, and price effects:	+ 1.15

So, while the GDP *partial* elasticity is 1.24, the overall *total* elasticity is 1.15 today.

Note that the long-term *total* elasticity for China for this study is only 0.7, which would be unprecedentedly low. Note that in Japan, Korea, and Germany in the most recent year for which data are available, the total elasticity was 1.4, 1.8, and 0.65, respectively. Data sources include official Japanese statistics (www.stat.go.jp), the World Bank and, for Germany, http://epp.eurostat.ec.europa.eu. See also *World Development Indicators*, World Bank.

[37] "Stranded costs" (plants shut down before their useful life has ended) could become an issue in this scenario. But in fact all of the coal-fired plants closed after 2040 will have been operated for at least 20 years, and others the assumed financial lifetime of 30 years for coal-fired plants. The lifetimes assumed for all major supply systems are provided in Appendix I.

[38] See Wayne J. Graham, "A Procedure for Estimating Loss of Life Caused by Dam Failure," US 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. And 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.

[39] 12th Five-Year Comprehensive Work Plan for Energy Conservation and Emission Reduction, 国务院关于印发"十二五"节能减排综合性工作方案的通知，国发，2011, 26 号http://www.gov.cn/zwgk/2011-09/07/content_1941731.htm.

[40] DSM Administrative Measures, 国家发展和改革委员会［等5个部门］，关于印发《电力需求侧管理办法》的通知，发改运行（2010）2643号http://www.sdpc.gov.cn/zcfb/zcfbtz/2010tz/t20101116_380549.htm.

[41] Interim Carbon Trading Regulations, 国家发展改革委关于印发《温室气体自愿减排交易管理暂行办法》发改气候（2012）1668号http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2894.pdf.

[42] Early reports from China's first carbon market, in Shenzhen, have not been favorable. The problem appears to be that caps on carbon emissions were set so high they created a lot of sellers and few buyers. See, for instance: China Carbon Permits Exceeding EU Prices, *ClimateWire*, 22 August 2013, http://www.eenews.net.climatewire/stories/1059986303; "The Cap Doesn't Fit," *The Economist*, 19 June 2013, http://www.economist.com/blogs/analects/2013/06/carbon-emissions; "China Carbon Permits Trade 22% Below Europe on Market Debut," *Bloomberg*, 18 June 2013; http://www.bloomberg.com/news/2013-06-18/china-carbon-permits-trade-22-below-europe-s-on-market-debut.html.

[43] "Medium and Long-term Development Plan for Renewable Energy in China," National Development and Reform Commission, September 2007; http://www.chinaenvironmentallaw.com/wp-content/uploads/2008/04/medium-and-long-term-development-plan-for-renewable-energy.pdf.

[44] "The Renewable Energy Law of the People's Republic of China," enacted 2005 and amended 2009; http://www.npc.gov.cn/ englishnpc/Special/CombatingClimateChange/2009-08/25/content_1515301.htm.

[45] For an overview of these policies, see Li Yanfang and Cao Wei, "Framework of Laws and Policies on Renewable Energy and Relevant Systems in China Under the Background of Climate Change," *Vermont Journal of Environmental Law*, Vol. 13, 2012, pp. 823–863.

[46] Administrative Measures on Energy-Saving Dispatch (for Trial Implementation), 节能发电调度办法实施细则（试行）（2007）53号; http://www.gov.cn/zwgk/2007-08/07/content_708486.htm.

[47] Conventional power generators build plants in the hope or expectation that they will be able to sell power on a predictable basis. But when variable sources are available and regulations require that the grid take power first from the variable sources and only then from the conventional sources, the latter experience higher costs and lower profits. That in turn results in political opposition to the construction of and preference for variable sources. In China, the conventional power generators are large, state-owned companies. With their size and revenues comes considerable political influence, which may put smaller, sometimes private, often start-up companies at a disadvantage.

[48] For an overview of China's power sector, see *China's Power Sector: A Backgrounder for International Regulators and Policy Advisors*, Regulatory Assistance Project, February 2008.

[49] The closure of the State Electric Regulatory Commission was announced in March 2013. See, "Energy Mix Adjustment Among Challenges for New Head," *China Daily*, March 20, 2013. The future of electric power regulation in China remains uncertain as we go to press.

[50] William Chandler et al., China Power: Benefits and Costs of the "Strong, Smart Grid," Energy Transition Research Institute, May 2012; China's Power Sector Reforms: Where to Next, International Energy Agency, 2006.

[51] See《国务院关于印发大气污染防治行动计划的通知》(State Council Issued Notice of Action Plan for Air Pollution and Control), 9 September 2013, Beijing. Retrieved from http://news.xinhuanet.com/english/china/2013-09/12/c_132715799.htm. See also《环保部细化京津冀鲁控煤目标 火电厂西迁趋势明显》(Ministry of Environmental Protection policy to control electric power plants in Beijing, Tianjin, Hebei, and Shandong shows clear intention to shift coal to the west), retrieved from http://news.cnfol.com/130923/101,1277,16018241,00.shtml, October 2013 (Fujian Gold Online, 23 September 2013).

[52] See, for example, National Renewable Energy Laboratory, *Renewable Electricity Futures Study*, Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory; http://www.nrel.gov/analysis/re_futures/, 2012.

[53] We are aware that China has faced criticism and legal action—as have other countries—for non-competitive use of equipment standards in violation of World Trade Organization (WTO) agreements. However, process efficiency standards in industrial production are not subject to WTO regulation. Coordination of international standards setting for consumer equipment would, however, be necessary to avoid trade conflicts.

[54] State Grid Corporation first introduced its vision for a "strong, smart grid" in 2009 at a conference on ultra-high voltage power transmission and has since focused its "smart grid" efforts almost exclusively on construction of an ultra-high voltage transmission network. State Grid's published plans barely acknowledge the potential role of the consumer in the electricity demand or supply chain. For more detail see, Chandler *op. cit.*, China Power: Benefits and Costs of the "Strong, Smart Grid," at www.etransition.org.

[55] John Plunkett, Frederick Weston, and David Crossley, "Government Oversight of Grid Company Demand-Side Management Activities in China: Recommendations From International Experience," Regulatory Assistance Project, September 2012.

[56] We base this conclusion on model runs designed to test the effect of different levels of a carbon tax. A tax of US$40 (250 RMB) per ton of carbon is the minimum level required to make coal more expensive than other power generating sources by 2025.

[57] We understand that both income and price elasticities of demand can and do change over time at different levels of income and different levels of prices. Elasticity, rather than being fixed by some economic law, can vary in response to education levels, public information campaigns, increasing leisure time, and disposable income. We chose to use constant elasticities in estimating future demand, however, partly because we cannot guess how these measures of behavior will change, and mainly because we wanted to be explicit about changes in behavior and technology that could make big differences in demand. Therefore, the econometric equation that relates future income and prices to demand and price response is simply the first step in estimating demand and demand response. A demand curve is first estimated in that initial step and then deflected up or down by changes in economic structure, technology, regulatory policy, and saturation of demand. We make those changes explicitly in the model and try to report them to model users in our detailed report on methodology. See William Chandler, Chen Shiping, Holly Gwin, Lin Ruosida, Wang Yanjia, "The China Electric Power Grid Model: Methodology and Overview," Entri, 30 September 2013.

[58] For details on the Clean Air Act carbon standard, see http://www.epa.gov/climatechange/EPAactivities/regulatory-initiatives.html.

[59]《9月11日，国务院公布大气污染防治新方案，部署能源结构调整》State Council on 11 September 2013 Announced New Scheme of Air Pollution and Control," www.sina.com, 12 September 2013.

[60] See, for example, Asian Development Bank, *Asian Development Outlook 2013: Asia's Energy Challenge*, Manila, Philippines, 2013, www.adb.org.

[61] "Huge Waste of Wind-Generated Electricity in 2011, Research Finds," *Caixin*, April 12, 2102, http://english.caixin.com/print/print_en.jsp.

[62] See, for example, *China Set to Subsidize Renewable Energy*, China.org.cn, December 20, 2012, http://www.china.org.cn/business/2012-12/20/content_27467852.htm, *China Set to Pay Renewable-Power Subsidies After Two-Year Delay*, Bloomberg News, 4 December 2012, http://www.bloomberg.com/news/print/2012-12-04/china-set-to.

[63] The Beijing municipal government has long discussed but never implemented such a tariff scheme.

[64] Note that large industrial consumers already pay a demand charge.

[65] Peaking gas-fired or pumped hydroelectric capacity in China would cost at least US$1,000 per kilowatt installed, so that a total of 80 GW of peaking capacity would add at least US$80 billion in capital costs.

[66] See, for example, Xiaochun Zhang and John E. Parsons, "Market Power and Electricity Market Reform in Northeast China," Center for Energy and Environmental Policy Research, January 2008; Russell Pitman and Vanessa Yanhua Zhang, "Electricity Restructuring in China: The Elusive Quest for Competition," Economic Analysis Group Discussion Paper, April 2008.

[67] "Smog, Poor Management, Dim Clean Energy Prospects for China's Buildings," *ClimateWire*, 21 August 2013, http://www.eenews.net/ climatewire/stories/1059986258.

[68] Yuhong Zhao, "Assessing the Environmental Impact of Projects: A Critique of the EIA Legal Regime in China," *Natural Resources Journal*, Vol. 49, Spring 2009, pp. 485–524.

[69] Allison Cameron, Vermont Law School, and Luo Wei, Renmin University School of Law, " An Environmental Impact Assessment for Hydropower Development in China," 2012.

[70] Sub-critical coal plants amounted to roughly 200 GW in 2011 but coal-fired generation in this study was modeled as a single type. That slightly understates the amount of carbon generated by coal in 2011 but does not affect emissions after 2025. This was done for all scenarios.

[71] This paper on the methodology of the China 8760 Grid Model builds on an earlier model that provided annual results. See William Chandler, Chen Shiping, Holly Gwin, Wang Yanjia, "The China Electric Power Grid Model: Methodology and Overview," Energy Transition Research Institute, www.etransition.org, 2012.

[72] Previous studies do exist, however, and one noteworthy example includes 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.

[73] For excellent studies of smart grid technologies and their impacts, see R.G. Pratt, P.J. Balducci, C. Gerkensmeyer, S. Katipamula, M.C.W. Kintner-Meyer, T.F. Sanquist, K.P. Schneider, and T.J. Secrest, "The Smart Grid: An Estimation of the Energy and CO_2 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.

[74] 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, 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 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 5 March 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, 8 December 2002.

[75] Advocates sometimes use statistics to advocate for more subsidies for wind and other renewable energy sources using only power capacity (megawatts, for example) figures and do not mention capacity factor or availability (megawatt-hours, for example). Readers may be confused by comparison of megawatts of supply options that vary in availability by a factor of up to six times. See, for example, Li Junfeng and Ma Lingjuan, Wang Shannon, Yu Wuming, Lu Fang, Qin Shiping, Liu Xin, Tong Jiandong Tong, "Recommendations for Improving the Effectiveness of Renewable Energy Policies in China," published by REN21 Secretariat Gesellschaft für Technische Zusammenarbeit GmbH and United Nations Environment Programme, October 2009.

[76] Chinese population forecasts were taken from summary report of *World Population Prospects* (2011 revision), United Nations, see http://www.prb.org/pdf11/ 2011 population-data-sheet_eng.pdf. For one example in recent years of unusually strong 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. Also, see PENG, *op. cit.*

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